SAFETY & TRANSPORT

FIRE RESEARCH

proFLASH: Methanol fire detection and extinguishment

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Abstract

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Stricter emission requirements have led to ship operation on low flashpoint fuels, such as liquefied natural gas and methanol. These differ in many ways from traditional fuels (e.g. heavy fuel oil and marine gas oil), but requirements and guidelines for fire detection and extinguishment have been sparse. This was addressed in the proFLASH project, first theoretically and then experimentally. This report documents the experimental part of the project, focusing on methanol, and gives technical guidance for fire detection and extinguishing systems. It was for example concluded that methanol flames exhibit similar radiation to ethanol in the IR spectrum, despite limited observability in the visual spectrum. Approved IR flame detectors (tested against ethanol) are thereby likely suitable to detect methanol fire; tested detectors could even detect fully obstructed methanol fire. The design concentration of carbon dioxide gas fire-extinguishing systems should be increased from 40 % to 55 % to achieve the same safety margin for methanol as for traditional fuels. The primary extinguishing mechanism of a water-based fire-extinguishing system used against methanol is dilution, but almost 90 % water may be necessary for extinguishment. Furthermore, dilution makes the methanol flames increasingly invisible. It is recommended to use alcohol resistant foam injection with fixed water-based extinguishing systems, since this significantly reduces the time required for extinguishment. The effectiveness of the system depends on the foam/water application rate. Hence, a higher discharge rate is more effective and a concealed pool is difficult to extinguish. In different compartment fire test scenarios, water-spray with foam injection was more effective against methanol than water-spray without foam against standardized fuels. High and low pressure water mist performed better than water spray against standardized fuels but worse against methanol (with foam injection).

Key words: Methanol, extinguishment, detection, flashpoint, water, machinery space.

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Content

Acknowledgments

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Summary

Stricter emission requirements imply that ships will increasingly operate on alternative fuels with a low flashpoint, such as liquefied natural gas and methanol. However, requirements and guidelines from the International Maritime Organization for the design of fire detection and extinguishing systems for such fuels have been sparse. The proFLASH project aimed to address this need, initially by a review of the fuel properties and a theoretical investigation of how they can affect detection and extinguishment. A literature study was also made of relevant regulations and class rules and conclusions were made regarding the needs for fire testing. This concluded phase 1 of the project, reported by Blomqvist, Evegren, Willstrand, and Arvidson (2015). Phase 2 of the project is documented in this report and was experimental, focusing on characterization of methanol fire, detection, and extinguishment. Five test series were performed and the test reports are appended.

The tests confirmed that methanol burns with clean combustion (no soot) and with a relatively low heat release rate (1/3 compared to diesel and 1/5 compared to gasoline). The flames are weakly blue and almost invisible in daylight. Methanol is soluble in water, but both the heat release rate and the visibility of flames reduce with increased water content.

Despite the limited visibility of methanol flames, they exhibit similar radiation to ethanol in the IR spectrum. Approved IR flame detectors, tested against ethanol, are thereby likely also suitable to detect methanol fire; tested detectors could even detect fully obstructed methanol fire. However, there are also other types of flame detectors which are generally not suitable, e.g. visual detectors.

Prescriptive gas fire-extinguishing systems (carbon dioxide) in ship machinery spaces are required to have a design concentration of 40 %, while diesel is extinguished at about 20 %. To achieve the same safety margin (100 %) with methanol, a design concentration of 55 % is recommended. According to regulations, alternative agents are only required to have a safety margin of 20 %, against heptane, based on that full scale verification tests are performed. This approach can also be recommended for methanol, for carbon dioxide as well as for alternative agents.

When using water-based extinguishing systems on methanol, vaporization of water is limited due to the low heat release rate. Combustion will likely continue until the fuel has been sufficiently diluted (reducing the fuel vaporization rate), which may not occur until the water content is almost 90 % (at this stage, flames are completely invisible). To achieve quicker extinguishment of methanol with water-based extinguishing systems, it is recommended to inject alcohol resistant foam, which impedes radiation to the surface and blocks vaporized fuel. The effectiveness of the system depends on the foam/water application rate. Hence, a higher discharge rate is more effective and a concealed pool is difficult to extinguish. In different performed pool fire tests and standardized compartment fire scenarios (high pressure spray, concealed pool, wood crib in pool, and bilge pool), water-spray with foam injection was more effective against methanol than prescriptive water-spray (without foam) against standardized fuels. High and low pressure water mist performed better than water spray against standardized fuels but worse against methanol (with foam injection).

Sammanfattning (Swedish summary)

Striktare utsläppskrav innebär att fartyg i allt större utsträckning kommer att drivas på alternativa bränslen med låg flampunkt, såsom exempelvis flytande naturgas och metanol. Krav och riktlinjer från International Maritime Organization för design av branddetektions- och släcksystem för denna typ av bränslen har dock varit begränsade. ProFLASH-projektet syftade till att adressera detta behov, initialt genom en granskning av bränsleegenskaperna och en teoretisk utredning av hur dessa kan påverka detektion och släckning. En litteraturstudie gjordes också av relevanta regelverk och slutsatser drogs avseende behov av brandförsök. Detta avslutade fas 1 av projektet, rapporterat av Blomqvist et al. (2015). Fas 2 av projektet dokumenteras i denna rapport och var experimentell, med inriktning på karakterisering av metanolbrand, detektion och släckning. Fem testserier genomfördes och testrapporterna finns bifogade.

Brandförsöken bekräftade att metanol brinner med ren förbränning (ingen sot) och med relativt låg värmeeffekt (1/3 jämfört med diesel och 1/5 jämfört med bensin). Flammorna är svagt blåa och nästan osynliga i dagsljus. Metanol är lösligt i vatten, men såväl värmeeffekten som flammornas synlighet minskar med ökad vattenhalt.

Trots den begränsade synligheten av metanolflammor uppvisar de liknande strålning som etanol i IR-spektrumet. Godkända IR-flamdetektorer, testade mot etanol, är därmed sannolikt också lämpliga för att detektera metanolbrand; de testade detektorerna kunde till och med detektera helt dolda metanolbränder. Emellertid finns det också andra typer av flamdetektorer som i allmänhet inte är lämpliga, såsom visuella detektorer.

Föreskrivna gas-brandsläckningssystem (koldioxid) i fartygsmaskinrum måste ha en designkoncentration på 40 %, medan diesel släcks vid ca 20 %. För att uppnå samma säkerhetsmarginal (100 %) med metanol rekommenderas en designkoncentration på 55 %. Enligt gällande krävs för alternativa släckgaser endast en säkerhetsmarginal på 20 %, mot heptan, baserat på att fullskaliga verifieringsförsök utförs. Denna approach kan också rekommenderas för metanol, oavsett användning av koldioxid eller alternativa släckgaser.

Vid användning av vattenbaserade släcksystem mot metanol så är förångning av vatten begränsad, på grund av den låga värmeeffekten. Förbränningen fortsätter sannolikt därför tills bränslet är tillräckligt utspätt (minskar bränsleförångningen), vilket eventuellt sker förrän vatteninnehållet är nästan 90 % (i detta skede är flammorna helt osynliga). För att uppnå snabbare släckning av metanol med vattenbaserade släcksystem rekommenderas injicering av alkoholbeständigt skum, vilket hindrar strålning mot bränsleytan och blockerar förångat bränsle. Systemets effektivitet beror på skumvattenpåföringshastigheten. Följaktligen är en högre påföringshastighet mer effektiv och en dold pool är svår att släcka. I olika genomförda pölbrandförsök och standardiserade rumsbrandscenarier (högtrycksspray, dold pöl, träribbstapel i pöl och pöl under durk) var vattenspray med skuminjektion effektivare mot metanol än föreskriven vattenspray (utan skum) mot standardiserade bränslen. Hög- och lågtrycksvattendimma presterade i allmänhet bättre än vattenspray mot de traditionella bränslena men sämre mot metanol (med skuminjektion).

1 Introduction

Requirements on sulphur content in bunker fuel are regulated by the MARPOL Convention (International Convention for the Prevention of Pollution from Ships). The 1 January 2015, the requirements for bunker fuels were made stricter for ships operating in so-called SECA areas (Sulphur Emission Control Area), including the Baltic Sea, North Sea, and English Channel. With the new requirements, a maximum of only 0.10 weight percent sulphur is allowed in the fuel. Several more areas may become SECA areas in the future and there are also general reduction plans which will restrict the allowed sulphur content in ships' fuel in any other area to 0.5 weight percent.

The practical implication of the SECA regulations has been to either equip the vessel with an emission cleaning system (scrubber) or to use low-sulphur fuel instead of the traditionally used heavy fuel oil (HFO). The latter includes several alternatives, including low-flashpoint fuels such as methanol and liquefied natural gas (LNG). These fuels are interesting not least since they to some extent can be produced from bio-materials. However, the fuels differ from traditional bunker fuels in many ways, which introduces new risks. One important difference is their low flashpoint, but there are also other differences which affect fire risks. Methanol for example gives a clean fire with flames that can be invisible and has oxygen bound to the molecule (it can burn at relatively low oxygen concentrations). LNG has a very low boiling point and cannot be extinguished with water. Hence, these low-flashpoint fuels have properties which can affect the possibilities for fire detection and extinguishment.

In order for low-flashpoint fuels (LFFs) to be handled in a harmonized and safe way, the International Maritime Organization (IMO) is developing applicable regulations to be incorporated in the so-called IGF Code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels). The primary work is done through a correspondence group (currently led by Sweden) for the sub-committee Carriage of Cargoes and Containers (CCC). The IGF code was formally adopted by the Maritime Safety Committee (MSC) in June 2015. Then the code included regulations for LNG, whilst regulations applicable to methanol are still being developed. The sparse regulations concerning the design of active fire protection systems (detection and extinguishing systems) for LNG and methanol caused formation of the proFLASH project.

The proFLASH project aimed to develop technical guidance for detection and extinguishing systems, to ensure adequate protection against fire involving low-flashpoint fuels; in particular methanol and LNG. The project focused on these fuels since their use was expected to become widespread and because they well represent the challenges of new alternative fuels for active fire protection systems. The project was divided in two phases. Phase 1 was a preliminary study investigating fuel properties and potential hazards as well as limitations of traditional fire protection systems to manage the hazards. Furthermore, different detection and extinguishing system solutions were discussed as well as ways to verify sufficient performance. This worked as basis for phase 2, where different detection and extinguishing systems and conditions were tested, with focus on methanol. Phase 2 included five experimental parts:

1. Minimum extinguishing concentration
2. Pool fire and extinguishment
3. Total compartment fire extinguishment
4. Spectral flame radiation
5. Flame detection

This report summarizes the experimental parts (phase 2) of the proFLASH project and concludes technical guidance for methanol fire detection and extinguishment. The test reports from the five experimental parts are added to this document as annexes:

- Annex A: Minimum extinguishing concentration to extinguish methanol
- Annex B: Methanol pool fire and extinguishment tests
- Annex C: Total compartment fire extinguishing tests with methanol
- Annex D: Spectral radiation measurements of radiation emitted from open pool fires of methanol and other liquid fuels
- Annex E: Methanol flame detection tests

The proFLASH project included the following participants:

– RISE Research Institutes of Sweden	(research institute)
– Swedish Transport Agency	(Flag State)
– Lloyd's Register	(classification society)
– Stena	(ship owner)
– Marinvest	(ship owner)
– ScandiNAOS	(ship designer)
– Tyco	(system supplier)
– Ultrafog	(system supplier)
– Fomtec	(system supplier)
– Consilium	(system supplier)
– Draeger	(system supplier)
– Det-Tronics/Autronica	(system supplier)

The participants funded the project to different degrees with internal resources (in-kind). Furthermore, the project was provided with direct funding by the Swedish Mercantile Marine Foundation (Stiftelsen Sveriges Sjömanshus), the Swedish Maritime Administration (Sjöfartsverket), Stena, Region Västra Götaland, and RISE Research Institutes of Sweden.

2 Methanol fire characteristics

Methanol pool fire tests were performed in the proFLASH project to characterize burning behavior, as reported in *Annex A: Minimum extinguishing concentration to extinguish methanol*. The results have also worked as input to a revision of the fire safety chapter in the 4th edition of the Methanol Safe Handling Manual (Methanol Institute, 2017). The main fire characteristics of methanol are presented below, divided in flammability, heat radiation, mass loss rate, and heat release rate.

2.1 Flammability

A liquid fuel releases vapors depending on its temperature. Methanol has a true vapor pressure of about 100 mm Hg at 20 °C, which means that it releases more vapor than diesel but less than gasoline. It is the vapors that burn in a fire and the flammability of a fuel depends on this tendency to release vapor in combination with the fuel flammability limits. The latter determine between what vapor concentrations the fuel can burn in air. The lower flammability limit of methanol is 6 vol% and the upper flammability limit is 36 vol%. The lower flammability limit in combination with the tendency to release vapor can be translated to the temperature at which sufficient vapor is generated above the liquid surface to enable ignition. This temperature is referred to as the flashpoint and is an important fuel property. If the whole flammability range is translated to temperatures, methanol burns between 11 °C and 41 °C, whilst gasoline burns at -43 to -10 °C and diesel at 60–150 °C. Thereby, methanol in a container is in the flammable range at normal temperatures, whilst gasoline is generally too warm and diesel is generally too cold. However, the upper flammability limit/temperature is only applicable for fuel in a container or compartment. At normal temperatures an open diesel pool is too cold to generate sufficient vapor for ignition, whilst methanol and gasoline are ignitable. Furthermore, if the temperature is far above the flashpoint, much vapor can be generated, which causes the lower flammability limit to be reached far from the fuel pool (particularly likely for gasoline). This can cause a flash fire (explosion).

2.2 Heat radiation

Methanol has a low total heat of combustion of 20 kJ/g (gasoline: 38 kJ/g, diesel: 40 kJ/g, heptane: 41 kJ/g, ethanol: 25 kJ/g) (Methanol Institute, 2011; Morgan et al., 2016). How this heat is transferred is influenced by the fact that methanol is combusted very efficiently. It produces little residual soot particles, which usually make flames luminously yellow. Most flammable liquid fires transfer a large amount of the heat through radiation from the flames. A heptane pool fire, for example, transfers 36 % of the heat by radiation (and the rest by convection, i.e. heating up surrounding gases/air), but methanol only transfers around 17 % of the heat by radiation (Koseki, 1989). Hence, methanol produces less heat and transfers relatively less heat to surroundings by radiation than many liquid fuels, and it only displays weakly blue flames (almost invisible in daylight, as shown on the front page). When exposed to a water-based fire extinguishing system, the flames immediately become suppressed and bright yellow, as illustrated in Figure 1.

Figure 1. Flames from a methanol pool fire, free-burning and exposed to water-mist.

The incident radiation heat flux from methanol pool fires has been measured from small and large pool fires, up to 50 m², which generated the approximation in Figure 2. The largest pool fire showed that the radiation heat flux at a distance of 2 m was about 10 kW/m² [1], which is very low for this size fire (Holmstedt, Ryderman, Carlsson, & Lennmalm, 1980). Diesel emitted 5-7 times more radiation than the same size methanol pool fires at a distance of 2 m. The receding dependence of the heat radiation on pool size implies that a firefighter will be able to approach any size methanol fire, to a certain magnitude, which significantly alleviates fire fighting.

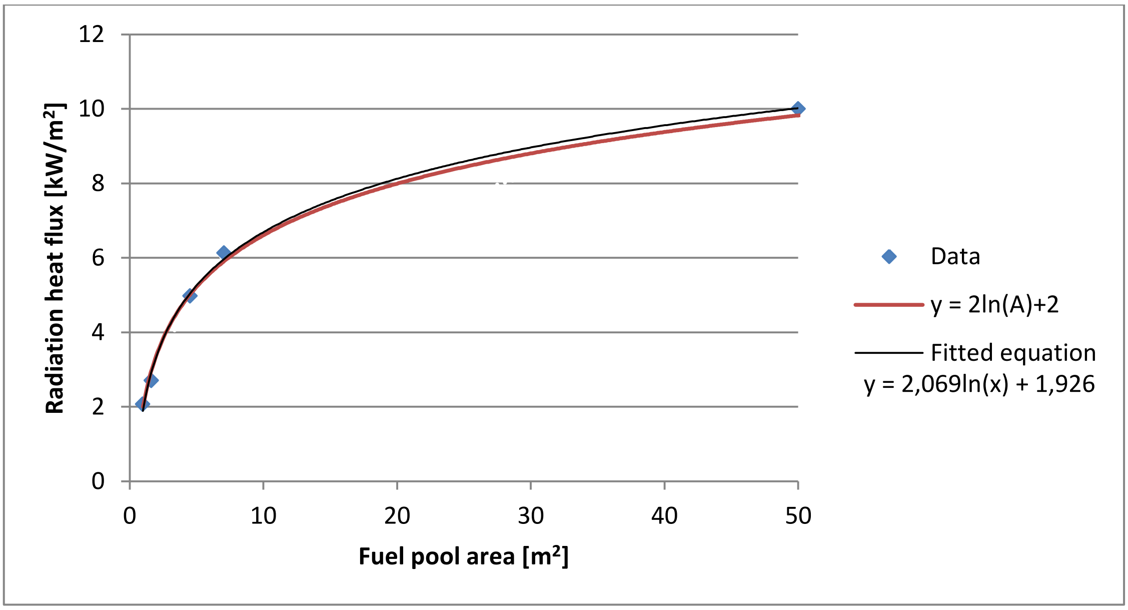

Figure 2. Relation between the methanol pool fire size and the radiation heat flux at 2.0 m.

The heat flux is largely affected by the distance to the object, but also by present smoke. Most fuels burn with smoke, which blocks radiation from the center of the flame and only allows the flame perimeter to radiate. This is often expressed as a decrease in the radiative fraction with the pool size (diameter). For most fuels, the radiative fraction is constant (35-45%) for small pool sizes but decreases rapidly above pool diameters of about 2 m. The decrease is significant and for pool diameters of 20 m the radiative faction is about 5-10%. However, for ethanol, which burns with luminous flames but without much smoke, radiation can be transmitted from the full thickness of the flame

[1] 40 kW/m² results in instantaneous death; 10 kW/m² results in pain after 3 s skin exposure; 5 kw/m² is typically a safe exposure level.

and the radiative fraction is almost independent of fire size (Sjöström, Appel, Amon, & Persson, 2015). This causes a larger radiative heat flux from ethanol than from gasoline in large fires, while the opposite applies in small fires. Hence, extrapolations cannot be made for alcohols (and particularly methanol) in the same way as for other fuels.

2.3 Mass loss rate

The radiation from a fire is important since it affects the potential for fire spread but also since it affects the mass loss rate (vaporization) of the fuel (and hence the heat release rate). Since the average radiation towards the fuel surface increases with the fire size, up to a certain level, the mass loss rate (per unit area) generally increases as well. A wide range of mass loss rates have been proposed for methanol in different sources. Based on the literature and the performed tests it was concluded that the mass loss rate of methanol increases about linearly from about 0.021 kg/m²·s for 1 m² pools to about 0.027 kg/m²·s for 7 m² pools, as illustrated in Figure 3. However, it is not clear to what extent the mass loss rate continues to increase with the pool area for larger pools. Babrauskas (2016) claims that the mass loss rate for methanol (and ethanol) pools larger than 7 m² is 0.029 kg/m²·s at the same time as Holmstedt et al. (1980) measured a mass loss rate of 0.024 kg/m²·s for a 50 m² methanol pool. The mass loss rate for moderately sized methanol pools (1–7 m²) around 0.024 kg/m²s can be compared to mass loss rates of up to 0.036 kg/m²s for diesel, 0.062 kg/m²s for gasoline, and 0.081 kg/m²s for M15 (Holmstedt et al., 1980; Methanol Institute, 2011).

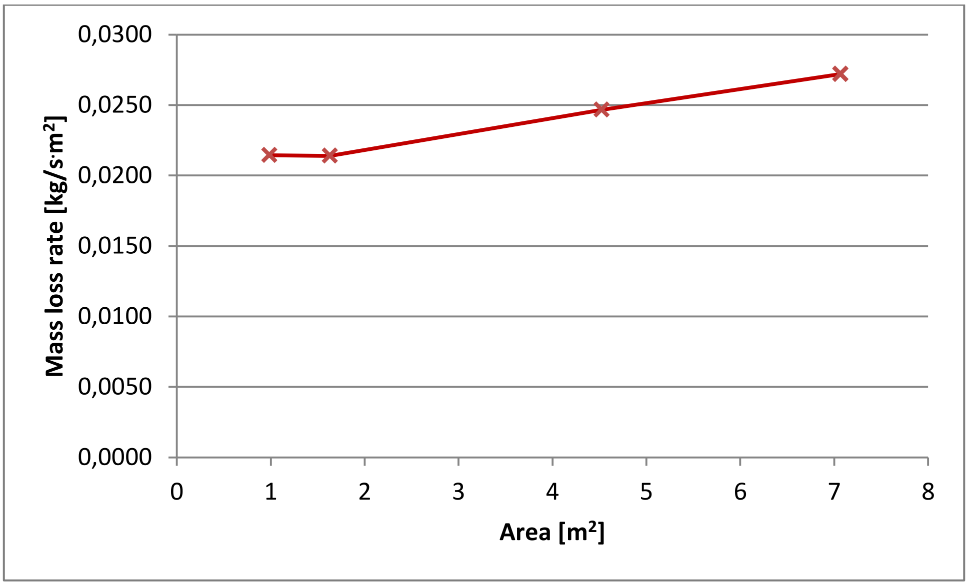

Figure 3. Summarized mass loss rates recorded in the test series.

2.4 Heat release rate

The combustion efficiency of methanol is close to unity (Heskestad, 1981); 96 % is for example stated in ISO 24473 (ISO, 2008) and in the tests an efficiency of 90-99 % was measured. However, the relatively low mass loss rate and total heat of combustion result in a low heat release rate per unit area. For pure methanol, the heat release rate per unit area is 400-500 kW/m², depending on the pool area, as illustrated in Figure 4. It is not known if the heat release rate per unit area continues to increase with the pool area of if it stabilizes or decreases for pool areas above 7 m^2, as discussed above for the mass loss rate. The heat release rate per unit area of methanol is about 1/3 compared to diesel and 1/5 compared to gasoline. Furthermore, the heat release rate is reduced with water content.

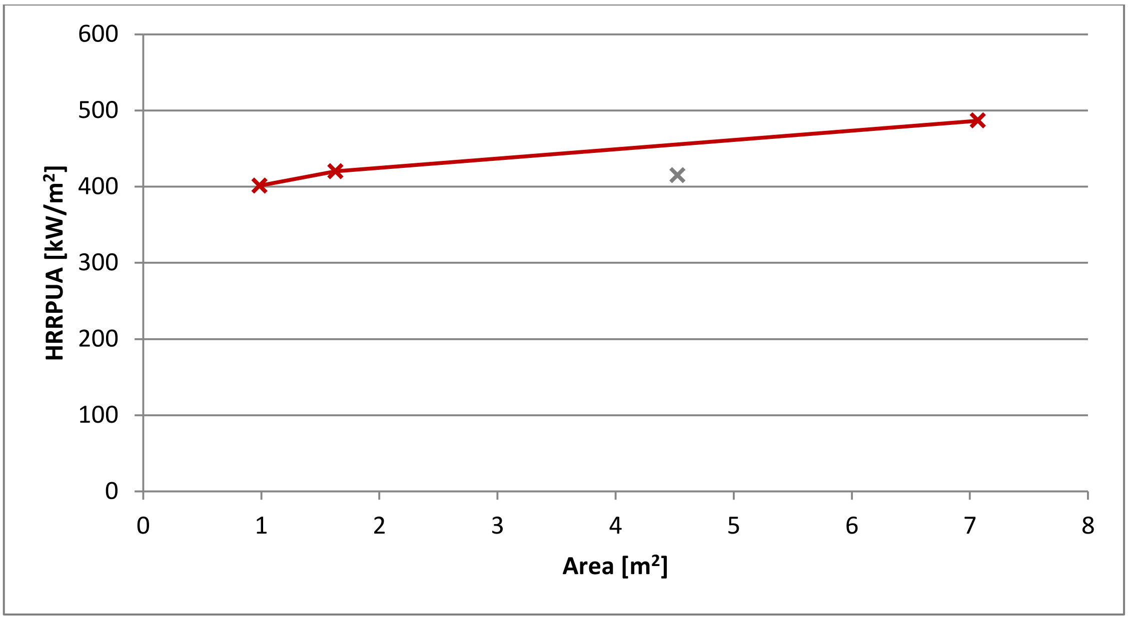

Figure 4. Heat release rate per unit area, calculated from oxygen depletion measurements (one inaccurate measurement was not considered and is marked grey).

3 Methanol fire detection

Flame detectors are often tested against the European standard EN 54-10, 5.5 Fire sensitivity, which includes fire detection tests with n-heptane and methylated spirit (mainly ethanol). The latter represents a non-sooty fire, but methylated spirit flames are characteristically different from methanol flames. Methylated spirit gives off clear yellow flames (but little/no smoke) whilst methanol only displays weakly blue flames, almost invisible in daylight. Fire tests were therefore performed based on EN 54-10 to evaluate differences in the possibilities for fire detection between the fuels with different detectors. Tests were also performed with other fuels (including diluted methanol), with different obstructions, and in other types of scenarios. These tests are presented in *Annex E: Methanol flame detection tests*. Furthermore, the radiation emitted from methanol in comparison to other fuels was characterized by spectral radiation measurements, presented in *Annex D: Spectral radiation measurements of radiation emitted from open pool fires of methanol and other liquid fuels*.

Flame detectors operate by observing changes in radiation at certain narrow spectral bands when different molecules are reformed, such as water (providing radiation absorption around 5-7 µm) and carbon dioxide (providing radiation at 4.3 µm). From Figure 5, presenting spectrometer test measurements, it can be observed that non-sooty methanol flames emit radiation in the carbon dioxide band and that radiation is absorbed in the water band, but little overall blackbody radiation is emitted. Sooty flames, from e.g. diesel, emit much blackbody radiation (reduced by water) and also peak in the carbon dioxide band. Furthermore, the measurements showed that the radiation emitted from burning methanol, ethanol, and methylated spirit is similar in the IR region. Hence, triple-band IR detectors tested with for one of the fuels should likely also be suitable to detect the others. However, it is important that a flame detector for methanol applications analyses the bands corresponding to carbon dioxide and water. It should be noted that all approved flame detectors are not suitable to detect methanol; there are different types and some are not suitable, for example visual detectors.

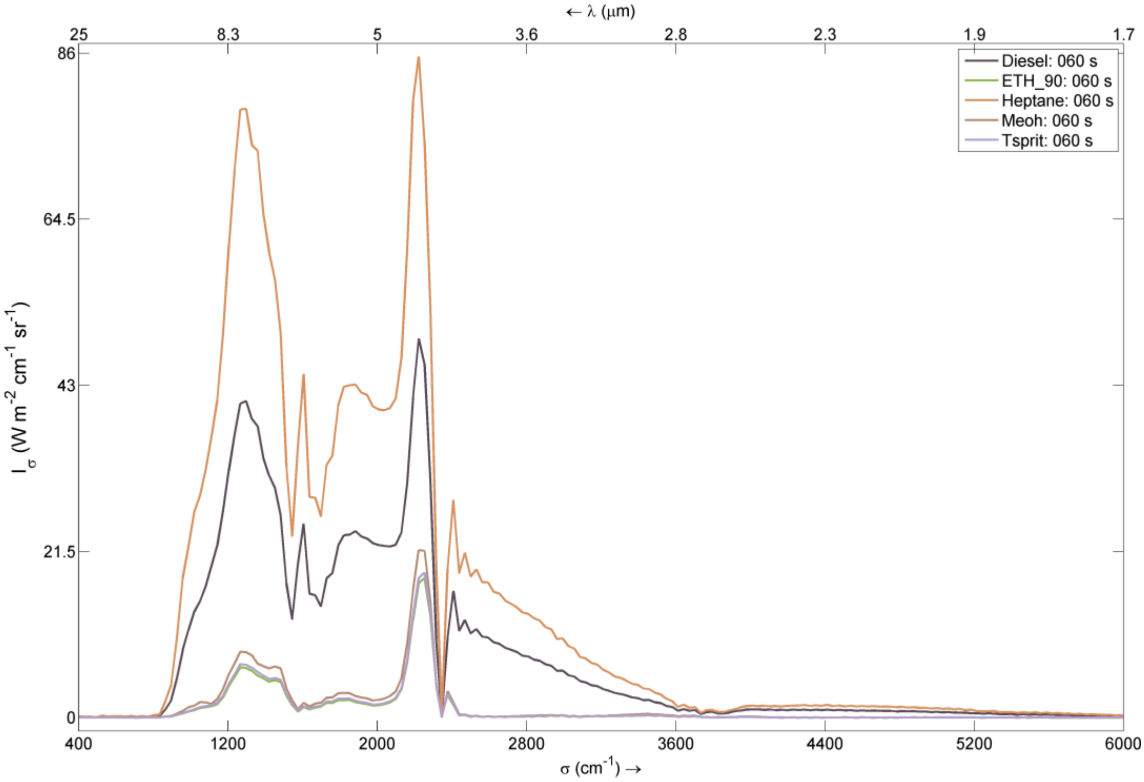

Figure 5. Comparison of spectrally resolved radiation from different fuels (ETH_90 is ethanol, Meoh is methanol, and Tsprit is methylated spirit).

From the detection tests it could be verified that the IR detectors tested with methylated spirit (in accordance with EN 54-10) could easily detect methanol fires. The detectors could even detect methanol fires fully obstructed and when placed behind the detectors. The tests were performed in space with metal surfaces, which on the other hand is typical in typical in machinery spaces. However, it should be noted that the sensitivity setting of detectors is crucial for such elevated detection capacity and needs to be in balance considering the risk of false alarms. None of the detectors indicated (false) alarm with a hot surface set-up, unless modulations were generated. With modulations, generated randomly by waving with solid objects in front of the detectors, some of the detectors indicated an alarm.

The differences in detection times between the tested IR detectors were very small. No significant differences were noted between detection of methanol and detection of other fuels, although slightly longer response times were recorded for diluted methanol. It is possible that such effects on the response time could be relevant also for other fuels (e.g. methylated spirit), since dilution affects the magnitude of radiation. It was also noted that higher background radiation (hot surface in combination with fire) did not affect the response times when the fire was unobstructed. However, for an obstructed fire and high background radiation, the response times are much longer (less radiation from the fire, in comparison to background radiation, reaches the detector).

4 Methanol gas fire extinguishment

As mentioned above, the flammability range of methanol is 6-36 vol%. This can be compared to 1.4–7.6 vol% for gasoline and 1–6 vol% for diesel. The flammability range of methanol is hence relatively high, likely associated with that methanol has oxygen incorporated in the molecule. Methanol can therefore also burn at relatively low oxygen concentrations, down to about 7.6 vol% (about 13-15 vol% is a limit for many fuels) (Osterberg et al., 2015). Hence, methanol can be demanding to extinguish by oxygen depletion, which is a primary extinguishing mechanism of a water-mist fire-extinguishing system. It is also more demanding to extinguish with inert gas fire-extinguishing systems, even if their effectiveness is rather dependent on the heat capacity (and amount) of the used gas (i.e. gas cooling rather than oxygen depletion).

Fixed carbon dioxide gas fire-extinguishing systems in machinery spaces and cargo pump rooms shall have capacity to give a minimum volume of free gas equal to 40 % of the gross volume of the largest space (excluding the casing, or 35 % including the casing) (IMO, 2007). If another inert gas or halogenated agent is desired, the design concentration shall be based on the minimum extinguishing concentration (MEC) of the agent when applied to n-heptane. This is determined by a cup burner test, e.g. specified in Annex B in ISO 14520-1 (ISO, 2006). The design concentration shall be at least 20 % above the MEC (IMO, 1998) and the performance of the system shall be verified by large-scale tests, primarily to verify distribution of the agent (IMO, 1998). The same methodology can be used for methanol applications. The minimum extinguishing concentrations determined from cup burner tests for some extinguishants (including carbon dioxide) applied on methanol were therefore investigated, as presented in *Annex A: Minimum extinguishing concentration to extinguish methanol*. A summary of the results is presented in Table 1.

Table 1. Minimum extinguishing concentrations for different agents applied on methanol

MEC for fuel: *Extinguishant*	***Diesel*** *[vol%]*	***Heptane*** *[vol%]*	***Methanol*** *[vol%]*	*Relation* *(Meth/Hept)*	Meth +20% [vol%]*	Meth +100% [vol%]$^{+}$
Carbon Dioxide	21-23	19.6	27.5	1.40	33.0	55
Nitrogen	no data	33.0	41.0	1.24	49.2	82
Argon	27.0	42.0	52.0	1.24	62.4	(104)
Argonite	26.0	36.5	45.4	1.24	54.5	91
Inergen	35.8	33.8	44.2	1.31	53.0	88
Halon 1301	2.6	2.9	5.9	2.03	7.1	12
FM 200	6.7	5.8	10.0	1.72	12.0	20
NOVEC 1230	4.5	5.9	8.5	1.44	10.2	17

* Recommendable minimum design concentration *with* full scale performance verification.
$^{+}$ Recommendable minimum design concentration *without* full scale performance verification.

From Table 1, the minimum extinguishing concentrations for carbon dioxide to extinguish diesel and heptane are about 20 %. Hence, the required 40 % for prescriptive systems derives a safety margin of 100 %. The same safety margin is recommended for gas fire-extinguishing systems for alternative fuels, such as methanol, if large scale verification is omitted (see values in rightmost column in Table 1). With large scale verification based on MSC/Circ.848, a minimum design concentration corresponding to the minimum extinguishing concentration, with an addition of 20 % can be used (see values next to the rightmost column in Table 1). However, the large scale verification tests based on MSC/Circ.848 should include design fires with the alternative fuel (such as methanol).

5 Water-based fire extinguishment of methanol

Tests have been performed to evaluate the effectiveness of different water-based fire-extinguishing systems, in particular:

- Water spray (prescriptive)
- Water spray with foam injection
- Low pressure water mist
- Low pressure water mist with foam injection
- High pressure water mist
- High pressure water mist with foam injection

The systems were tested in open pool and in compartment fire applications, as documented in *Annex B: Methanol pool fire and extinguishment tests* and *Annex C: Total compartment fire extinguishing tests with methanol*. Below the results are summarized and discussed.

5.1 Extinguishment with water (only)

The methanol open pool fire extinguishing tests, documented in *Annex B: Methanol pool fire and extinguishment tests*, showed that water on its own (mist or spray) has limited effects on a methanol fire. Gas phase (flame) cooling is not very effective since methanol produces relatively little heat (hence, relatively little heat is lost to vaporization of water). The limited vaporization of water further affects the effectiveness of oxygen depletion. Moreover, methanol is already quite insensitive to oxygen depletion since it has oxygen in the molecule (discussed in *Chapter 4. Methanol gas fire extinguishment*). A liquid fuel can also be extinguished by effects to the fuel vaporization rate, for example by direct cooling of the fuel by impinging water, but methanol has such a low flashpoint (11 °C) that this is not very effective. The above limited extinguishing mechanisms reduce the heat release rate to about half (and diminish radiation heat flux to surroundings), but a methanol fire will not be extinguished solely by water, at least not instantly.

In addition to the above extinguishing mechanisms, methanol is fully soluble with water and can be diluted. This gradually further reduces the fuel vaporization rate and will eventually lead to extinguishment of a methanol fire. This occurs when the fuel (at least the surface layers) have reach a water content of almost 90 %. This should not be confused with the flashpoint dependence on water-content, which only determines ignitability. Such tests have shown that a small ignition source can ignite methanol with up about 65 % water at normal room temperature (Nilsson, 2005). However, there is a significant difference between ignitability and to reduce of the fuel vaporization rate of a burning liquid until it no longer supports combustion. Hence, extinguishment by water dilution can require nine times more water than the methanol spill, which can imply a significant reserve and also puts large requirements on management of water runoff, to avoid a running fire. Furthermore, it was observed in the tests that methanol flames become increasingly invisible with water-content. Even though the tests were conducted in an enclosed fire hall with black walls, the flames of well diluted methanol were completely invisible to the naked eye, as illustrated in Figure 6. In the IR camera, the flames were visible with slightly reduced flame height and radiation compared to neat methanol. This hence also adds to the hazards of methanol fire extinguishment. In this regard it can be noted that methanol flames exposed to water spray or mist immediately turn from weakly blue to suppressed bright yellow (see Figure 1). The yellow flames become less bright and visible the more diluted the methanol becomes and will become virtually invisible before extinguishment is achieved. If extinguishment is interrupted while the yellow flames are visible, it is still possible that no weakly blue flames will be visible if the remaining diluted methanol is allowed to burn freely. There is hence a risk to believe that a methanol fire extinguishes when suppression by water mist or spray is interrupted, since the yellow flames disappear and no blue flames will be visible.

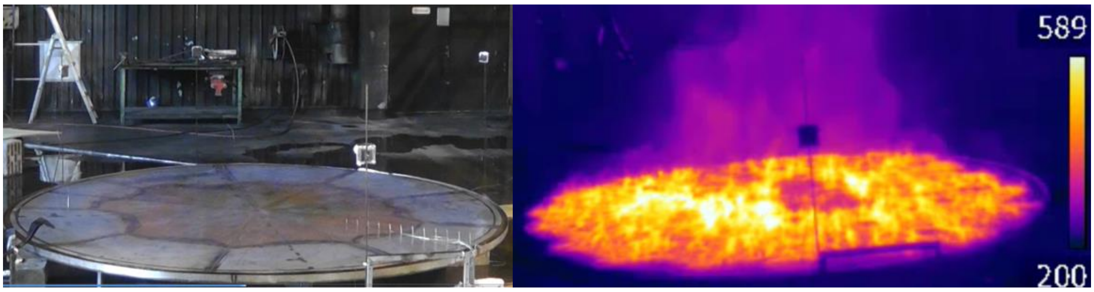

Figure 6. Water diluted methanol fire after interrupted fire extinguishing test, due to runoff risk.

None of the tested water-based fire extinguishing systems extinguished the open methanol pool fires, but they were effectively suppressed the remaining heat was attenuated. The prescriptive water-spraying system (5 l/m²·min) had a slightly better effect. In particular in the long run, since it provided quicker dilution of the methanol and eventual extinguishment. In this regard it should also be noted that neither the prescriptive water-spraying system (5 l/m²·min) nor the water-mist system extinguished the same size (area) diesel fire. On the contrary, they were even less effective on diesel when combusted in an open pool fire scenario set-up. It has previously been shown that a higher discharge rate than what is prescribed for machinery spaces (7.5 l/m²·min instead of 5 l/m²·min) is necessary for a water spray to reach down to and extinguish a large diesel pool fire in an open space (Arvidson & Ingason, 2005).

5.2 Extinguishment with foam

In the methanol open pool fire extinguishing test series, documented in *Annex B: Methanol pool fire and extinguishment tests*, experiments were also carried out with foam injected to the water spray and mist. The tests showed that (alcohol-resistant) foam is necessary to provide effective and efficient extinguishment of methanol fire with a water-based system. Application of a fire-extinguishing foam generally creates a thick foam layer which blocks the heat radiation from the flames towards the fuel surface. Cooling of the fuel is also provided as the foam drains. The result is a reduced fuel vaporization rate, which for film-forming foams is also contributed by the film formed on the fuel surface, preventing mixing of the fuel vapor with air. Conventional fire-extinguishing foam will be destroyed if used for a fire in methanol or other polar fuels, since the foam concentrates are water based and dilute into the fuels. For methanol it is therefore necessary to use alcohol resistant foam, which forms a film on top of the fuel, separating the foam from the fuel. This is an important effect when mixing foam concentrate into the water spray or mist, since it may not result in a thick foam layer. In the tests the foam layer was less than 10 mm and the foam injection rather worked as a film-forming additive than a means to create a thick foam layer.

Adding foam concentrate to the extinguishing water gave improved performance of the tested water-based systems when applied to methanol fire. Similar to when not using foam, both the water-mist and the water-spraying system instantly suppressed the methanol fire, reducing the heat release rate in about half. The flames were then reduced and pushed towards to edges of the pool, before the last small flames were finally extinguished. These stages and the full extinguishment appeared quicker with the water-spraying system than with the water-mist system. Fuel by obstructions and objects penetrating the surface are the is the most demanding to extinguish, due to screening (reduced application) and since heat from objects increases fuel vaporization. This makes it more challenging to form a sealed foam/film layer around objects.

5.3 Extinguishment of compartment fires

Water-based fire-extinguishing systems in machinery spaces and pump rooms shall be of water-spray type in accordance with prescriptive requirements (5 $l/m^2 \cdot min$). Alternative water-based systems shall be approved in accordance with MSC/Circ.1165 (IMO, 2005), which specifies 11 test fire scenarios around an engine mock-up located in a >500 m^3 test compartment. Four of the scenarios were selected and tested in full scale:

- High pressure spray fire
- Concealed pool fire
- Wood crib in fuel pool fire
- Small pool fire in bilge area

The tests were performed with diesel and heptane, as specified in the circular, as well as with methanol. Differences in extinguishing times and in compartment temperature were used to evaluate the effect of fuel change when using prescriptive water-spray, low pressure water-mist, and high pressure water-mist (with foam when applied to methanol).

In addition to the standardized fire test scenarios, some simple extinguishing tests were performed with differently sized pool fires of diesel and methanol centered in the compartment. Instead of using the same size trays for the fuels, pools were used achieving similar heat release rates of 0.5 MW, 1 MW, and 2 MW. The same extinguishing systems were applied (foam injection was used for all methanol fire scenarios). The tests are fully documented in *Annex C: Total compartment fire extinguishing tests with methanol* and the key results are discussed below.

5.3.1.1 Standardized test fire scenarios

Continuous high pressure methanol spray fires are less likely than diesel spray fires, since the former are only flammable with an ignition source present (methanol high pressure spray fires self-extinguish if the ignition source is removed). Even with a re-ignition source, methanol spray fires can be quickly extinguished with water-mist and water-spraying systems (with foam injection).

Concealed heptane pool fires are manageable by water-mist systems (without foam), but not by prescriptive water-spray. The extinguishing performance of water spray systems is dependent on water impinging the fire pool. Likewise, none of the systems (with foam) managed to extinguish the corresponding concealed methanol fire. Both dilution and application of foam to a pool, which are the primary extinguishing mechanisms of methanol, require impingement of the water to the pool. Hence, a concealed methanol pool fire will be difficult to extinguish if it is not reachable by direct impingement of the water. It could still be possible if extinguishing foam water drains to the same place as the fuel pool.

A wood crib in the liquid fuel pool makes it more difficult to extinguish. The wood crib in heptane was extinguished by both water spray and water mist, but a wood crib in methanol was only extinguished by the water spray (with foam). The water-mist systems generated a too low application rate of foam (and dilution) to the fuel surface.

A small pool fire in the bilge area was also used in the tests, but it was not extinguished by any of the extinguishing systems, regardless of fuel and extinguishing system. Extinguishment failed primarily due to the systems not reaching the fire with the test installation requirements. None of the systems were approved for this application.

5.3.1.2 Centered open pool fires

With regards to simple centered open pool fires, the water spray with foam injection achieved extinguishment of the methanol pools to which it was applied (for 0.5 MW and 1.0 MW). The low pressure water-mist system also achieved extinguishment in these scenarios, but not in the 2.0 MW scenario. The low pressure water-mist system and the water-spraying system hence extinguished the same size methanol pool fires, but the former required a significantly longer time for extinguishment. The high pressure water-mist system did not achieve sufficient application of foam water to achieve extinguishment of any of the open methanol pool fires. However, both the water-spraying and the water-mist systems tested cooled the compartment well, regardless of fire.

With regards to diesel pools fires, the water-spray without foam did not extinguish any of the pools to which it was applied, which is noteworthy for a prescriptive system. Furthermore, the tested and approved water-mist systems only extinguished the diesel pool with the largest effect. This is typical for water-mist systems, that the smallest diesel pool fires are the most difficult to extinguish. The opposite appeared to apply for methanol fires in this kind of compartment (small open pool fires appeared easier to extinguish).

6 Conclusions

The five experimental test series performed with methanol in phase 2 of the proFLASH project gave new knowledge and led to technical guidance for the design of methanol fire detection and extinguishing systems.

The combustion efficiency of methanol is close to unity but its relatively low mass loss rate in combination with a low total heat of combustion result in a low heat release rate per unit area (400-500 kW/m^2, increasing with the pool area and reducing with water content). This is about 1/3 compared to diesel and 1/5 compared to gasoline.

Alcohols exhibit similar radiation in the IR region. IR flame detectors suitable to detect methylated spirit (required in accordance with standards) are thereby likely also suitable to detect methanol fire. Tested IR flame detectors quickly detected even fully obstructed methanol fires, but the detector sensitivity must be in balance with the likelihood of false alarm. Approval of a flame detector does not ensure suitability for detection of methanol fire (e.g. visual detectors are generally not suitable).

Several of the extinguishing mechanisms of water build upon water vaporization, but this is ineffective with methanol since relatively little heat is produced. Methanol is therefore difficult to extinguish with only water and combustion will continue until the fuel has been sufficiently diluted (reducing the fuel vaporization rate). This may not occur until the water content is almost 90 %, which puts large requirements on management of water runoff. Furthermore, increased water content makes the normally weakly blue methanol flames increasingly invisible, which could be hazardous. To achieve more effective extinguishment, injection of alcohol resistant foam is recommended for water-based systems (impedes radiation to the surface and blocks vaporized fuel).

In different pool and standardized test fire scenarios (high pressure spray, concealed pool, wood crib in pool, and bilge pool), water-spray with foam injection was more effective against methanol than prescriptive water-spray (without foam) against standardized fuels (heptane and diesel). With high and low pressure water mist, the performance was generally better than with water spray against the conventional fuels but worse against methanol (with foam injection). Regardless of use of foam or only water, the extinguishment effectiveness depends on the foam/water application rate. A higher discharge rate is therefore more effective and a concealed pool is difficult to extinguish.

A prescriptive gas fire-extinguishing system (carbon dioxide) in a ship machinery space shall have a design concentration of 40 % and extinguishes heptane at about 20 %. Methanol is extinguished at 27.5 % and to achieve the same safety margin (100 %), a recommendable design concentration is 55 %. According to regulations, alternative agents are only required to have a design concentration which is 20 % higher than the concentration at which they extinguish heptane. This approach can also be applied for methanol, but the lower safety margin requires that the system performance is verified in full scale.

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Part of the proFLASH research project

Minimum extinguishing concentration to extinguish methanol

(1 appendix)

1 Background

The stricter regulations for Sulphur content in bunker fuel have stimulated use of alternative fuels such as LNG and methanol, which differ from traditional bunker fuels in many ways. One important difference is their low flashpoint, which increases the probability of ignition in case of leakage. There are also other differences which increase fire risks, not least properties which affect the possibilities for fire detection and extinguishment. Methanol flames can for example be invisible and oxygen is bound to the molecule. LNG has a very low boiling point and is difficult to extinguish with water.

The purpose of the proFLASH project was to increase knowledge and to influence regulations regarding fire detection and fire extinguishment of low-flashpoint fuels, in particular LNG and methanol. The project consisted of a preliminary study and large-scale fire test phase, evaluating the suitability of relevant detection and extinguishing system solutions. It was decided to focus the experimental part of the project on methanol.

This report documents one of the planned test series in the proFLASH project, but which was relieved thanks to data made available to the project. The minimum extinguishing concentration of a certain gas is the basis for the design of fixed gas fire-extinguishing systems. It is determined by a so called cup burner test and is specific to the applied gas and the burning fuel. The minimum extinguishing concentrations of different gases to extinguish methanol are presented in this report.

2 Introduction

In accordance with prescriptive requirements in SOLAS II-2/10.4.1.1 IMO (1974), machinery spaces of category A shall be protected with either:

- a fixed gas fire-extinguishing system;
- a fixed high-expansion foam fire-extinguishing system; or
- a fixed pressure water-spraying fire-extinguihsing system.

Their design and performance shall be in compliance with the Fire Safety Systems (FSS) Code (IMO, 2007). For gas fire-extinguishing systems it specifies that carbon dioxide shall be used and that the system shall be designed to give a minimum volume of free gas equal to at least 40 % of the space (excluding the casing, or 35 % including the casing). If another inert gas or halogenated agent is desired or if the system deviates from any other specifications in the FSS Code, it needs to be verified equivalent in accordance with the IMO guidelines in MSC/Circ.848 (IMO, 1998). The guidelines state that the design concentration of alternative systems shall be based on the minimum extinguishing concentration (MEC) of the agent. It is

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determined by a cup burner test, specified e.g. in Annex B in ISO 14520-1 (ISO, 2006). The design concentration shall be at least 20 % above the MEC (IMO, 1998) and the performance of the system shall be verified by large-scale tests according to MSC/Circ.848 (IMO, 1998). In the test it is for example required that the system extinguishes different combinations of heptane pool fires, light diesel spray fires, and wood crib fires in a simulated machinery space. It can be noted that design concentrations in ISO 14520 (ISO, 2006) are 30 % higher than the MEC.

Carbon dioxide or an alternative extinguishant may be used for methanol ship installation, but primarily methanol is an alteranative fuel. This makes it relevant to evaluate MEC from both a fuel as well as an extinguishant point of view.

3 Experimental setup and procedure

The cup burner test determines the flame-extinguishing concentration of gaseous extinguishants in air for inflammable liquids and gases (ISO, 2006). Diffusion flames of the fuel burns in a round cup reservoir, centrally positioned in a coaxially flowing air stream (ISO, 2006). The flames are extinguished by adding a gaseous extinguishing agent to the supplied air, as illustrated in Figure 1 (ISO, 2006).

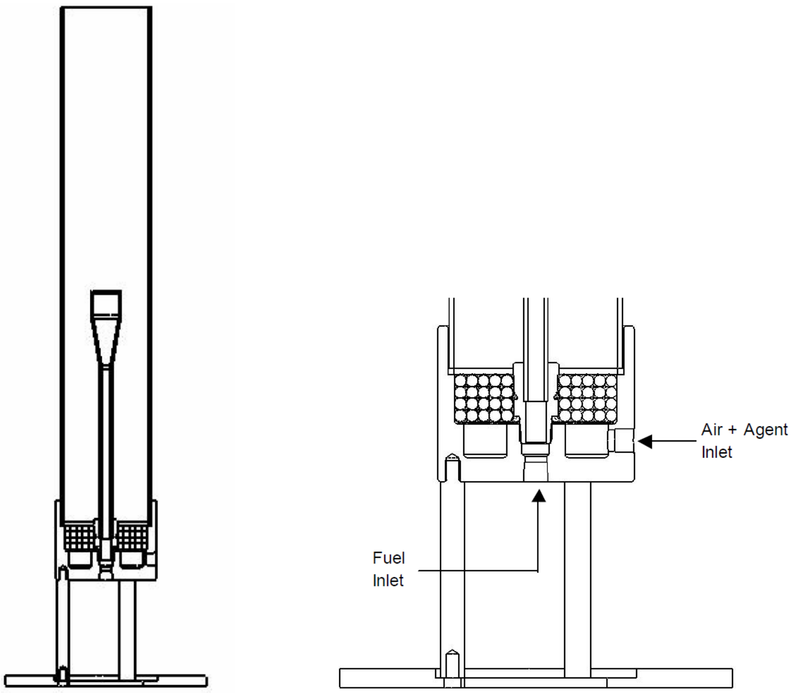

Figure 1. Cup burner apparatus (Senecal, 2005b).

The test procedure is initiated by supplying fuel to a level 5-10 mm from the top of the cup and adjusting the surrounding airflow to 40 l/min. The fuel is ignited but before the extinguishant is supplied to the air, the fuel level is adjusted within 1 mm from the top of the cup. The extinguishant flow rate is increased until the flame is extinguished. The test is repeated four more times and the minimum extinguishing concentration of the extinguishant is determined as the average of the five tests (ISO, 2006).

4 Results

A few decades ago, many cup burner tests were performed with for example inert gases, in large efforts to find efficient agents to replace Halon 1301. The most common extinguishant on ships is carbon dioxide, but several other inert gases can be relevant, e.g. nitrogen, argon, Argonite, and Inergen. These are often referred to by their inert gas designations: IG-XYZ, where the numbers (XYZ) correspond to the mixture relation of the gases nitrogen, argon, and carbon dioxide (sometimes omitted if 0). The cup burner test results for these physical agents are presented, along with some other extinguishants for reference, namely the chemical catalytic Halon 1301 as well as the chemically scavenging FM-200 and NOVEC 1230. Many tests have been performed with heptane, since this is often used reference fuel. For each extinguishant, data was collected for methanol and heptane (n-heptane if data was available, otherwise commercial heptane), as well as for diesel as reference. For some combinations of fuel and extinguishant there were much data and for some combinations data was lacking. The complete table of MEC data and their references is found in *Appendix A. Review of cup burner test MEC data for methanol*, but a summary of the data is presented in Table 1.

Table 1. Summary of methanol minimum extinguishing concentrations with different agents

	MEC for fuel:	*Diesel*	*Heptane*	*Methanol*	*Relation*	Meth +20%	Meth +100%
Extinguishant	*Designation*	*[vol%]*	*[vol%]*	*[vol%]*	*(Meth/Hept)*	[vol%]*	[vol%]+
Carbon Dioxide	IG-001	21-23	19.6	27.5	1.40	33.0	55
Nitrogen	IG-100	-	33.0	41.0	1.24	49.2	82
Argon	IG-01	27.0	42.0	52.0	1.24	62.4	(104)
Argonite	IG-55	26.0	36.5	45.4	1.24	54.5	91
Inergen	IG-541	35.8	33.8	44.2	1.31	53.0	88
Halon 1301	CF3BR	2.6	2.9	5.9	2.03	7.1	12
FM 200	HFC-227ea	6.7	5.8	10.0	1.72	12.0	20
NOVEC 1230	C6F12O	4.5	5.9	8.5	1.44	10.2	17

* Recommendable minimum design concentration *with* full scale performance verification.
+ Recommendable minimum design concentration *without* full scale performance verification.

5 Discussions

The study of minimum extinguishing concentration data for different agents shows that methanol requires significantly increased concentrations for extinguishment than for example heptane. The required increase varies between a factor of 1.24-1.4 for the most common inert gases. Carbon dioxide requires the largest increase (40 %), at the same time as it is the most efficient of the common inert gases to extinguish methanol (MEC is about 27.5 %). Inert gases (including carbon dioxide) work primarily by physical mechanisms and their effect is proportional to the heat capacity of the gas. Thereby, if exact MEC data for a physical agent is not known, it can be calculated from another physical agent for which data exists for the particular fuel (Senecal, 2005a). (This is how the MEC for carbon dioxide applied to diesel was calculated in Table 1.) For agents extinguishing by other means (catalytic, chemically, etc.), the suppression differential appears greater than for the inert gases (>2x for Halon 1301).

When using alternative extinguishing agents to carbon dioxide, the design concentration should be based on the minimum extinguishing concentration with an addition of 20 % (IMO, 1998). The performance of the system should be demonstrated in full scale tests in accordance with MSC/Circ.848 (IMO, 1998), where the primary concern is to show that the agent is well distributed. The design concentration calculated in this way for carbondioxide to extinguish methanol is 33 %. It may be noted that this lower than the design concentration (36 %)

recommended in ISO 14520 (where a 30 % safety margin is added) and lower than the minimum design concentration for methanol installations required by BSi (2001), which is 40 %. Furthermore, it is *lower* than the 40 % required according to the prescriptive requirements in the FSS Code (IMO, 2007), which applies to conventional fuels. Hence, this is in contradiction to that a higher MEC is required for methanol than for e.g. diesel and heptane. The reason is that the 40 % concentration includes a safety margin required when large-scale verification is omitted. Considering the MEC for heptane and diesel (~20 %), which are the primary fuels included in the large scale verification tests in MSC/Circ.848 (IMO, 1998), the prescriptive safety margin is about 100 %. Consequently, it would be reasonable to apply the same safety margin if using a carbon dioxide system for an alternative fuel (e.g. methanol) without full scale verification. With full scale verification based on MSC/Circ.848, the MEC with an added safety margin of 20 % for the particular agent (including carbon dioxide) chould serve as the minimum system design concentration. However, in the verification tests based on MSC/Circ.848, design fires with methanol must then be added, similar to the design fires currently used with heptane and diesel.

6 Conclusions

A carbon dioxide gas fire-extinguishing system in a SOLAS ship machinery space should have a design concentration of 40 % (or 35 % including the casing), in accordance with prescriptive requirements in the FSS Code. If another extinguishing agent is used, the system design concentration should be at least 20 % higher than the minimum extinguishing concentration (MEC) for the agent to extinguish heptane, determined by a cup burner test (e.g. ISO 14520-1). The system performance should also be verified in full scale in accordance with MSC/Circ.848. This study shows that the common inert gases (including carbon dioxide) are required to have 24-40 % higher concentrations to extinguish methanol compared to heptane. Carbon dioxide required the lowest volume concentration of the studied physical agents to extinguish methanol and had a MEC of about 27.5 % (19.6 % against heptane).

Considering the MEC for heptane, the prescriptive carbon dioxide design concentration of 40 % includes a ~100 % safety margin. The same safety margin is recommended to apply to gas fire-extinguishing systems used for alternative fuels, such as methanol, without large scale verification. The minimum design concentration for a carbon dioxide system would hence be 55 % *without* large scale verification. *With* large scale verification based on MSC/Circ.848, a minimum design concentration corresponding to the MEC with an addition of 20 % for the particular fuel and extinguishing agent is recommended. For a carbon dioxide system, the minimum design concentration would hence be 33 % *with* large scale verification. The large scale verification based on MSC/Circ.848 should include tests with corresponding design fires with the alternative fuel (such as methanol).

Hence, based on this study it is recommended that gas fire extinguishing systems for alternative fuels should have a minimum design concentration equal to:

- the MEC* plus a safety margin of 100 %, if full scale verification is omitted;
- the MEC* plus a safety margin of 20 %, if full scale verification is performed,

*for the particular extinguishant and fuel.

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Appendices

1. Review of cup burner test MEC data for methanol

Review of cup burner test MEC data for methanol

The minimum extinguishing concentration (vol%) for different agents to extinguish methanol and the reference fuels heptane and diesel are presented below. based on cup burner test results. The data referred to in Table 1 above are marked blue below. The priorities in the references to Table 1 were the following:

1. Data from standard with data for methanol and heptane
2. Data from reference with data for all fuels
3. Data from reference with data for methanol and heptane
4. Data from standard
5. Data from latest reference

In calculations of average values in the tables below, no consideration was taken to that some of the data below are summarized “best-values”, which may include some of the other listed data.

Carbon dioxide. IG-001 *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
Calculated	21-23		
Moore, Weitz, and Tapscott (1996)		20.4	
Senecal (2005a)		20.9	
Hirst and Booth (1977)		20.5	
Saito, Ogawa, Saso, Liao, and Sakei (1996)		22	
Sheinson, Penner-Hahn, and Indritz (1998)		21	
Takahashi, Linteris, and Katta (2003)			27
VdS (1998)		19.6	27.5
Linteris and Chelliah (2001)			27.2
Average		*20.7*	*27.3*

Nitrogen. IG-100 *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
ISO (2013b)		32.3	
Moore et al. (1996)		30	
Senecal (2005a)		31.9	
Hirst and Booth (1977)		30.2	
Dlugogorski, Kennedy, and Morris (1996)		29	
Saito et al. (1996)		33.6	
Sheinson et al. (1998)		30	
NFPA 2001 (2004)		31	
Tapscott (1999)		33	41
VdS (1998)		30.9	38.5
Average		***31.1***	***39.8***

Appendix 1

Argon. IG-01 *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
ISO (2013a)		39.1	
Moore et al. (1996)	25	38	38(?)
Senecal (2005a)		42.5	
Dlugogorski et al. (1996)		39	
Saito et al. (1996)		43.3	
Sheinson et al. (1998)		41	
NFPA 2001 (2004)		42	
Tapscott (1999)	27	42	52
VdS (1998)		40.9	52.2
Average		***40.9***	-

Argonite. IG-55 *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
ISO (2013c)		36.5	45.4
Moore et al. (1996)	22	28	34
Senecal (2005a)		36.4	
NFPA 2001 (2004)		35	
AS 4214 (2002)		32.3	
Tapscott (1999)	26	35	39
Average		***33.9***	***39.5***

Inergen. IG-541 *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
ISO (2013d)	35.8	33.8	44.2
Moore et al. (1996)		29	44
Senecal (2005a)		34.3	
Dlugogorski et al. (1996)		32	
Saito et al. (1996)		35.6	
NFPA 2001 (2004)		31	
AS 4214 (2002)		33.8	
Tapscott (1999)		33	41
VdS (1998)		33	41.1
Average		***32.8***	***42.6***

Halon 1301. CF3Br *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
Moore et al. (1996)	2.6	2.9	5.9
Tapscott (1999)		3.4	7.8

Appendix 1

FM 200. HFC-227ea *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
Moore et al. (1996, Great Lakes)	6.7	5.8	10
Moore et al. (1996, 3M)		7.5	10.1
Tapscott (1999)		6.6	9.7
Robin (1994)	6.7		10

NOVEC 1230. C6F12O *Reference*	Diesel [vol%]	Heptane [vol%]	Methanol [vol%]
3M (2009)	4.5	5.9	8.5

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Part of the proFLASH research project

Methanol pool fire and extinguishing tests

(1 appendix)

1 Background

The stricter regulations for Sulphur content in bunker fuel have stimulated use of alternative fuels such as LNG and methanol, which differ from traditional bunker fuels in many ways. One important difference is their low flashpoint, which increases the probability of ignition in case of leakage. There are also other differences which increase fire risks, not least properties which affect the possibilities for fire detection and extinguishment. Methanol flames can for example be invisible and oxygen is bound to the molecule. LNG has a very low boiling point and is difficult to extinguish with water.

The purpose of the proFLASH project was to increase knowledge and to influence regulations regarding fire detection and fire extinguishment of low-flashpoint fuels, in particular LNG and methanol. The project consisted of a preliminary study and large-scale fire test phase, evaluating the suitability of relevant detection and extinguishing system solutions. It was decided to focus the experimental part of the project on methanol.

This report documents one of the test series performed in the proFLASH project. Free burning methanol pool fire tests were performed to characterize the fuel, and tests with different trays and extinguishing systems were performed to evaluate the systems' suitability and realistic efficiency.

2 Experimental setup and procedure

The fire test series consisted of three parts:

- Free burning tests with differently sized flat trays
- Extinguishing tests with flat tray
- Extinguishing tests with conical tray

The extinguishing tests were performed with a conventional water-spraying system (low pressure) and with a water-mist system (high pressure). Both were tested with and without foam injection. Conventional trays with flat bottom were used in the tests and also a tray with conical bottom, as illustrated in Figure 1.

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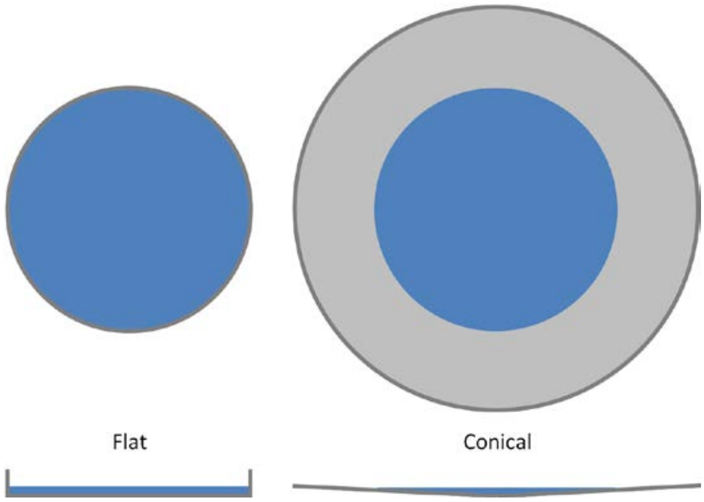

Figure 1. Illustration of the two types of pool fire trays used in the tests (top and side views).

Flat bottomed circular or square trays are very common in fire testing. The conical fire tray was constructed exclusively for this test series to capture the potential risk of increasing the fire size as water is added to the (soluble) fuel pool by the extinguishing system. It also captures effects from water and foam draining to the same place as the fuel pool.

The pool fire and extinguishing test program, with the different trays and extinguishing systems, is presented in Table 1.

Table 1. Test program for the pool fire and extinguishing tests performed within proFLASH

Test denotation	*Tray (bottom)*	*Pool diameter [m]*	*Fuel*	Extinguishing system
F1120-Meoh	Flat	1.12	Methanol	-
F1440-Meoh	Flat	1.44	Methanol	-
F2400-low-Meoh	Flat	2.40	Methanol	-
F2400-low-Meoh+	Flag	2.40	Methanol	-
F3000-low-Meoh	Flat	3.00	Methanol	-
F3000-Meoh				
C-Meoh	Conical	2.40*	Methanol	-
F-MeohWS	Flat	2.40	Methanol	Water spray
F-MeohWS-f	Flat	2.40	Methanol	Water spray with foam
F-DiesWM	Flat	2.40	Diesel	Water-mist
F-MeohWM	Flat	2.40	Methanol	Water-mist
F-MeohWM-f	Flat	2.40	Methanol	Water-mist with foam
C-MeohWS	Conical	2.40*	Methanol	Water spray
C-MeohWS-f	Conical	2.40*	Methanol	Water spray with foam
C-MeohWM	Conical	2.40*	Methanol	Water-mist
C-MeohWM-f	Conical	2.40*	Methanol	Water-mist with foam

+ Tray was filled with 200 l of fuel, to acquire a longer steady state period; see section 2.2.
***** Average fuel pool size at ignition; conical tray diameter was 4.00 m.
low Signifies that the test was performed with the tray on the floor, not raised closer to the hood.

In addition to the test program above, test results were for comparison obtained from previous extinguishing tests with diesel (Arvidson & Ingason, 2005). These tests were performed with similar conditions, as specified in Table 2.

Table 2. Tests performed previously and used for reference

Test denotation	*Tray (bottom)*	*Fuel*	*Diameter [m]*	Extinguishing system
F1100-Dies	Flat	Diesel	1.10	-
F1440-Dies	Flat	Diesel	1.44	-
F2400-Dies	Flat	Diesel	2.40	-
F-DiesWS	Flat	Diesel	2.40	Water spray
F-DiesWS-7.5^{+}	Flat	Diesel	3.00	Water spray

+ Discharge rate was in this test increased to 7.5 mm/min.

Below follow further descriptions of the equipment, instrumentation, and arrangements in the tests.

2.1 Pool fire trays

All the used pool fire trays were circular and constructed in steel; the flat bottomed trays in 2 mm steel and the conical tray in 3 mm steel. The two largest flat bottomed trays, specified in Table 1, were the only trays of stainless quality and they had a rim of 0.20 m. The tray with a diameter of 1.12 m had a 0.15 m rim and the tray with a diameter of 1.44 m had a 0.20 m rim. The conical tray was 4.00 m in diameter and had no rim. However, it had an overfill protection gutter, as illustrated in Figure 2, and the inclination over the 2.00 m radius was 0.10 m.

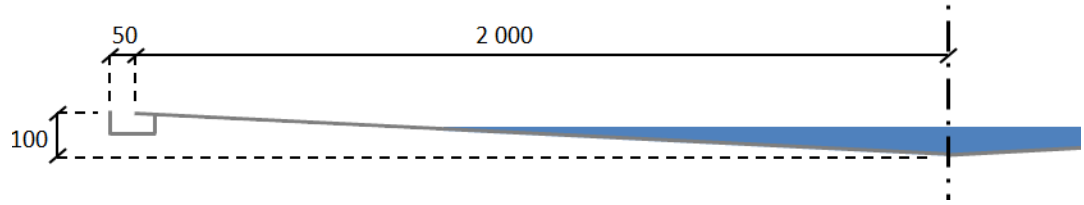

Figure 2. Illustration with measurements (mm) of the conical pool fire tray in side view (half).

The conical tray was filled to attain a fuel pool with a diameter of approximately (on average) 2.40 m at ignition, as in the extinguishing tests with the flat bottomed trays. The conical and the flat bottomed trays are shown in Figure 3 and Figure 4, respectively.

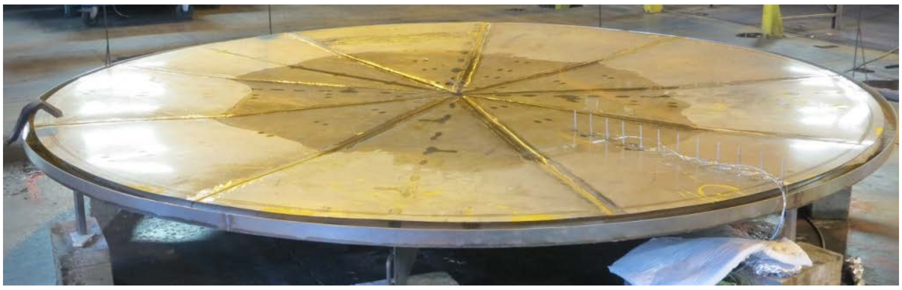

Figure 3. The conical bottomed tray (Ø4.0 m) with an about Ø2.4 m methanol pool (90 l).

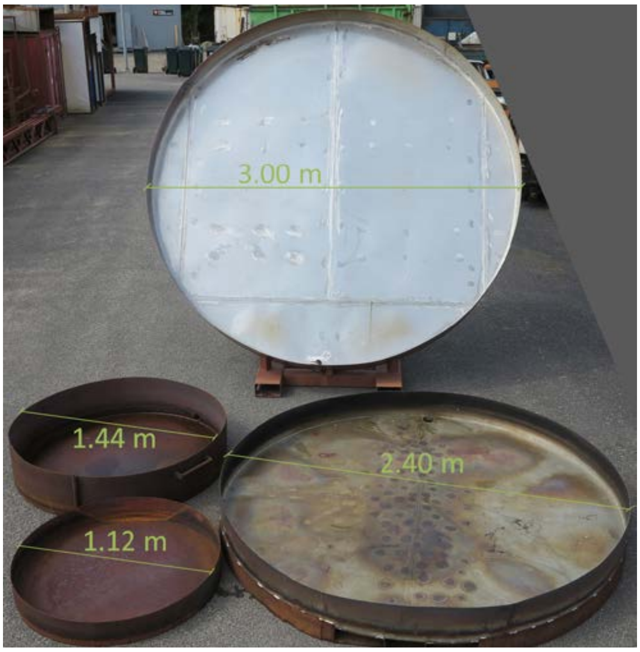

Figure 4. Flat bottomed pool fire trays used in the tests.

The Ø2.4 m flat bottomed pool was placed on the floor in the free burning tests, as reference to the extinguishing tests where this was necessary. This is indicated in Table 1 as “low”. To evaluate potential effects on the possibilities for collecting all the smoke (and determining the heat release rate), tests with the largest tray (Ø3.0 m) were performed both on the floor and raised to about 2.5 m. The smaller trays were raised to about 2 m from the floor.

2.2 Fuels and nominal heat release rates

Methanol and diesel were used as fuels in the tests. The diesel was a Shell CityDiesel® with the following properties (according to standard in parenthesis):

Density at 15 °C:	812 kg/m^3 (ISO 12185)
Flash point:	74 °C (ISO 2719)
Water content:	34 mg/kg (ISO 12937)
Heat of combustion:	39.7 MJ/kg (ASTM D 2624)
Boiling point:	185-290 °C [IBP-95 % V/V recov.] (SS-EN ISO 3405:2000)

The methanol was an Univar Methanol 160K DNN with the following properties (according to standard in parenthesis):

Density at 20 °C:	791.2 kg/m^3 (ASTM D 4052)
Flash point:	11 °C (ISO 2719)
Water content:	0.011 mg/kg (ASTM D 1364)
Heat of combustion:	19.9 MJ/kg (ASTM D 2624)

The amounts of fuel used in the different trays are specified in Table 3, which also specifies the nominal fuel pool thickness at ignition for the methanol fires. The amounts used depended on the flatness of the bottom surface of the flat bottomed trays, which deform as a result of the heat exposure in the tests. To attain a steady mass loss rate and combustion, they were filled at least 20 mm above the highest point of the tray bottom. For comparison, one test was performed with a thicker layer of methanol in the 2.4 m diameter tray, resulting in a longer steady state period (F2400-low-Meoh+); all extinguishing tests were then performed with the thicker layer/increased amount of methanol (200 l). In the test with the Ø3.0 m pool raised from the floor, the amount of methanol was doubles, once again to attain a longer steady state period. With diesel it is possible to use a layer of water under the fuel to level the burning surface and to avoid thin layer effects, but this is not possible with methanol since it is soluble in water. Instead, relatively thick layers of methanol were used. In this test series, the same amounts of fuel were used in the diesel tests as in the methanol tests. In the tests referred to in Arvidson (2006) and in Arvidson and Ingason (2005), 10 mm of diesel was filled on a 140 mm bed of water. The amounts of fuel used in this test series and the resulting nominal fuel pool thicknesses are specified in Table 3, which also specifies nominal heat release rates (HRR) for the different sizes of diesel and methanol pool fires (Morgan et al., 2016). The combustion efficiency of diesel was assumed to be 70 % and for methanol 96 % in the calculations of nominal values.

Table 3. Fuel amounts and heat release rates (HRR) in the different trays

Tray (bottom)	*Pool diam. [m]*	*Pool area [m^2]*	*Nominal HRR diesel [MW]*	*Nominal HRR MeOH [MW]*	*Amount of MeOH [l]*	*Nominal pool thickness[mm]*
Flat	1.12	0.99	1.12[-]	0.41	20	20
Flat	1.44	1.63	2.07	0.68	41	25
Flat	2.40	4.52	6.18	1.90	160	35
Flat	2.40	4.52	6.18	1.90	200	44
Flat	3.00	7.07	9.76	2.96	176	25
Flat	6.00	7.07	9.76	2.96	370	53
Conical	2.40[+]	4.52	6.18	1.90	90	60*

[+] Average fuel pool size at ignition; conical tray diameter was 4.00 m.

[-] Diesel test was performed in a tray with diameter 1.1 m (area: 0.95 m^2); nominal value corresponds to this area.

* Pool thickness at center of tray.

2.3 Extinguishing systems

Two types of extinguishing systems were included in the tests. A conventional low pressure water-spraying fire-extinguishing system and a high pressure water-mist fire-extinguishing system, both for compartment fire protection in machinery spaces. The two systems were tested with and without foam and are further described below.

2.3.1 Water-spraying system

A hydraulically balanced single feed “H” piping arrangement was installed to minimize flow rate differences between sprinkler nozzles. The system was centered with four nozzles at 3.5 m above the pool fire tray, as illustrated in Figure 5. The pipe-work was constructed of 2" (DN50) steel pipe and the branch line pair provided a sprinkler spacing of 3.05 m by 3.05 m (10 ft. by 10 ft.). Each of the nozzles hence covered an area of 9.3 m^2 (100 ft^2).

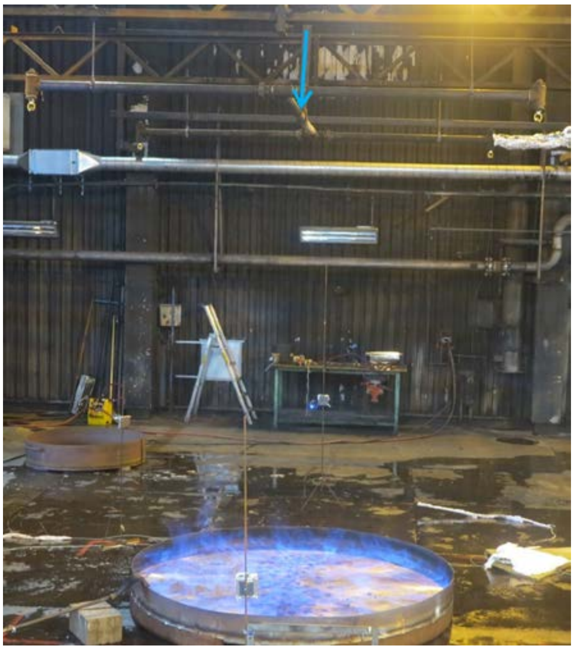

Figure 5. Hydraulically balanced water-spraying system with single feed (marked by blue arrow).

The water-spray nozzles used in the tests was made by Tyco and designated Protectospray D3 18-95 (Tyco, 2016). The nozzle is shown in Figure 6 and had a K-factor of 25.9 (metric) and a spray angle of 95º.

Figure 6. Water spray (left) and water-mist (right) nozzles used in the extinguishing tests.

When only water was used (without foam), the water system piping was connected directly to the municipal water supply connection inside the fire test hall. No pump was used, but the water supply pressure was controlled via a diaphragm control valve connected to a compressed air supply. The control valve provided a constant pressure downstream the valve, irrespective of the inlet pressure. The flow rate and corresponding pressure was fine-tuned by an operator to achieve the desired total flow rate.

When water spray was used with foam, pressure was provided by a pump operated to maintain the desired total flow rate. The foam used with the water-spraying system was provided by Fomtec and designated Fomtec ARC 1x1 NV. This is an alcohol resistant aqueous film forming foam (AFFF) and was premixed at 1 % with water in a 3 m^3 tank before the tests. The system with pump and water tank used in the water spray foam tests is illustrated in Figure 7.

It should be noted that use of a foam concentrate in a water spray system works as a film-forming additive rather than a means to build up a thick foam layer (< 10 mm in the tests).

Figure 7. Water tank with premixed foam and pump (left) for the water-spraying system to provide 5 l/m^2/min (right).

The total flow rate of water was in both set-ups (without and with foam) measured using a Krohne 0-2000 l/min flow meter on the single feed pipe. The pressure was measured by a pressure transducer at one of the nozzles. A flowing pressure of about 3.25 bar (nominally 3.23 bar) was utilized throughout the tests to achieve a total flow rate of 186 l/min. This corresponds to a flow rate per nozzle of 46.5 l/min and hence a nominal discharge density of 5.0 mm/min, in accordance with SOLAS (IMO, 1974) and the FSS Code (IMO, 2007). The activated water-spraying system is illustrated in Figure 7 (in this case with foam).

2.3.2 Water-mist system

The water-mist fire extinguishing system was provided, installed, and operated by Ultra Fog®. The installation was made on top of to the water-spraying system and arranged in a similar way. A hydraulically balanced single feed “X” pipe system was used and the system was centered with four nozzles at 3.5 m above the pool fire tray, as illustrated in Figure 5. The pipe-work was constructed of 12 mm stainless steel high pressure pipes, denoted Ultra Fog W Heat-tube, and is illustrated in Figure 8.

The water-mist nozzles used in the water-mist tests was made by Ultrafog and designated Ultra Fog 950606-021 1518/M15178. The nozzle type had a K-factor of 2.4 (metric) and is shown in Figure 6. The nozzles are certified for total compartment water-mist fire-extinguishment in machinery spaces (IMO, 2005) with nozzle spacing up to 5 m. In these tests they were installed with a spacing of 4.00 m by 4.00 m. Each nozzle thus covered an area of 16 m^2 and provided nominally 1.5 l/m^2/min, which is about 50 % more water than when using the maximum spacing.

Figure 8. Hydraulically balanced water-mist system with a center single feed (foiled).

High pressure pumps and control unit were provided by Ultra Fog and operated at a pressure of about 100 bar, providing a total flow rate of 96 l/min. The activated water-mist system is illustrated in Figure 9 (in this case without foam).

Figure 9. Acitvated Ultra Fog water-mist system providing nominally 1.5 l/m^2/min.

The foam used with the water-mist system was provided by Solberg and designated Arctic™ 1x1 LV ATC™. It is an AR-AFFF (alcohol resistant aqueous film forming foam) concentrate and was injected directly to the high pressure pump housing during the tests. It should be noted that a foam concentrate in a water mist system works as a film-forming additive rather than a means to build up a thick foam layer (about 1 mm in the tests).

2.4 Measurements and instrumentation

Measurements and documentation of the tests were made in several ways. The tests were documented by conventional photo and video in the visible spectrum as well as by video in the infrared (IR) spectrum, where indicated in Figure 10. An IR camera converts radiation to temperature and thus provides a temperature profile of the pool fire. The IR camera used in the tests was of model FLIR T420 2.0 and operated in the temperature range 250-1 200 °C and with the emissivity set to 0.4.

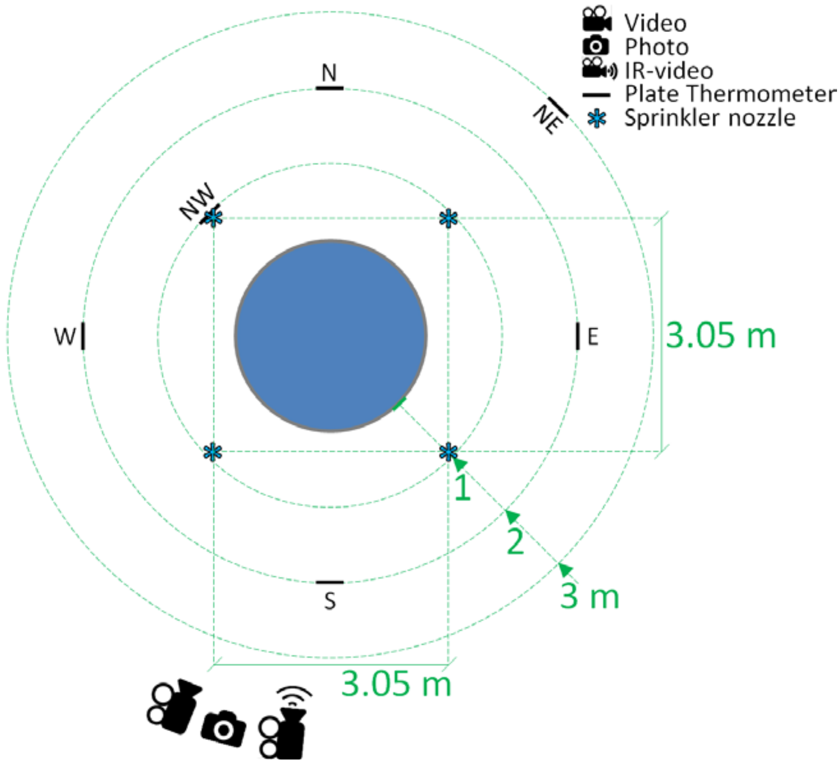

Figure 10. Top view of instrumentation in the tests (here with Ø2.4 m flat pool and water spray).

In all of the tests, measurements were made of the heat release rate and the heat radiation from the pool fires, as further described below. Furthermore, in the free burning tests, measurements were made of the weight loss of the pool tray, determining the mass loss rate of methanol fires of different sizes. A spectrometer was also used in the free burning tests to characterize the radiation from a methanol fire, but this data is documented in a separate report of the proFLASH project [Ochoterena, *Spectral radiation measurements from methanol and other pool fires*, BRd6081-04]. For the tests in the tray with conical bottom, measurements were also made of the tray temperature to monitor the fuel pool size. Measurements and instrumentation is schematically indicated in Figure 10 and further detailed below.

2.4.1 Heat radiation

The incident heat radiation can be calculated from an instrument called the Plate Thermometer. The Plate Thermometer was developed at SP Fire Research and full descriptions can be found in Wickström (1989) and Wickström (1994). In brief it consists of a 0.7 mm thick steel plate with a front face measuring 100x100 mm. A sheathed thermocouple is spot-welded to the backside of plate and covered by 10 mm of insulation. The device is sensitive to both heat convection and heat radiation, whereas a conventional thermocouple mostly captures heat convection.

In these tests, a newly designed plate thermometer was used, illustrated in Figure 11. This Plate Thermometer has a thinner 0.4 mm steel plate to improve the response time and also a thicker 30 mm layer of insulation. Compared to the standard Plate Thermometer, developed for furnace control, the thicker insulation reduces thermal losses when the instrument is used in ambient temperature conditions.

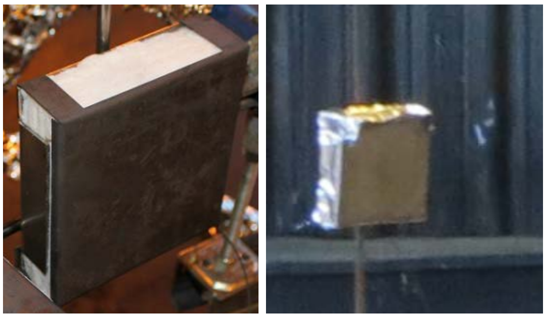

Figure 11. The type of Plate Thermometer used in the tests, and the instrument water protected.

The plate thermometers simply measure the temperature of the steel plate, but it can be used for accurate calculations of the incident heat radiation. The calculation method is based on a study by Ingason and Wickström (2007) and has been refined for the new Plate Thermometer with increased insulation (Sjöström, Appel, Amon, & Persson, 2015). It takes into account incident and emitted heat flux, convective heat transfer at the plate surface, combined energy losses through conduction and convection at the back side, as well as energy storage due to heating of the metal and insulation. The incident radiant heat flux, $\dot{q}''_{inc}$, is calculated through equation 1:

$$\dot{q}''_{inc} = \sigma T_{PT}^4 + \frac{(h+K_{PT})(T_{PT}-T_\infty)+C_{PT}\frac{dT_{PT}}{dt}}{\varepsilon_{PT}}. \qquad (1)$$

where T_{PT} and T_∞ are the temperatures of the Plate Thermometer (PT) and the ambient air, respectively, ε_{PT} is the plate emissivity, K_{PT} is the loss correction factor (4 W/m^{2}K for the insulated PT), and C_{PT} is the storage correction factor due to the heat capacity of the insulated Plate Thermometer (3000 J/m^{2}K) (Häggkvist, Sjöström, & Wickström, 2013). The storage correction factor compensates for the finite time constant of the insulated Plate Thermometer. The convective heat transfer coefficient, h, was assumed constant and estimated to 12 kW/m^2 (Holman, 1992). To reduce errors and scattered results, the derivative in equation 1 is a floating point central difference using time steps of ± 20 seconds. Further information about the accuracy of this method is presented by Häggkvist et al. (2013).

Six Plate Thermometers were used in the tests and positioned around the pool fires with their center points 1.0 m above the bottom of the trays. The Plate Thermometers were positioned at different distances from the pool fires, as indicated in Figure 10. Four plate thermometers were positioned around the pools at a distance of 2 m from the pool and two plate thermometers were positioned at 1 m and 3 m from the pool. It should be noted that the distance was measured from the fuel pool before ignition, which in the tests with the conical tray was about 0.8 m from the tray edge.

In the tests with extinguishing systems the Plate Thermometers were not shielded from direct water impingent. Therefore the sides were carefully protected with aluminum tape to prevent water from entering into the instrument, as illustrated in Figure 11. In the test with the Ø3.0 m pool, measurements of radiation were only made with the tray on the floor (F3000-low-Meoh). With the Ø2.4 m pool, measurements of radiation were only made in the test without increased about of fuel (F2400-low-Meoh).

2.4.2 Weight loss rate

In the free burning tests, the flat bottomed pool fire trays were placed on two load cells to determine the weight loss rate of methanol. The load cells were calibrated up to 650 kg, which was sufficient in this test series, and connected to the central measurement system.

2.4.3 Heat release rate

The tests were conducted under the Industry Calorimeter, a large hood connected to an extraction system capable of collecting the combustion gases produced by the fire. The hood is 6 m in diameter with its lower rim 7.2 m above the floor. No skirt was used on the rim of the hood, except in the Ø3.0 m test raised from the floor. The distance from the floor to the tray was about 2.5 m in this test, and the two smallest free burning fires were raised about 2 m from the floor.

The hood leads all combustion gases to a duct, where measurements are made of gas temperature, velocity, and concentration of gaseous species such as CO_2, CO, and O_2. Based on these measurements, both the convective and the total heat release rate can be calculated. The convective heat release rate is calculated based on the gas temperature and mass flow rate whilst the total heat release rate is calculated based on the oxygen depletion in the calorimeter system. The total heat release rate (here denoted HRR) comprises both the convective and the radiative heat releases.

2.5 Test procedure

Each test followed a similar test procedure:

-02:00	Start of measurement
-01:00	Start of video camera
-00:30	Start of IR video camera
00:00	Ignition
02:00	Activation of extinguishing system for diesel pool fire
03:00	Activation of extinguishing system for methanol pool fire

Photos were taken before ignition, at ignition, every 60 seconds as well as in association with observed changes in fire behavior. The methanol fuel pools were ignited using a torch and were allowed to burn for 3 minutes before activation of extinguishing systems. Free burning fires were allowed to finish burning. For diesel pool fires, a small amount (500 ml) of n-Heptane was poured into the tray seconds before ignition with a torch. Diesel reaches a steady state quicker than methanol and was allowed to burn for 2 minutes before activation of the extinguishing systems. This applied in the current test series as well as in the diesel tests referenced in Arvidson and Ingason (2005) and Arvidson (2006).

3 Results

The results are presented below, divided on heat radiation, mass loss rate, heat release rate, as well as observations.

3.1 Heat radiation

As described above and illustrated in Figure 10, temperatures were measured with plate thermometers around the pool to estimate the heat radiation from the fires. Four measurements were made at a 2 m distance from the fuel pool perimeter (denominated N, E, S, and W), one measurement was made 1 m from the pool (denominated NW), and one measurement was made 3 m from the pool (denominated NE). These measurements were made in all of the tests in this test series. However, in the diesel tests by Arvidson and Ingason (2005), only one measurement was made 2 m from the pool fire.

The calculated average radiation heat flux of the four measurements at a distance of 2 m from the free-burning methanol fires is presented in Figure 12, together with the radiation from the same size diesel pool fires (from Arvidson & Ingason, 2005). The Ø2.4 m diesel pool fire is for illustration supplied with a potential maximum radiation heat flux, based on the peak value of the curve.

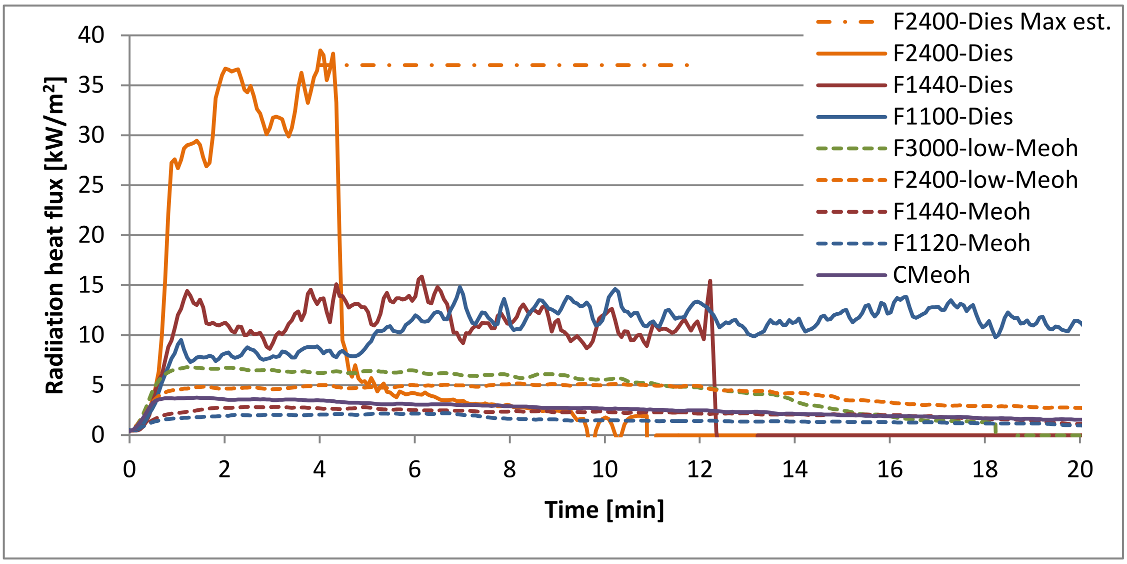

Figure 12. Average radiation heat flux 2 m from free-burning methanol and diesel fires.

The maximum average values for each curve in Figure 12 were plotted against the fire size, which describes the radiation heat flux dependence on the fire size at a 2 m distance, presented in Figure 13.

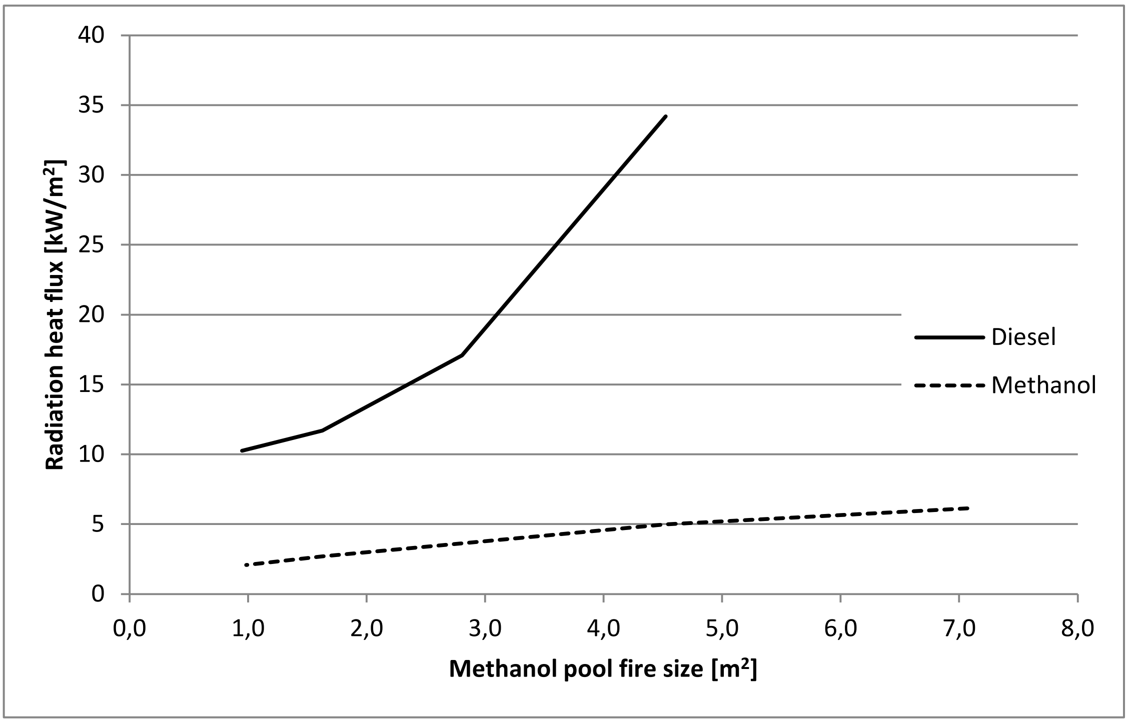

Figure 13. Average constant/maximum radiation heat flux 2.0 m from methanol pool fires.

The dependence of the radiation heat flux on the distance from the methanol pool can also be derived from the test data, as illustrated in Figure 14.

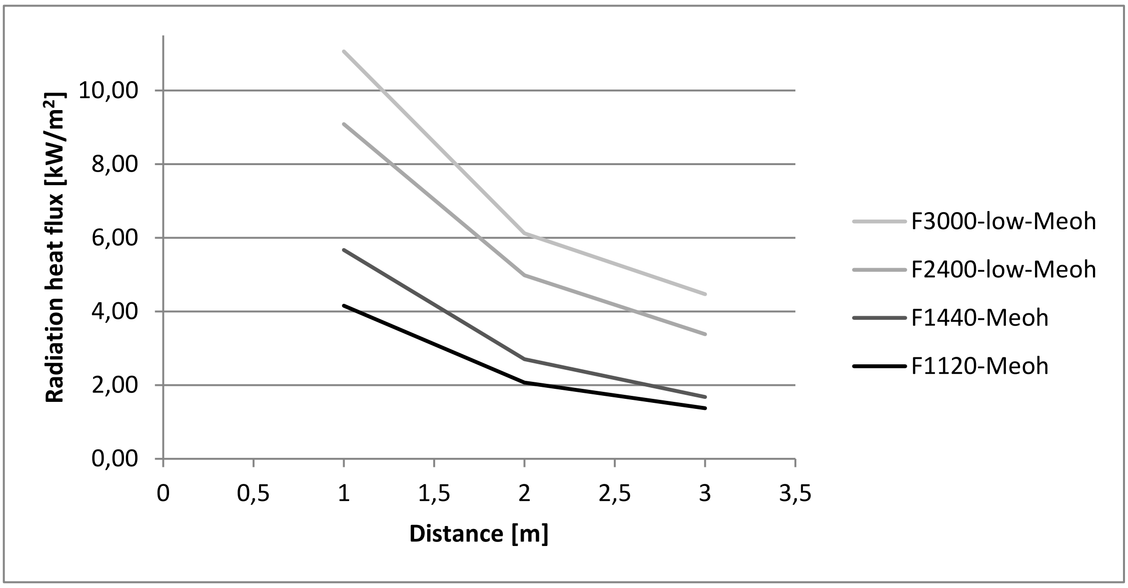

Figure 14. Radiation heat flux dependence on the distance from a methanol fire.

The calculated average radiation heat flux at a distance of 2 m in the extinguishing tests with methanol pool fires in the Ø2.4 m flat-bottomed tray are presented in Figure 15. The corresponding test results but with diesel (and only one measurement point) are presented in Figure 16 (partly from Arvidson & Ingason, 2005). The estimated maximum radiation heat flux for the Ø2.4 m diesel pool fire is supplied for illustration. The differing scales in these figures should be noted, as well as the effects of the extinguishing systems on the radiation from the same size methanol and diesel fires. In the methanol extinguishing tests the systems were activated after 3 minutes, and with diesel after 2 minutes.

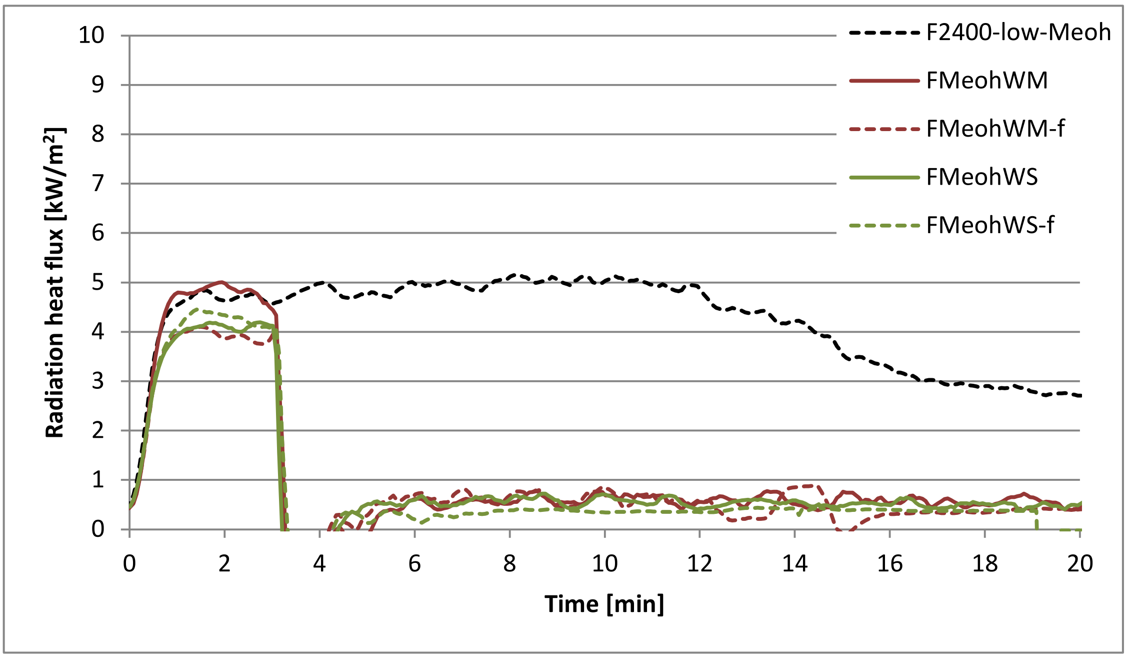

Figure 15. Average radiation heat flux at 2.0 m in the methanol extinguishing tests in the flat-bottomed tray.

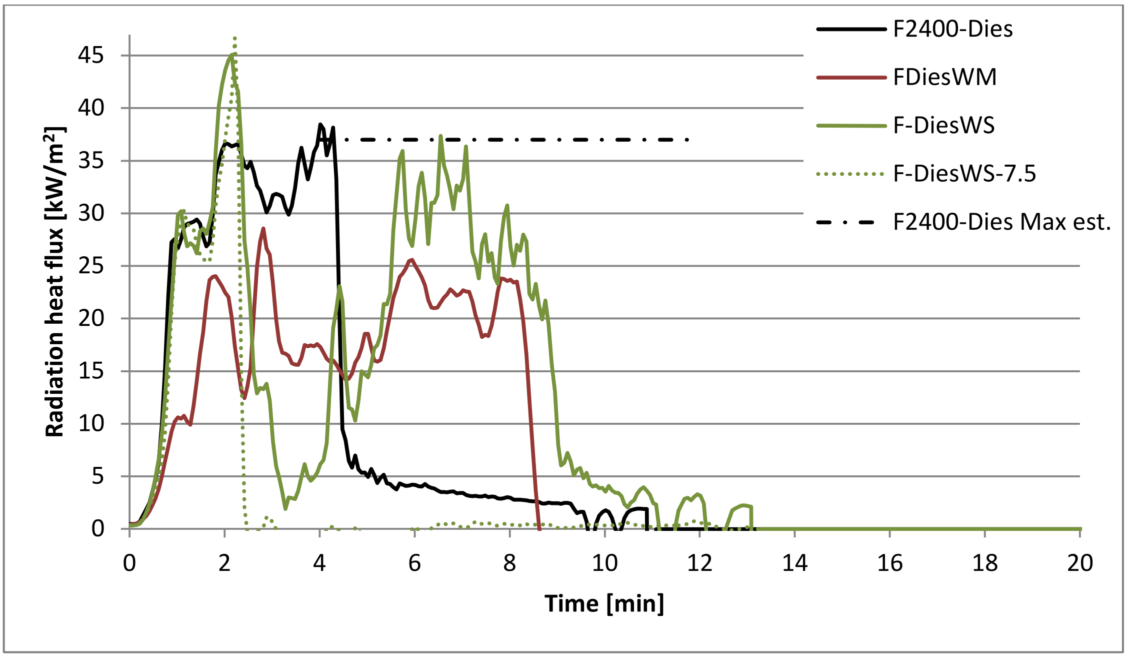

Figure 16. Radiation heat flux at 2.0 m in diesel extinguishing tests in a flat-bottomed tray.

The effects of extinguishing systems on methanol fire in the conical tray are presented in Figure 17.

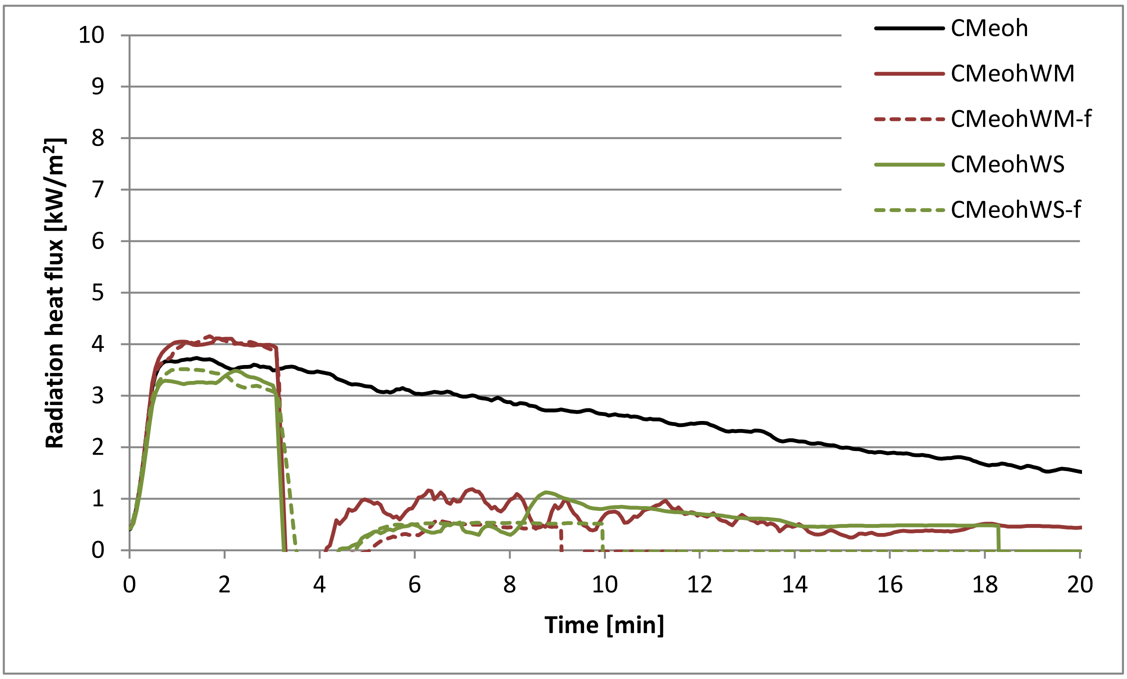

Figure 17. Average radiation heat flux at 2.0 m in the extinguishing tests in the conical tray.

The full distribution of heat fluxes for a methanol fire extinguishing test is exemplified in Figure 18. The results followed the same behavior in all of the methanol fire extinguishing tests, i.e. the calculated radiation heat flux became insignificant upon activation of the extinguishing systems.

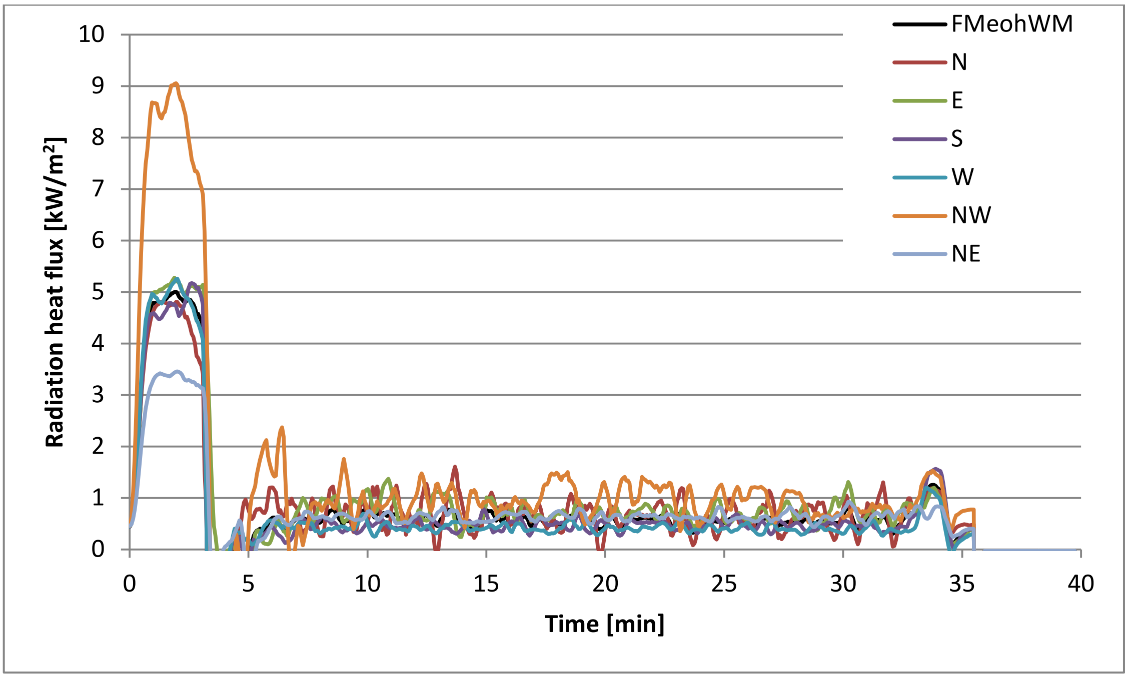

Figure 18. The full distribution of heat fluxes from a Ø2.4 m methanol fire suppressed by water mist (activation at 3 min but extinguishment not achieved).

The full distributions of heat fluxes for the free-burning fires are presented in *Appendix A. Radiation heat flux from measurements*. An example is presented in Figure 19 for the Ø2.4 m free-burning methanol fire with increased amount (200 l) of methanol. It also illustrates some of the measurement "errors" occurring in some of the tests. The data from plate thermometers S and W are significantly lower than the data from N and E (even lower than that from NE, which was placed further away from the pool fire). Such differences could signify some type of error in the measurements. For example it could be a consequence of that the flame in the test was tilted away from the instruments giving low readings. However, no distinguished such flame tilt could be confirmed from the video recordings in the tests with errors. The errors could also have been caused by water incurred in extinguishing tests performed before the particular test, which is likely since the readings reached maximum temperatures of around 100 °C. The errors also occurred in extinguishing tests due to incursion of water, even though the plate thermometers were shielded. The instruments giving faulty readings were (except S and W described above) N and NW in tests F-MeohWS, F-MeohWS-f, C-MeohWS, and C-MeohWS-f, and W in tests C-Meoh, FDiesWM, F-MeohWM-f, C-MeohWM, and C-MeohWM-f. The faulty readings were excluded from the calculated averages. In this regard it can be noted that none of the free-burning tests performed with flat-bottommed trays included errors (except the repeated test with increased amount of fuel presented below).

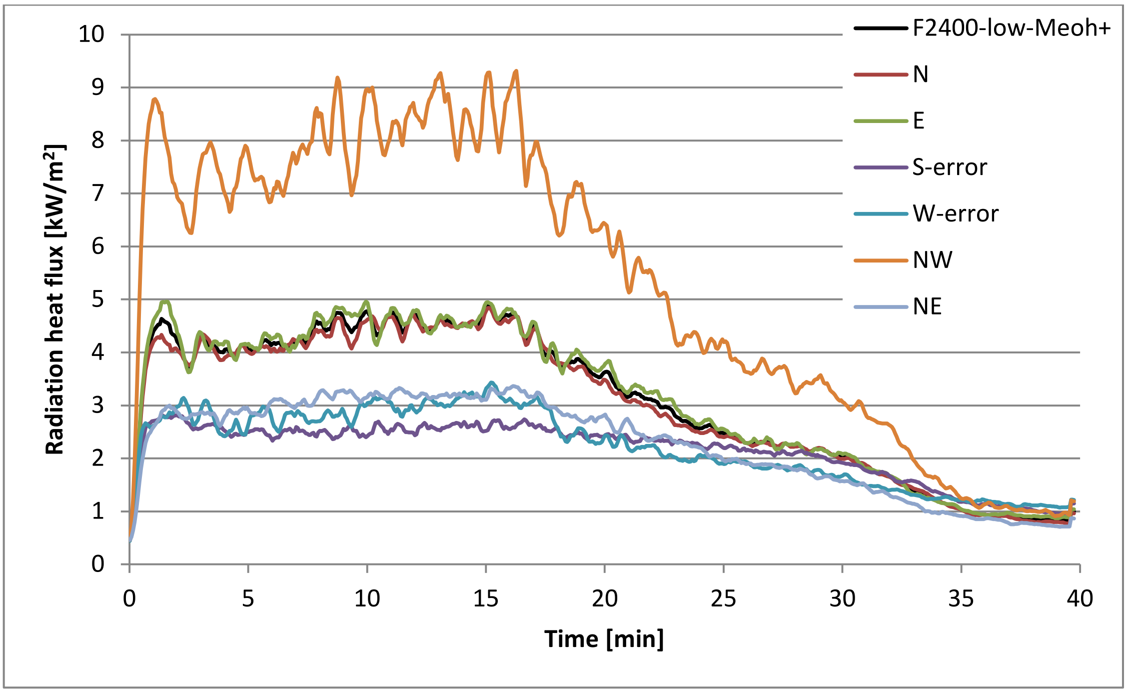

Figure 19. The full distribution of heat fluxes from free-burning methanol in a Ø2.4 flat-bottomed tray (with measurement errors for plate thermometers S and W).

3.2 Mass loss rate

The measured mass loss rate is presented in Figure 20, averaged over 1 minute seconds to reduce scatter.

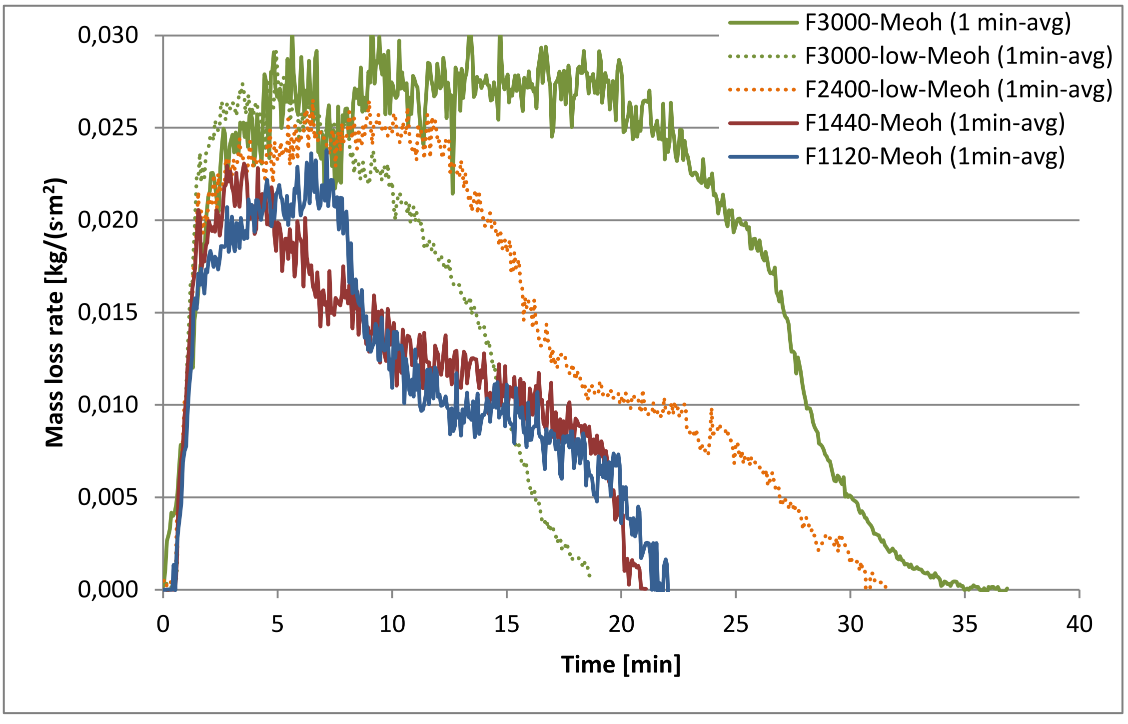

Figure 20. Mass loss rate measured (averaged over 1 min).

The mass loss rate can also be expressed as the heat release per unit area (HRRPUA), as presented in Table 4. For comparison, assuming a mass loss rate of 0.022 kg/m^2·s and a burning efficiency of 96 % (ISO, 2008) gives a heat release rate per unit area of 419 kW/m^2.

Table 4. Nominal and average heat release rates calculated from mass loss measurements

Pool		*Nominal*	*HRR from mass*	*Time*	*HRRPUA from mass*
Diam. [mm]	*Area [m^2]*	*HRR [kW]*	*loss measurements [kW]*	*period [min:s]*	*loss measurements [kW/m^2]*
1120	0.99	413	407	3:00-7:30	408
1440	1.63	682	663	2:00-6:00	407
2400	4.52	1 895	2 124	9:00-13:00	470
3000	7.07	2 960	3 465[1]	5:25-9:25	490
3000	7.07	2 960	3 659	5:00-20:00	518

1 Test performed with pool tray on the floor and with about half the amount of fuel (compared to below).

3.3 Heat release rate

The total heat release rate in the methanol tests was calculated based on the measured oxygen depletion in the calorimeter system. In the free burning tests, the heat release rate can also be calculated based on the mass loss rates measured by the load cells. The results from these measurements and calculations are presented in Figure 21. The results indicate that all the smoke was not collected from the large pool fires when the trays were placed on the floor. This was nevertheless necessary in the extinguishing tests. The too low data are marked grey in Figure 21.

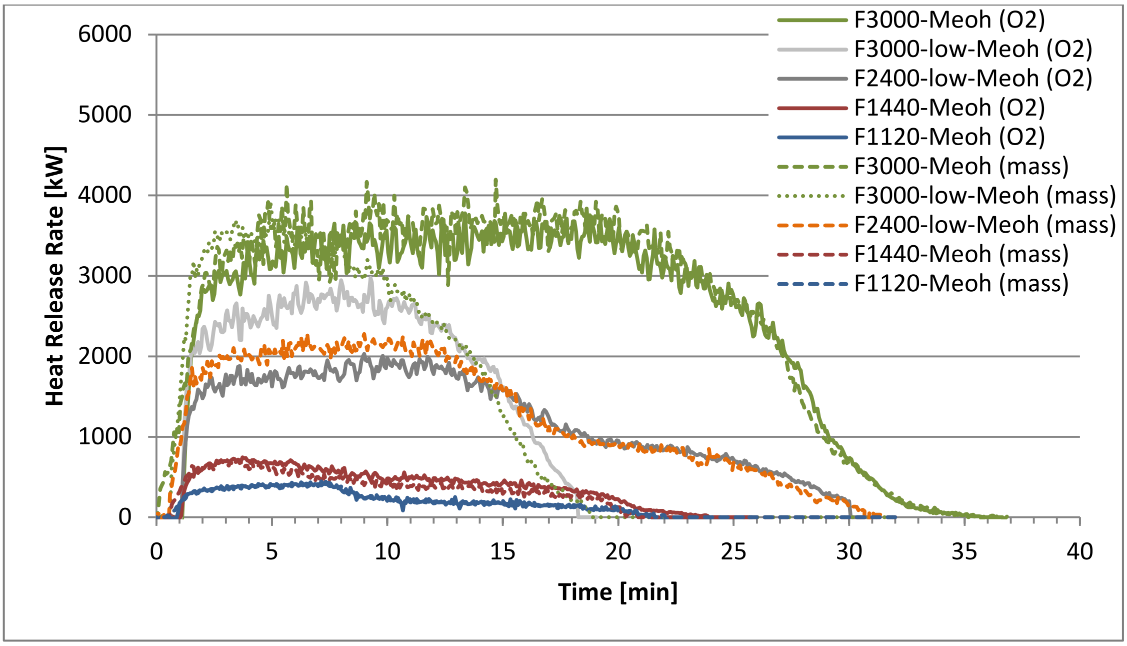

Figure 21. Heat release rates of free burning methanol (calculated from O_2 depletion and mass loss) – inaccurate measurements are marked grey.

The heat release rate form the free burning methanol can be compared to that from free burning diesel (from Arvidson & Ingason, 2005), as presented in Figure 22 (note that all smoke was not collected for *F2400-low-Meoh (O2)*, and value is thus too low).

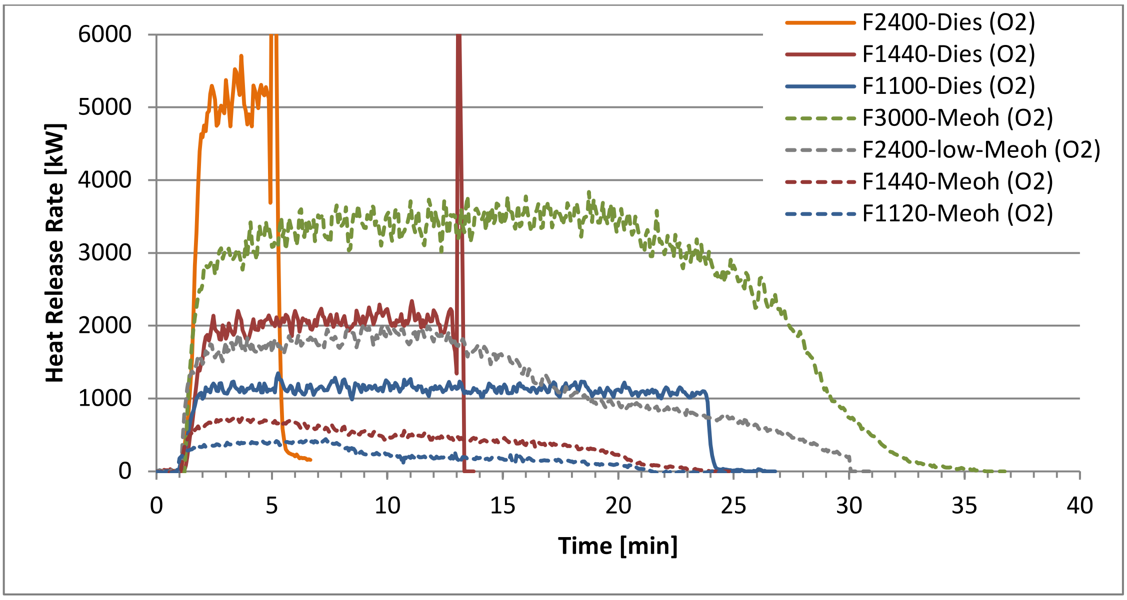

Figure 22. Heat release rates of free burning methanol and diesel (calculated from O_2 depletion) (inaccurate measurement is marked grey, peak for F1440-Dies is due to extinguishment).

The average maximum heat release rate was determined during a steady state period for each free burning fire, summarized in Table 5 in comparison with nominal values. In calculations of nominal values, a mass loss rate of 0.022 kg/m^2 was used for methanol.

Table 5. Nominal and average heat release rates calculated from oxygen depletion measurements

Pool Diam. [mm]	*Area [m^2]*	*Nominal HRR Dies. [kW]*	*Measured HRR Dies. [kW]$^+$*	*Nominal HRR MeOH [kW]*	*Measured HRR MeOH [kW]*	*Time period [min:s]*	*Measured HRRPUA [kW/m^2]*
1120	0.99	1117$^-$	1150$^-$	413	395	3:00-7:30	401
1440	1.63	2067	2060	682	684	2:00-6:00	420
2400	4.52	6180	5140*	1 895	1 878^l	9:00-13:00	415
3000	7.07	9762	*Not tested*	2 960	3 440	5:00-20:00	487

$^+$ Values from (Arvidson & Ingason, 2005).
$^-$ Nominal and measured values are based on a diesel pool with a diameter of 1100 mm (area: 0.95 m^2).
* Combustion gases escaped the Industry Calorimeter, thereby reducing the measured HRR.
l Test performed with pool tray on the floor (reduced possibility to collect all smoke and to get valid data).

In tests with extinguishing systems, the heat release rate cannot be measured by mass loss. Since the pool was placed on the floor (with a large distance to the hood), not all the smoke was collected even in the free burning test. Furthermore, in the extinguishing tests the systems cause a lot of turbulence which pushes away smoke from the hood. Nevertheless, an indication of the affected heat release rate is given by the oxygen depletion measurements. The heat release rates calculated from oxygen depletion measurements in the methanol extinguishing tests with the flat-bottomed tray are presented in Figure 23 and the heat release rates from the extinguishing tests with the conical tray are presented in Figure 24. In each of these graphs, the average constant/maximum heat release rate is also illustrated for the corresponding free burning fires.

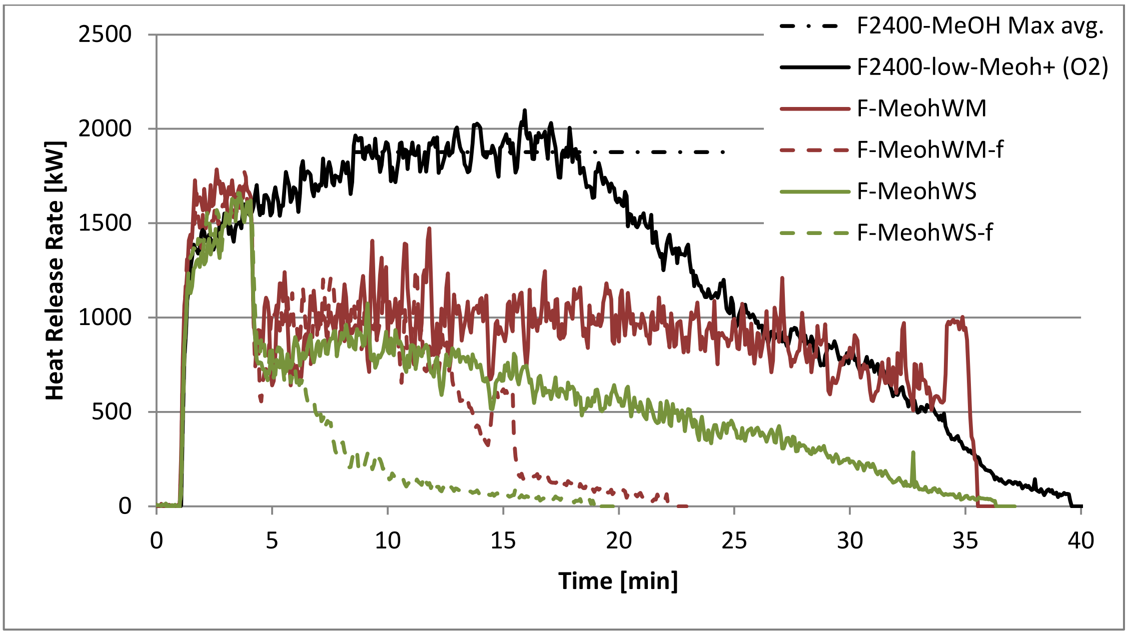

Figure 23. Heat release rates in extinguishing test with methanol in flat-bottomed tray.

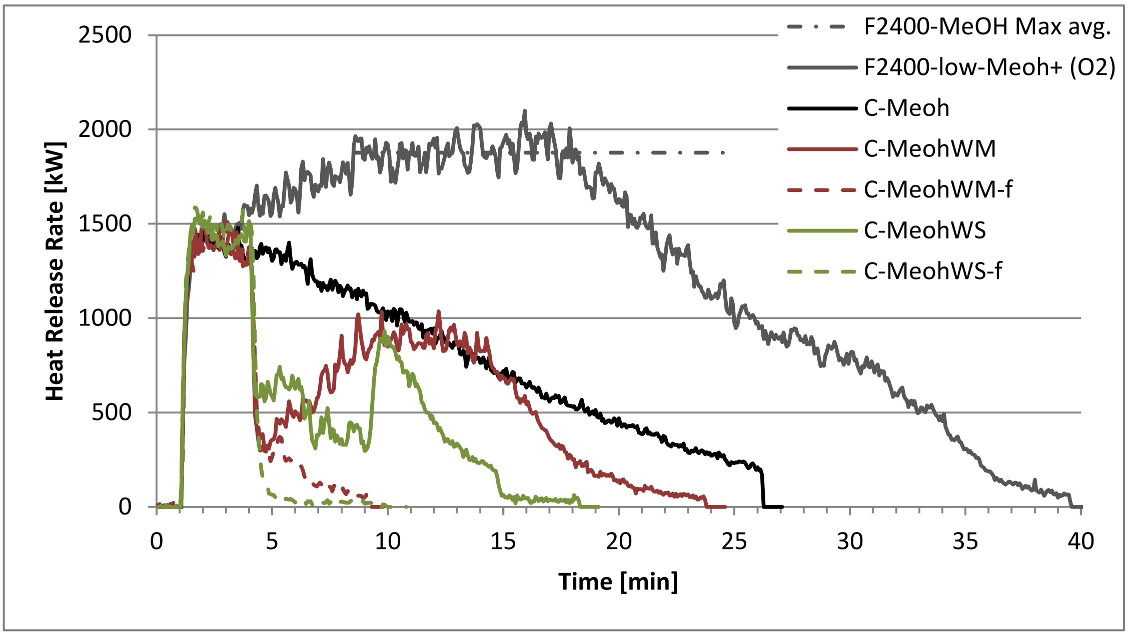

Figure 24. Heat release rate in extinguishing test with methanol in conical tray (except black curve).

Similar fire extinguishing tests were also performed with diesel and a water-mist fire extinguishing system. Data for the corresponding free burning diesel fire and with application of water spray were retrieved from Arvidson and Ingason (2005). The water spray fire extinguishing system had the same set-up as the one used in this test series, but one test was also performed with an increased discharge rate (7.5 mm/min in addition to 5 mm/min). The heat release rates calculated from oxygen depletion in the diesel free burning and fire extinguishing tests are presented in Figure 25. Note the differences in scales in comparison to previous graphs.

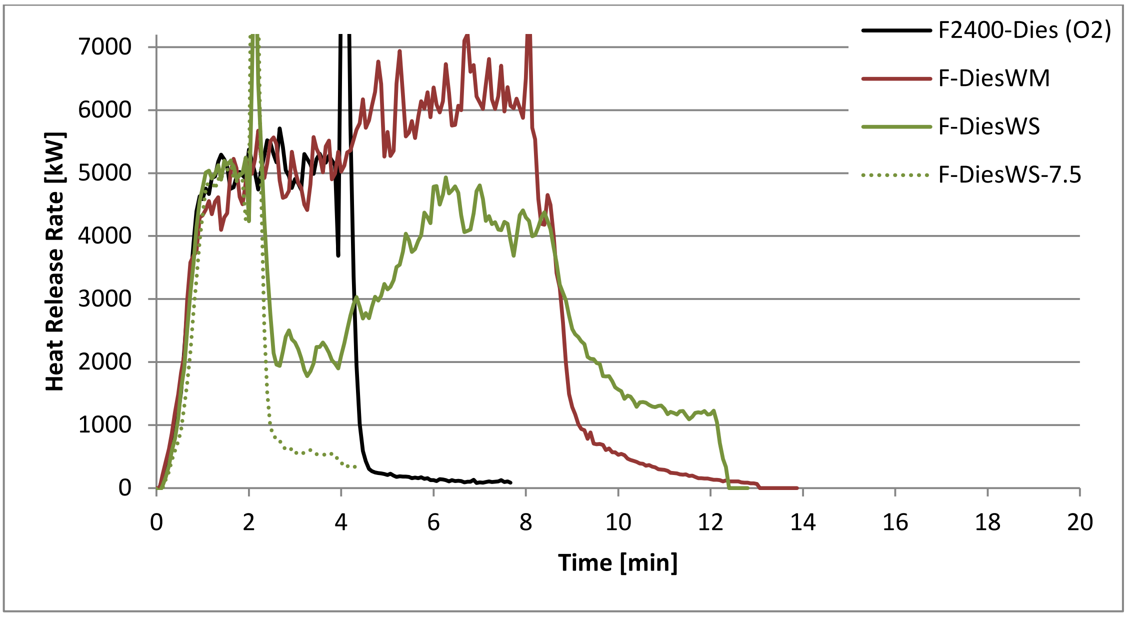

Figure 25. Heat release rate in extinguishing test with diesel in flat-bottomed tray.

3.4 Observations

The water mist system failed to extinguish the flat-bottomed methanol pool fire without foam and was stopped 30 minutes after activation. With foam it extinguished the last flames after about 16.5 minutes (13.5 minutes after activation). The water-spraying system without foam extinguished the fire 29 minutes after activation. With foam the last flames were extinguished 9.5 minutes after activation.

The fire extinguishing test with diesel performed with a water-mist system in this test series was aborted 6 minutes after activation of the system (activated 2 minutes after ignition) due to lack of any visible suppression effect of the system. The prescriptive water spraying system with a discharge rate of 5 l/m^{2}·min (reported by Arvidson & Ingason, 2005) initially suppressed the fire, but then the fire continued growing until it burned out. With increased discharge rate the fire was quickly extinguished.

For the conical tray the water-spraying system was stopped after 8 minutes (5 minutes after activation) due to overflow in the tray. The fire had then not been extinguished, but to the naked eye it appeared to become extinguished as the system was turned off, since no flames at all were visible from the diluted fuel. The IR-camera on the other hand showed how the suppressed fire slowly spread over the full surface of the tray. The pool was partly drained and extinguished manually. The water mist system (without foam) extinguished the fire after 15.5 minutes (12.5 minutes after activation). With foam the system significantly suppressed the fire and extinguished the last flames after about 5.5 minutes (2.5 minutes after activation). The water-spraying system with foam extinguished the fire 35 seconds after activation.

The times until extinguishment in the pool fire extinguishing tests are summarized in

Table **6**.

Table 6. Summary of times until extinguishment in the tests

Test denotation	*Time until extinguishment (after activation)*
F-MeohWS	29.0 min
F-MeohWS-f	9.5 min
F-MeohWM	No ext. (test aborted after 30 min)
F-MeohWM-f	13.5 min
C-MeohWS	No ext. (test aborted after 5 min)
C-MeohWS-f	0.5 min
C-MeohWM	12.5 min
C-MeohWM-f	2.5 min
F-DiesWS	No ext.
F-DiesWS-7.5	0.5 min
F-DiesWM	No ext. (test aborted after 6 min)

4 Discussion

The results of the study are discussed below, divided in the areas heat radiation, mass loss rate, heat release rate, as well as general discussions on fire suppression and extinguishment of methanol.

4.1 Heat radiation

Methanol has a low total heat of combustion of 20 kJ/g (gasoline: 38 kJ/g, diesel: 40 kJ/g, heptane: 41 kJ/g, ethanol: 25 kJ/g) (Methanol Institute, 2011; Morgan et al., 2016). How this heat is transferred is influenced by the fact that methanol is combusted very efficiently. It produces little residual products or soot particles, which usually make flames luminously yellow. Most flammable liquid fires transfer a large amount of the heat through radiation from the flames. A heptane pool fire, for example, transfers 36 % of the heat by radiation (and the rest by convection, i.e. heating up surrounding gases/air), but literature states that methanol only transfers 17 % of the heat by radiation (Koseki, 1989). Hence, methanol produces less heat and transfers relatively less heat to surroundings by radiation than many flammable liquids, and it only displays weakly blue flames (almost invisible in daylight).

The test results confirmed that the radiation heat flux from a methanol fire was low, in particular in comparison to diesel (diesel emitted 5-6 times more radiation than methanol at 2 m). The radiation from diesel was 5-7 times higher than from the corresponding methanol pool fires at a distance of 2 m. Furthermore, Figure 13 shows that the radiation a few meters from a methanol fire is rather independent of the fuel pool size, unlike the radiation from diesel, which is heavily depending on the fuel pool size. Hence, regardless of the size of a methanol pool fire, a fire fighter will be able to approach the fire to improve fire fighting.

The incident radiation heat flux from methanol pool fires has been measured from small and large pool fires, up to 50 m^2. The largest pool fire showed that the radiation heat flux at a distance of 2 m was about 10 kW/m^2, which is very low for this size fire (Holmstedt, Ryderman, Carlsson, & Lennmalm, 1980). Adding this information to the test data allows fitting an equation predicting the radiation heat flux at a distance of 2.0 m from methanol pool fires of a large size range. As illustrated in Figure 26, the radiation heat flux from a methanol pool fire approximately follows the function $2\ln(A) + 2$ kW (where A is the methanol pool area in m^2).

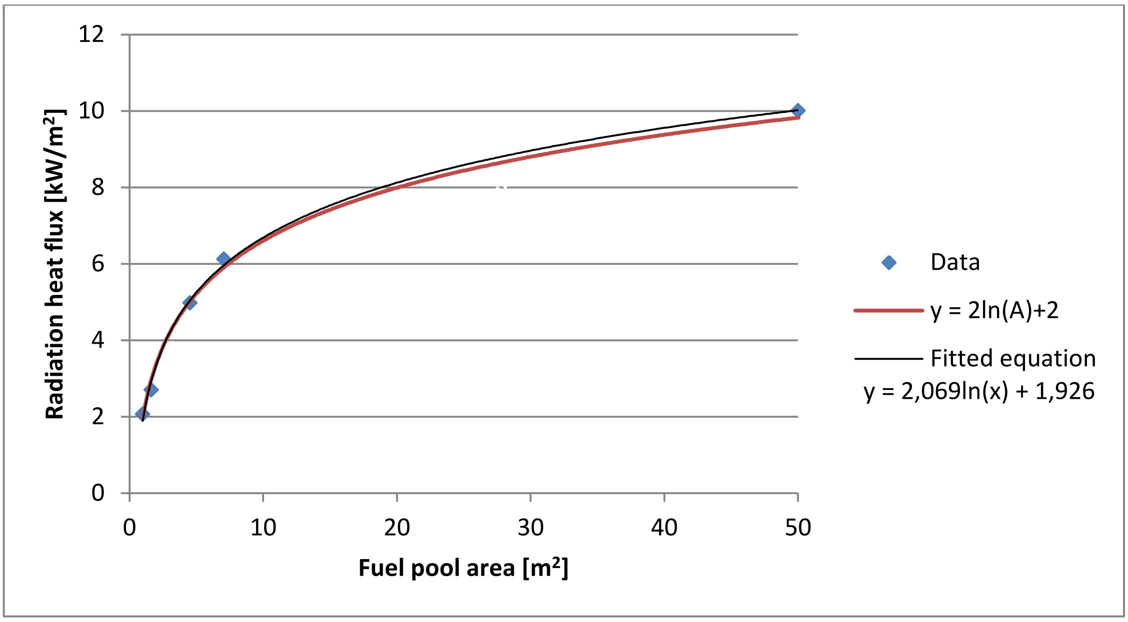

Figure 26. Relation between a methanol pool fire in size and the radiation heat flux at 2.0 m.

Furthermore, the results showed that the radiation heat flux was reduced with the distance from the methanol fire. Figure 14 indicates that the radiation was about proportional to the distance inversed, i.e. the radiation was reduced to about half at 2 m and to about a third at 3 m, compared to the radiation at 1 m. This is in line with conventional calculations of radiation heat transfer from flames.

When methanol was suppressed by water mist or water spray (with or without foam), the radiation heat flux around the pool was reduced to insignificance, whilst the radiation from diesel was reduced in half by the prescriptive extinguishing systems (applied in the open test setting).

4.2 Mass loss rate from free burning fires

The radiation from a fire is important since it affects the potential for fire spread but also by affecting the mass loss rate (vaporization) of the fuel and hence the heat release rate. Another parameter affecting the mass loss rate is the ability of the liquid to absorb heat radiation. Ethanol, which in many ways is similar to methanol, has a high absorptivity of 90 % (heptane for example absorbs 65 %) (Suo-Anttila, Blanchat, Ricks, & Brown, 2009). Since the average radiation towards a fuel surface increases with the fire size up to a certain level, it is common that the mass loss rate (per unit area) increases as well. Mass loss rates for methanol pool fires have been proposed between 0.013-0.029 kg/m^{2}s (Babrauskas, 2016; Holmstedt et al., 1980; Khan, Tewarson, & Chaos, 2016; Kung & Stavrianidis, 1982; McGrattan, Baum, & Hamins, 2000), which is quite a wide range. Babrauskas (2016) claims that some unspecified new test results show a clear diameter effect, although it cannot be expressed in standard form, and he recommends the following values for both methanol and ethanol [kg/m^{2}s]: 0.015 (D < 0.6 m); 0.022 (0.6 < D < 3.0 m); and 0.029 (D > 3.0 m). At the same time, Khan et al. (2016) and Koseki (1989) state mass loss rates of 0.024–0.025 kg/m^{2}s for 1.0–2.4 diameter fires and Holmstedt et al. (1980) measured a mass loss rate of 0.024 kg/m^{2}s for a 50 m^2 methanol pool (D = 3 m gives 7 m^2).

In the tests in this series, performed with 1–7 m^2 methanol pools, mass loss rates of 0.021–0.027 kg/m^{2}s were recorded, as summarized in Figure 27. This is in line with the majority of the data in studied literature. Furthermore, in the tests the recorded mass loss rates increased linearly with the pool area in this range. However, it is not clear to what extent the mass loss rate continues to increase with the pool area. Babrauskas (2016) claims that the mass loss rate for methanol (and ethanol) pools larger than 3.0 m in diameter is 0.029 (D > 3.0 m). At the same time, Holmstedt et al. (1980) measured a mass loss rate of 0.024 kg/m^{2}s for a 50 m^2 methanol pool (D = 3 m gives 7 m^2). Hence, it is not clear if effects appear which cause continued increase or sudden decrease of the mass loss rate with the pool area.

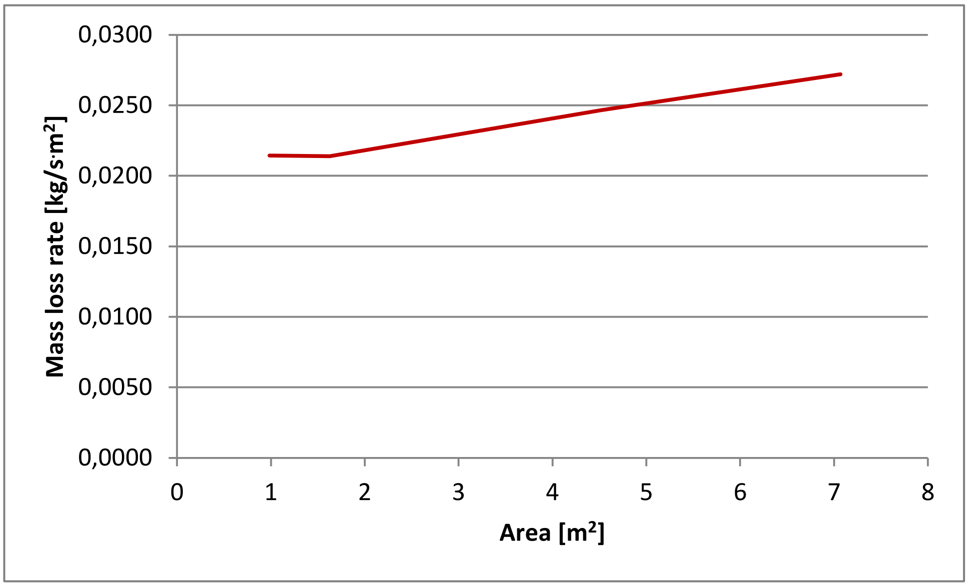

Figure 27. Summarized mass loss rates recorded in the test series.

The mass loss rate for medium sized methanol pools (1–7 m^2) around 0.024 kg/m^{2}s can be compared to mass loss rates of up to 0.036 kg/m^{2}s for diesel, 0.062 kg/m^{2}s for gasoline, and 0.081 kg/m^{2}s for M15 (Holmstedt et al., 1980; Methanol Institute, 2011).

4.3 Heat release rate from free burning fires

The combustion efficiency of methanol is close to unity (Heskestad, 1981); 96 % is for example stated in ISO 24473 (ISO, 2008). However, its relatively low mass loss rate in combination with a low total heat of combustion results in a low heat release rate per unit area. For pure methanol (the heat release rate is reduced with water content), literature state heat release rates per unit area of 400-500 kW/m^2. This was confirmed by the performed free burning fire tests, which also showed that the level in this range depends on the pool area. This dependency is summarized in Figure 28. As noted above for the mass loss rate, it is not known if the heat release rate per unit are continues to increase with the pool area of if it stabilizes or decreases for pool areas above 7 m^2. The heat release rates per unit area of methanol of 400-500 kW/m^2 can compare to about 1 400 kW/m^2 for diesel and about 2 300 kW/m^2 for gasoline (Methanol Institute, 2011). The heat release rates for the diesel pool fires were close to nominal values and generally three times higher than for the methanol pool fires (per unit area).

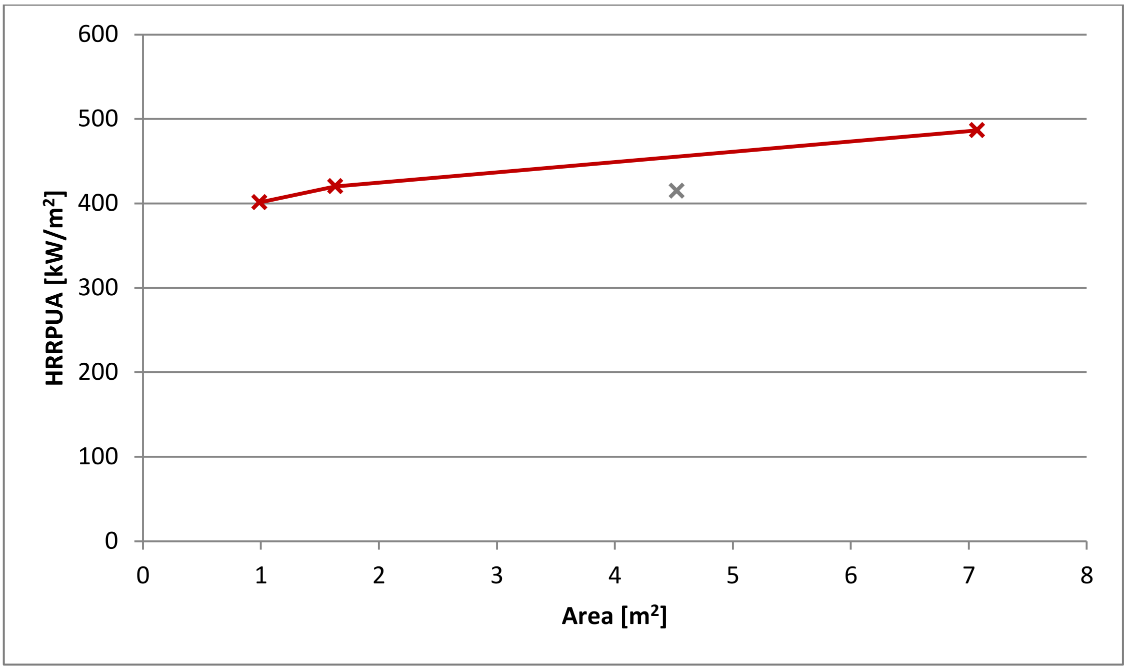

Figure 28. Heat release rates per unit area calculated from oxygen depletion measurements – inaccurate measurement is not considered/marked grey.

The data from the Ø2.4 m pool on the floor was excluded from the curve in Figure 28 since all the combustion gases were not properly collected. This was verified by the two Ø3.0 m pool fire tests performed on the floor and raised closer to the hood. Figure 21 illustrates a large difference in heat release rate calculated from mass loss and calculated oxygen depletion for the Ø3.0 m pool and also a noteworthy difference for the Ø2.4 m pool. The reason for this is that air entrains the fire plume along its full height, resulting in an increasing mass flow with the distance from the fire source to the power of 5/3 (Karlsson & Quintiere, 2000). A large pool and a large distance between the fire source and the collecting hood thus put large requirements on the hood capacity if all the combustion gases are to be collected by the hood.

Comparing the heat release rates calculated from mass loss and from oxygen depletion (se Figure 21) for the raised pools can also give an indication of the combustion efficiency. It appears that the combustion efficiency decreased from about 94-99 % for the small fires to about 90 % for the Ø3.0 m pool fire. However, it should be noted that these figures are within the measurement uncertainty limits.

4.4 Suppression and extinguishment of methanol fire

The extinguishing tests in both the flat and the conically-bottomed trays indicate that foam injection is necessary to swiftly extinguish a methanol fire. The tests with the flat-bottomed tray, presented in Figure 23, show quite similar results regardless of the use of water mist with foam or water spray with foam. Both systems suppressed fire instantly with foam, even if some time was required to extinguish the last small flames, in particular for the water mist system. As illustrated in Figure 24, the time until complete extinguishment was significantly shortened with the conical tray, which helped collecting foam-water beyond the fuel pool and facilitated gentle application. This is quite realistic in a ship machinery space, where most fuel and extinguishing water is collected in the bilge.

Without foam the extinguishing systems had limited effects on the methanol pool fires in the flat-bottomed tray. The results show that the heat release rate was instantly reduced to about half compared to the free burning fire, illustrated in Figure 23. Part of this reduction in heat release is due to cooling of the flames, attenuation of radiant heat to the fuel surface, and dispersion of oxygen and fuel vapor. However, some of the difference likely also appears due to the systems pushing away the combustion gases from the Industrial Calorimeter hood and that the cooled combustion gases loose buoyancy and are thereby not collected. The whole reduction is thus likely not real, but it can still be used for relative comparisons. For example, the graphs (for the water mist and water-spraying systems without foam) show an increasing difference in heat release rate. This indicates that the water-spraying system finally extinguished the fire by dilution of the surface layers, owing to the larger discharge density. Hence, in line with Rasbash, Rogowski, and Stark (1960) it can be concluded that the dominating extinguishing mechanism for methanol is dilution of the surface layers. This reduces the generation rate of combustible vapor from the liquid until it is below the value required to support flame, i.e. the flashpoint of the fuel-water solution is increased above the current temperature.

Comparing with extinguishing results on the same size diesel pool fire, the water spray and (particularly) the water-mist system were even less effective on diesel. This is due to the significantly higher heat release rate from diesel and the open fire scenario set-up. Arvidson and Ingason (2005) showed that a quite high discharge rate (7.5 mm/min) is necessary for the water to reach down to and extinguish such a large diesel pool fire in such an open space (more water than prescribed for machinery spaces). It should be noted that even if the methanol fires were not quickly extinguished with only water, the heat from the fires was effectively attenuated.

For the conical tray, Figure 24 shows a significant decrease in heat release rate from the methanol fire when the extinguishing systems are activated without foam. However, this significant reduction was not as apparent in observations of the fires. As discussed above, it is likely that the systems push away the combustion gases from the hood, which causes a part of this apparent reduction. This is also supported by that the heat release rate with the water-mist system eventually returns to that of the free burning reference fire (conical). The real reduction in heat release rate over time is, as concluded for the flat-bottomed pool above, likely due to dilution in the surface layers. For the conical tray this is achieved faster than for the flat-bottomed tray since water was collected over the whole Ø4.0 m tray, hence also outside the burning fuel pool.

4.4.1 Foam fire extinguishment

A conclusion from above is that (alcohol-resistant) foam is necessary to provide effective and efficient water-based fire extinguishment of a methanol fire. Even if the time until complete extinguishment of the fires, in particular in the flat-bottomed tray, required some time, the suppression systems quickly left only small flames around the edges of the pools when using foam injection. As discussed above, fuel by objects is the most demanding to extinguish due to screening (reduced cooling/dilution effects) and since the heat from an object increases vaporization. This makes it challenging to form a sealed foam/film layer around objects. The last small flames are obviously important to extinguish to avoid reoccurring fire escalation, but it can be considered more important that the fire is significantly suppressed and controlled. This reduces heat exposure to surrounding equipment and also allows safe ingress and manual extinguishment of the last flames. The differences between the water mist and water-spraying systems can therefore be considered of minor importance, even if the larger discharge rate gave improved results.

Application of fire-extinguishing foam creates a foam layer which blocks the heat radiation from the flames towards the fuel surface and cools the fuel through drainage. This reduces the release of fuel vapor from the surface, which for film-forming foams is also contributed by the film formed on the fuel surface. The effect is suppressed combustion. A thick foam layer contributes by blocking radiatnt heat and by preventing mixing of the fuel vapor with air. However, conventional fire-extinguishing foam will be destroyed if used for a fire in methanol or other polar fuels, since the foam concentrates are water based and dilute into the fuels. It is therefore necessary to use alcohol resistant foam if injected into a sprinkler system covering methanol installations. Such foams have been tested for acetone and IPA (isopropyl alcohol), which in the development of the test methods for alcohol resistant foams (e.g. "Fire extinguishing media - Foam concentrates - Part 3: Specification for low expansion foam concentrates for surface application to water-immiscible liquids," 1999; IMO, 2009; ISO7203-1, 1995) were proven to be more difficult to extinguish than e.g. methanol[1]. Hence, by achieving the fire tests and applicable requirements for alcohol resistant foams in the above referenced standards, such foams can be considered effective for methanol.

4.4.2 Extinguishment by dilution

The flashpoint depends on the water-content of the methanol. Small-scale experiments have been performed which show that methanol water solutions are ignitable up to about 65 % volume composition of water at normal room temperature (Nilsson, 2005). It has therefore been promoted as a general rule that burning methanol must be diluted by 75 % water to achieve extinguishment (Allicance Consulting International, 2008). Liaw and Chiu (2003) derived a method to theoretically calculate the flashpoint dependence of water diluted methanol and compared it with data. It showed that the 75 % dilution corresponds to a flashpoint of 35 °C, which means that the liquid (room) temperature would need to be below 35 °C to avoid piloted ignition.

However, there is a significant difference between the concept flashpoint and to reduce the generation rate of combustible vapor from a burning liquid until it no longer supports combustion. The flashpoint is determined by introducing a small test flame (3x5 mm) as ignition source over a fuel surface (at a given temperature) (ISO, 2016). A fuel on fire obviously has a significantly higher temperature than the surrounding ambient temperature and therefore generates significantly more vapor than suggested by the flashpoint. Another kind of ignitability tests were performed by Louis (1939) [secondary from (Coward & Jones, 1952)] claiming that the vapors of a liquid containing methanol and 80 % water was difficult to inflame in any mixture of the vapor and air at 105 °C, and that vapors of methanol and 85 % water was impossible to inflame.

To evaluate flammability and extinguishment limits further, the water content was chemically analyzed after one of the tests in the series; the test where the water-spraying system (without foam) extinguished the methanol fire in the flat-bottomed pool. The system was stopped seconds after extinguishment of the fire and the sample was taken from the surface layer of the pool directly after. The sample analysis showed water content of 87.6 vol%, which indicates that the flashpoint dependence on water-content is a poor basis for estimating the dilution by water required for extinguishment of methanol. Hence, it should be stressed that the flashpoint only suggests limits for ignitability by a small ignition source. In this regard it can be noted that methanol diluted with 75 % water was tested easy to ignite by a larger ignition source, e.g. a small torch.

The significant amount of water required to extinguish methanol makes it essential that water is used wisely. For example, if much water is used to cool surrounding equipment, and if water

[1] Initially a DNV method was developed in the ´80s based on (Holmstedt et al., 1980), including fire tests with acetone, IPA, methyl ethyl ketone (MEK), n-Butyl acetate and methanol; only the first two fuels were included in the further developed test method NT Fire 023 (NORDTEST, 1993) and in the further developed ISO and EN standards since those fuels in all scenarios were the most difficult to extinguish.

runoff mixes with burning methanol, then the solution can cause a so-called “running fire”. With methanol this is particularly hazardous since such propagation of fire may not be immediately noticed by responders due to methanol producing an almost invisible flame in daylight. Furthermore, something that was observed in the tests, and has not been found elsewhere in literature, is that methanol flames become increasingly invisible with water-content. Even though the tests were conducted in an enclosed fire hall with black walls, the flames of well diluted methanol were completely invisible to the naked eye. In the IR camera the flames were visible with slightly reduced flame height and radiation.

5 Conclusions

The combustion efficiency of methanol is close to unity (90-99 % in the tests, reducing with increased pool area) but its relatively low mass loss rate in combination with a low total heat of combustion result in a low heat release rate per unit area. The mass loss rate of methanol (per unit area) increases with the pool size and for 1–7 m^2 pools it in the range 0.021–0.027 kg/m^2s. The resulting heat release rate per unit area of medium sized methanol pools thereby increases with the pool area and is in the range 400-500 kW/m^2. This is about 1/3 compared to diesel and 1/5 compared to gasoline. The heat release rate of methanol is reduced with water content.

There are different extinguishing mechanisms when using water for extinguishment. Gas phase (flame) cooling and radiation attenuation by vaporization of water droplets are not sufficient effects when extinguishing methanol, likely due to the relatively low heat produced and the limited flames. Methanol further has a low oxygen index (due to oxygen in the molecule) and is less sensitive to oxygen depletion and vapor dilution than fuels like diesel. With a water-based system, combustion of methanol is instead primarily interrupted by diminishing vaporization of the fuel. With methanol, this is primarily done by dilution of the fuel surface layer (contributed by cooling of the fuel, which however is not very effective due to the low fuel flashpoint).

The film-forming function in alcohol resistant foams is effective in blocking vaporization gases and the foam impedes radiation from the flames (and thus vaporization). In the tests, foam injection gave significantly reduced times until extinguishment (compared to without foam) and significantly improved suppression of the fires. Foam injection is therefore required in water mist and water-spraying systems to achieve swift and efficient extinguishment of a methanol fire.

When using water mist and water-spraying systems without foam, dilution of the methanol surface layer is the dominating mechanism for extinguishment. However, extinguishment is not expectable until reaching very high water content. Analysis after extinguishment showed water content of almost 90 %, which could put large requirements on management of water runoff to avoid a running fire. Extinguishment of diluted methanol should not be confused with the flashpoint dependence on water-content, which only determines ignitability by a small ignition source. Furthermore, it was shown that increased water content in methanol makes the normally weakly blue flames increasingly invisible, which adds to the hazards of methanol fire extinguishment.

The water-spraying system used in the tests generally performed better than the water-mist system, which primarily had challenges to extinguish the last small flames around the edges of the open pool fires. However, both systems effectively suppressed and attenuated the heat from the methanol fires, in particular in comparison with the same size (area) diesel fires.

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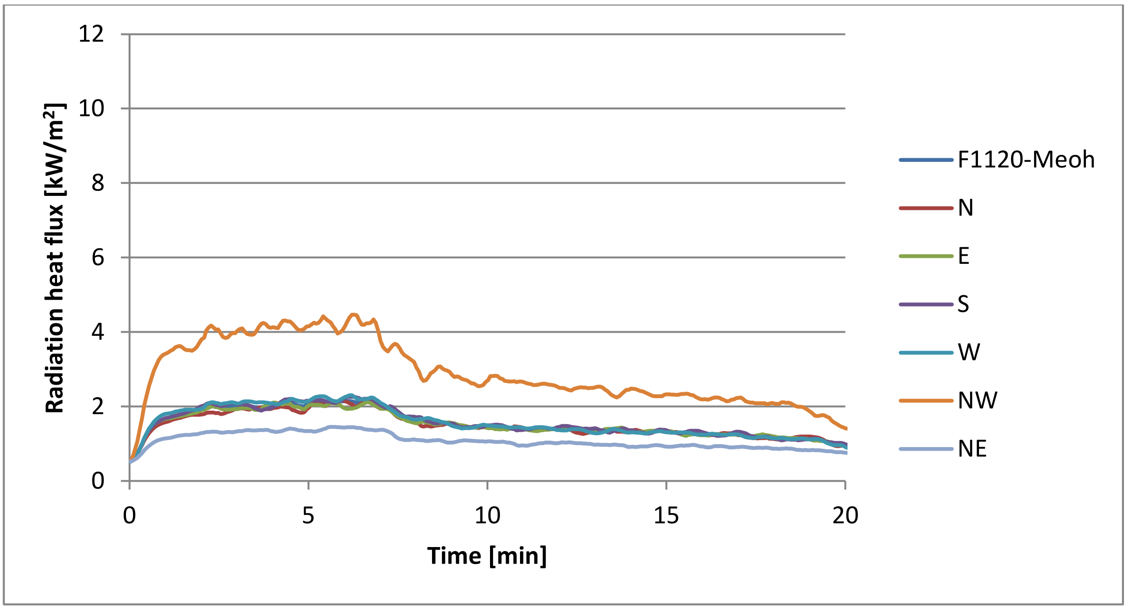
Appendices

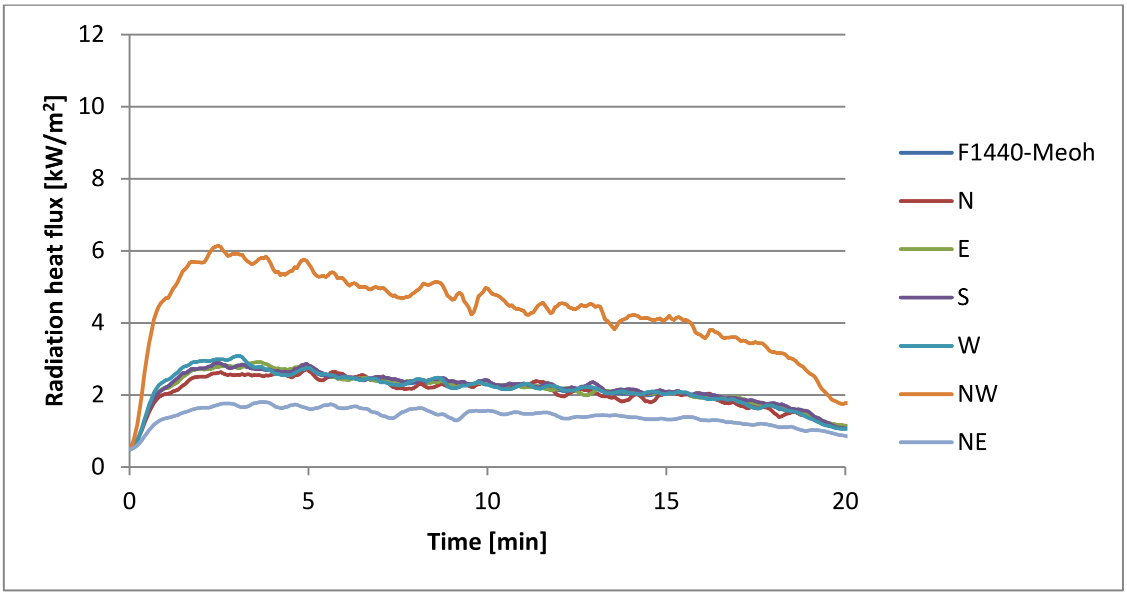
1. Radiation heat flux from measurements

Appendix 1

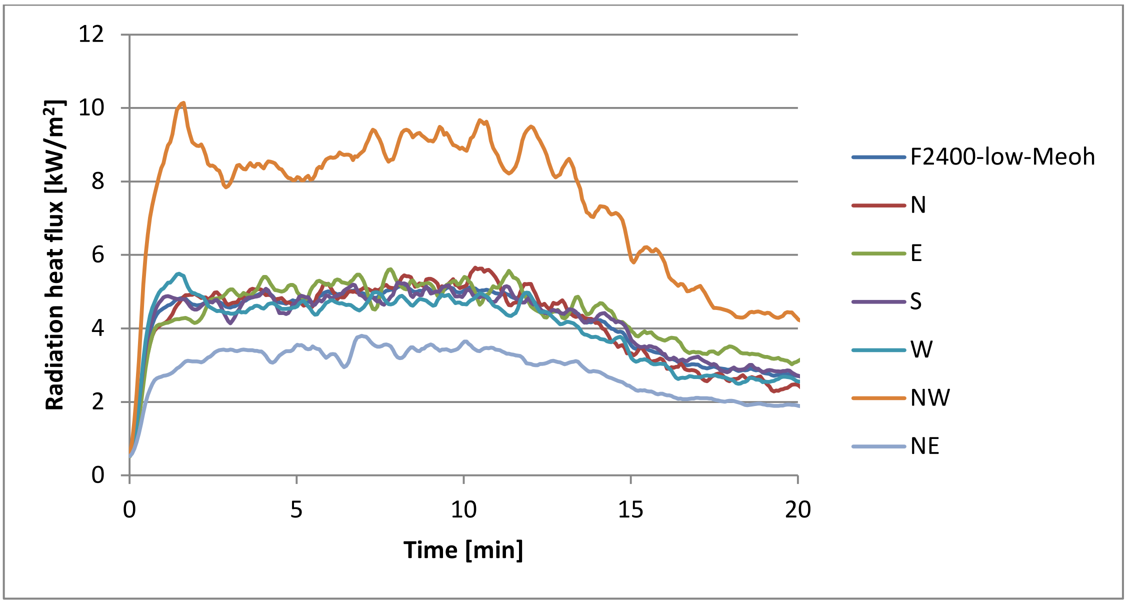
Radiation heat flux from measurements

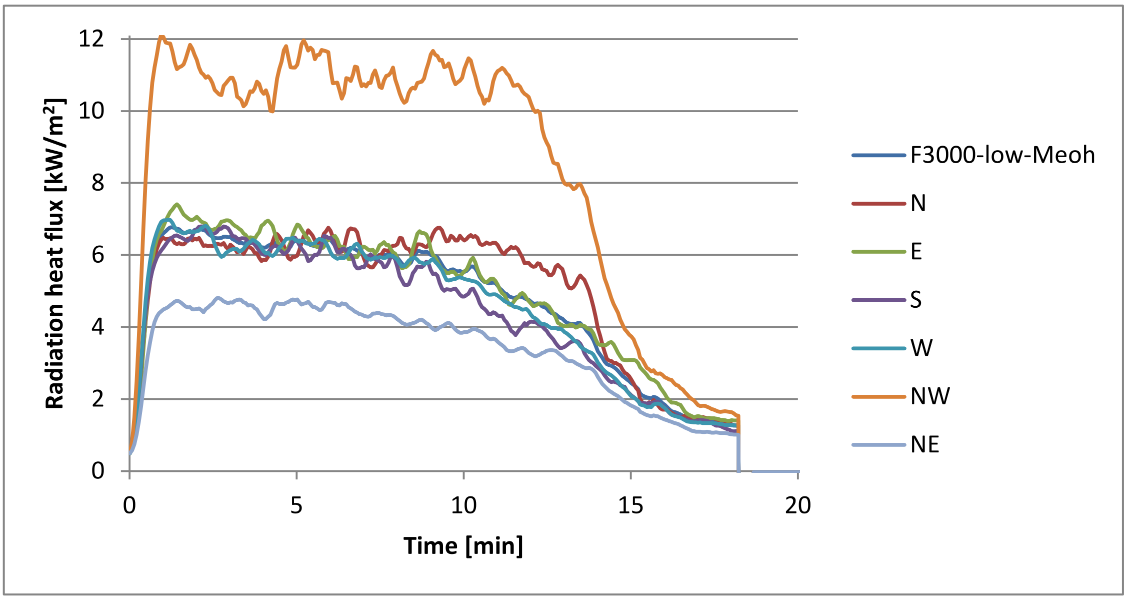
Below are presented full distributions of radiation heat fluxes for free-burning methanol in circular trays of different size and type. The flat-bottomed trays had a diameter of 1.12 m, 1.44 m, 2.4 m, and 3.0 m, and the tray with conical bottom was filled to attain a pool diameter of about 2.4 m at ignition. For the tray with a conical bottom, no plate thermometer was placed 1 m (NW) from the pool perimeter (at ignition).



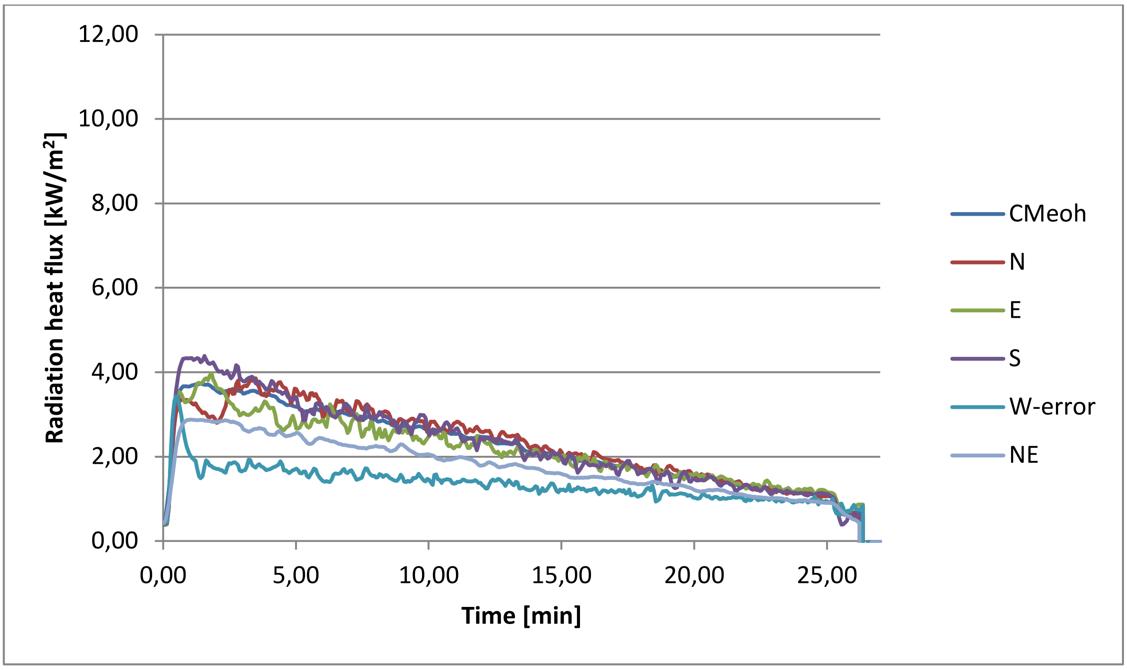


Appendix 1


Radiation heat flux [kW/m²]
Time [min]
0
2
4
6
8
10
12
0
5
10
15
20
F2400-low-Meoh
N
E
S
W
NW
NE


Radiation heat flux [kW/m²]
Time [min]
0
2
4
6
8
10
12
0
5
10
15
20
F3000-low-Meoh
N
E
S
W
NW
NE

Appendix 1


12,00
10,00
8,00
6,00
4,00
2,00
0,00
Radiation heat flux [kW/m²]
0,00
5,00
10,00
15,00
20,00
25,00
Time [min]
CMeoh
N
E
S
W-error
NE

Contact person
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Date
2017-05-10

Reference
BRd6081-03

Part of the proFLASH research project

Total compartment fire extinguishing tests with methanol

(1 appendix)

1 Background

The stricter regulations for Sulphur content in bunker fuel have stimulated use of alternative fuels such as LNG and methanol, which differ from traditional bunker fuels in many ways. One important difference is their low flashpoint, which increases the probability of ignition in case of leakage. There are also other differences which increase fire risks, not least properties which affect the possibilities for fire detection and extinguishment. Methanol flames can for example be invisible and oxygen is bound to the molecule. LNG has a very low boiling point and is difficult to extinguish with water.

The purpose of the proFLASH project was to increase knowledge and to influence regulations regarding fire detection and fire extinguishment of low-flashpoint fuels, in particular LNG and methanol. The project consisted of a preliminary study and large-scale fire test phase, evaluating the suitability of relevant detection and extinguishing system solutions. It was decided to focus the experimental part of the project on methanol.

This report documents one of the test series performed in the proFLASH project, evaluating water-based fire extinguishing systems (with foam injection) for machinery spaces (cat. A). The large scale tests were based on the approval guidelines in MSC/Circ.1165 (IMO, 2005) and included some of the required tests, as well as the corresponding tests but with the fuel replaced by methanol.

2 Experimental setup and procedure

In accordance with SOLAS (IMO, 1974), machinery spaces of category A shall generally be provided with a fixed fire-extinguishing system, with either:

- gas;
- high-expansion foam; or
- pressure water spray.

The system should comply with the provisions of the Fire Safety Systems (FSS) Code (IMO, 2007). It specifies that pressure water-spraying systems shall be arranged to ensure an effective average distribution of water of at least 5 l/m^2/min. Furthermore, it specifies that water-mist fire-extinguishing systems can also be used after approval based on the guidelines in MSC/Circ.1165 (IMO, 2005). In addition to technical specifications, the guidelines require that the water-mist system can achieve extinguishment within 15 minutes (no re-ignition) in a number of fire tests. The tests are performed in an at least 500 m^3 compartment with a 4 m^2 doorway opening. The design fires are located around an engine mock-up in the middle of the compartment and consist of diesel and heptane pool and spray fires as well as a wood crib. The engine mock-up is illustrated in Figure 1 and the performed test fire scenarios are marked in Figure 2 and further detailed in Table 1 and Table 2.

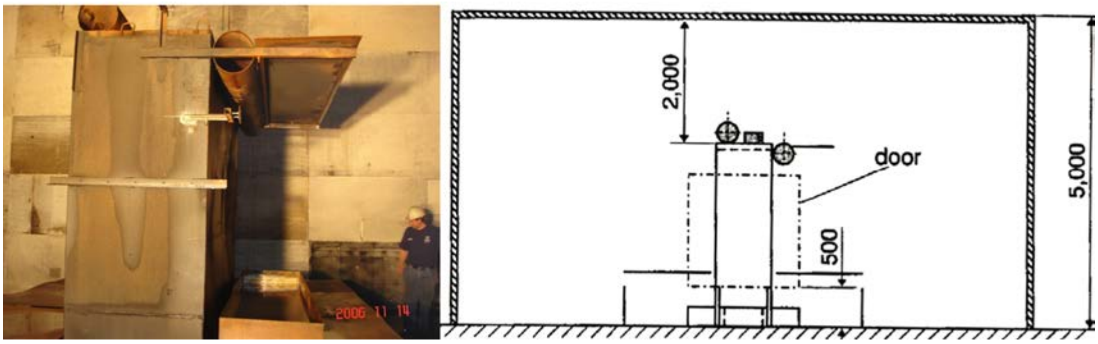

Figure 1. Test compartment with the engine mock-up in the center.

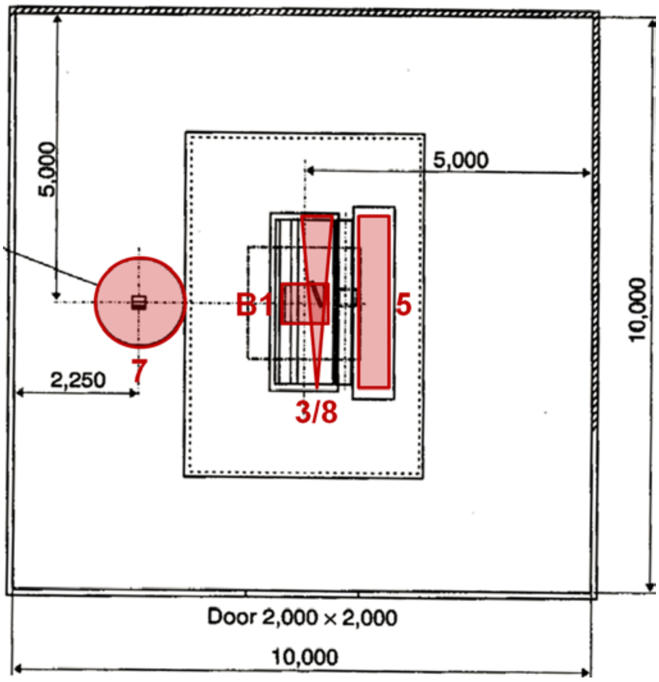

Figure 2. Illustrations of test fire scenarios around the engine-mock-up.

Table 1. Fire scenarios performed for ceiling nozzles in accordance with MSC/Circ.1165

Test No.	Fire Scenario	Test Fuel
1	Low pressure horizontal spray on top of simulated engine between agent nozzles.	Commercial fuel oil or light diesel oil
2	Low pressure spray in top of simulated engine centred with nozzle angled upward at a 45° angle to strike a 12-15 mm diameter rod 1 m away.	Commercial fuel oil or light diesel oil
3	High pressure horizontal spray on top of the simulated engine.	Commercial fuel oil or light diesel oil
4	Low pressure concealed horizontal spray fire on the side of simulated engine with oil spray nozzle positioned 0.1 m in from the end of the engine and 0.1 m^2 tray positioned on tope of the bilge plate 1.4 m in from the engine end at the edge of the bilge plate closest to the engine.	Commercial fuel oil or light diesel oil
5	Concealed 0.7 m × 3.0 m fire tray on top of bilge plate centred under exhaust plate.	Heptane
6	Flowing fire 0.25 kg/s from top of mock-up (see figure 3).	Heptane
7	Class A fires wood crib (see Note) in 2 m^2 pool fire with 30 s preburn. The test tray should be positioned 0.75 m above the floor as shown in figure 1.	Heptane
8	A steel plate (30 cm × 60 cm × 5 cm) offset 20° to the spray is heated to 350°C by the top low pressure spray nozzle positioned horizontally 0.5 m from the front edge of the plate. When the plate reaches 350°C, the system is activated. Following system shutoff, no reignition of spray is permitted.	Heptane

Table 2. Fire scenarios performed for bilge nozzles in accordance with MSC/Circ.1165

Test No.	Fire Scenario	Test Fuel
B1	0.5 m^2 central under mock-up	Heptane
B2	0.5 m^2 central under mock-up	SAE 10W30 mineral based lubrication oil
B3	4 m^2 tray under mock-up	Commercial fuel oil or light diesel oil

The test fire scenarios described in Table 1 (1-8) are performed for nozzles placed in the compartment ceiling and the tests in Table 2 (B1-B3) are performed for nozzles in the bilge area (the area between the solid engine-room floor plates and the bottom of the engine room) (IMO, 2005). Out of the test fire scenarios required for type approval of an equivalent water-based fire-extinguishing system for machinery spaces and pump-rooms, four characteristically different scenarios were selected for this test series, namely number 3, 5, 7, and B1. However, since a sustainable flame was not attainable with methanol in test scenario 3, the scenario was replaced by test scenario 8 (containing a re-ignition/heat source), but keeping the high pressure spray used in test scenario 3. Hence, this was a combination of scenario 3 and scenario 8. Each test scenario was performed with both the fuel according to the standard and with methanol.

In addition to the fire test scenarios based on the guidelines in MSC/Circ.1165, simple pool fire extinguishing tests were performed in the 500 m^3 test compartment (with a 4 m^2 doorway opening). The tests were performed with differently sized pool fires of diesel and methanol. Instead of using the same size trays for the fuels, the ambition was to achieve similar heat release rates of 0.5 MW, 1 MW, and 2 MW. The pools were placed in the center of the compartment and different extinguishing systems were applied (described further below).

The compartment fire extinguishing test program, with the different fire scenarios, fuels, and extinguishing systems, is presented in Table 3. The test ID in the first column is for the tests based on MSC/Circ.1165 defined as *XY-WZp-f*, where *X* is the test number in the guidelines (see Table 1), *Y* is the fuel used, *W* stands for water and *Z* denotes spray (*S*) or mist (*M*), *p* denotes the pressure for the water mist (*l* for low or *h* for high), and *f* is added if foam was used in the test (specified in the rightmost column). For the centered open pool fire scenarios the test ID was derived in a similar manner, but without the initial test number and an added effect designation (*0.5*, *1.0*, or *2.0* MW) following after the fuel indication.

Table 3. Test program for the pool fire and extinguishing tests performed within proFLASH

Test ID	*Fire scenario*	*Fuel*	*Extinguishing system*	*Foam*
3D-WS	High pressure spray	Diesel	Water spray	-
3D-WMl	High pressure spray	Diesel	Water mist (LP)	-
3D-WMh	High pressure spray	Diesel	Water mist (HP)	-
3M-WS-f	High pressure spray	Methanol	Water spray	ARC 1x1 NV
8M-WS-f [+]	High pressure spray + reign.	Methanol	Water spray	ARC 1x1 NV
8M-WMl-f	High pressure spray + reign.	Methanol	Water mist (LP)	Tyco
8M-WMh-f	High pressure spray + reign.	Methanol	Water mist (HP)	Arctic 1x1 LV
5H-WS	Concealed pool	Heptane	Water Spray	-
5H-WMl	Concealed pool	Heptane	Water mist (LP)	-
5H-WMh	Concealed pool	Heptane	Water mist (HP)	-
5M-WS-f	Concealed pool	Methanol	Water spray	ARC 1x1 NV
5M-WMl-f	Concealed pool	Methanol	Water mist (LP)	Tyco
5M-WMh-f	Concealed pool	Methanol	Water mist (HP)	Arctic 1x1 LV
7H-WS	Wood crib in fuel pool	Heptane	Water Spray	-
7H-WMl	Wood crib in fuel pool	Heptane	Water mist (LP)	-
7H-WMh	Wood crib in fuel pool	Heptane	Water mist (HP)	-
7M-WS-f	Wood crib in fuel pool	Methanol	Water spray	ARC 1x1 NV
7M-WMl-f	Wood crib in fuel pool	Methanol	Water mist (LP)	Tyco
7M-WMh-f	Wood crib in fuel pool	Methanol	Water mist (HP)	Arctic 1x1 LV
BH-WS	Small pool in bilge area	Heptane	Water Spray	-
BH-WMl	Small pool in bilge area	Heptane	Water mist (LP)	-
BM-WS-f	Small pool in bilge area	Methanol	Water spray	ARC 1x1 NV
BM-WS-f [-]	Small pool in bilge area	Methanol	Water spray	ARC 1x1 NV
BM-WMl-f	Small pool in bilge area	Methanol	Water mist (LP)	Tyco
D0.5-WS	Centered open pool, 0.5 MW	Diesel	Water spray	-
D0.5-WMl	Centered open pool, 0.5 MW	Diesel	Water mist (LP)	
M0.5-WS-f	Centered open pool, 0.5 MW	Methanol	Water spray	ARC 1x1 NV
M0.5-WMl-f	Centered open pool, 0.5 MW	Methanol	Water mist (LP)	Tyco
M0.5-WMh-f	Centered open pool, 0.5 MW	Methanol	Water mist (HP)	Arctic 1x1 LV
D1.0-WS	Centered open pool, 1.0 MW	Diesel	Water spray	-
D1.0-WMl	Centered open pool, 1.0 MW	Diesel	Water mist (LP)	-
D1.0-WMh	Centered open pool, 1.0 MW	Diesel	Water mist (HP)	-
M1.0-WS-f	Centered open pool, 1.0 MW	Methanol	Water spray	ARC 1x1 NV
M1.0-WS-f3	Centered open pool, 1.0 MW	Methanol	Water spray	ARC 3x3 S
M1.0-WS-fef	Centered open pool, 1.0 MW	Methanol	Water spray	Fluor Free
M1.0-WMl-f	Centered open pool, 1.0 MW	Methanol	Water mist (LP)	Tyco
M1.0-WMh-f	Centered open pool, 1.0 MW	Methanol	Water mist (HP)	Arctic 1x1 LV
D2.0-WMl	Centered open pool, 2.0 MW	Diesel	Water Mist (LP)	-
D2.0-WMh-2	Centered open pool, 2.0 MW	Diesel	Water Mist (HP)	-
D2.0-WMh	Centered open pool, 2.0 MW	Diesel	Water Mist (HP)	-
M2.0-WMl-f	Centered open pool, 2.0 MW	Methanol	Water Mist (LP)	Tyco
M2.0-WMh-f	Centered open pool, 2.0 MW	Methanol	Water Mist (HP)	Arctic 1x1 LV

[+] Test was performed with the wrong fuel spray nozzle, resulting in a significantly higher flow than prescribed.
[-] The system was lowered to a height of 45 cm instead of 50 cm, since the spray otherwise hit the construction.

With regards to the 42 tests in the test program in Table 3, a few notes can be made. Firstly, to make the test series list complete, a few further tests should have been performed:

- BM-WMh-f
- D0.5-WMh
- D2.0-WS
- M2.0-WS-f

The first of these tests (BM-WMh-f) was excluded since the manufacturer uses a low pressure system in the bilge area (already tested). D0.5-WMh was excluded since the larger methanol pools, which are generally easier to extinguish, were not extinguished by the system. The large pool fire extinguishing tests with the water-spraying system were excluded due to priorities in the test program, in favor of some added tests:

- BM-WS-f-
- M1.0-WS-f3
- M1.0-WS-fef
- D2.0-WMh-2

The first test (BM-WS-f-) was performed with a lower nozzle installation, since the prior installation hit the deck construction and the spray therefore did not reach the tray. The following tests, M1.0-WS-f3 and M1.0-WS-fef, were added to compare the effectiveness of two other foam agents, a more common concentrate as well as with a more environmentally friendly product (further described below). Finally, test D2.0-WMh-2 was performed with two less nozzles for the water-mist fire extinguishing system, i.e. with four nozzles instead of six. The corresponding test was also performed with six nozzles (D2.0-WMh) to provide a complete set of tests for the six nozzle system.

Below follow further descriptions of the fuels, equipment, instrumentation, and other arrangements of the tests.

2.1 Fuels and nominal heat release rates

Methanol, heptane, and diesel were used as fuels in the tests. The methanol was an Univar Methanol 160K DNN with the following properties (according to standard in parenthesis):

Density at 20 °C:	791.2 kg/m^3 (ASTM D 4052)
Flash point:	11 °C (ISO 2719)
Water content:	0.011 mg/kg (ASTM D 1364)
Heat of combustion:	19.9 MJ/kg (ASTM D 2624)

The heptane was an Exxol™ Heptane with the following properties (according to standard in parenthesis):

Density at 15 °C:	722 kg/m^3 (ISO 12185)
Flash point:	-4 °C (ASTM D-56)
Heat of combustion:	44.6.7 MJ/kg (ASTM D 2624)
Boiling point:	94 °C (ASTM D 1078)

The diesel was a Shell CityDiesel® with the following properties (according to standard in parenthesis):

Density at 15 °C:	812 kg/m^3 (ISO 12185)
Flash point:	74 °C (ISO 2719)
Water content:	34 mg/kg (ISO 12937)
Heat of combustion:	39.7 MJ/kg (ASTM D 2624)
Boiling point:	185-290 °C [IBP-95 % V/V recov.] (SS-EN ISO 3405:2000)

The heat release rates in the pool fire test scenarios varied with the fuel and with the trays used. For the concealed pool (scenario 5) a long rectangular tray was used, for the wood crib scenario (7) a circular tray was used and for the bilge scenario a small square tray was, as specified in the guidelines (IMO, 2005). These trays had a rim of 150 mm and were filled with 50 mm of heptane and 50 mm of water in accordance with the guidelines. In the corresponding methanol tests they were only filled with 100 mm of methanol. For the simplified pool fire extinguishing tests, different trays were used for diesel and methanol with the ambition to achieve heat release rates of 0.5 MW, 1 MW, and 2 MW. For methanol, nominal heat release rates were calculated based on the test data in the pool fire extinguishing tests (Evegren, 2017). A total heat of combustion of 19.83 kJ/g and a combustion efficiency of 0.96 were assumed, and for the current trays a mass loss rate of $0.02 + 0.001A$ kg/m$^{2}\cdot$s was assumed, where A is the pool area in square meters (only applicable for 1-7 m^2 pools). For diesel (and heptane) pools, the heat release rates were calculated with values from the SFPE handbook (Babrauskas, 2016). Specifications of the trays are given in Table 4, along with nominal heat release rates for the applied fuels.

Table 4. Fuel amounts and heat release rates (HRR) in the different trays

Test scenario	*Pool size [m]*	*Pool area [m^2]*	*Fuel*	*Nominal HRR [MW]*	*Fuel pool thickness [mm]*
5	0.70x3.00	2.1	Heptane	4.53	50 (+50 water)
			Methanol	0.88	100
7	Ø1.60	2	Heptane	2.60	50 (+50 water)
			Methanol	0.83	100
B	0.71x0.71	0.5	Heptane	0.52	50 (+50 water)
			Methanol	0.20	100
D0.5	Ø0.79	0.49	Diesel	0.50	50 (+50 water)
D1.0	Ø1.05	0.87	Diesel	1.00	50 (+50 water)
D2.0	Ø1.44	1.63	Diesel	2.07	50 (+50 water)
M0.5	Ø1.25	1.23	Methanol	0.50	100
M1.0	Ø1.71	2.30	Methanol	0.98	100
M2.0	Ø2.40	4.52	Methanol	2.11	100

For the high pressure spray fire scenarios, the guidelines (IMO, 2005) specify to use a full cone spray type nozzle at 150 bar, resulting in a fuel flow of about 0.050 kg/s. This results in a nominal heat release for diesel of about 1.8 MW. The same conditions were applied for the methanol spray, except that a different nozzle was used suitable for alcohol fuels. It was used achieving about the same fuel flow as specified in the guidelines, i.e. 0.050 kg/s and thus a nominal heat release rate of about 0.9-1.0 MW with methanol. However, in one test (8M-WS-f) the diesel nozzle was used by mistake, initially resulting in a higher fuel flow until the pressure was reduced to achieve (visually) about the same heat release rate.

2.2 Extinguishing systems

Three types of total compartment fire-extinguishing systems were included in the test series. One of the systems was a conventional low pressure water-spraying fire-extinguishing system. The two other systems were high pressure and low pressure water-mist fire-extinguishing systems. All three systems were approved for machinery spaces and cargo pump rooms; the water-spraying system by complying with prescriptive requirements and the water-mist systems by approval in accordance with MSC/Circ.1165 (IMO, 2005). In addition to the total compartment fire-extinguishing systems, two bilge systems were tested; one water-spraying system and one low pressure water mist system. The water-mist system was not approved in the configurations used. When used against methanol fires, the sprinkler water for all systems was added with an alcohol resistant foam concentrate, as concluded necessary in the pool fire extinguishing tests (Evegren, 2017). The different types of systems and foams used are further described below.

2.2.1 Water-spraying system

A single feed fork piping arrangement with three branches was installed from one of the compartment sides. The feeding "T" pipe-work was constructed of 2" steel pipe and the three branch lines were constructed of 1.5" steel pipes. The pipes were installed to uniformly arrange nine nozzles 4.9 m from the floor and with a spacing of 3.3 m by 3.3 m, i.e. leaving a 1.7 m distance to the walls. Each of the nozzles hence covered an area of 10.9 m^2 (117 ft^2).

Figure 3. Pipe-work providing 3.3x3.3 m spacing between sprinkler nozzles (two branches visible).

The water-spray nozzles were made by Tyco and designated Protectospray D3 18-180 (Tyco, 2016). The nozzle is shown in Figure 4 and had a K-factor of 25.9 (metric) and a spray angle of 180º.

Figure 4. Water spray nozzle used in the fire-extinguishing tests.

When only water was used (without foam), the water system piping was connected directly to the municipal water supply connection inside the fire test hall. No pump was used, but the water supply pressure was controlled via a diaphragm control valve connected to a compressed air supply. The control valve provided a constant pressure downstream the valve, irrespective of the inlet pressure. The flow rate and corresponding pressure was fine-tuned by an operator to achieve the desired total flow rate. When water spray was used with foam, pressure was provided by a pump operated to maintain the desired total flow rate. The total flow rate of water was in both set-ups (without and with foam) measured using a Krohne 0-2000 l/min flow meter on the feed pipe. The pressure was measured by a pressure transducer at one of the nozzles. A flowing pressure of about 2.8 bar (theoretically 2.71 bar should be used) was utilized throughout the tests to achieve a total flow rate of 490 l/min. This corresponds to a flow rate per nozzle of 54.4 l/min and hence a nominal discharge density of 5.0 mm/min, in accordance with SOLAS (IMO, 1974) and the FSS Code (IMO, 2007).

The foam generally used with the water-spraying system was provided by Fomtec and designated Fomtec ARC 1x1 NV. However, two tests were performed to try two other foams: one test (M1.0-WS-f3) was performed with one of their more common alcohol resistant foams Fomtec ARC 3x3 S, and one test (M1.0-WS-fef) was performed with Fomtec ARC 3x3 Ultra. All foams were alcohol resistant aqueous film forming foams (AFFF) and premixed with water in two tanks with a total volume of 6.5 m^3. The system with pump and one of the tanks used in the water spray foam tests is shown in Figure 5. It should be noted that use of a foam concentrate in a water spray system works as a film-forming additive rather than a means to build up a thick foam layer (< 10 mm in the tests).

Figure 5. Water tank with premixed foam and pump (left) for the water-spraying system.

For the bilge area, four Protectospray D3 (18-180) nozzles were initially installed with a spacing of 2.5 m by 2.5 m at a height of 0.5 m. The initial installation was then altered to a spacing of 2 m by 2 m and a height of 0.45 m since the water spray hit the deck construction and failed to reach into the pool fire tray. It should be noted that the tray rim is prescriptively 250 mm and that the deck plate is 500 mm above the floor, leaving only a 250 mm gap to reach into the tray with a water spray.

2.2.2 Low pressure water-mist system

The low pressure water-mist fire extinguishing system was installed using the same pipe-work as the water-spraying system described above and illustrated in Figure 3. The system was thus installed with the same spacing of 3.3 m by 3.3 m and with a 1.7 m distance to the wall. The low pressure water-mist nozzle was made by Tyco and designated Aquamist AM4 (Tyco, 2013). It is certified for total compartment water-mist fire-extinguishment in machinery spaces (IMO, 2005). The nozzle has a K-factor of 3.5 (metric) and is shown in Figure 4.

Figure 6. Low pressure water-mist nozzles used in the fire extinguishing tests.

A pump was operated to maintain a flowing pressure of about 15.5 bar (theoretically 13.3 bar should be used), resulting in a total flow rate of 115 l/min. This corresponds to a flow rate per nozzle of 12.7 l/min and hence a nominal discharge density of 1.17 mm/min (assuming that each nozzle covered an area of 10.9 m^2).

The foam used with the low pressure water-mist system was provided by Tyco and designated Towalex 3x3ARC Plus. It is an alcohol resistant aqueous film forming foam (AFFF) and was premixed with water in two tanks with a total volume of 6.5 m^3. It should be noted that use of a foam concentrate in a water mist system works as a film-forming additive rather than a means to build up a thick foam layer (< 10 mm in the tests).

For the bilge area, four Aquamist AM4 nozzles were installed with a spacing of 2 m by 2 m and a height from the floor of 0.45 m. It should be noted that the tray rim is prescriptively 250 mm and that the deck plate is 500 mm above the floor, leaving only a 250 mm gap to reach into the fire with a water mist.

2.2.3 High pressure water-mist system

The high pressure water-mist fire extinguishing system was provided, installed, and operated by Ultra Fog®. The installation was made of 12 mm stainless steel high pressure pipes on top of the compartment, with the nozzles penetrating the roof. A total of six nozzles were installed in the compartment about 4.5 m above the floor. They were installed in two rows of three nozzles with a 3.3 m spacing between the nozzles in each row and 6.6 m between the rows. One row of nozzles was installed to the left of the engine mock-up, 1.7 m from the left side enclosure wall while the other row was installed to the right of the engine mock-up, 1.7 m from the right side enclosure wall. The water-mist nozzles used in the high pressure water-mist tests were produced by Ultrafog and designated Ultra Fog 931028 1637/M17066. The nozzles are certified for total compartment water-mist fire-extinguishment in machinery spaces (IMO, 2005). The nozzle type has a K-factor of 0.73 (metric) and is shown in Figure 4.

Figure 7. High pressure water-mist nozzles used in the fire extinguishing tests.

High pressure pumps and control unit were provided by Ultra Fog and operated at a pressure of about 100 bar, providing a total flow rate of 43.8 l/min. This corresponds to a flow rate per nozzle of 7.3 l/min and hence a nominal discharge rate of 0.44 mm/min.

A pump was operated to maintain a flowing pressure of about 15.5 bar (theoretically 13.3 bar should be used), resulting in a total flow rate of 115 l/min. This corresponds to a flow rate per nozzle of 12.7 l/min and hence a nominal discharge density of 1.17 mm/min.

In one test, D2.0-WMh, a different high pressure water-mist arrangement was used with four nozzles having a higher K-factor of 2.09. These were also operated at 100 bar, providing a total flow rate of 83.6 l/min and thus a discharge rate of nominally 0.84 $l/m^2 \cdot min$.

The foam used with the water-mist system was provided by Solberg and designated Arctic™ 1x1 LV ATC™. It is an AR-AFFF (alcohol resistant aqueous film forming foam) concentrate and was injected directly to the high pressure pump housing during the tests. It should be noted that a foam concentrate in a water mist system works as a film-forming additive rather than a means to build up a thick foam layer (about 1 mm in the tests).

The system supplier does not provide a high pressure water-mist system for bilge area installations but uses a low pressure water-spraying system for such installations.

2.3 Measurements and documentation

Documentation of the tests was made in several ways; by conventional photo and video in the visible spectrum as well as by video in the infrared (IR) spectrum. An IR camera converts radiation to temperature and thus provides a temperature profile of the fire and surrounding engine mock-up and compartment. The IR camera used in the tests was of model FLIR T420 2.0 and operated in the temperature range 250-1 200 °C, with the emissivity set to 0.4.

The compartment was instrumented to measure both the gas temperatures and the gas concentrations, as further described below. The data was recorded at a rate of about one scan per second.

Two thermocouple trees were used to measure the gas temperatures inside the test compartment, located on the side of and behind the engine mock-up, as illustrated in Figure 8. Such measurements are in accordance with MSC/Circ.1165 made in so called thermal management tests, where compartment cooling by the system is evaluated while an obstructed fire is burning. Such tests were not performed, but the temperature measurements were made to evaluate fire suppression. In accordance with MSC/Circ.1165, five thermocouples are to be installed in each tree, 500 mm below the ceiling, 500 mm above the floor and three thermocouples evenly distributed between these, i.e. giving measurements every 1 000 mm.

However, in this test series, thermocouples were installed every 500 mm (i.e. nine thermocouples). Furthermore, one thermocouple was positioned at the ceiling (25 mm from the ceiling) and one thermocouple was positioned 250 mm from the ceiling. Hence a total of 11 thermocouples were used and each thermocouple (except that by the ceiling) was covered by small angle iron shields, to minimize wetting. Only the ten thermocouple (five from each thermocouple tree) readings prescribed by MSC/Circ.1165 were used to calculate the 60 s average temperatures.

All thermocouples were of type K (chromel-alumel) and made from 0.5 mm wire welded together, but the manufacturer Pentronic AB. The quality of the thermocouples was class 1, according to the IEC 584-1 standard, which implies an accuracy of ±1.5°C in the interval -40°C to 375°C, and an uncertainty of 0.04 % of the measured value above 375°C.

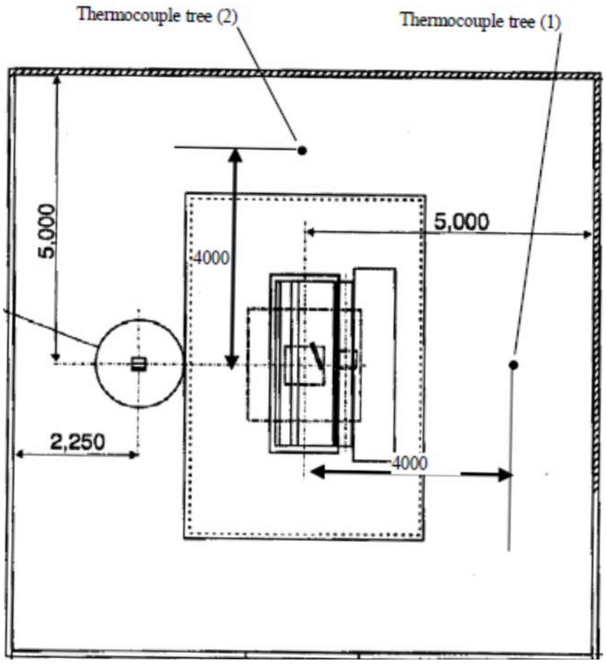

Figure 8. High pressure water-mist nozzles used in the fire extinguishing tests.

In the same location as thermocouple tree (2) in Figure 8, measurements were also made of the gas concentrations of oxygen (O_2), carbon monoxide (CO), and carbon dioxide (CO_2). Gas was collected 500 mm from the ceiling and 500 mm from the floor and the gases were dried (water was removed) before the gas analysis.

2.4 Test procedure

The test scenarios followed a similar procedure but with varying pre-burn times, based on MSC/Circ.1165 (IMO, 2005):

- At 00:00 the measurements, the video camera and the IR video camera were started.
- At the ignition time, stated in Table 5, the test fire was ignited.
- After a specific pre-burn time, stated in Table 6, the extinguishing system was activated.
- After extinguishment had been confirmed or 15 minutes after extinguishing system activation the tests and measurements were stopped[1]

[1] The tests with the water spray extinguishing system using a pre-mixture of water and foam additvie were stopped around 12 min after system activation due to volume limitations of the extinguishing agent container.

Table 5. Time of ignition for the different test scenarios

Test scenario	*Ignition time [min:s]*
High pressure spray	00:45
Concealed pool	00:45
Wood crib in fuel pool	00:30
Small pool in bilge area	00:45
Centered open pool	01:00

Table 6. Pre-burn times for the different test scenarios

Test scenario	*Diesel*	*Heptane*	*Methanol*
High pressure spray	5-15 s	-	5-15 s
Concealed pool	-	15 s	15 s
Wood crib in fuel pool	-	30 s	30 s
Small pool in bilge area	-	15 s	15 s
Centered open pool	2 min	-	3 min

Hence, the fire scenarios based on MSC.Circ.1165 were synchronized to achieve activation of the extinguishing system at the time 01:00. Furthermore, in these scenarios the pre-burn times were kept the same regardless of the used fuel.

For the centered open pool fire scenarios, the methanol fires were allowed a longer pre-burn time since methanol takes longer to reach steady state combustion than diesel. Methanol was allowed to burn for 3 minutes before activation of the extinguishing systems whilst diesel was allowed to burn for 2 minutes before activation. For the diesel pool fires, a small amount (500 ml) of heptane was poured into the tray seconds before ignition.

3 Results

The results are presented below, where observations and measurements of temperatures and gas concentrations are divided into groups depending on the fire scenario.[2] The compartment fire extinguishing test program, with the different fire scenarios, fuels, and extinguishing systems, is presented in Table 3.

Table 7. Extinguishment results for the compartment tests performed within proFLASH

Test ID	*Scenario*	*Fuel*	*System*	*Act.*	*Ext.*	*Observation*
3D-WS	HP spray	Dies	Spray	02:15	03:25	
3D-WMl	HP spray	Dies	Mist lp	01:00	02:00	
3D-WMh	HP spray	Dies	Mist hp	01:10	02:55	
3M-WS-f	HP spray	Meth	Spray	-	-	Self-extinguished
8M-WS-f +	HP spray+i	Meth	Spray	01:07	-	Pressure reduced to 12.5 bar at 03:00
8M-WMl-f	HP spray+i	Meth	Mist lp	01:08	02:42	Ext. 02:06, re-ign. 02:18
8M-WMh-f	HP spray+i	Meth	Mist hp	00:52	03:48	
5H-WS	Concealed	Hept	Spray	01:00	-	
5H-WMl	Concealed	Hept	Mist lp	01:00	04:20	
5H-WMh	Concealed	Hept	Mist hp	01:00	04:01	
5M-WS-f	Concealed	Meth	Spray	01:00	-	
5M-WMl-f	Concealed	Meth	Mist lp	01:00	-	
5M-WMh-f	Concealed	Meth	Mist hp	01:00	-	
7H-WS	Wood crib	Hept	Spray	01:00	10:52	
7H-WMl	Wood crib	Hept	Mist lp	00:59	09:25	105 l/min until 08:40
7H-WMh	Wood crib	Hept	Mist hp	01:00	04:56	
7M-WS-f	Wood crib	Meth	Spray	01:07	03:33	
7M-WMl-f	Wood crib	Meth	Mist lp	01:00	-	
7M-WMh-f	Wood crib	Meth	Mist hp	01:00	-	
BH-WS	Bilge pool	Hept	Spray	01:00	-	Spray did not reach tray
BH-WMl	Bilge pool	Hept	Mist lp	01:00	-	No visible effect on fire
BM-WS-f	Bilge pool	Meth	Spray	01:00	-	Spray did not reach tray
BM-WS-f -	Bilge pool	Meth	Spray	01:00	-	No visible effect on fire
BM-WMl-f	Bilge pool	Meth	Mist lp	01:00	-	
D0.5-WS	Open pool	Dies	Spray	03:00	-	
D0.5-WMl	Open pool	Dies	Mist lp	03:06	-	
M0.5-WS-f	Open pool	Meth	Spray	04:00	10:15	
M0.5-WMl-f	Open pool	Meth	Mist lp	04:00	15:30	150 l/min initially, then 113 l/min
M0.5-WMh-f	Open pool	Meth	Mist hp	04:00	-	
D1.0-WS	Open pool	Dies	Spray	03:00	-	
D1.0-WMl	Open pool	Dies	Mist lp	03:06	-	
D1.0-WMh	Open pool	Dies	Mist hp	03:00	-	
M1.0-WS-f	Open pool	Meth	Spray	04:00	09:45	
M1.0-WS-f3	Open pool	Meth	Spray	04:00	13:27	Switched foam tank at 10:00
M1.0-WS-fef	Open pool	Meth	Spray	04:00	-	Switched foam tank at 10:00
M1.0-WMl-f	Open pool	Meth	Mist lp	04:00	19:00	
M1.0-WMh-f	Open pool	Meth	Mist hp	04:00	-	
D2.0-WMl	Open pool	Dies	Mist lp	03:00	13:12	
D2.0-WMh-2	Open pool	Dies	Mist hp	03:00	-	Use of other nozzles, 4 instead of 6
D2.0-WMh	Open pool	Dies	Mist hp	03:00	06:50	
M2.0-WMl-f	Open pool	Meth	Mist lp	04:10	-	
M2.0-WMh-f	Open pool	Meth	Mist hp	04:00	-	

+ Test was performed with the wrong fuel spray nozzle, resulting in a significantly higher flow than prescribed.
- The system was lowered to a height of 45 cm instead of 50 cm, since the spray otherwise hit the construction.

[2] The high-pressure spray fire scenarios are only presented in Table 3 and in appendix 1.

3.1 Concealed pool (scenario 5)

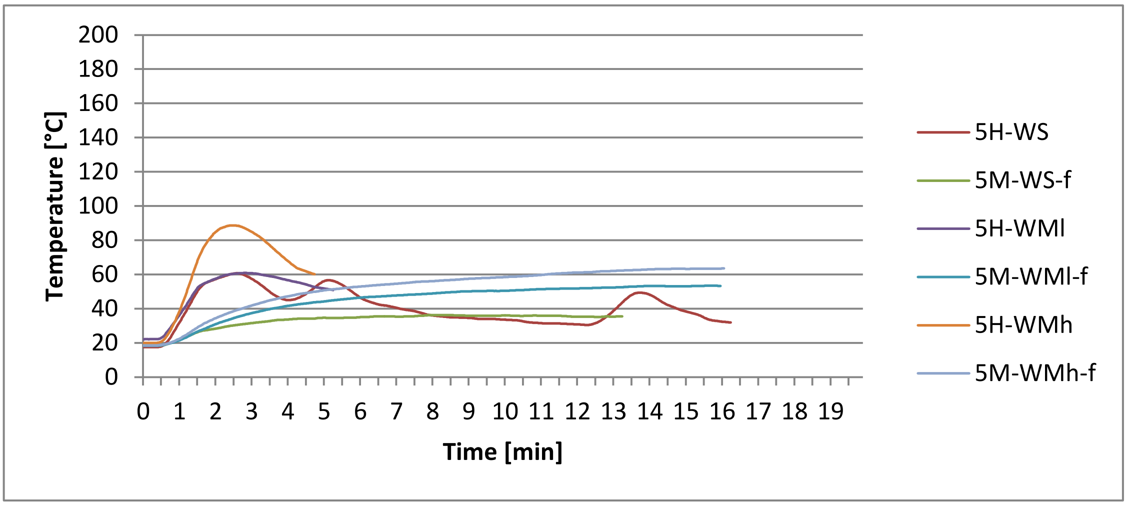

Figure 9. Average temperatures in the concealed pool fire tests (60 s averages)

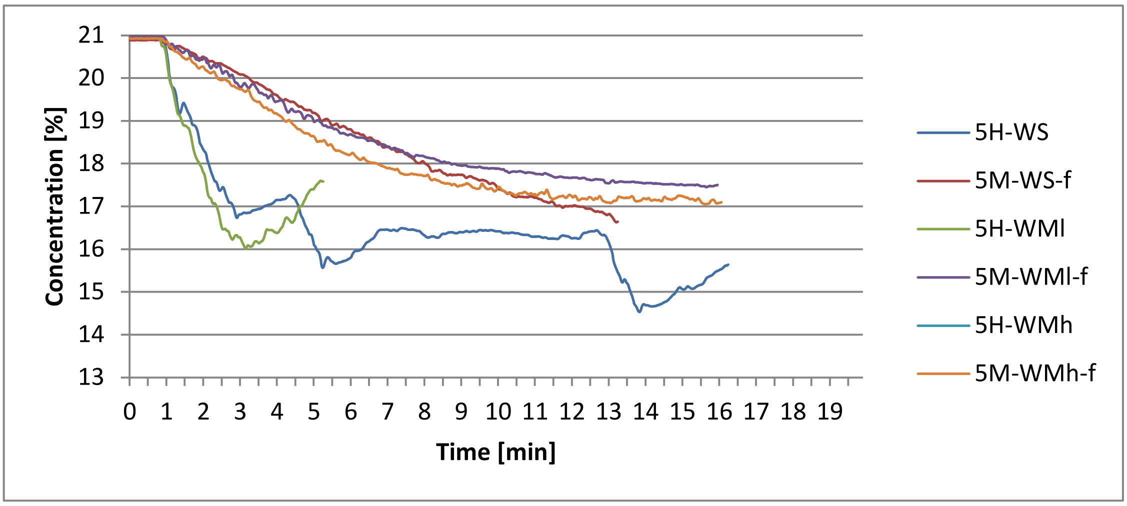

Figure 10. Oxygen concentration at 4.5 m during the concealed pool fire tests (5H-WMh gave erroneous results)

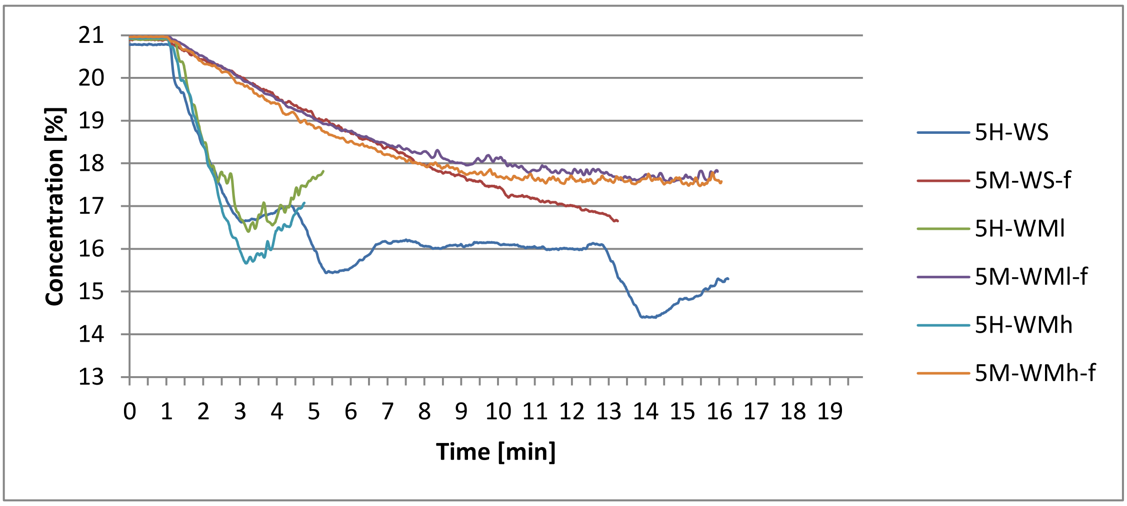

Figure 11. Oxygen concentration at 1 m during the concealed pool fire tests

3.2 Wood crib in fuel pool (scenario 7)

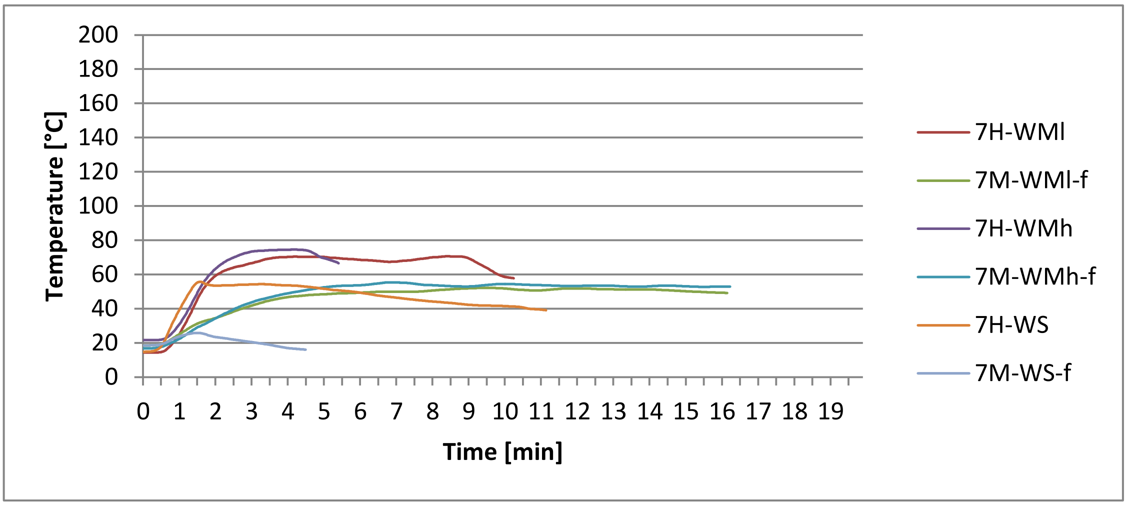

Figure 12. Average temperatures in the wood crib fire tests (60 s averages)

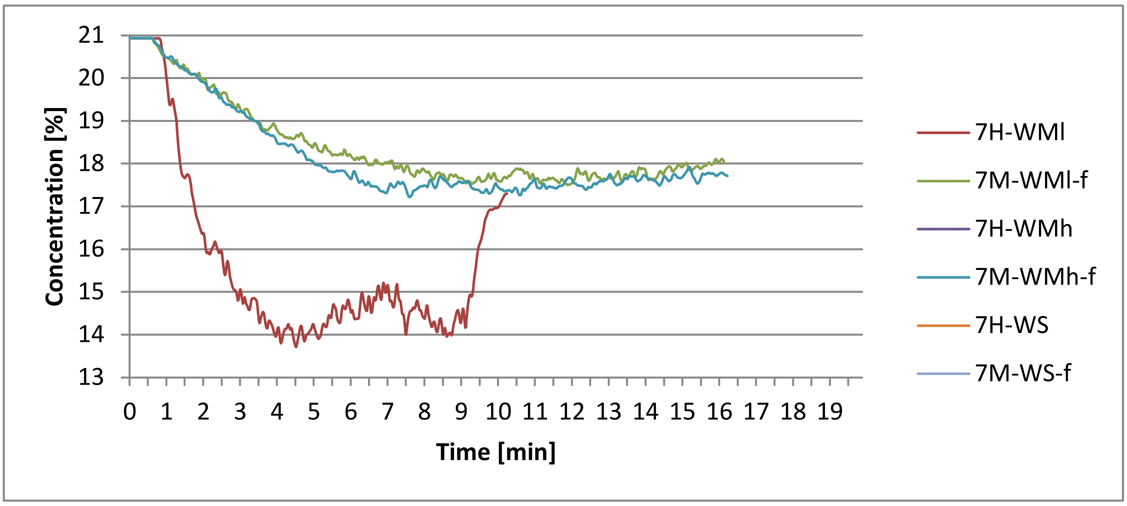

Figure 13. Oxygen concentration at 4.5 m during the wood crib fire tests

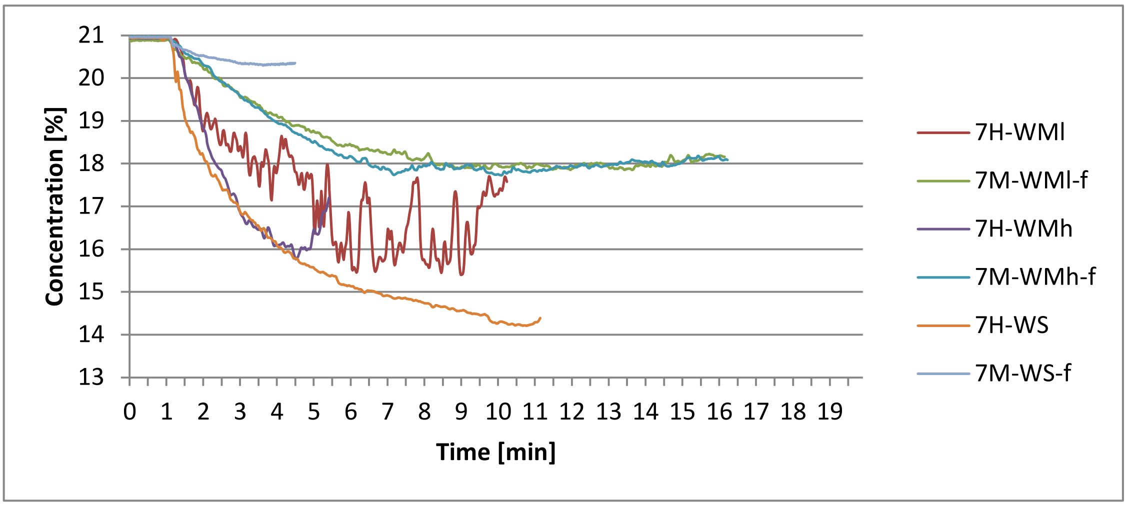

Figure 14. Oxygen concentration at 1 m during the wood crib fire tests

3.3 Small pool in bilge area (scenario B)

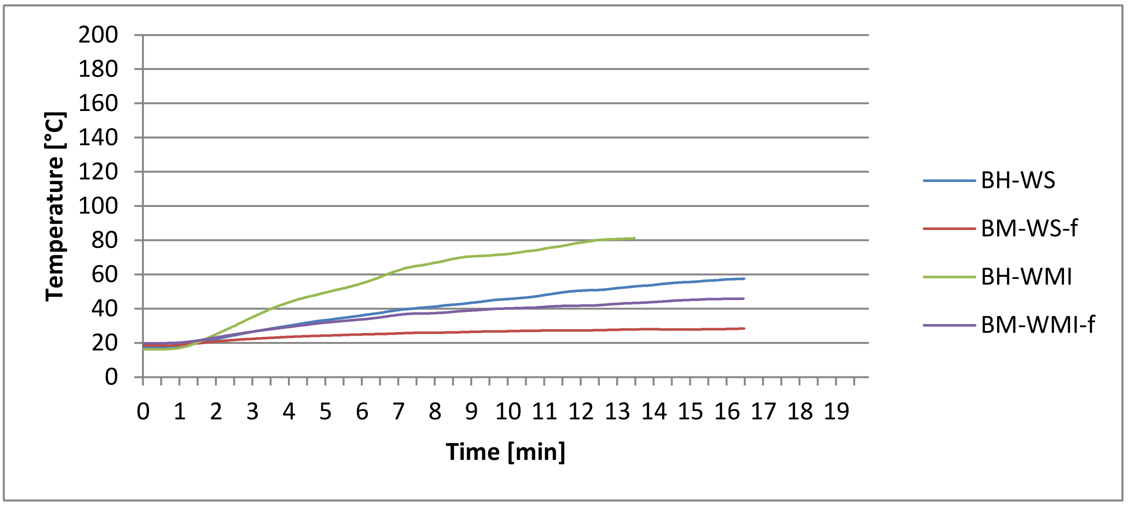

Figure 15. Average temperatures measured in the bilge fire tests (60 s averages).

Table 8. Oxygen concentration in the compartment at the end of the bilge fire tests.

Test denotation	**Oxygen concentration (1m)**	**Oxygen concentration (4.5m)**
BH-WS	20.5 %	18.6 %
BM-WS-f	20.8 %	20.8 %
BH-WMl	20.4 %	17.7 %
BM-WMl -f	20.7 %	19.9 %

3.4 Centred open pools

3.4.1 0.5 MW

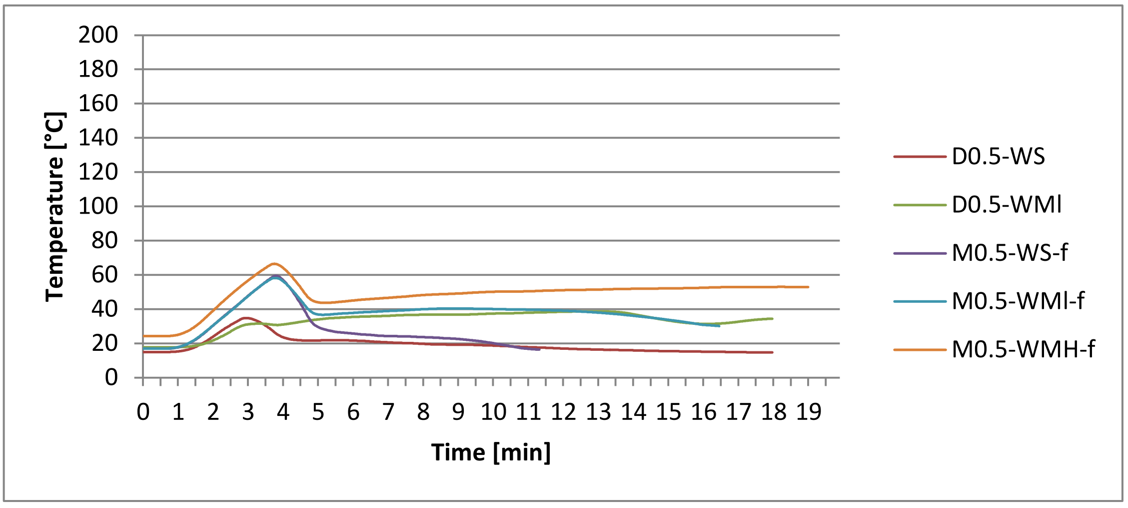

Figure 16. Average temperatures in the 0.5 MW centred pool fire tests (60 s averages).

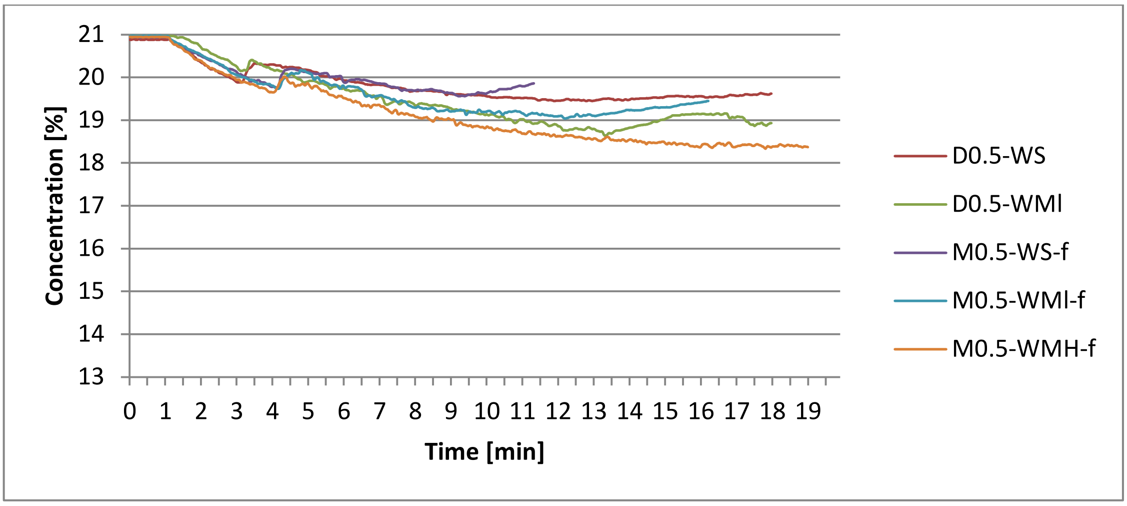

Figure 17. Oxygen concentration at 4.5 m during the 0.5 MW centred pool fire tests

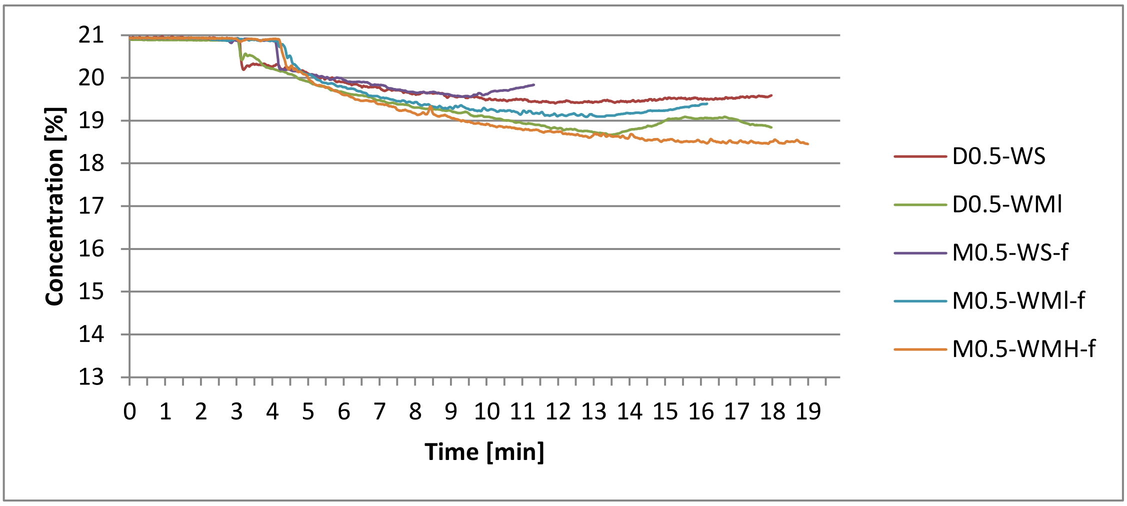

Figure 18. Oxygen concentration at 1 m during the 0.5 MW centred pool fire tests

3.4.2 1 MW

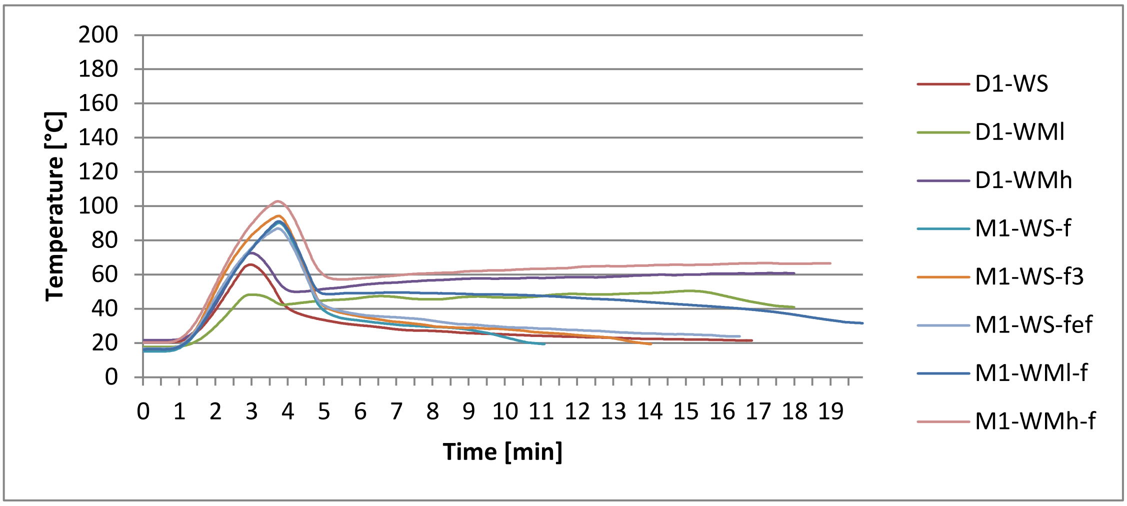

Figure 19. Average temperatures in the 1 MW centred pool fire tests (60 s averages).

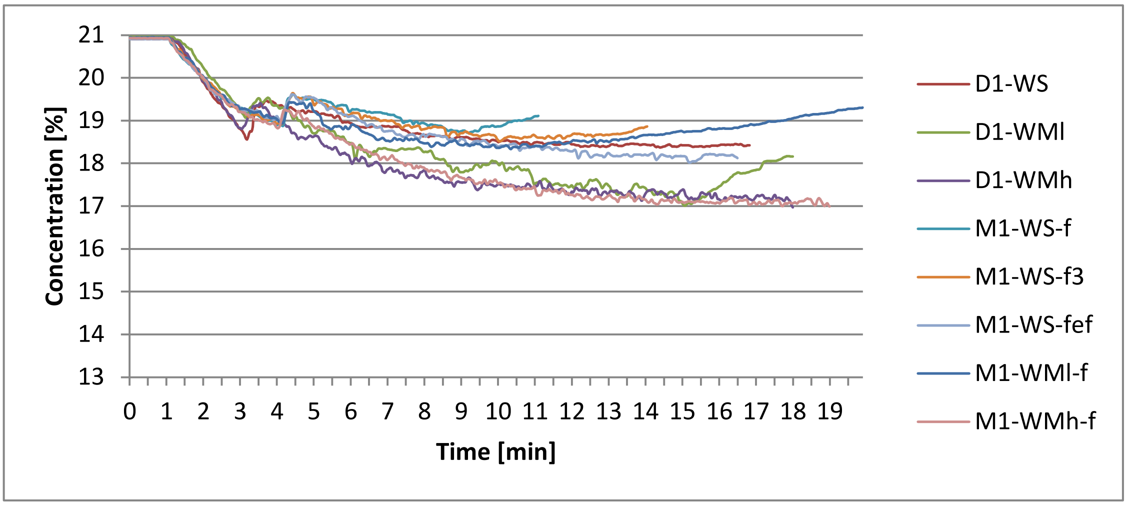

Figure 20. Oxygen concentration at 4.5 m during the 1 MW centred pool fire tests

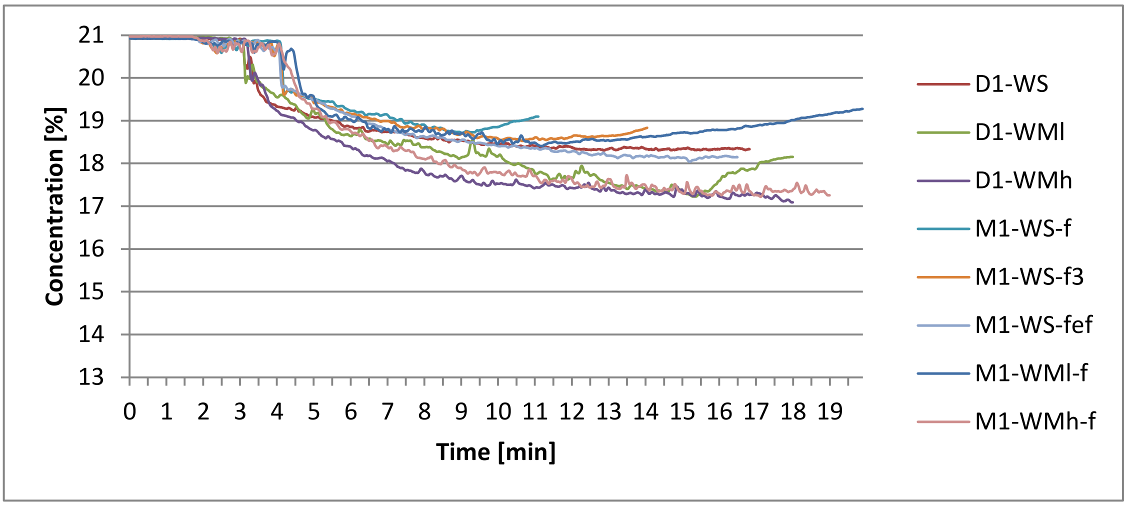

Figure 21. Oxygen concentration at 1 m during the 1 MW centred pool fire tests

3.4.3 2 MW

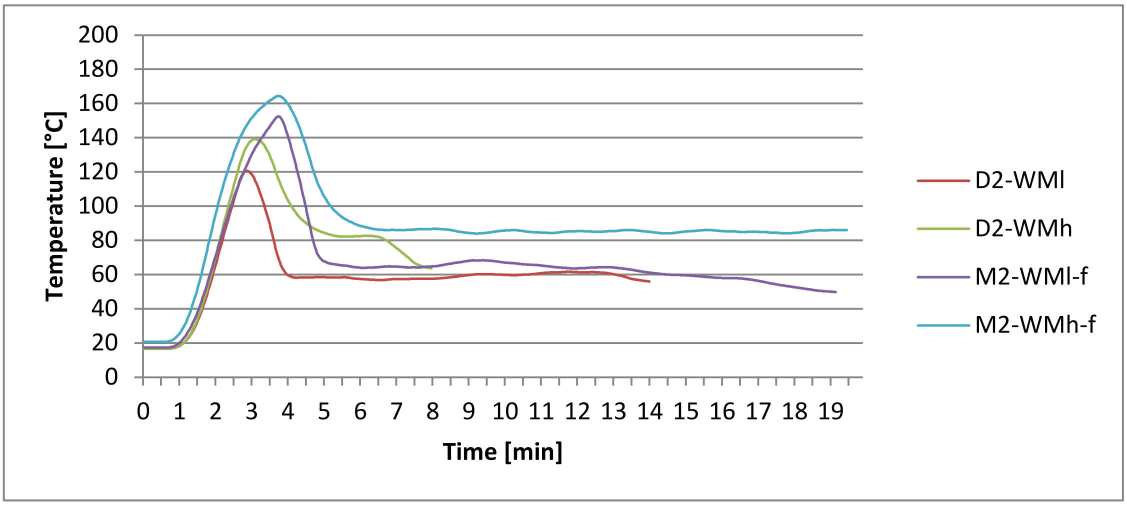

Figure 22. Average temperatures in the 2 MW centred pool fire tests (60 s averages).

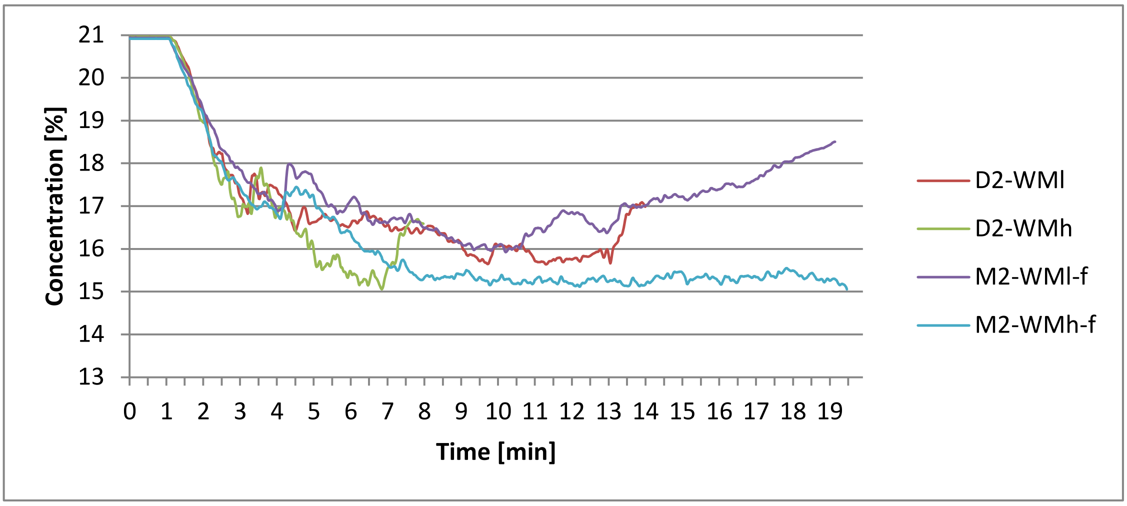

Figure 23. Oxygen concentration at 4.5 m during the 2 MW centred pool fire tests

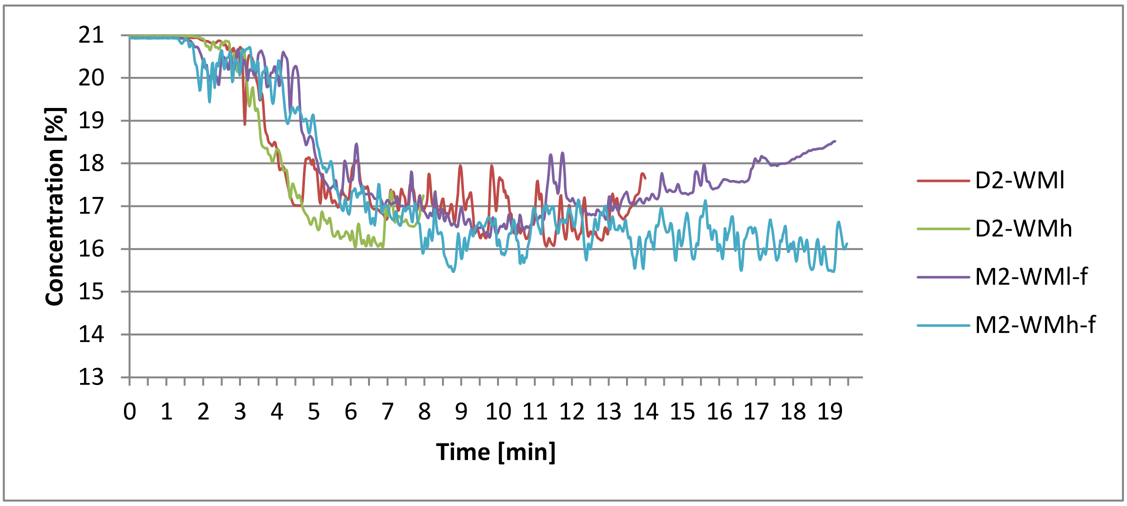

Figure 24. Oxygen concentration at 1 m during the 2 MW centred pool fire tests

4 Discussion

The results of the study are discussed below, divided in the areas heat radiation, mass loss rate, heat release rate, as well as general discussions on fire suppression and extinguishment of methanol.

4.1 High pressure spray fire

The high pressure diesel spray was ignited without problem and was extinguished within 1-2 minutes with the systems tested. However, when attempting to ignite the corresponding methanol spray, it self-extinguished as soon as the torch was removed. Use of a large metal plate initially heated to 350°C was sufficient to achieve a sustainable methanol spray fire (despite a high auto ignition temperature for methanol of about 460°C). The fact that it was not possible to attain a sustainable high pressure methanol spray fire without a significant ignition source reveals that the likelihood of a continuous methanol spray fire is lower than a diesel spray fire. With the re-ignition source, the methanol spray fires required 2-3 minutes for extinguishment (note that it is not known how long time diesel spray fires with a re-ignition source would have required for extinguishment). Hence, methanol spray fires appear to be manageable by conventional water-based fire extinguishing systems (with foam injection).

It should be noted that the high pressure water-mist system did not have nozzles in the central line above the spray fire and that this may have affected the efficiency of the system when dealing with the high pressure spray fires.

4.2 Concealed pool fire

The concealed heptane pool fire scenario was well managed by both the low pressure and the high pressure water mist system. However, the prescriptive water-spraying system did not manage to extinguish this fire, which alternative systems need to be verified against. None of the systems (with foam) managed to extinguish the corresponding methanol fire. This is reasonable based on the conclusions in the pool fire extinguishing tests (Evegren, 2017), i.e. that the main extinguishing mechanisms with a water-based system is application of foam if this is used, or otherwise dilution. Oxygen depletion, which is one of the primary mechanisms of a water-mist system, is not as effective against methanol since it has a low oxygen index/can burn at low oxygen concentrations. Hence, a concealed methanol pool fire will be difficult to extinguish if it is not reachable by direct impingement of the water.

It could although be the case that a fuel pool is formed in the same place as extinguishing water and foam drains. Hence, in a real case scenario it could be possible to extinguish a concealed pool fire even though it is not reached by direct impingement, but this is generally not considered.

Average temperatures in the compartment were kept low by all types of systems (below 50 °C after 300 s).

It should be noted that the methanol was not allowed a longer pre-burn time than heptane for this scenario. The methanol fires therefore did not get the possibility to reach their maximum heat release rate. This affects the possibilities for extinguishment by oxygen depletion.

4.3 Wood crib in fuel pool fire

The wood crib fire in the heptane pool was extinguished by all of the systems within 10 minutes (the high pressure water-mist system only required 4 minutes). It should be noted that the water-spraying system was used with a slightly too low discharge rate for the first 7.7 minutes. However, when the wood crib was in methanol, only the water-spraying system managed to extinguish the fire, and it did this in 2.5 minutes. The water-mist systems achieved a too low foam application (and dilution) rate to achieve sufficient suppression and extinguishment. However, the systems cooled the compartment well and kept the average temperature below 60 °C throughout the test (about 50 °C after 300 s).

It should be noted that the methanol was not allowed a longer pre-burn time than heptane for this scenario. The methanol fires therefore did not get the possibility to reach their maximum heat release rate. This affects the possibilities for extinguishment by oxygen depletion.

4.4 Small pool fire in bilge area

None of the bilge pool fires were extinguished by any of the extinguishing systems, including the prescriptive design with a water-spraying system applied to the conventional heptane fuel. Extinguishment failed primarily due to the systems not reaching the fire. A requirement for the verification tests for alternative systems is to place the nozzles at least one-half of the nozzle spacing away from the engine mock-up, which is 1 m wide. Furthermore, there is only a 250 mm gap between the tray rim and the floor plates, which makes it difficult to reach the fire with water. In this case there were also structures for the floor construction obstructing the water (obstructions such as structures, pipes, and other objects are very common in a real case scenario). It is hence difficult to reach the fire with a sufficient amount of water to achieve vaporization or direct impingement. For a water-mist system it is crucial to reach the fire with water to achieve vaporization and for a water-spraying system it is crucial to achieve direct impingement in the test scenario. Methanol is particularly difficult to extinguish without direct impingement and sufficient application of foam, regardless of the system used. None of the systems used achieved extinguishment, but temperatures were kept low, in particular for the methanol fire which does not produce much heat.

As noted above, it could be considered that extinguishing water and foam drains to the same place as the formed fuel pool, which could allow extinguishment in a real application. However, this is generally not considered.

It should be noted that the methanol was not allowed a longer pre-burn time than heptane for this scenario. The methanol fires therefore did not get the possibility to reach their maximum heat release rate. This affects the possibilities for extinguishment by oxygen depletion.

4.5 Centered open pool fires

With regards to methanol pool fires, the water-spraying system achieved extinguishment in the scenarios it was applied (for 0.5 MW and 1.0 MW). The low pressure water-mist system also achieved extinguishment in these scenarios, but not in the 2.0 MW scenario. The low pressure water-mist system and the water-spraying system hence extinguished the same size methanol pool fires, but the former required a significantly longer time for extinguishment. The high pressure water-mist system did not achieve sufficient application of foam water to achieve extinguishment of any of the open methanol pool fires.

With regards to diesel pools fires, the water-spraying system did not extinguish any of the pools to which it was applied, which is noteworthy for a prescriptive system. Furthermore, the tested and approved water-mist systems only extinguished the diesel pool with the largest heat release rate.

All systems cooled the compartment well and kept the average temperature well below 100 °C, 300 s after activation. This is a criterion with a 1 MW fire in thermal management tests according to the approval guidelines in MSC/Circ.1165 (IMO, 2005), but 100 °C was barely even reached at activation with any 1 MW fire.

The results are discussed further below for the differently sized pools.

4.5.1 2.0 MW

The 2.0 MW diesel pool fire was extinguished by the low pressure and high pressure water-mist systems, but unfortunately the test with water spray was not performed due to time constraints. The corresponding methanol fires were not extinguished with the water mist systems, despite foam injection. The fire slowly became increasingly suppressed by the low pressure water-mist system, but was not extinguished within the 15 minute criterion. A higher application rate of foam water is likely necessary to achieve extinguishment.

4.5.2 1.0 MW

The 1.0 MW diesel pool fire was not extinguished by any of the systems, likely since the fire did not produce sufficient heat for vaporization of water and resulting oxygen dispersion. Smaller fires are therefore typically more difficult to extinguish in this kind of environment. The methanol pool was extinguished by the water-spraying and the low pressure water-mist system, but not by the high pressure water-mist system. The low pressure water-mist system barely managed to extinguish the fire at the very end of the 15 minute period. These results further support that a sufficient amount of water with foam needs to reach the fuel surface to achieve extinguishment. The variation in the type of foam for the water-spraying system in this test indicates that the particular foam type makes a difference, even if all were alcohol resistant.

4.5.3 0.5 MW

The 0.5 MW diesel pool fire was not extinguished by any of the systems, which is in line with that smaller fires are more difficult to extinguish. As for the 1.0 MW methanol fire, the 0.5 MW methanol fire was extinguished by the water-spraying and the low pressure water-mist system, but not by the high pressure water-mist system.

5 Conclusions

The likelihood of a continuous methanol high-pressure spray fire is lower than a diesel spray fire, since a methanol spray is not self-sustained without a re-ignition source. With a re-ignition source, methanol spray fires are manageable with a water-based fire extinguishing system (with foam injection). Methanol pool fire extinguishment requires direct application of foam water to the fuel, which means that a concealed pool will be difficult to extinguish, unless it is reached by draining extinguishing foam water. Oxygen depletion, which is a significant mechanism of water-mist systems, is not as effective on methanol as it is on e.g. heptane. Prescriptive water-spraying systems are not effective for extinguishment of neither concealed heptane nor concealed methanol, since the fires require to be reached. However, both the water-spraying and the water-mist systems tested cooled the compartment well, regardless of fire.

The effectiveness of extinguishment of open methanol pools depends on the foam water application rate. Burning materials in the pool require an increased application rate and there were indications that the required application rate (per unit area) increases with the pool size. The largest tested methanol pool fire was not extinguished by any system but both the low and high pressure water-mist systems managed to extinguish the same effect diesel fire. For the smaller effect methanol and diesel pools, the results were the opposite. Hence, small methanol fires appear easier to extinguish for water-mist systems, whilst the opposite applies to diesel fires in this kind of compartment.

The main conclusions can be summarized as:

- A methanol spray fire is not as likely as a diesel spray fire and if it appears it is manageable with a water-based system.
- A concealed methanol fire is difficult to extinguish with a water-based system, unless it is reached by draining extinguishing foam water.
- The effectiveness of extinguishment of open methanol pools depends on the foam-water application rate (i.e. a higher discharge rate is generally more effective).
- The required application rate for a methanol fire depends on its size and if it contains burning materials.

6 References

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Appendices

1. Radiation heat flux from measurements

Appendix 1

Test result summary

A summary of the results of all the tests performed is presented in Table 1- 1. Below the table the temperature measurements and the CO and CO_2 measurements are presented for each of the tests. The locations of the thermocouple trees can be found in Figure 8 and the positions of the thermocouples are described in 2.3 Measurements and documentation where TC 1 of each tree is located 25 mm below the ceiling, TC 2 250 mm below the ceiling and TC3 is 250 mm below TC2, TC4 is 250 mm below TC3 etc.

Table 1- 1. Summary of test results

#	*Test ID*	*Ignition*	*System activation*	*Extinguishment*	*System shut-off*	*Remarks and observations*
1	5H-WS	00:45	01:00		16:15	Very nearly extinguished, only fire at the end towards the opening
2	BH-WS	00:45	01:00		16:00	Too far from the tray
3	3D-WS	02:00	02:15	03:25	03:35	
4	3M-WS-f					Spray fire self-extinguished when ignition source was removed
5	5M-WS-f	00:45	01:00		13:00	
6	BM-WS-f	00:45	01:00		17:30	Spray hit the table construction for the bilge, did not reach tray.
7	BM-WS-f	00:45	01:00		16:00	Spray reached the tray, but not enough
8	D0.5-WS	01:00	03:00		18:00	
9	M0.5-WS-f	01:00	04:00	10:15	11:20	
10	M1.0-WS-f	01:00	04:00	09:45	11:05	
11	M1.0-WS-f3	01:00	04:00	13:27	14:07	Switched foam containers at 10:00
12	M1.0-WS-fef	01:00	04:00		16:30	Switched foam containers at 10:00
13	BH-WMl	00:45	01:00		13:00	No effect on fire
14	7H-WMl	00:44	00:59	09:25	10:00	105 l/min until 08:40. 113 l/min after
15	5H-WMl	00:45	01:00	04:20	05:00	
16	3D-WMl	00:45	01:00	02:00	04:00	
17	3M-WMl-f	00:50	01:08	02:42	04:30	Extinguished at 02:06, but re-ignited at 02:18
18	5M-WMl-f	00:45	01:00		16:00	
19	7M-WMl-f	00:30	01:00		16:10	
20	BM-WMl-f	00:45	01:00		16:00	
21	M0.5-WMl-f	01:00	04:00	15:30	16:30	Flow started at 150 l/min. Lowered to 113 l/min.
22	M1.0-WMl-f	01:00	04:00	19:00	19:50	
23	M2.0-WMl-f	01:00	04:10		19:10	
24	D0.5-WMl	01:00	03:06		18:00	

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25	D1.0-WMl	01:00	03:06		18:00	
26	D2.0-WMl	01:00	03:00	13:12	13:43	
27	D2.0-WMh-2	01:00	03:00		18:00	4 nozzles K2.09 (100 bar, 20.9 l/min/nozzle) -No measurements
28	D2.0-WMh	01:00	03:00	06:50	07:45	6 nozzles K0.73 from now on (100 bar, 7.3 l/min/nozzle)
29	D1.0-WMh	01:00	03:00		18:00	
30	M1.0-WMh-f	01:00	04:00		19:00	
31	M0.5-WMH-f	01:00	04:00		19:00	
32	M2.0-WMh-f	01:00	04:00		19:20	
33	D1.0-WS	01:00	03:00		16:50	
34	7M-WMh-f	00:30	01:00		16:15	
35	5M-WMh-f	00:45	01:00		16:00	
36	3M-WMh-f	00:37	00:52	03:48	06:50	
37	5H-WMh	00:45	01:00	04:01	04:45	
38	7H-WMh	00:45	01:00	04:56	05:25	
39	7H-WS	00:30	01:00	10:52	11:10	
40	8M-WS-f	00:45	01:07		14:00	Diesel nozzle was used. 150 bar to start with. Lowered to 12.5 bar at 3:00 -Measurements failed
41	3D-WMh	00:55	01:10	02:55	03:30	
42	7M-WS-f	00:30	01:07	03:33	04:30	

3D-WS

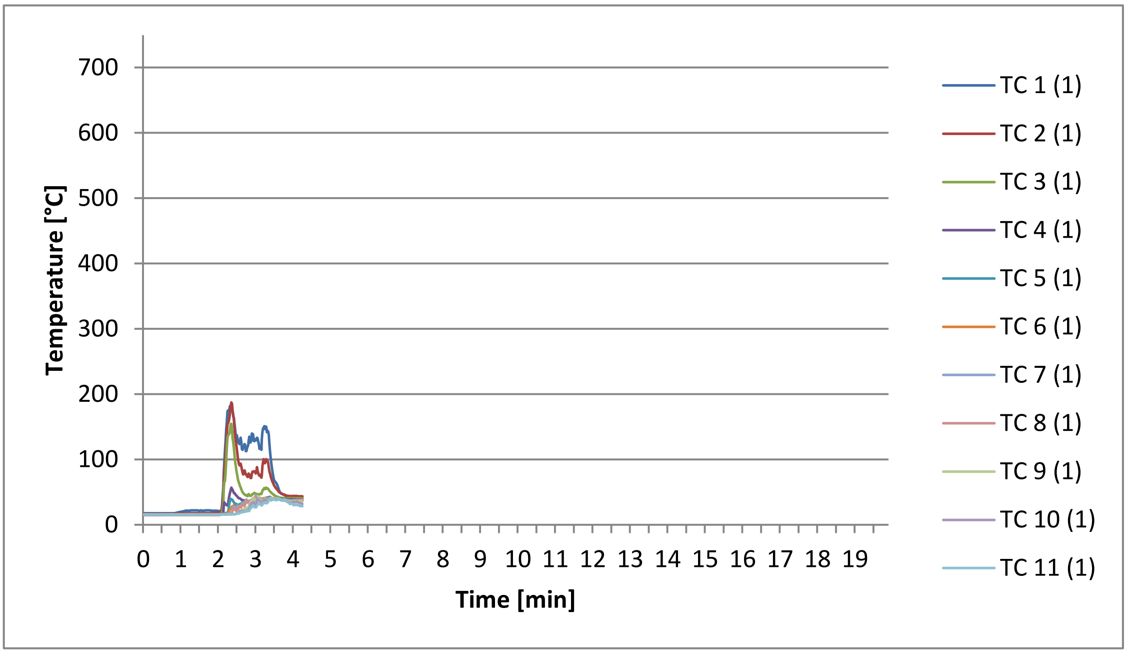

Figure 1- 1. Temperatures from thermocouple tree 1 during test denominated as 3D-WS.

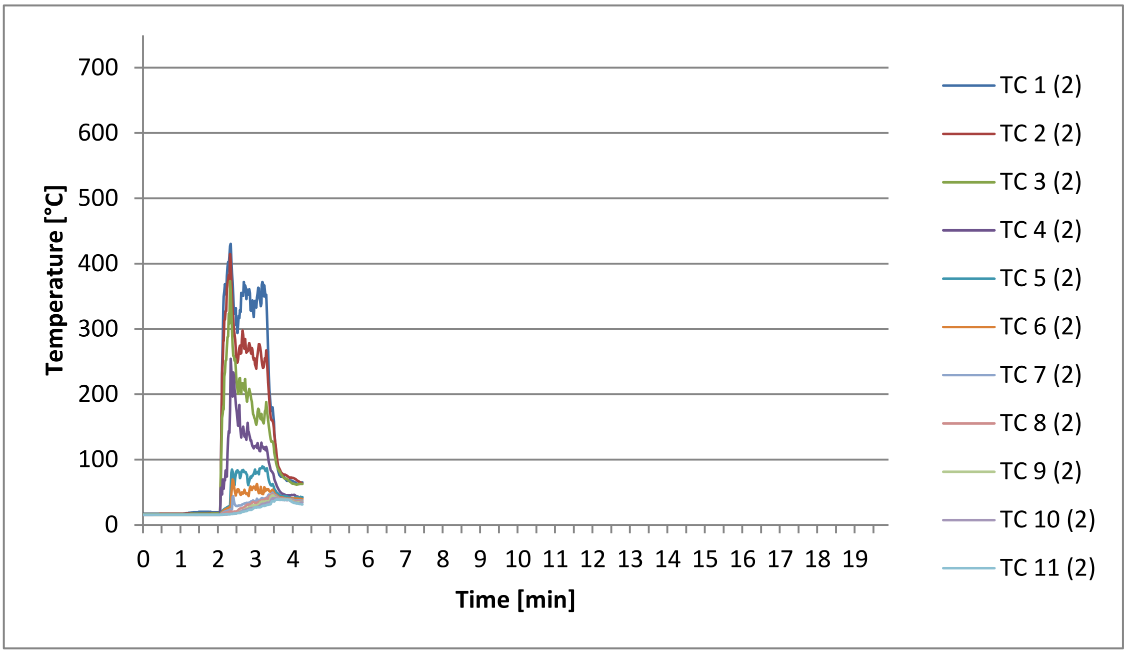

Figure 1- 2. Temperatures from thermocouple tree 2 during test denominated as 3D-WS.

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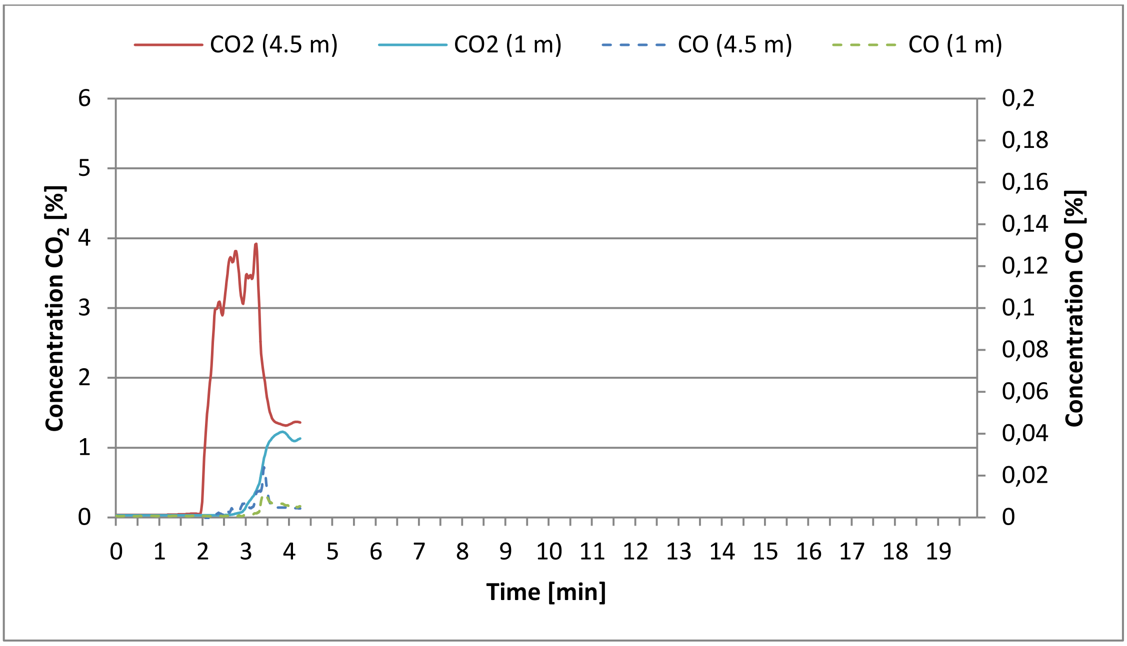

Figure 1- 3. CO and CO_2 measurements during test denominated as 3D-WS.

3D-WMI

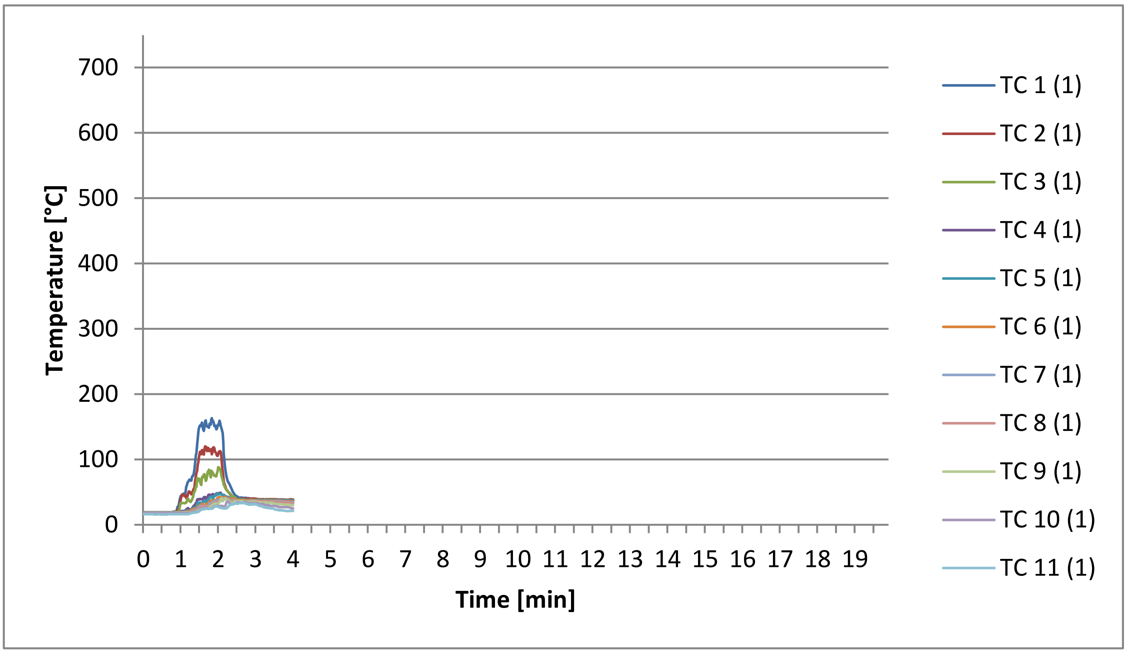

Figure 1- 4. Temperatures from thermocouple tree 1 during test denominated as 3D-WMI.

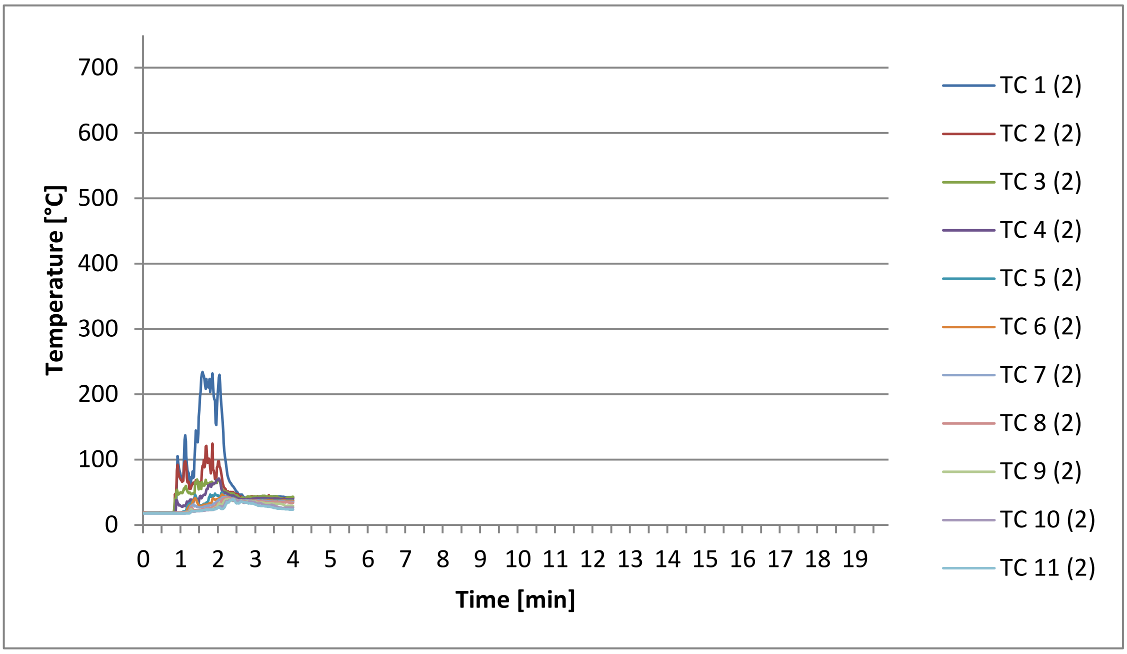

Figure 1- 5. Temperatures from thermocouple tree 2 during test denominated as 3D-WMI.

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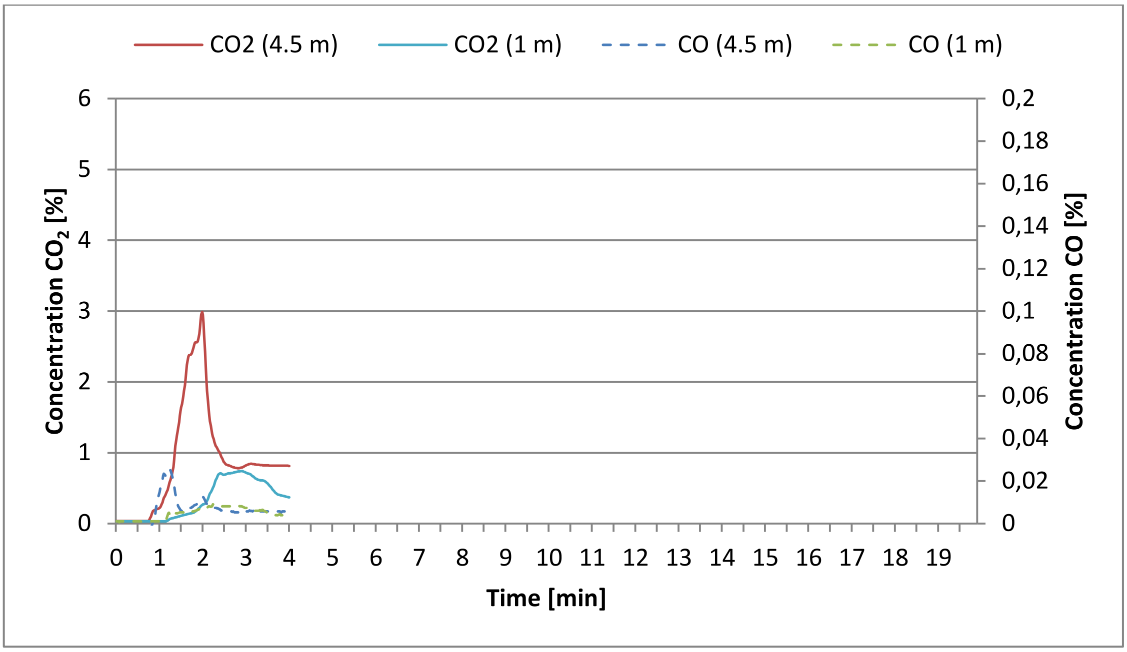

Figure 1- 6. CO and CO_2 measurements during test denominated as 3D-WMl.

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3D-WMh

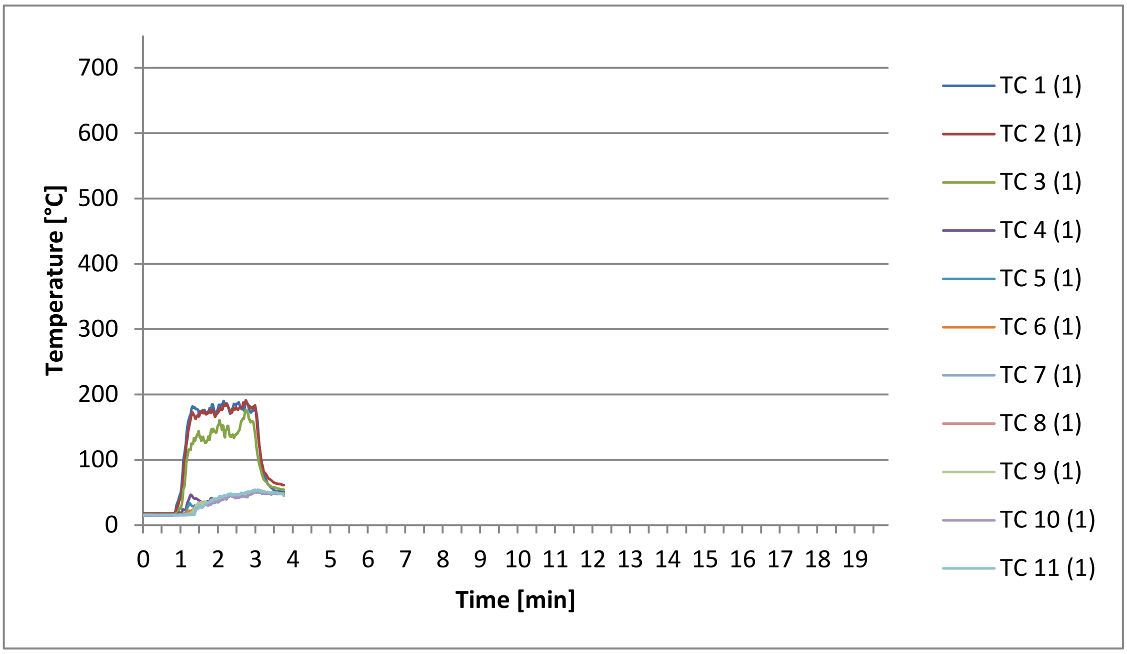

Figure 1- 7. Temperatures from thermocouple tree 1 during test denominated as 3D-WMh.

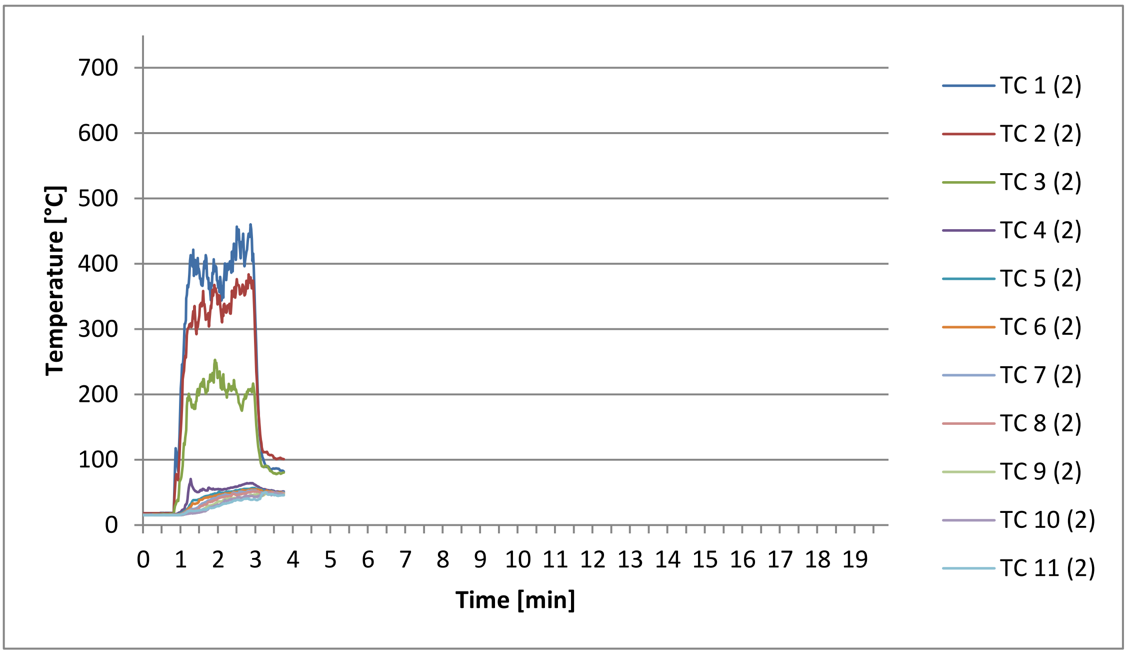

Figure 1- 8. Temperatures from thermocouple tree 2 during test denominated as 3D-WMh.

Appendix 1

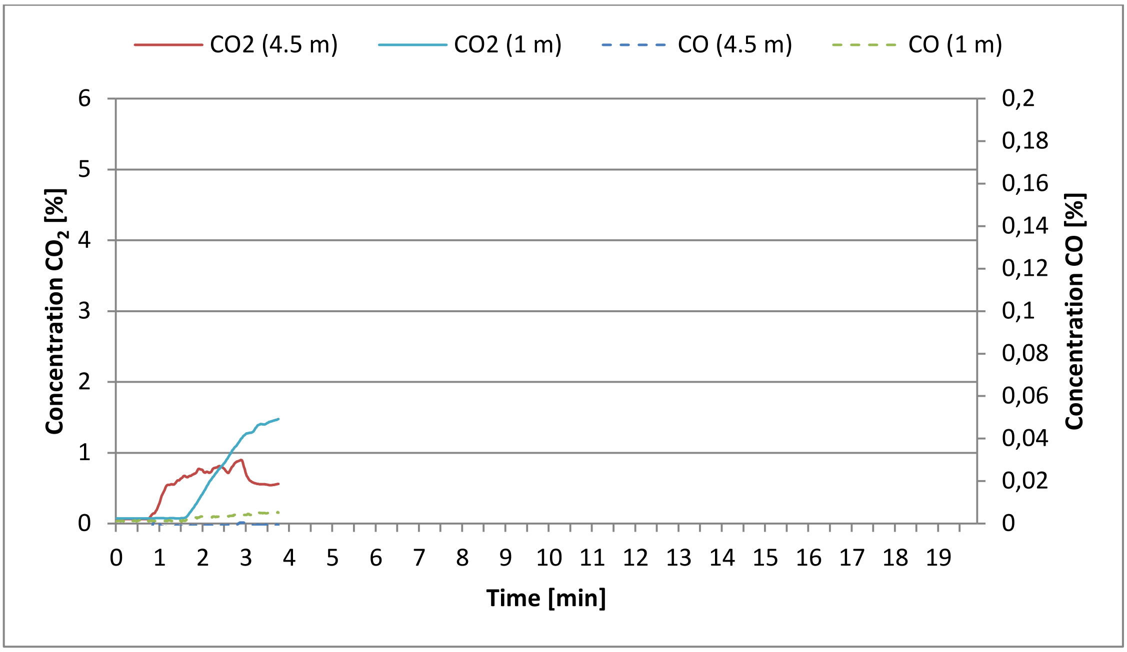

Figure 1- 9. CO and CO_2 measurements during test denominated as 3D-WMh.

3M-WS-f

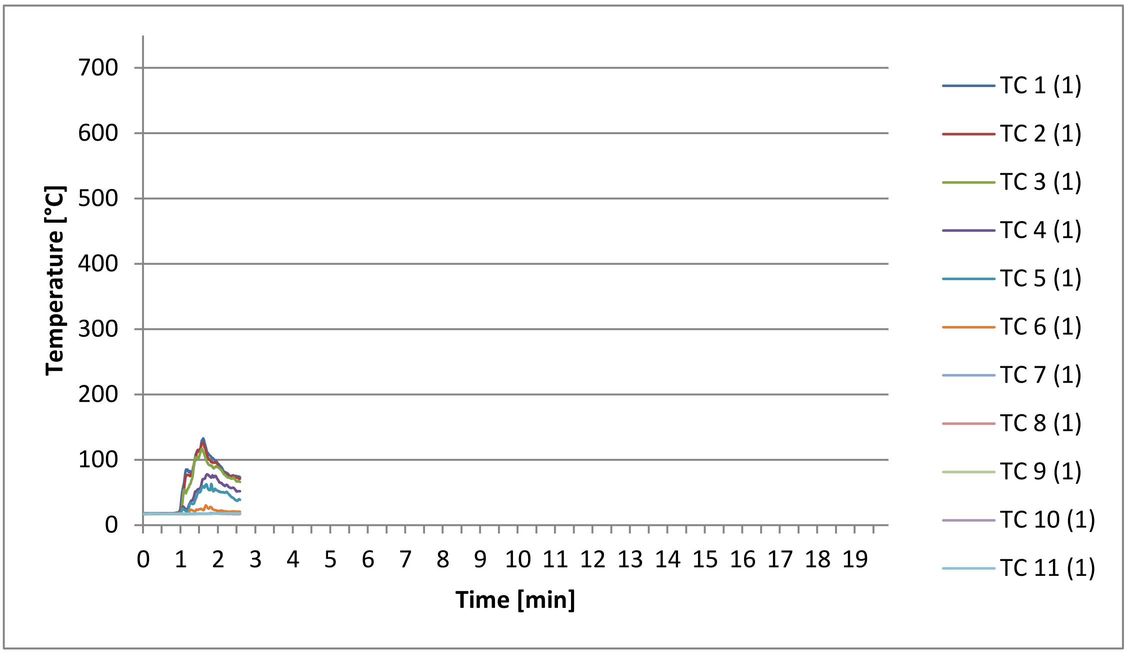

Figure 1- 10. Temperatures from thermocouple tree 1 during test denominated as 3M-WS-f.

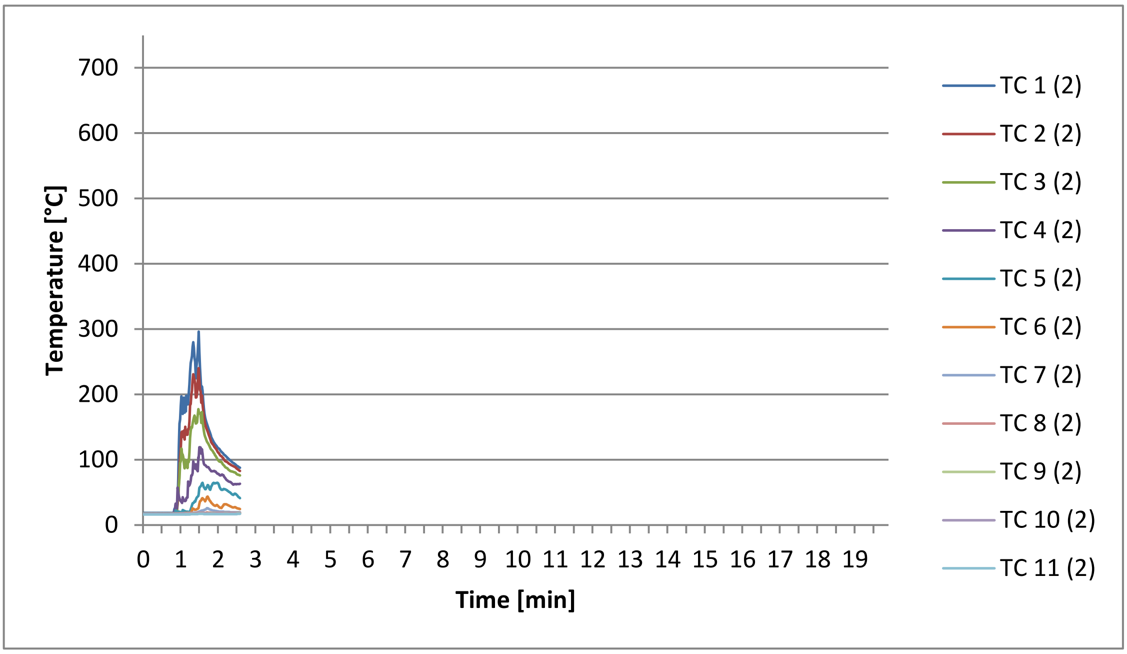

Figure 1- 11. Temperatures from thermocouple tree 2 during test denominated as 3M-WS-f.

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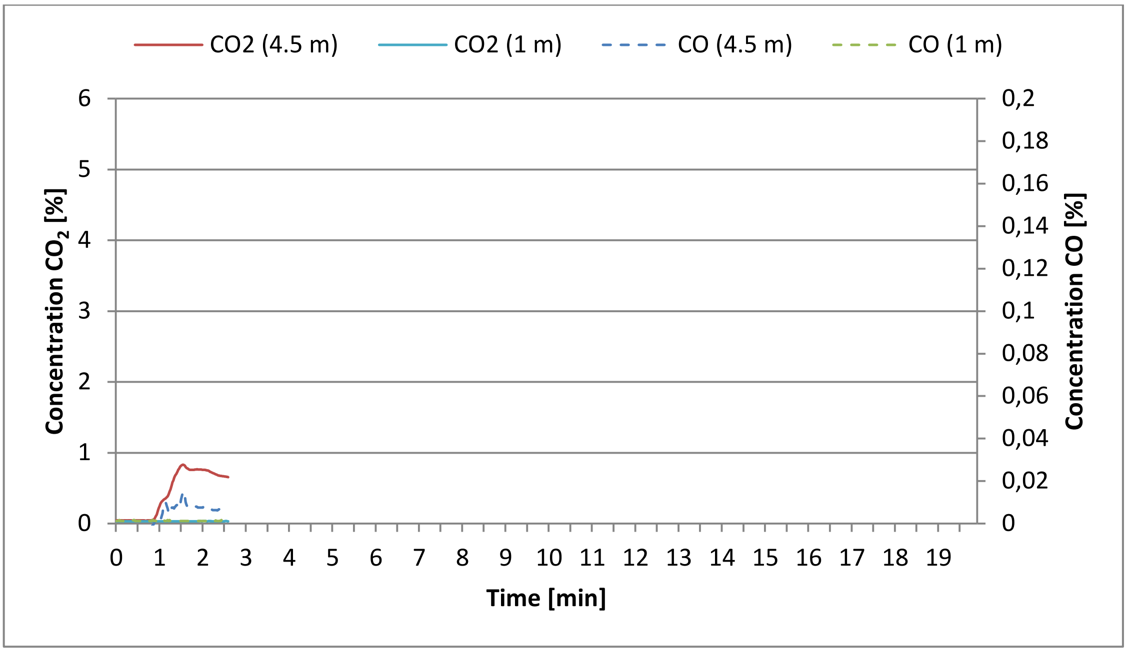

Figure 1- 12. CO and CO_2 measurements during test denominated as 3M-WS-f.

8M-WMl-f

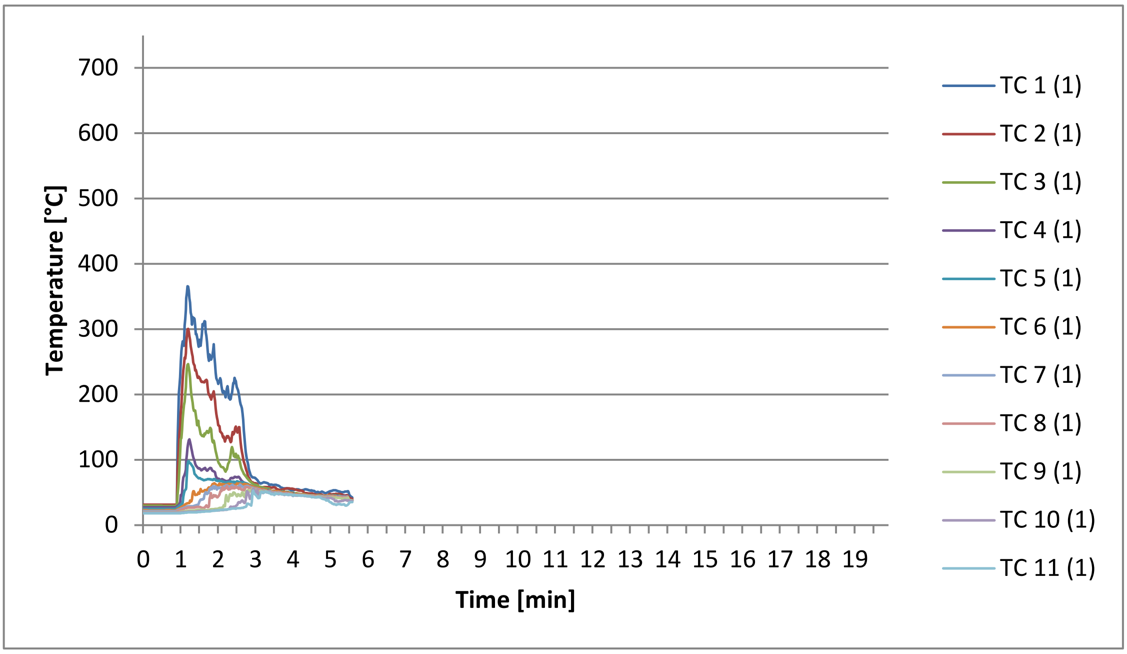

Figure 1- 13. Temperatures from thermocouple tree 1 during test denominated as 8M-WMl-f.

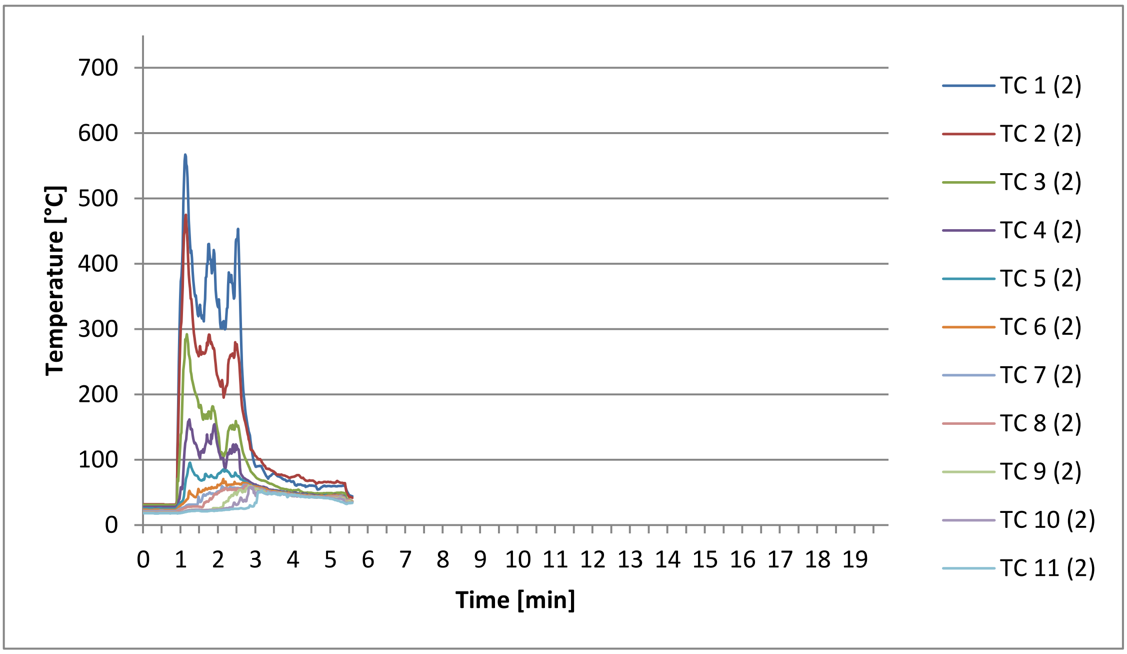

Figure 1- 14. Temperatures from thermocouple tree 2 during test denominated as 8M-WMl-f.

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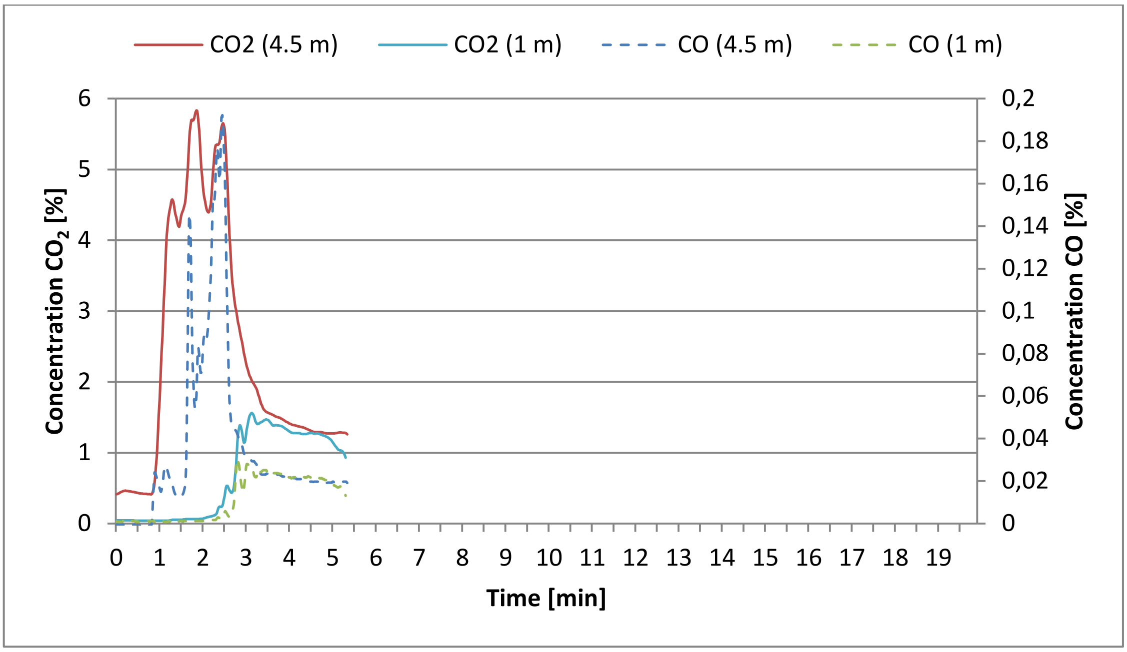

Figure 1- 15. CO and CO_2 measurements during test denominated as 8M-WMI-f.

8M-WMh-f

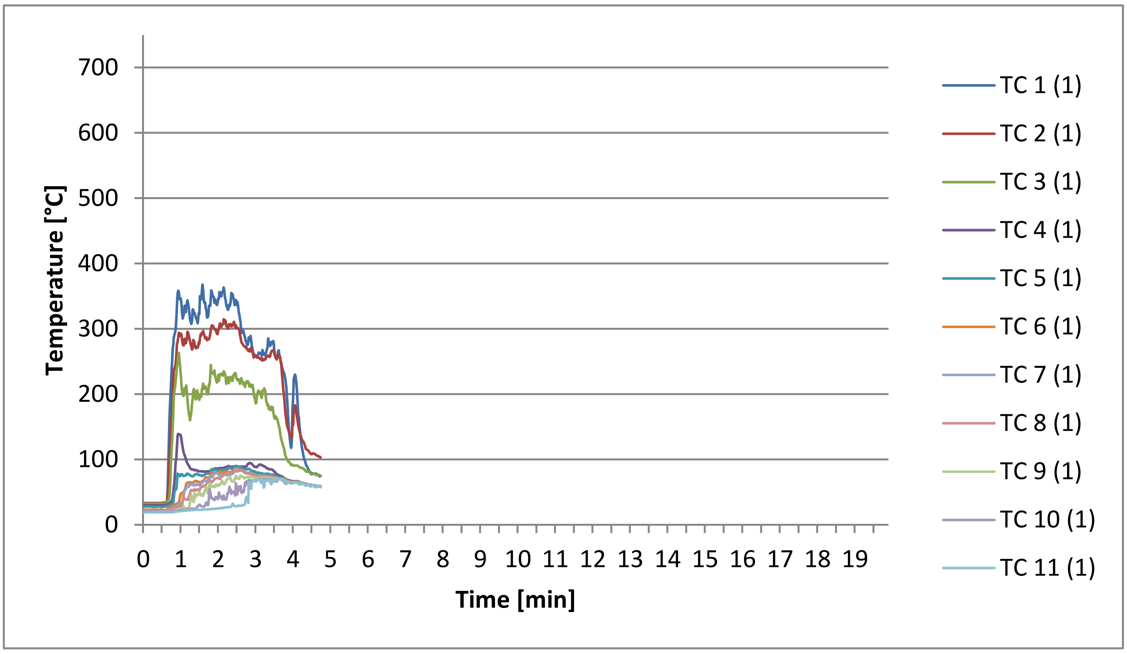

Figure 1- 16. Temperatures from thermocouple tree 1 during test denominated as 8M-WMh-f.

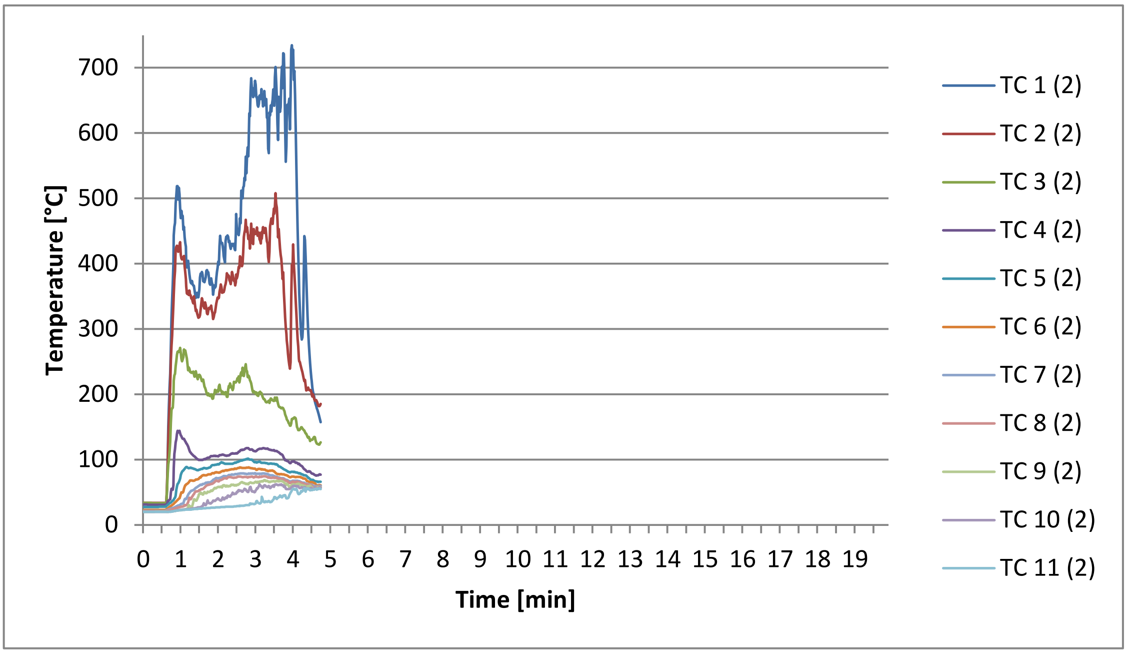

Figure 1- 17. Temperatures from thermocouple tree 2 during test denominated as 8M-WMh-f.

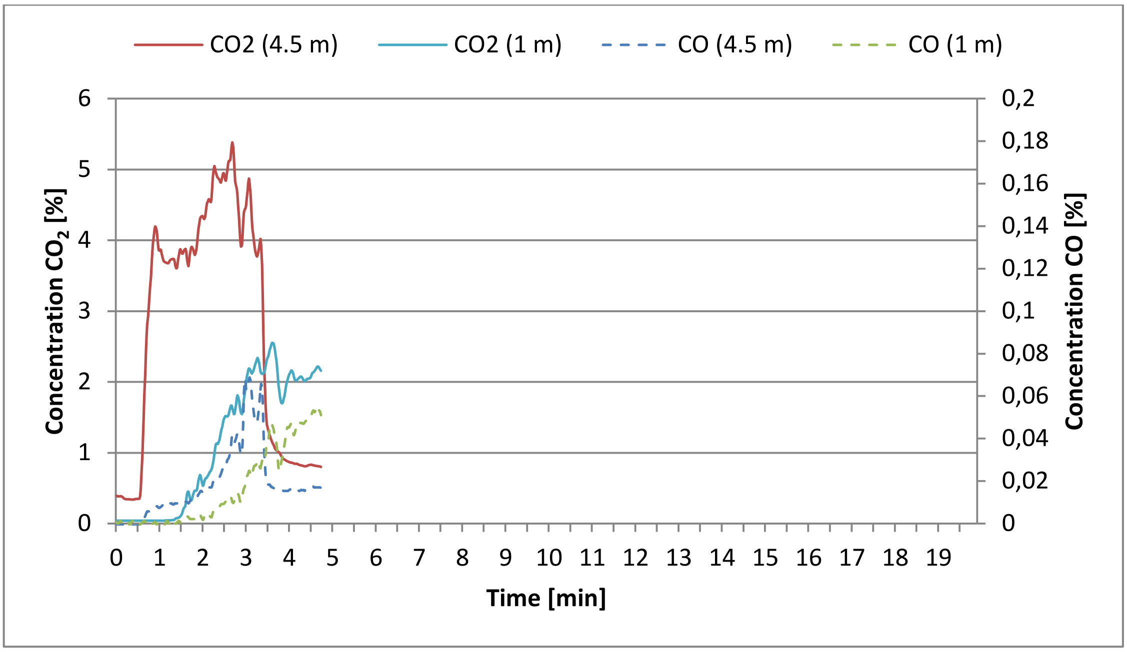

Figure 1- 18. CO and CO_2 measurements during test denominated as 8M-WMh-f.

5H-WS

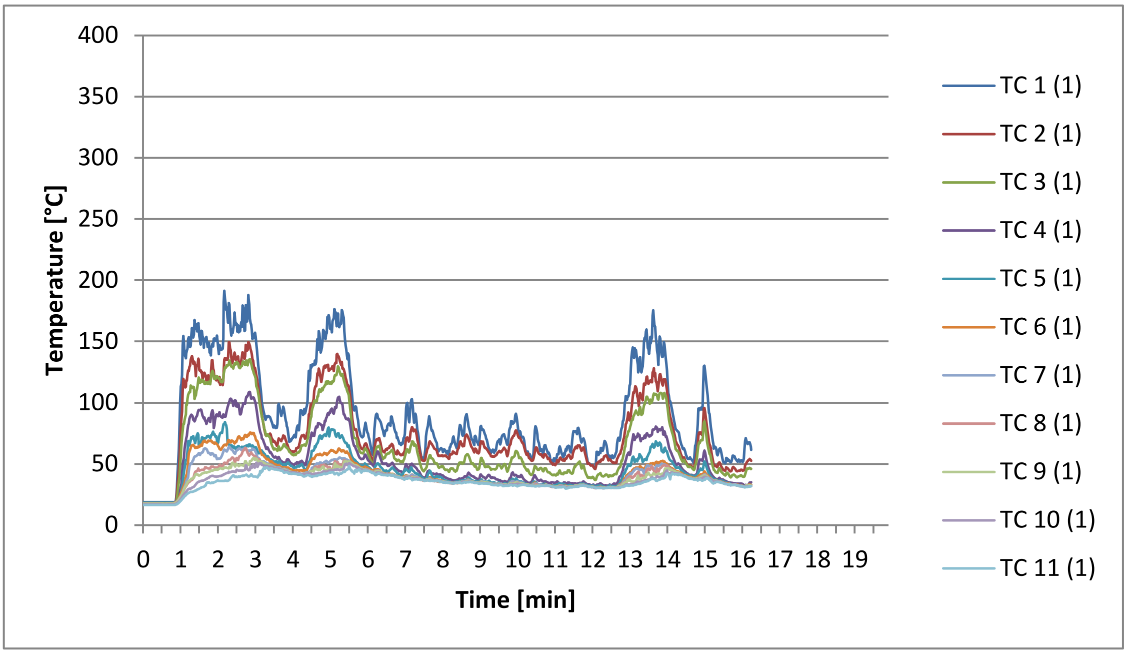

Figure 1- 19. Temperatures from thermocouple tree 1 during test denominated as 5H-WS.

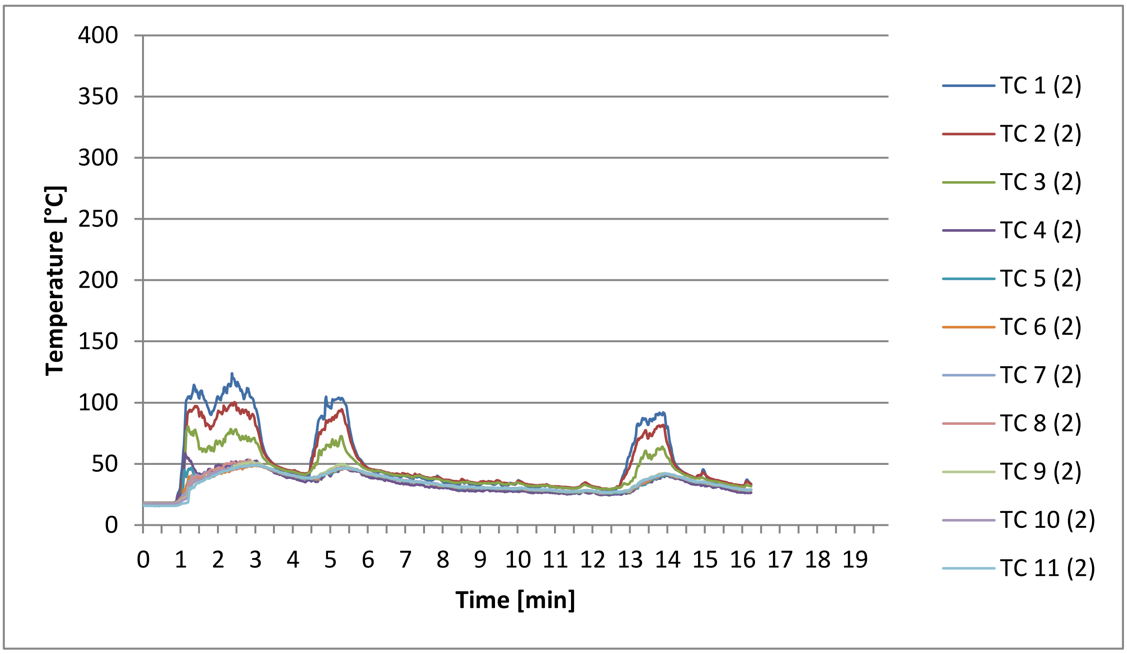

Figure 1- 20. Temperatures from thermocouple tree 2 during test denominated as 5H-WS.

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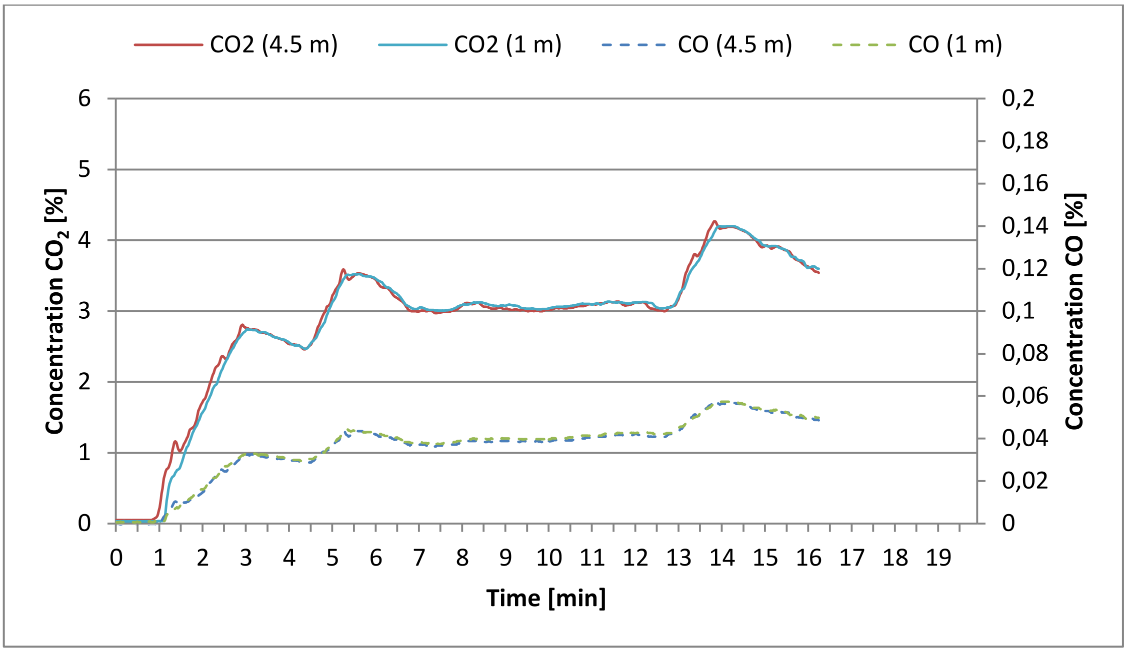

Figure 1- 21. CO and CO_2 measurements during test denominated as 5H-WS.

5H-WMl

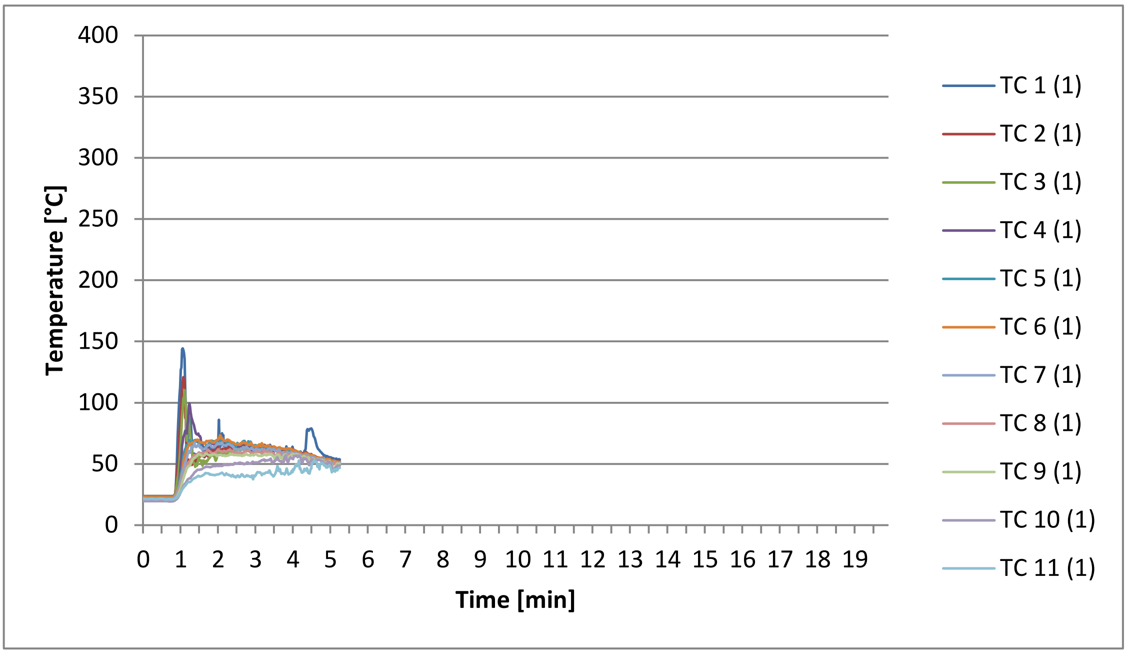

Figure 1- 22. Temperatures from thermocouple tree 1 during test denominated as 5H-WMl.

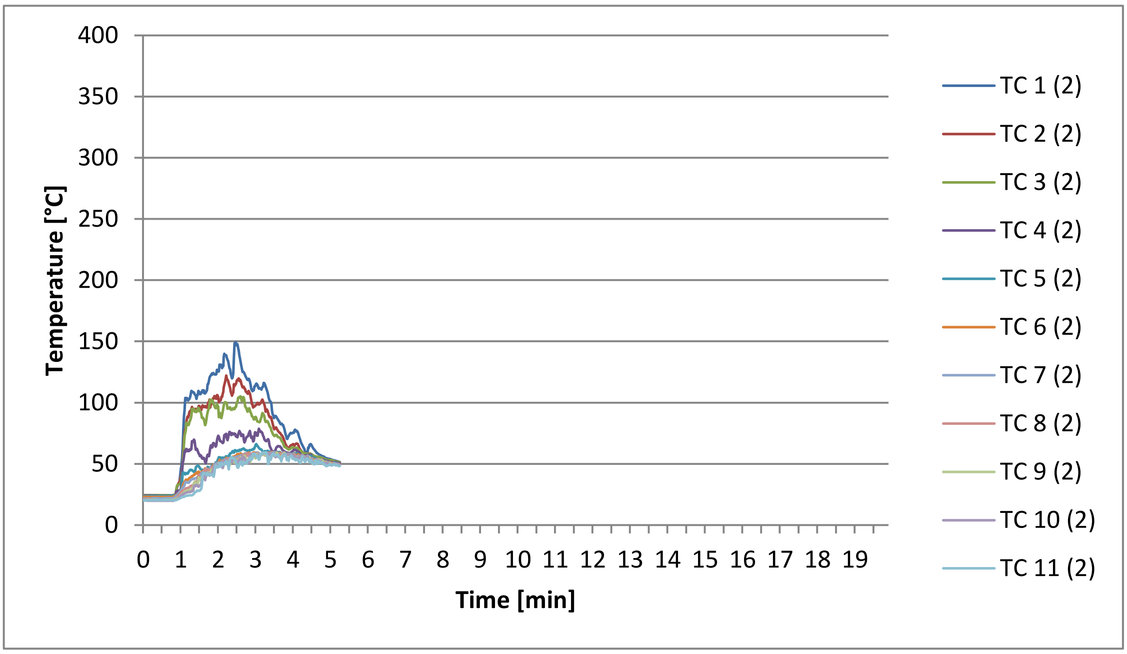

Figure 1- 23. Temperatures from thermocouple tree 2 during test denominated as 5H-WMl.

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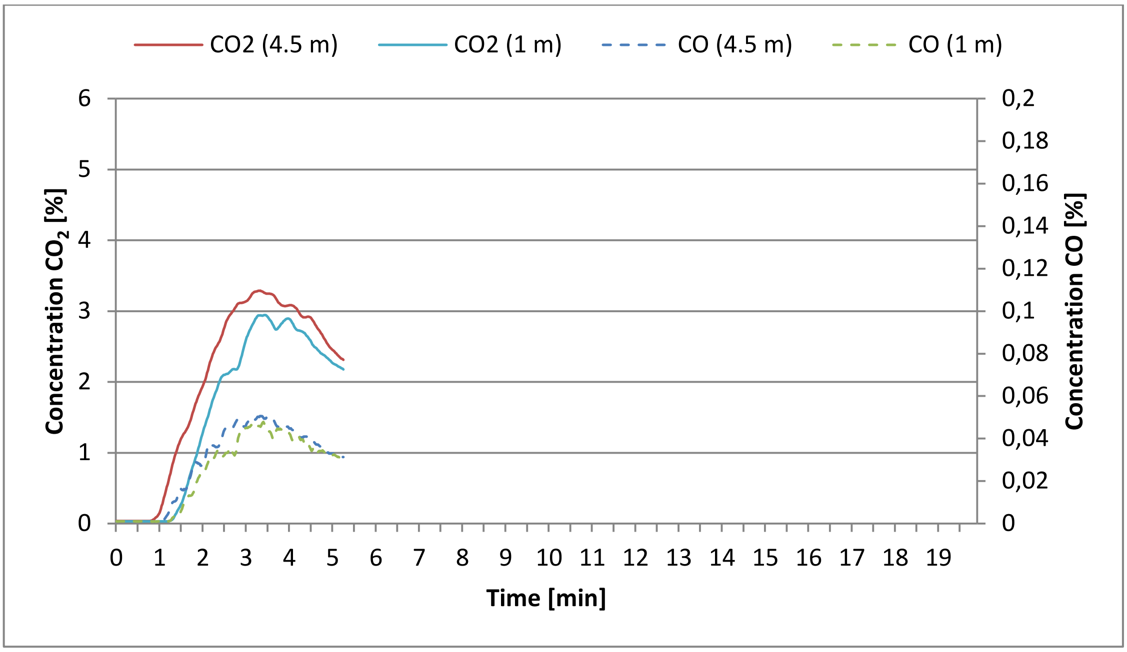

Figure 1- 24. CO and CO_2 measurements during test denominated as 5H-WMl.

5H-WMh

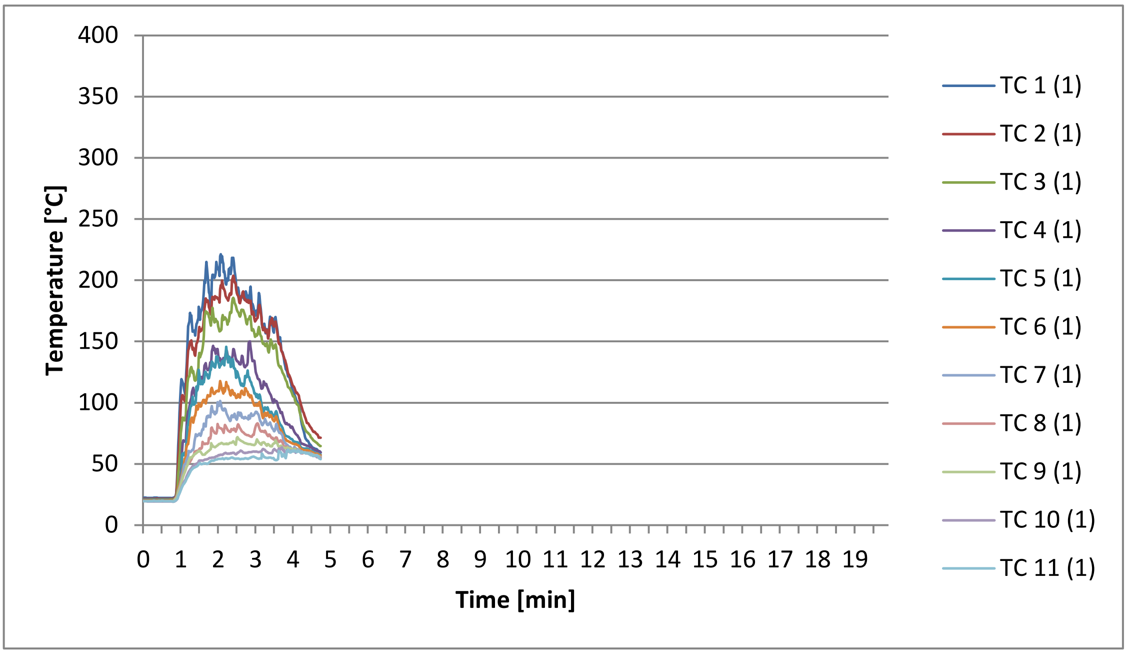

Figure 1- 25. Temperatures from thermocouple tree 1 during test denominated as 5H-WMh.

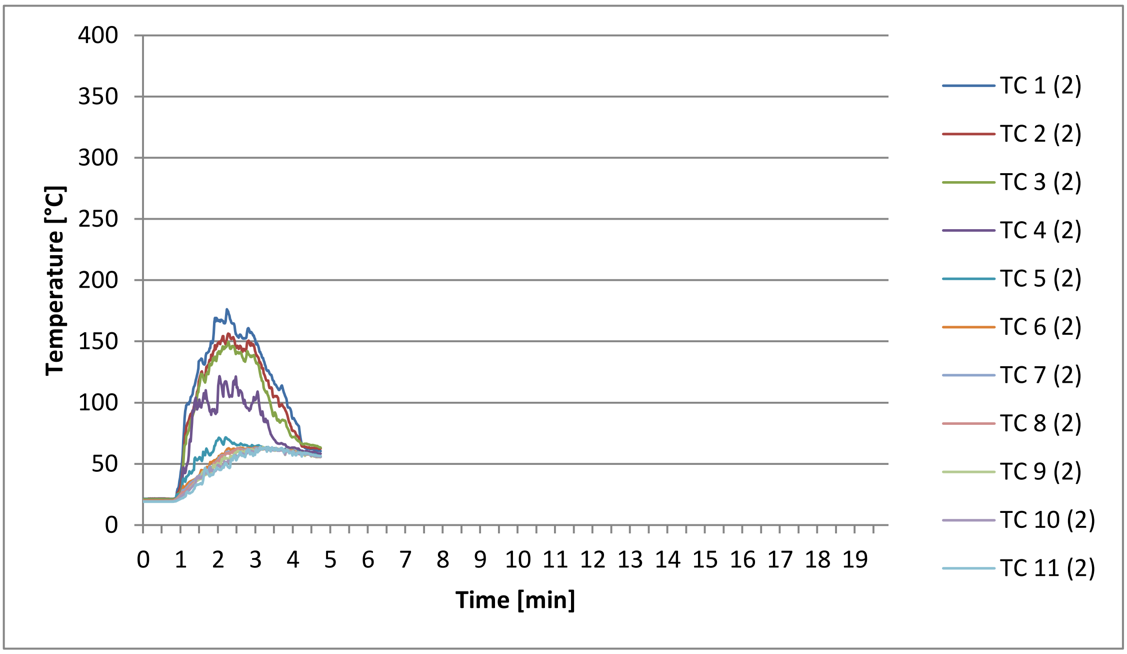

Figure 1- 26. Temperatures from thermocouple tree 2 during test denominated as 5H-WMh.

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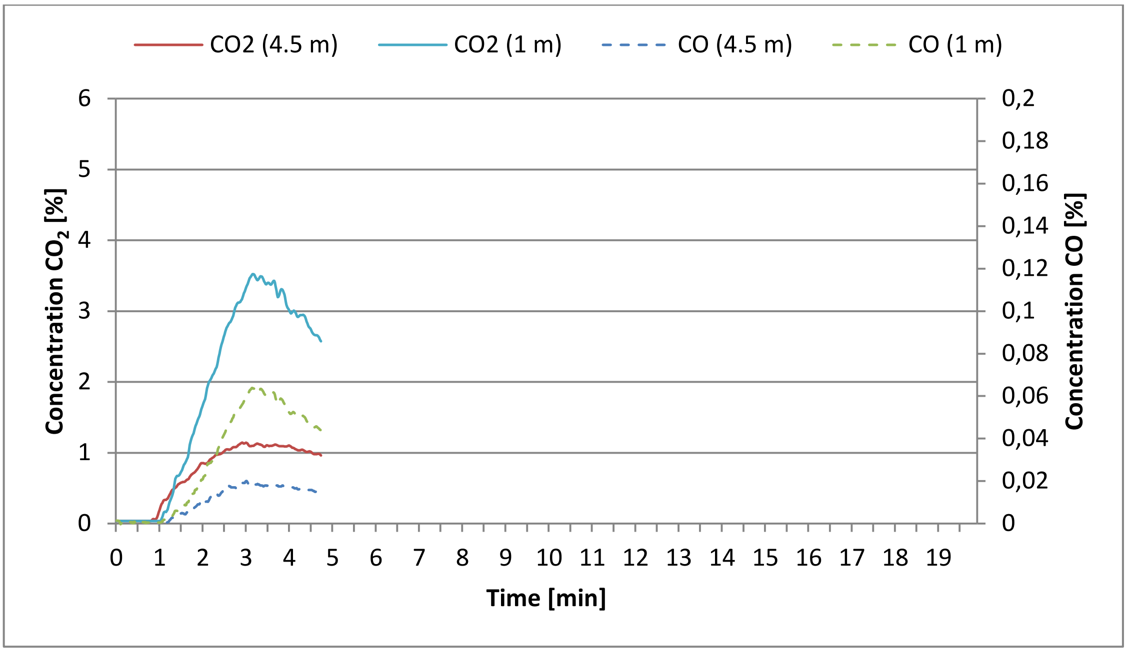

Figure 1- 27. CO and CO_2 measurements during test denominated as 5H-WMh.

5M-WS-f

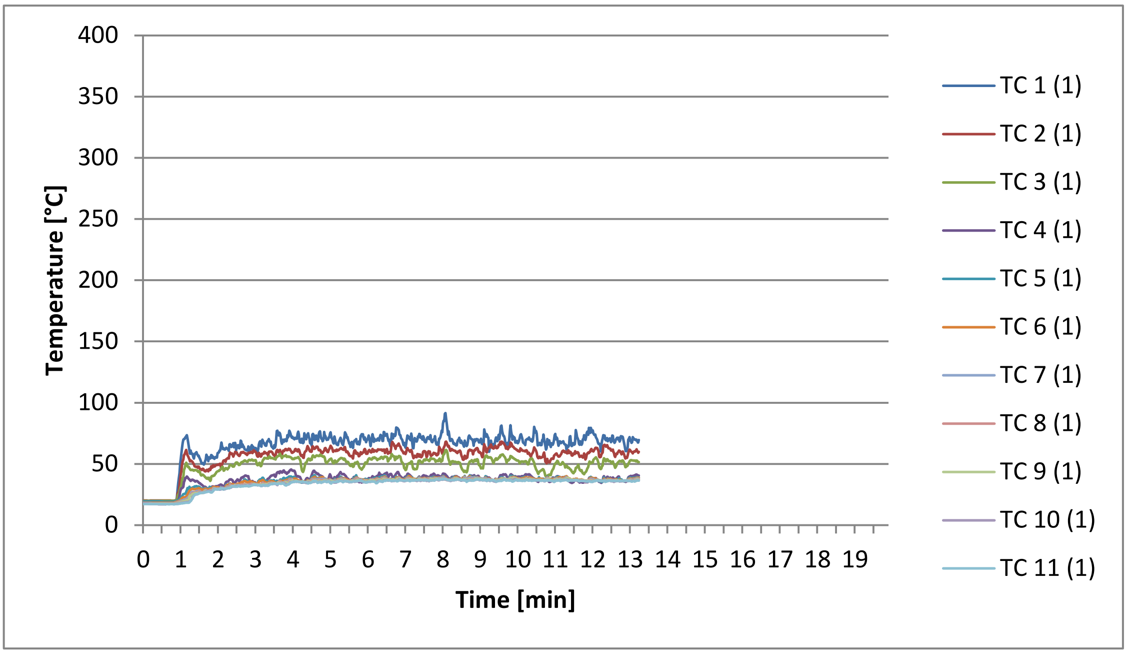

Figure 1- 28. Temperatures from thermocouple tree 1 during test denominated as 5M-WS-f.

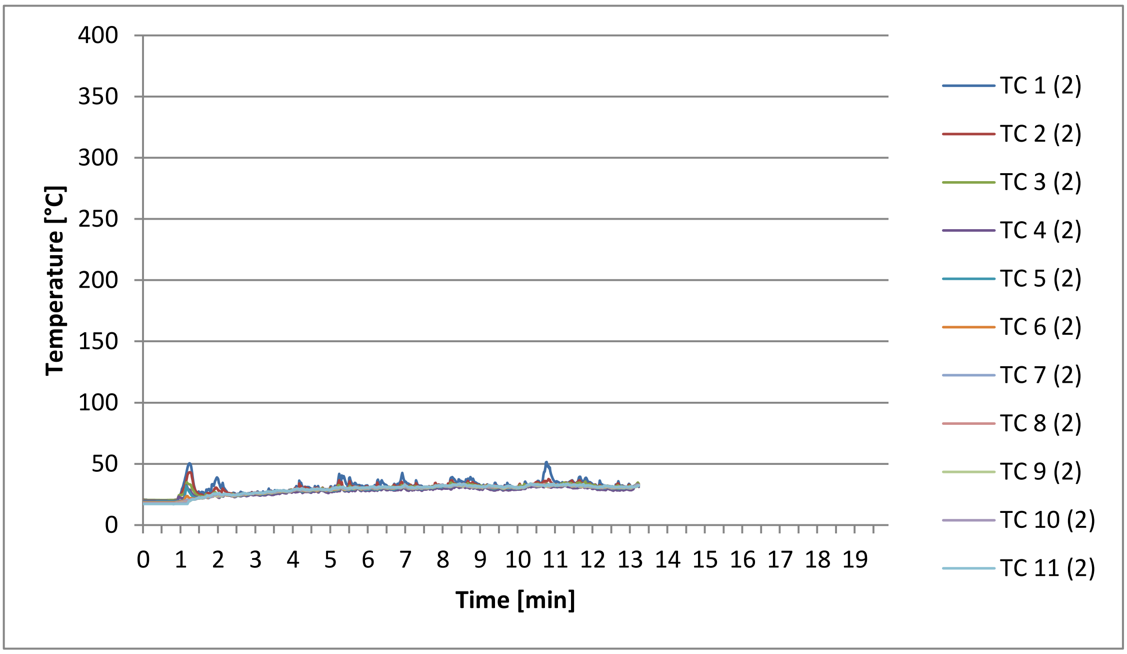

Figure 1- 29. Temperatures from thermocouple tree 2 during test denominated as 5M-WS-f.

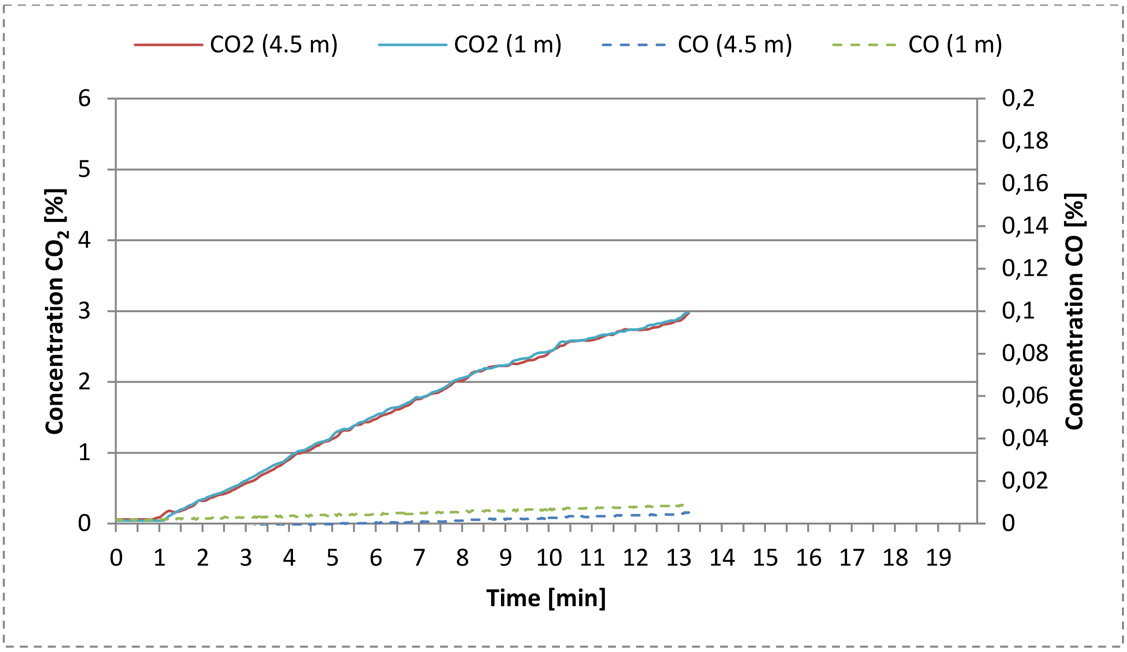

Figure 1- 30. CO and CO_2 measurements during test denominated as 5M-WS-f.

5M-WMl-f

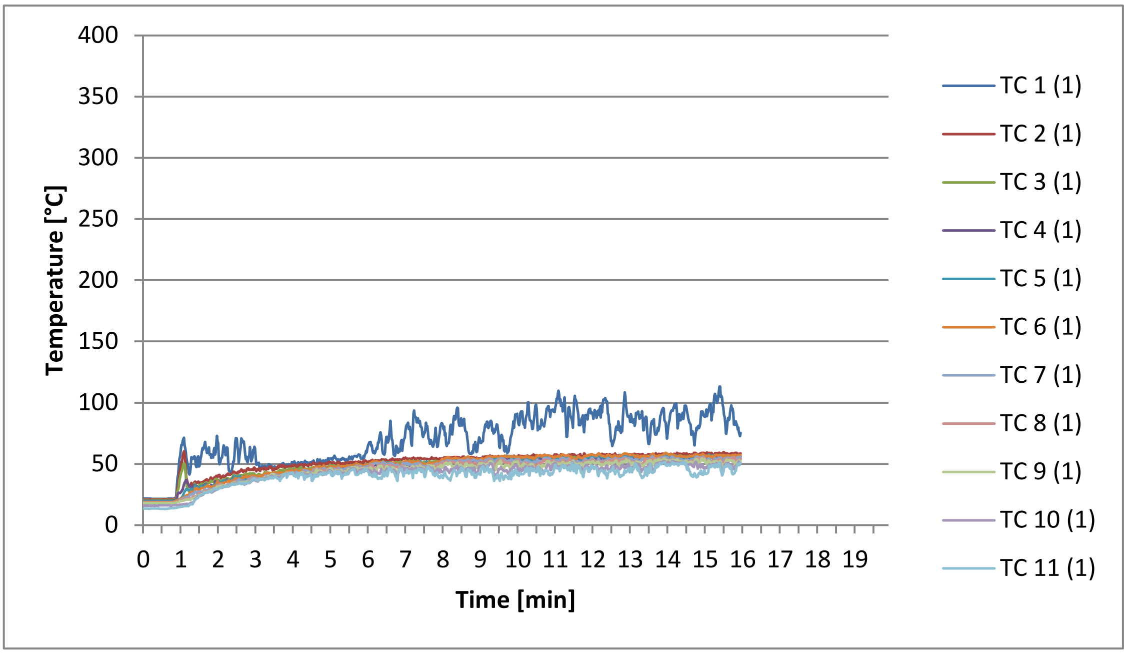

Figure 1- 31. Temperatures from thermocouple tree 1 during test denominated as 5M-WMl-f.

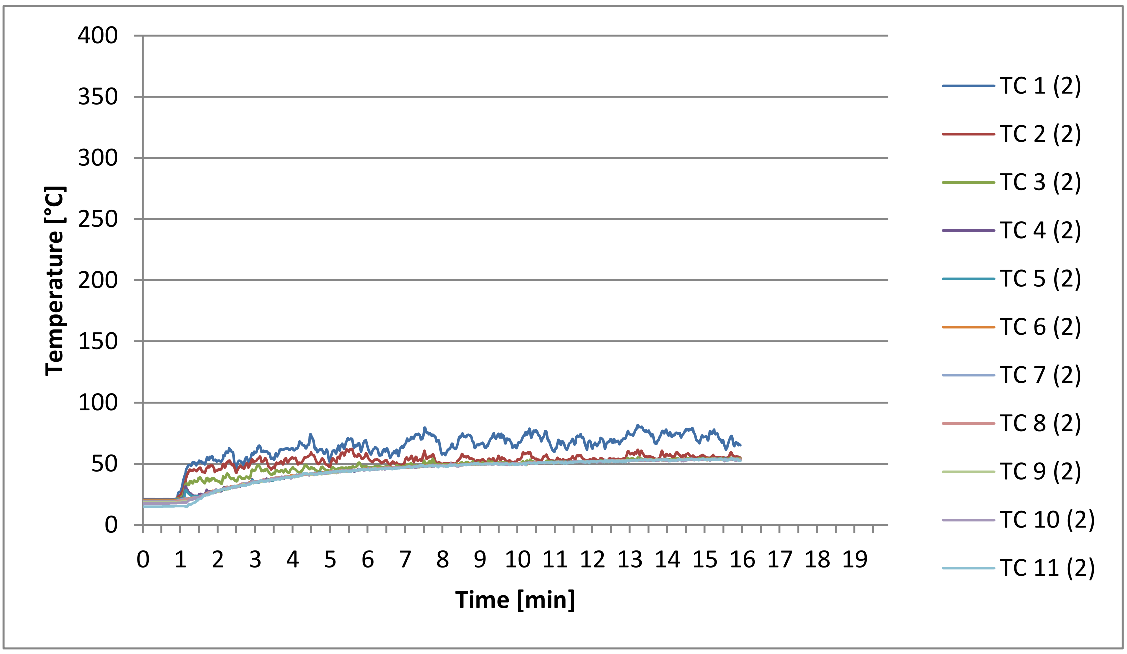

Figure 1- 32. Temperatures from thermocouple tree 2 during test denominated as 5M-WMl-f.

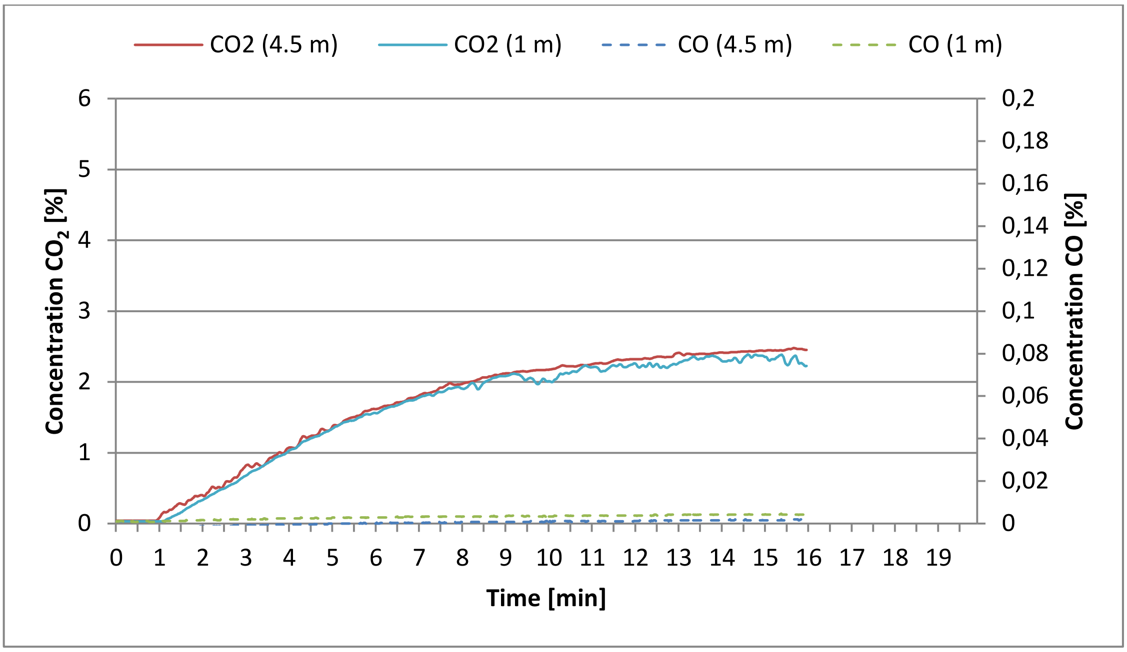

Figure 1- 33. CO and CO_2 measurements during test denominated as 5M-WMl-f.

5M-WMh-f

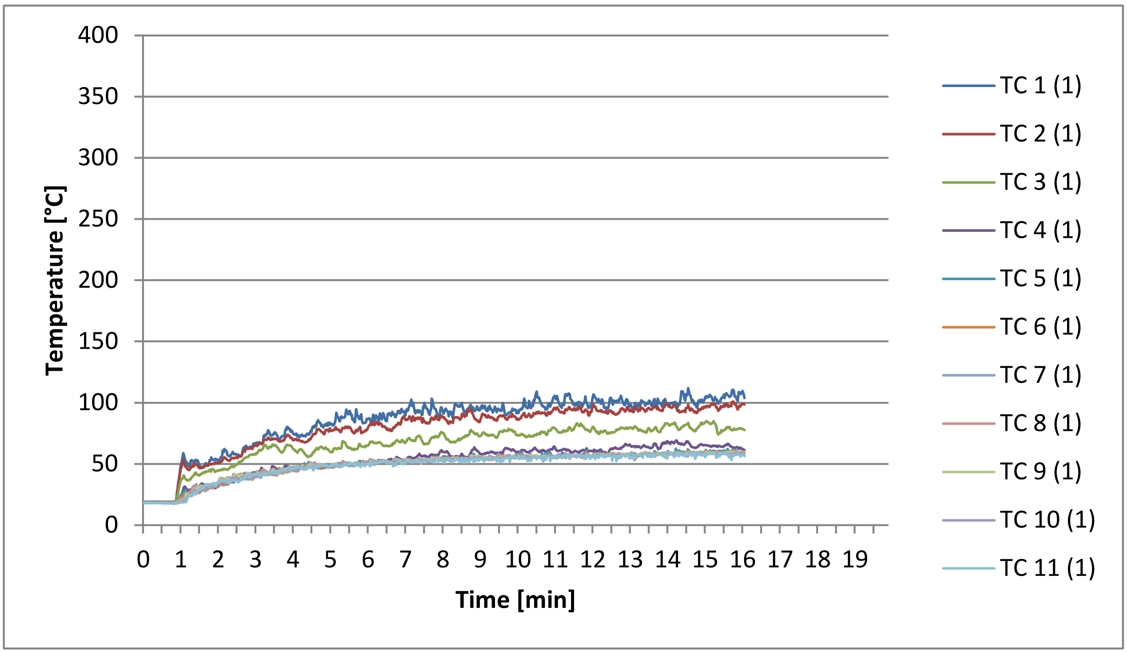

Figure 1- 34. Temperatures from thermocouple tree 1 during test denominated as 5M-WMh-f.

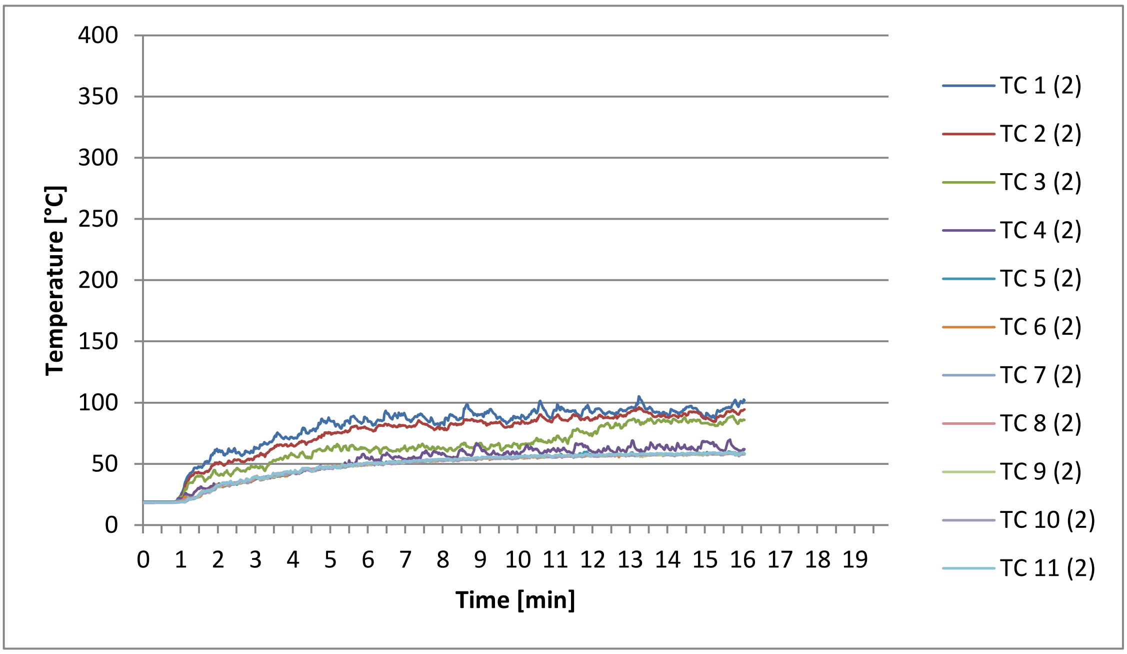

Figure 1- 35. Temperatures from thermocouple tree 2 during test denominated as 5M-WMh-f.

Appendix 1

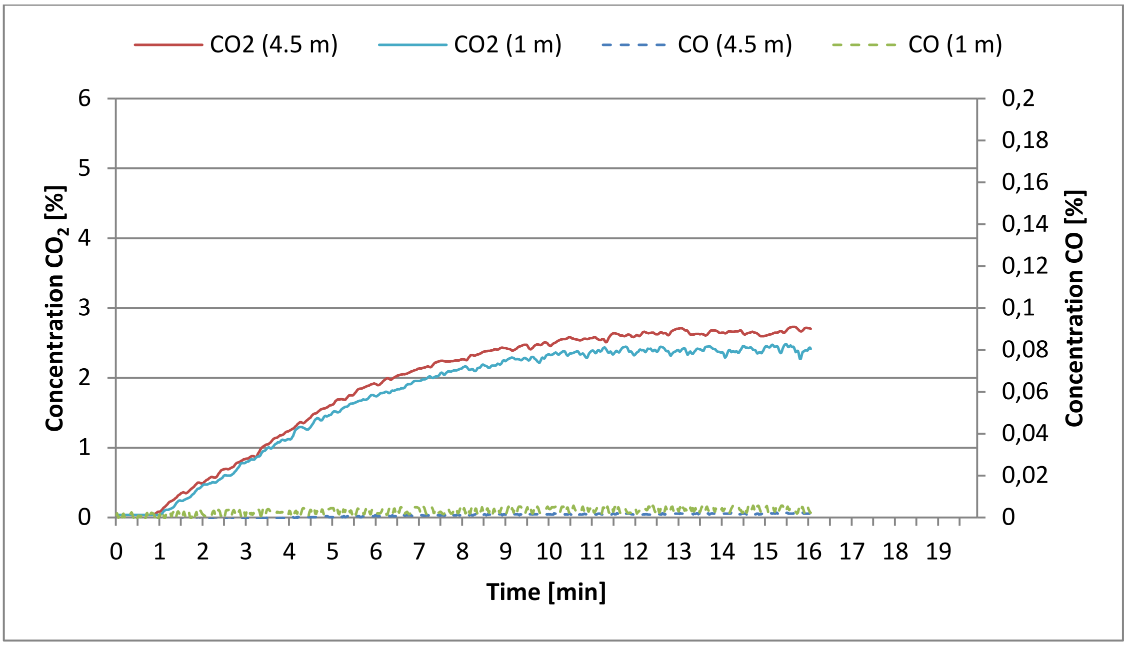

Figure 1- 36. CO and CO_2 measurements during test denominated as 5M-WMh-f.

Appendix 1

7H-WS

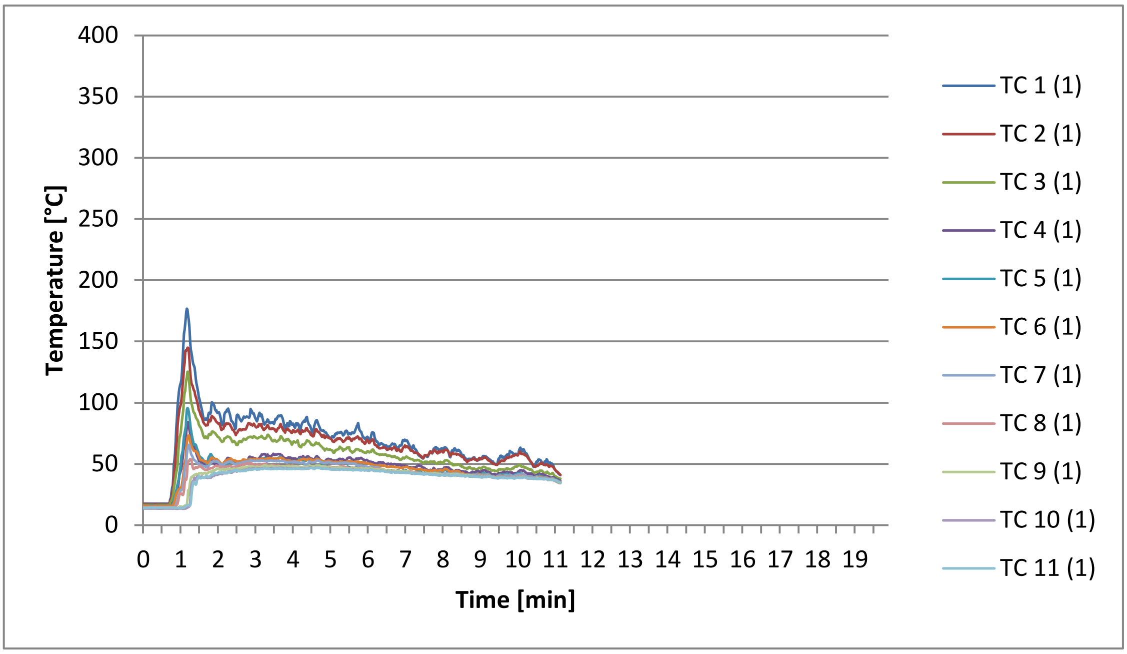

Figure 1- 37. Temperatures from thermocouple tree 1 during test denominated as 7H-WS.

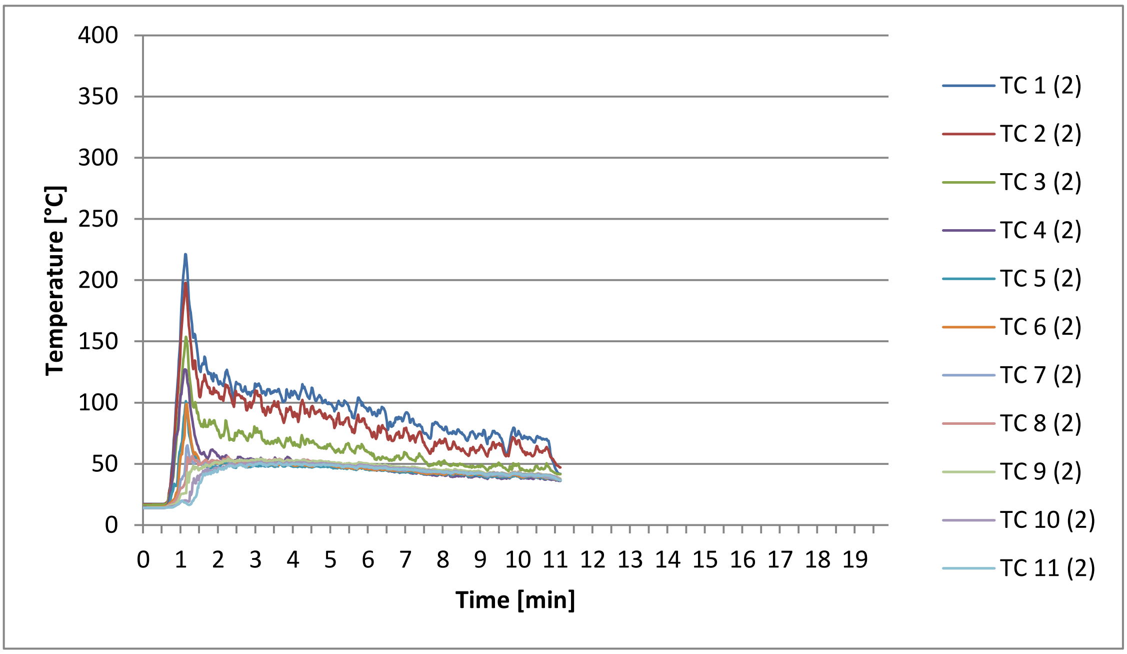

Figure 1- 38. Temperatures from thermocouple tree 2 during test denominated as 7H-WS.

Appendix 1

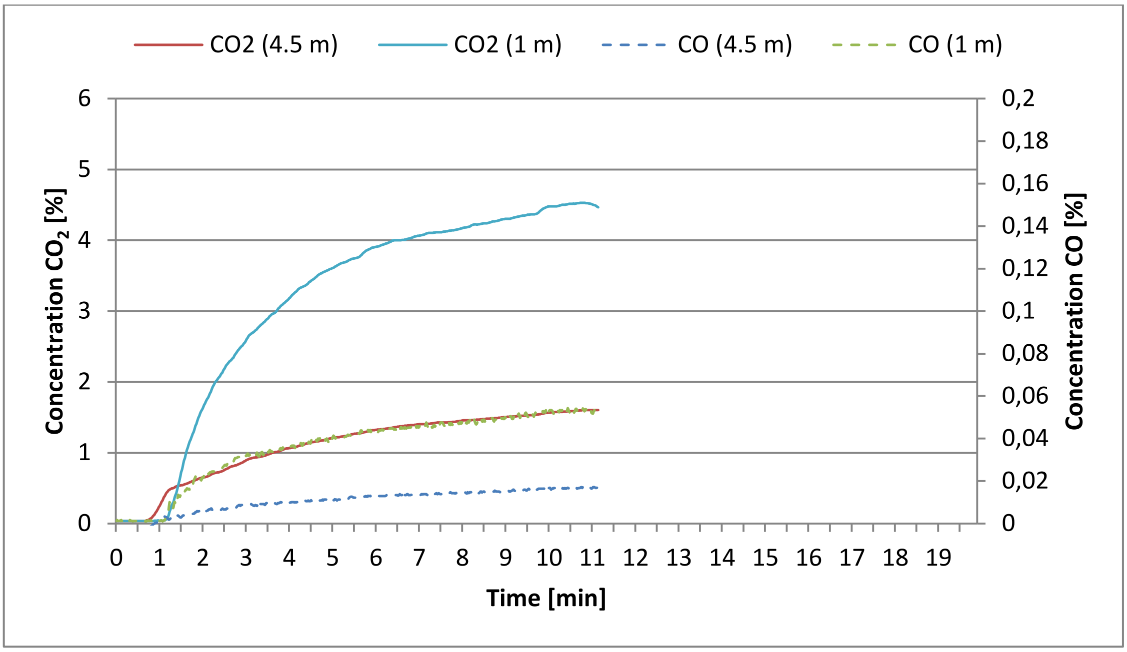

Figure 1- 39.CO and CO_2 measurements during test denominated as 7H-WS.

7H-WMl

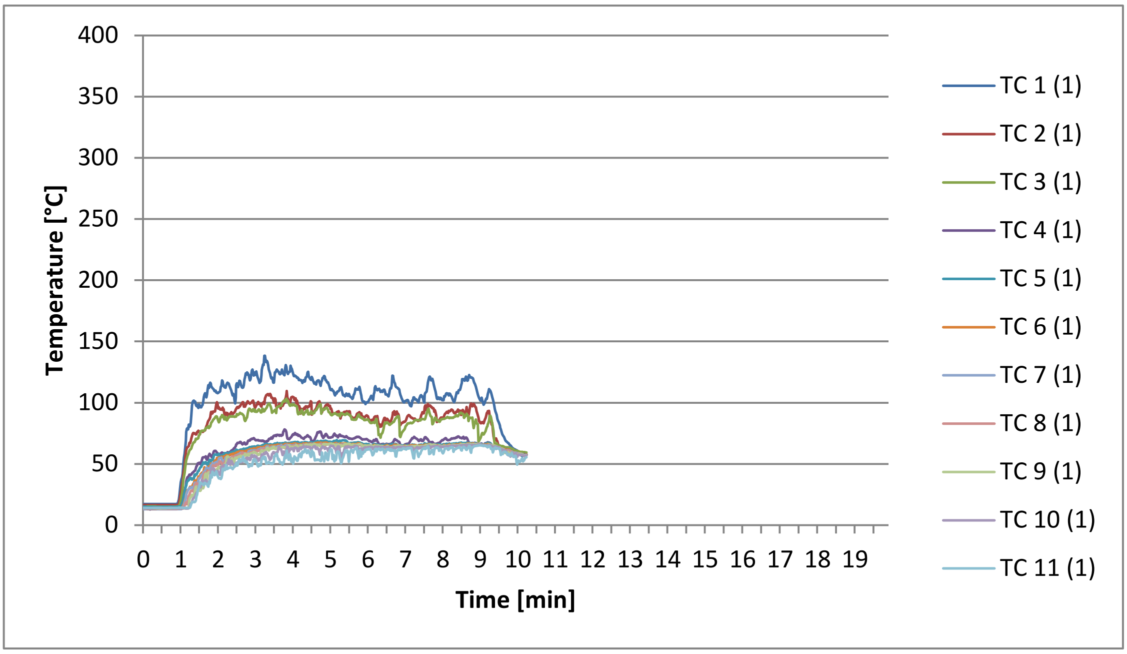

Figure 1- 40. Temperatures from thermocouple tree 1 during test denominated as 7H-WMl.

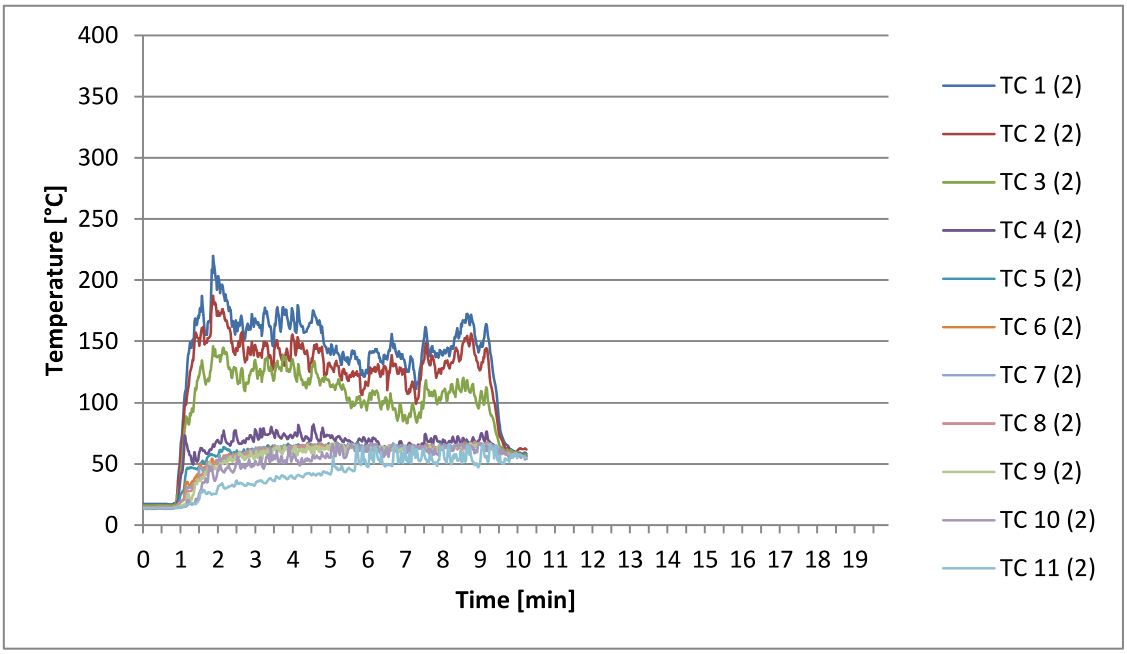

Figure 1- 41. Temperatures from thermocouple tree 2 during test denominated as 7H-WMl.

Appendix 1

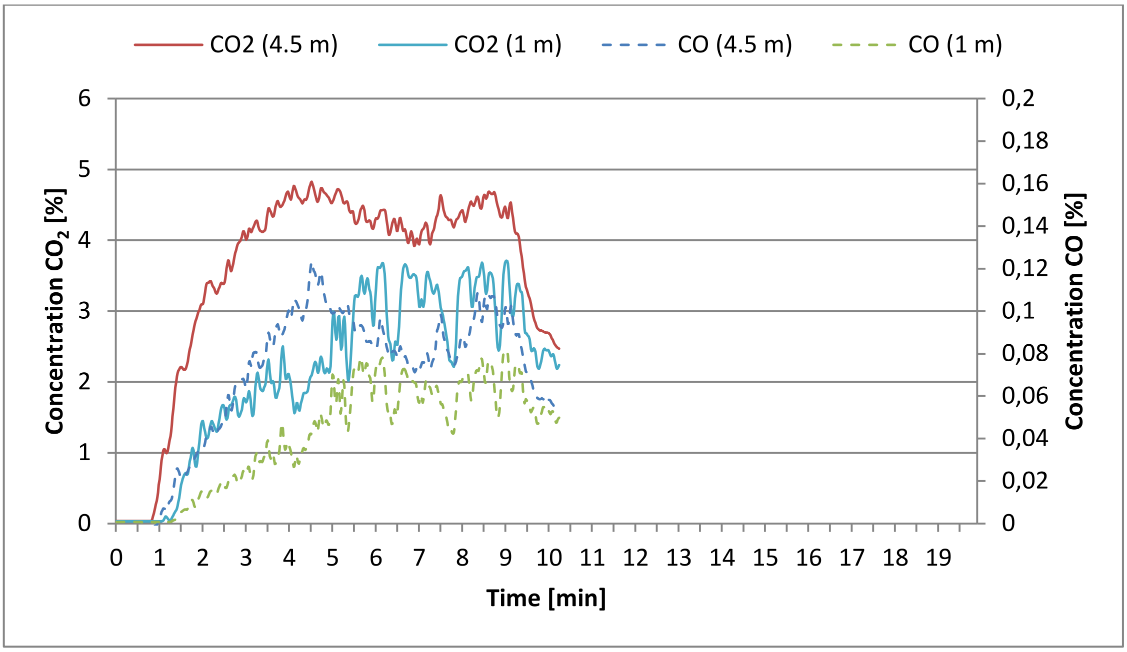

Figure 1- 42. CO and CO_2 measurements during test denominated as 7H-WMl.

7H-WMh

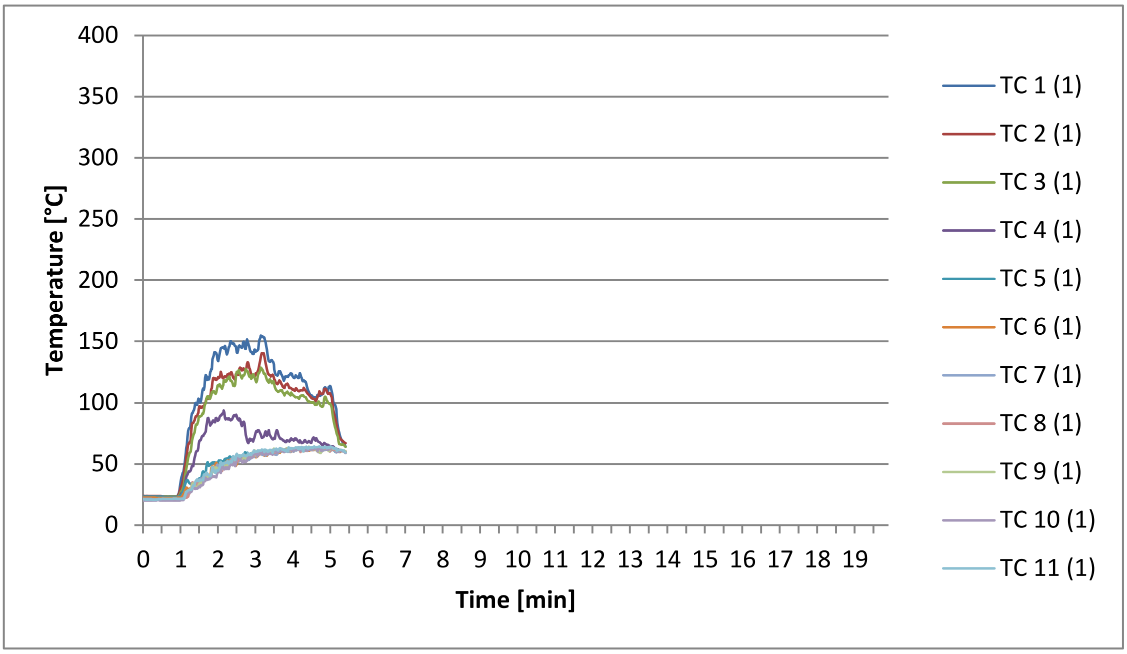

Figure 1- 43. Temperatures from thermocouple tree 1 during test denominated as 7H-WMh.

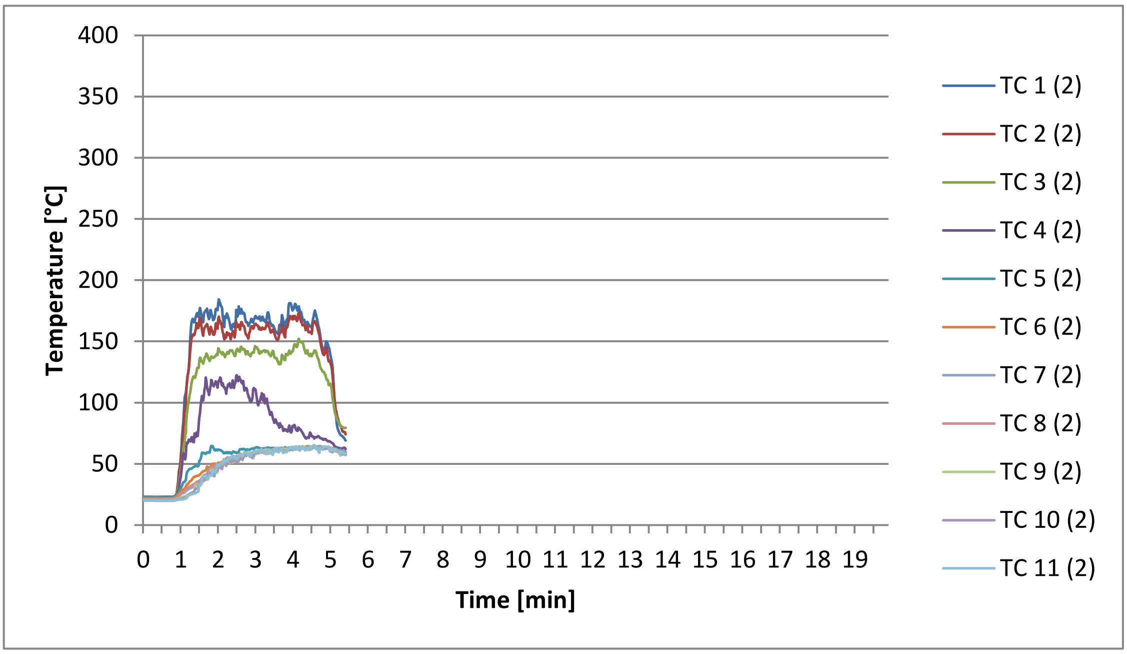

Figure 1- 44. Temperatures from thermocouple tree 2 during test denominated as 7H-WMh.

Appendix 1

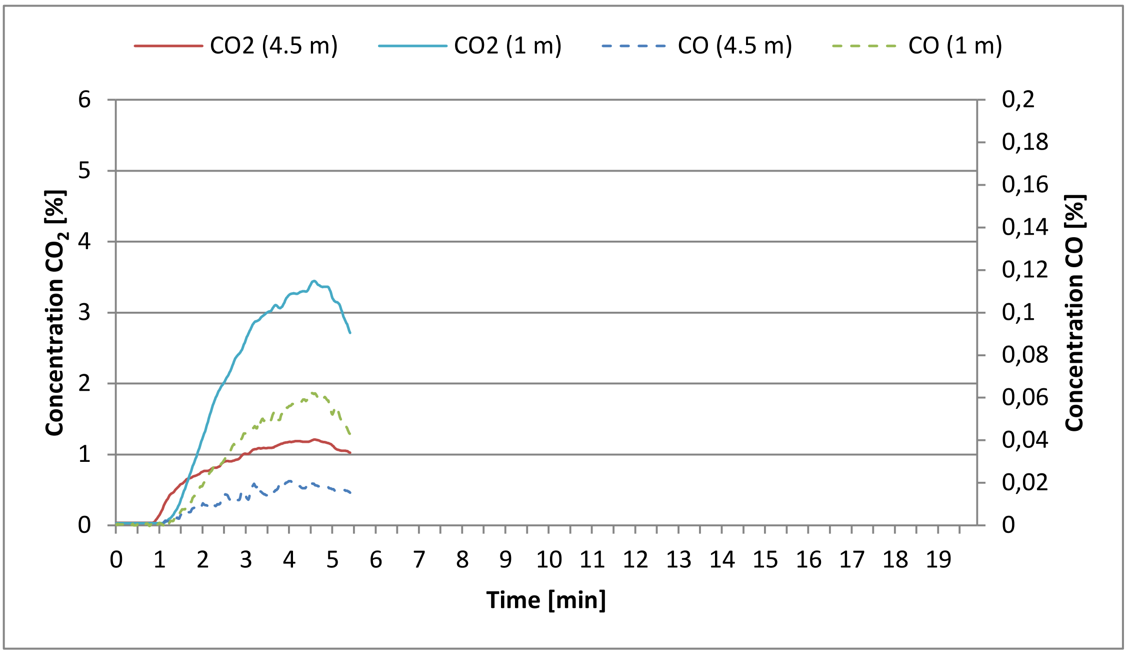

Figure 1- 45. CO and CO_2 measurements during test denominated as 7H-WMh.

7M-WS-f

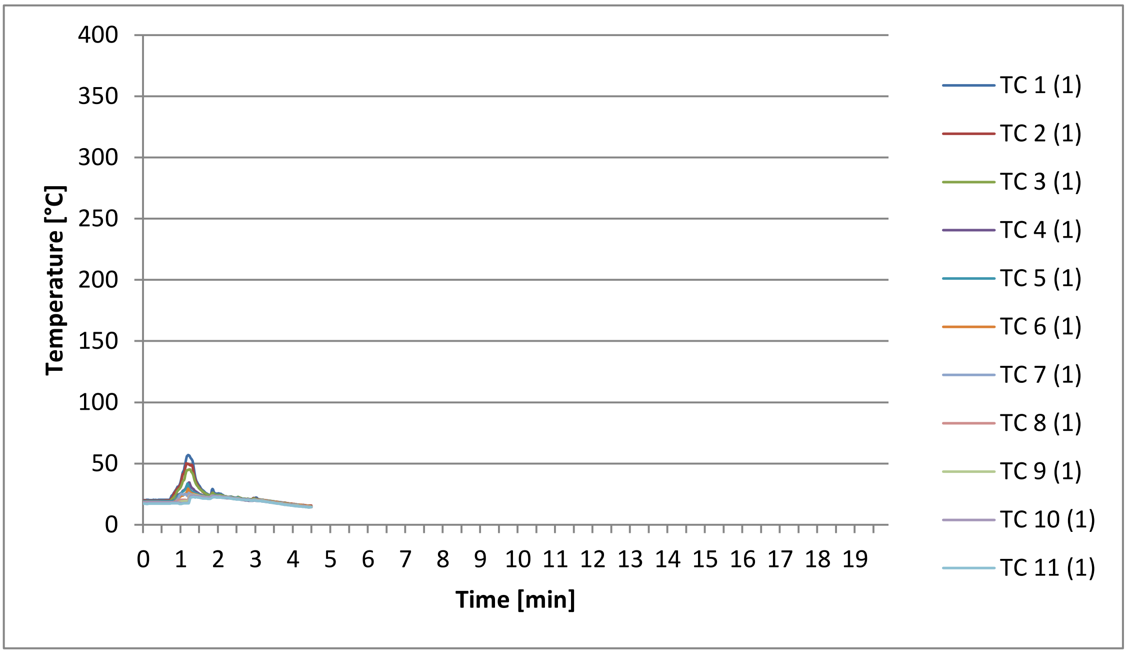

Figure 1- 46. Temperatures from thermocouple tree 1 during test denominated as 7M-WS-f.

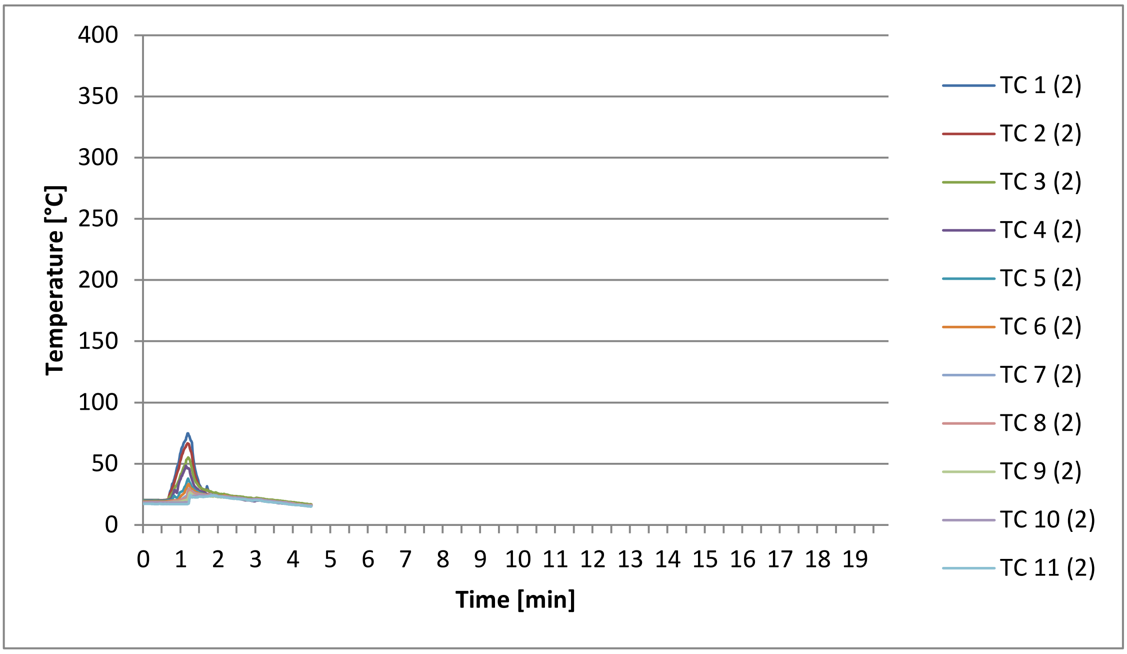

Figure 1- 47. Temperatures from thermocouple tree 2 during test denominated as 7M-WS-f.

Appendix 1

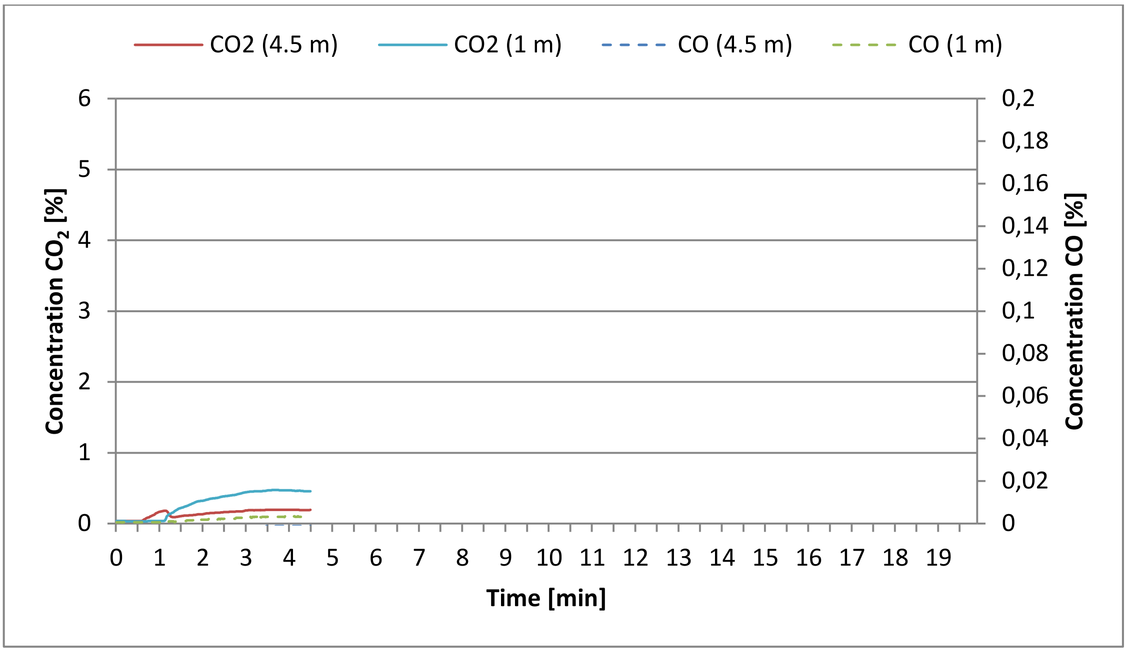

Figure 1- 48. CO and CO_2 measurements during test denominated as 7M-WS-f.

7M-WMl-f

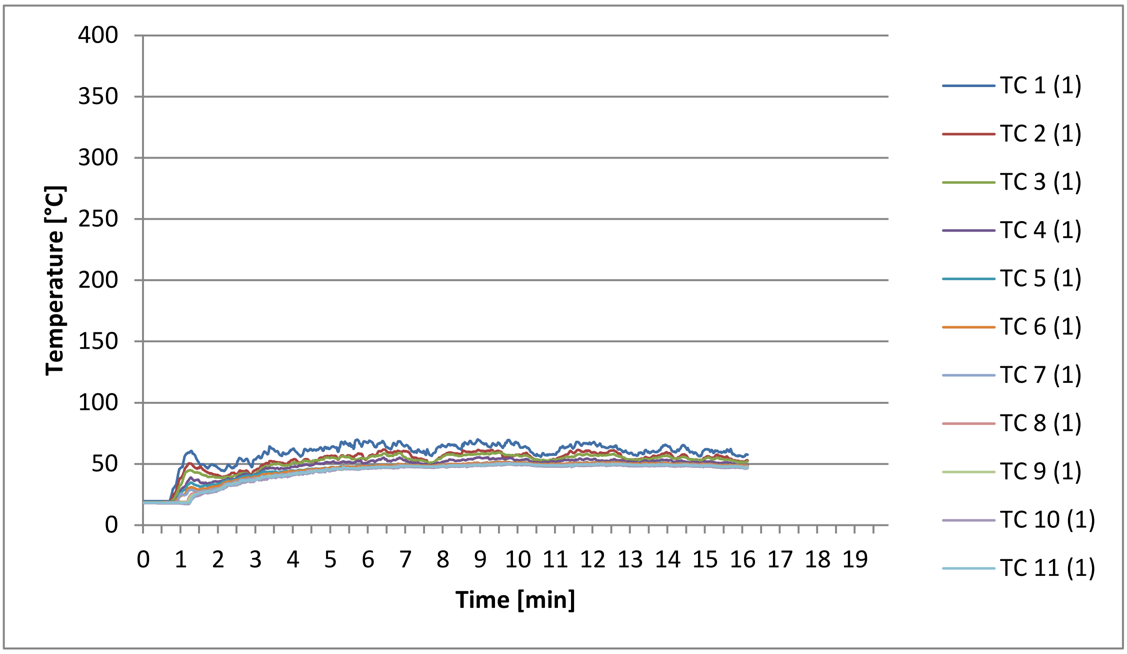

Figure 1- 49. Temperatures from thermocouple tree 1 during test denominated as 7M-WMl-f.

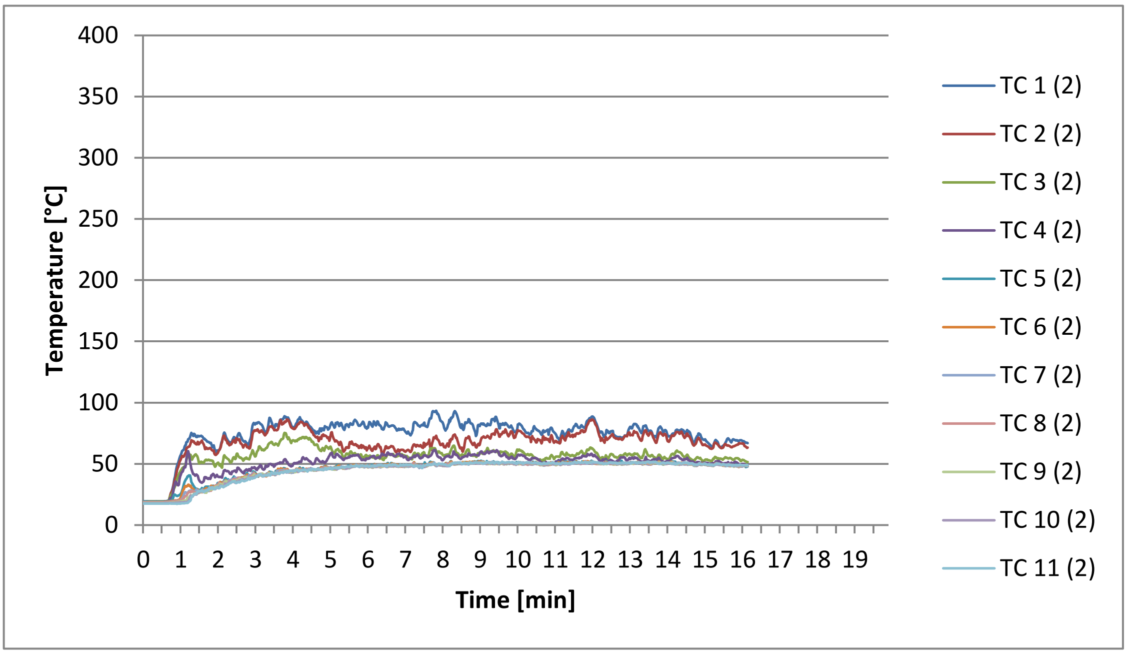

Figure 1- 50. Temperatures from thermocouple tree 2 during test denominated as 7M-WMl-f.

Appendix 1

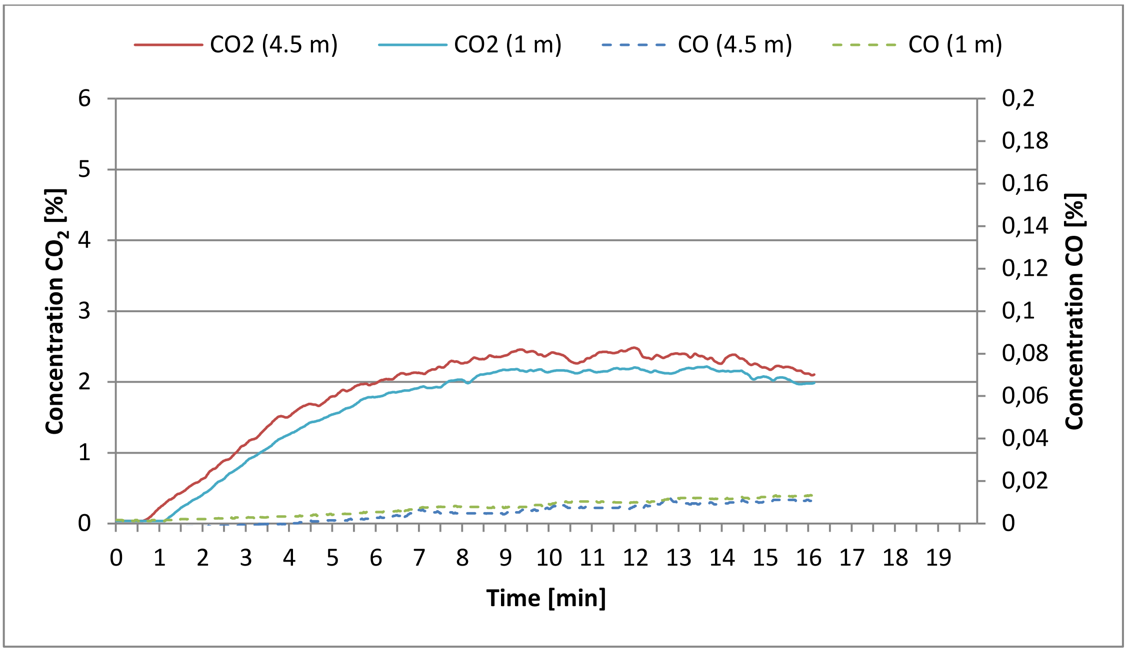

Figure 1- 51. CO and CO_2 measurements during test denominated as 7M-WMl-f.

7M-WMh-f

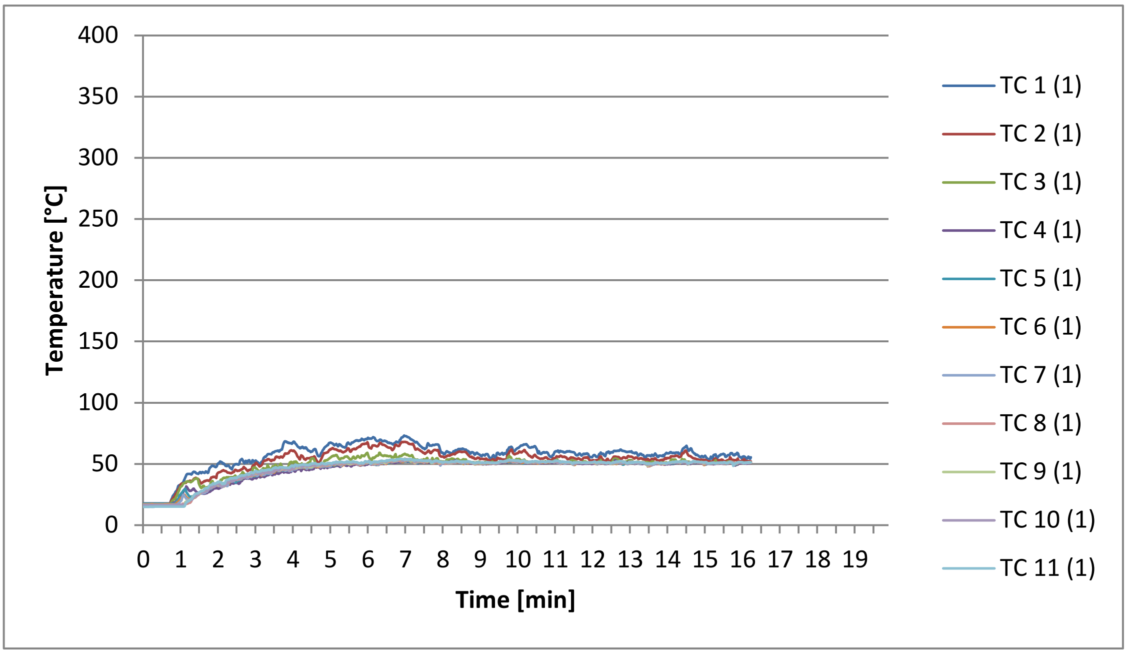

Figure 1- 52. Temperatures from thermocouple tree 1 during test denominated as 7M-WMh-f.

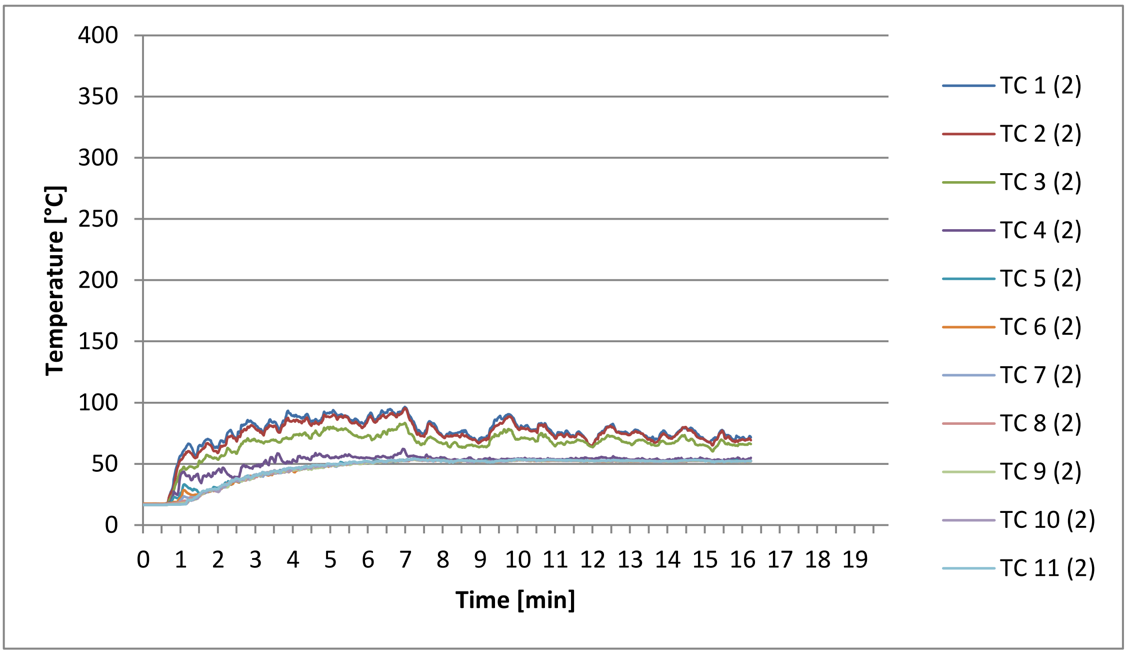

Figure 1- 53. Temperatures from thermocouple tree 2 during test denominated as 7M-WMh-f.

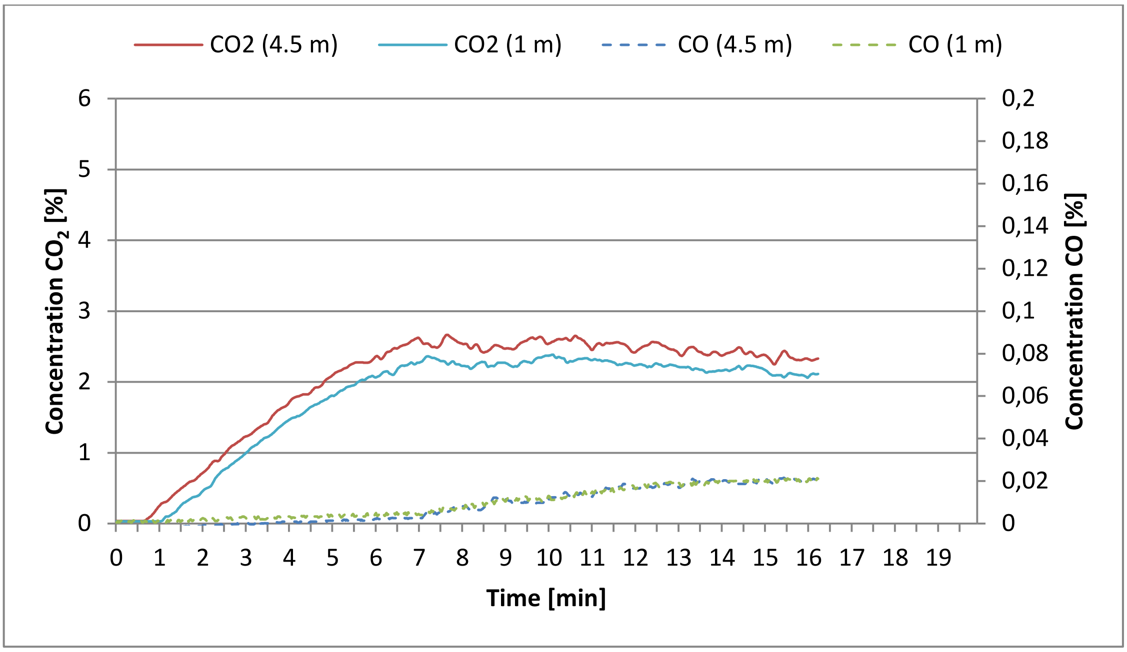

Figure 1- 54. CO and CO_2 measurements during test denominated as 7M-WMh-f.

BH-WS

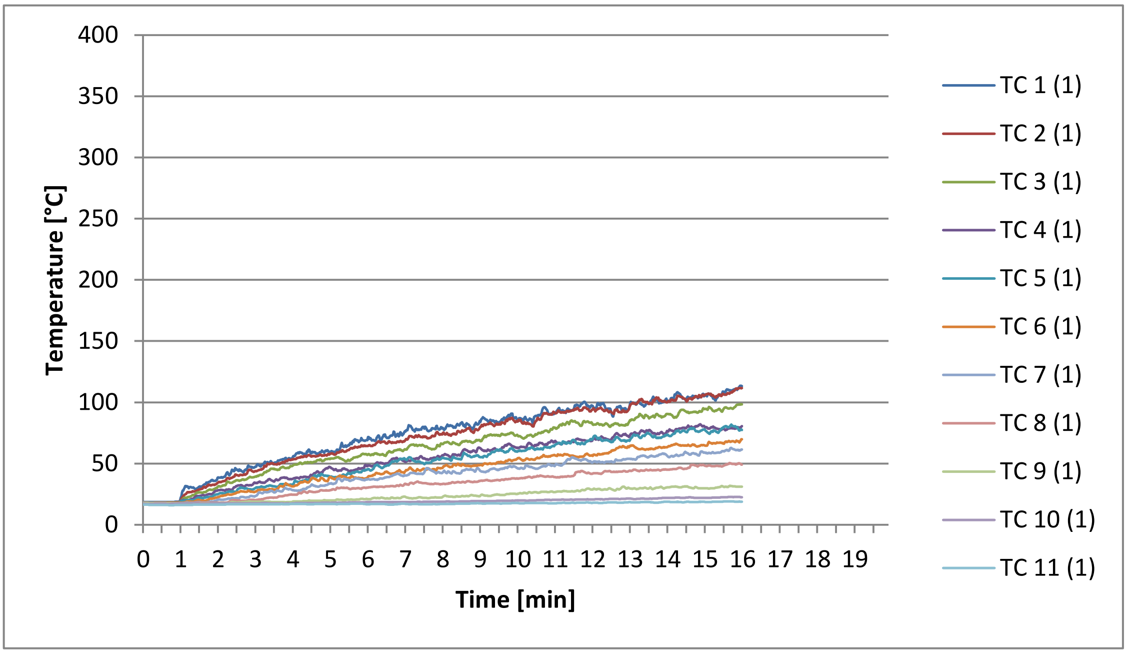

Figure 1- 55. Temperatures from thermocouple tree 1 during test denominated as BH-WS.

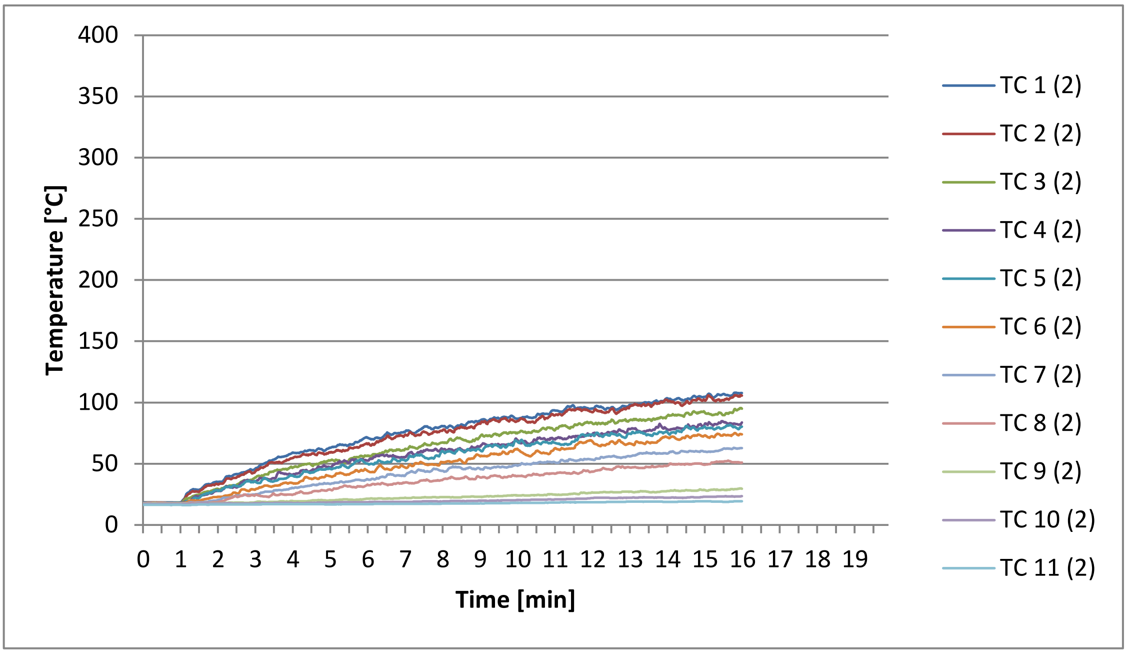

Figure 1- 56. Temperatures from thermocouple tree 2 during test denominated as BH-WS.

Appendix 1

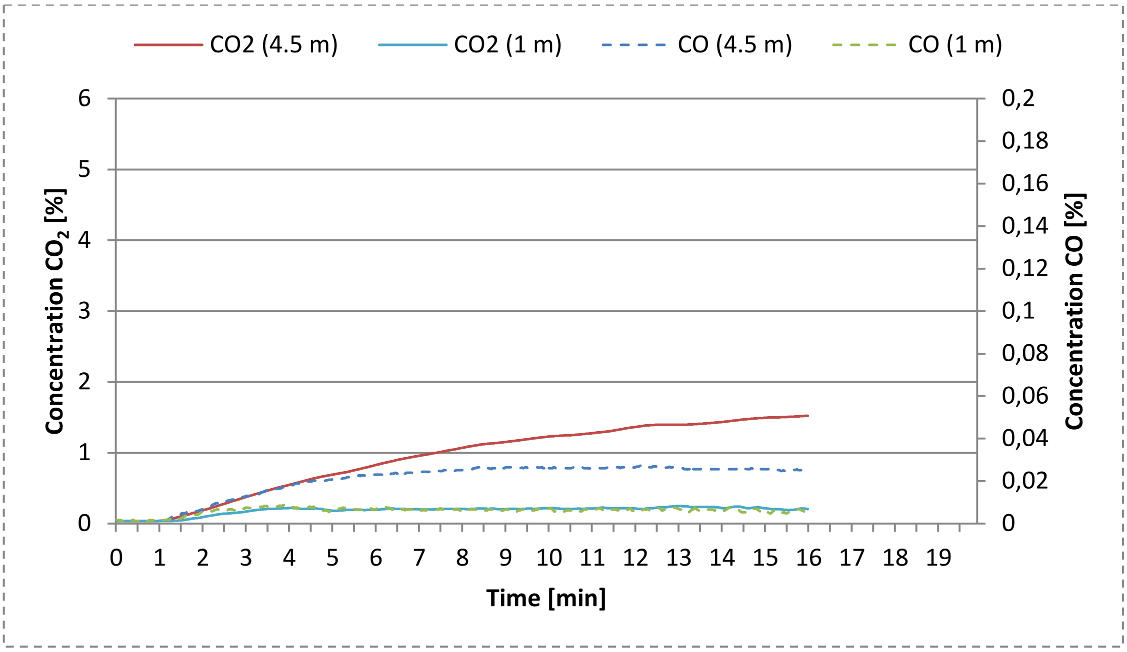

Figure 1- 57. CO and CO_2 measurements during test denominated as BH-WS.

BH-WMl

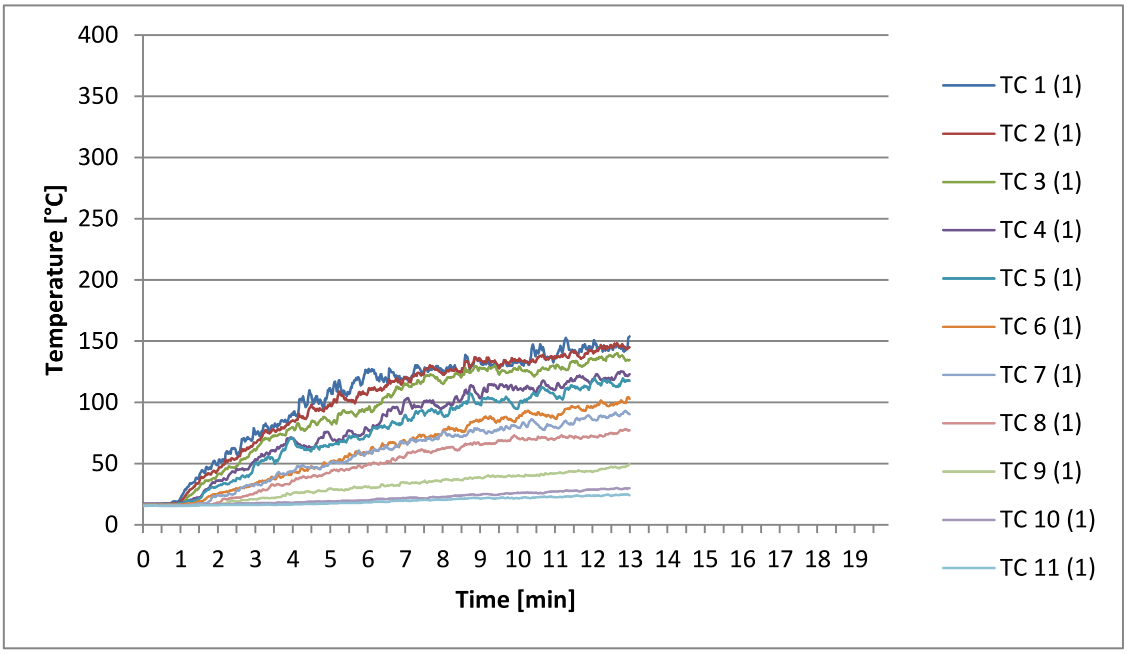

Figure 1- 58. Temperatures from thermocouple tree 1 during test denominated as BH-WMl.

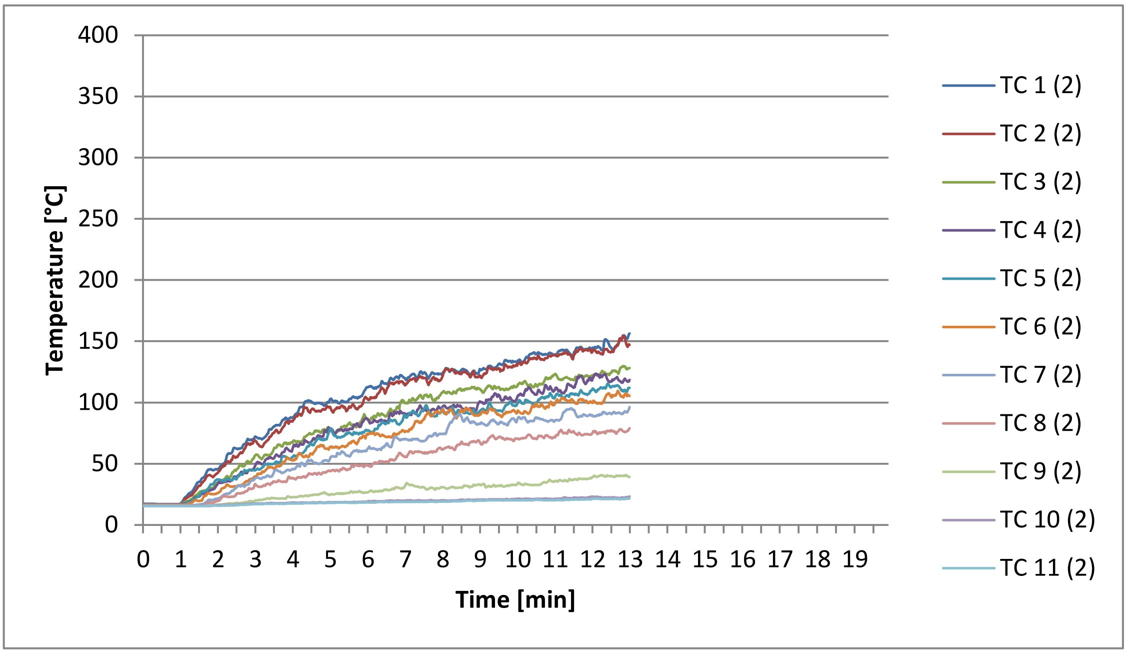

Figure 1- 59. Temperatures from thermocouple tree 2 during test denominated as BH-WMl.

Appendix 1

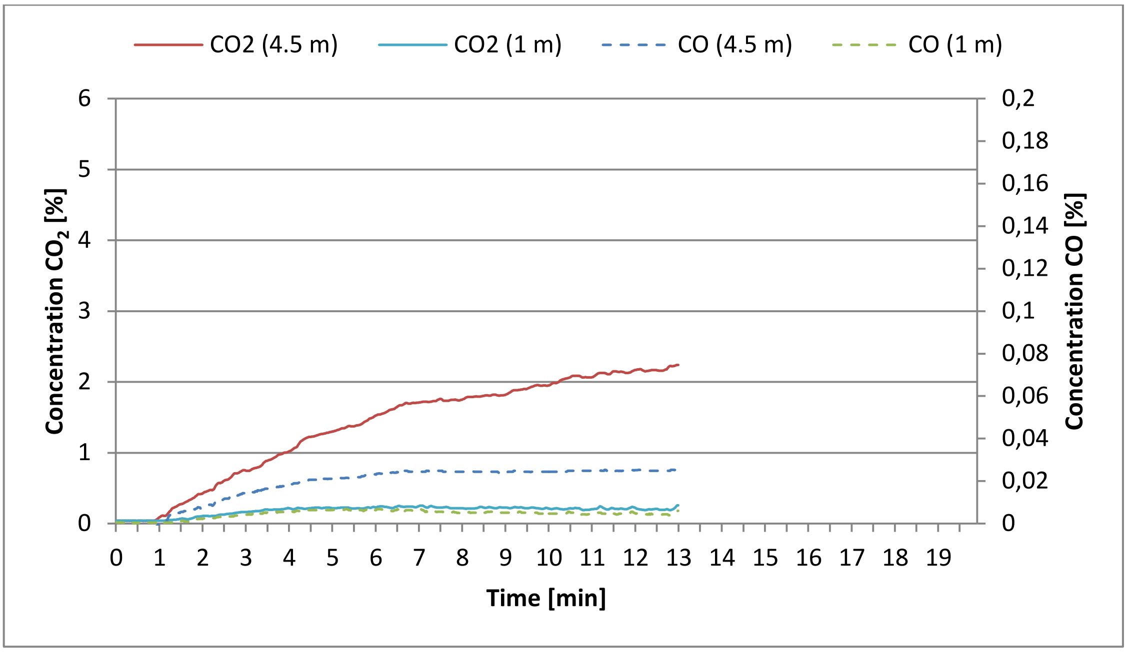

Figure 1- 60. CO and CO_2 measurements during test denominated as BH-WMl.

BM-WS-f

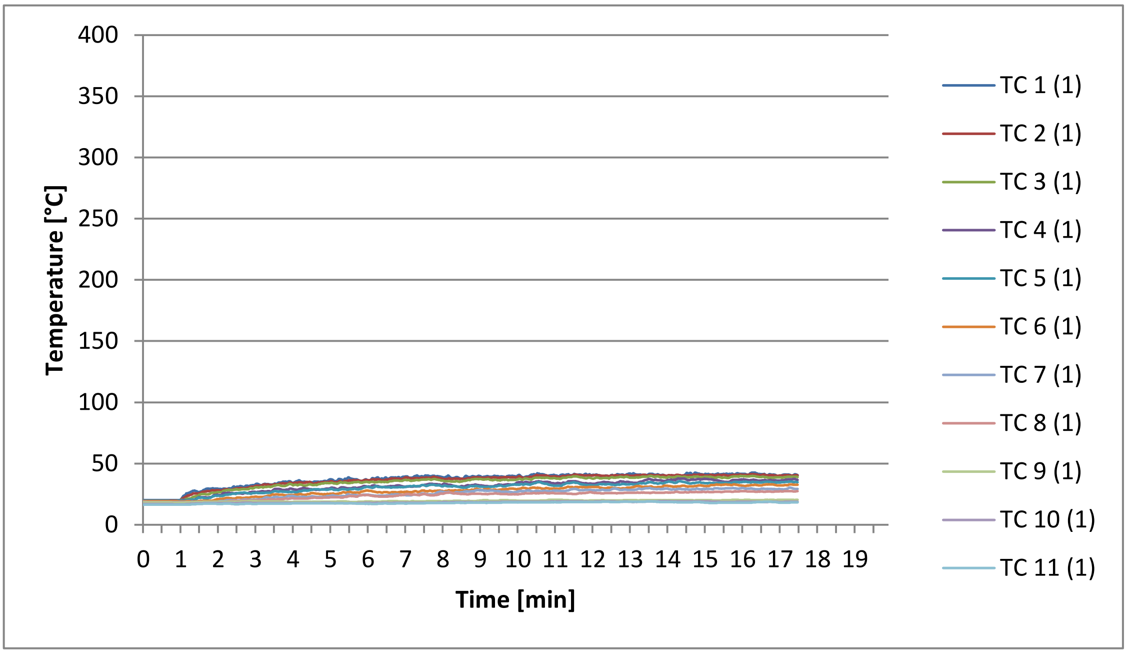

Figure 1- 61. Temperatures from thermocouple tree 1 during test denominated as BM-WS-f.

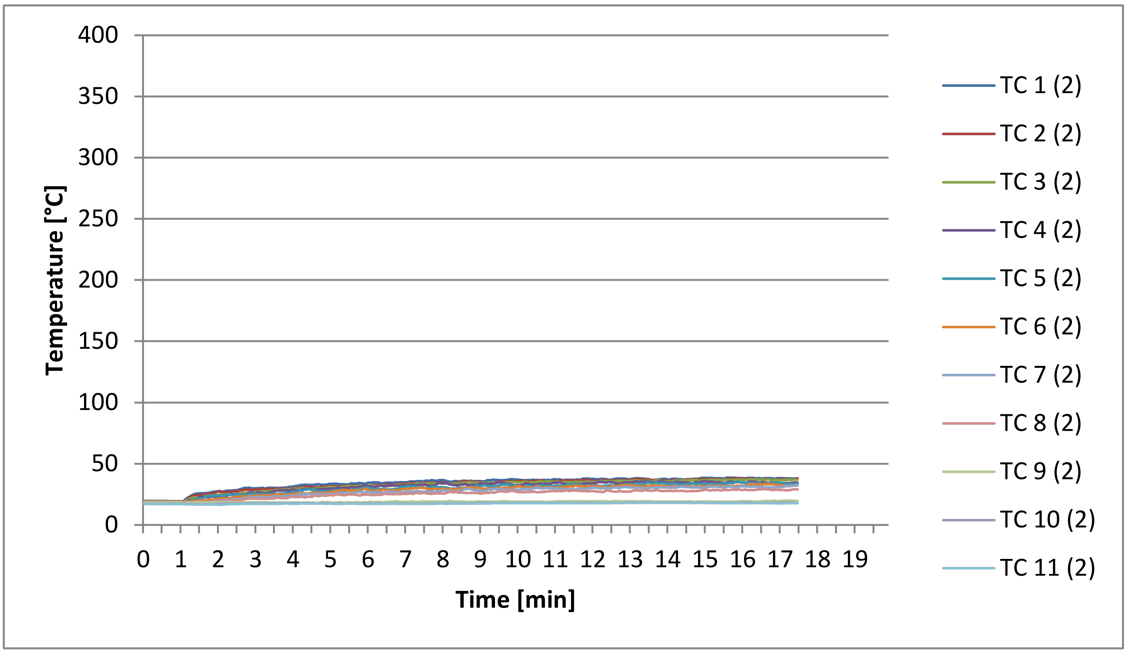

Figure 1- 62. Temperatures from thermocouple tree 2 during test denominated as BM-WS-f.

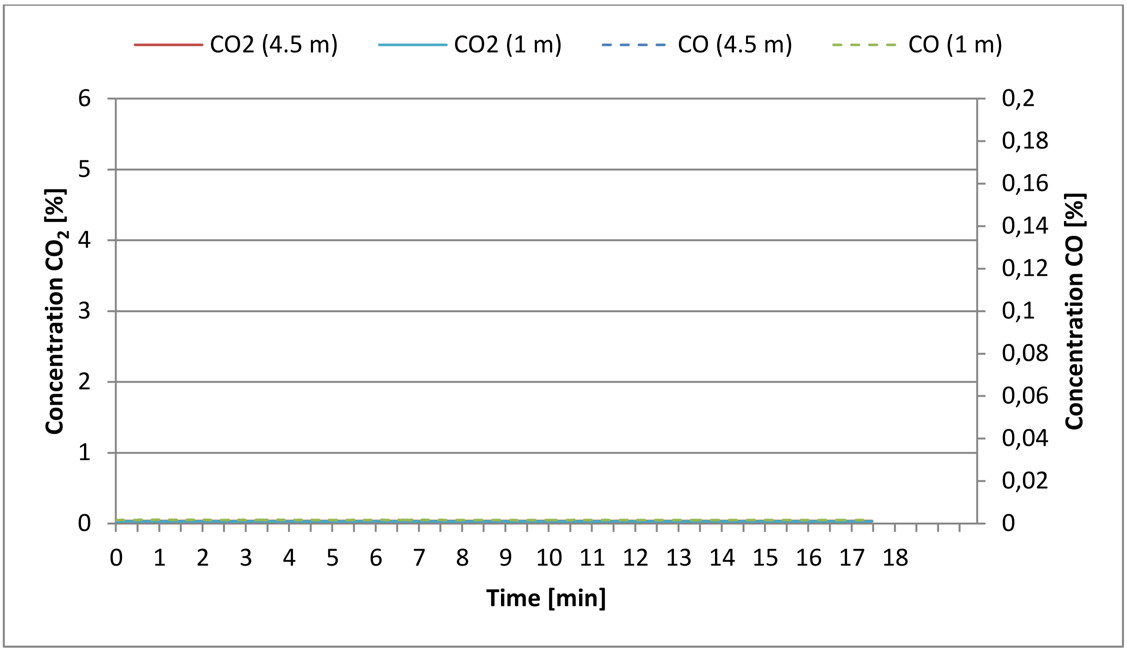

Figure 1- 63. CO and CO_2 measurements during test denominated as BM-WS-f.

BM-WS-f [−]

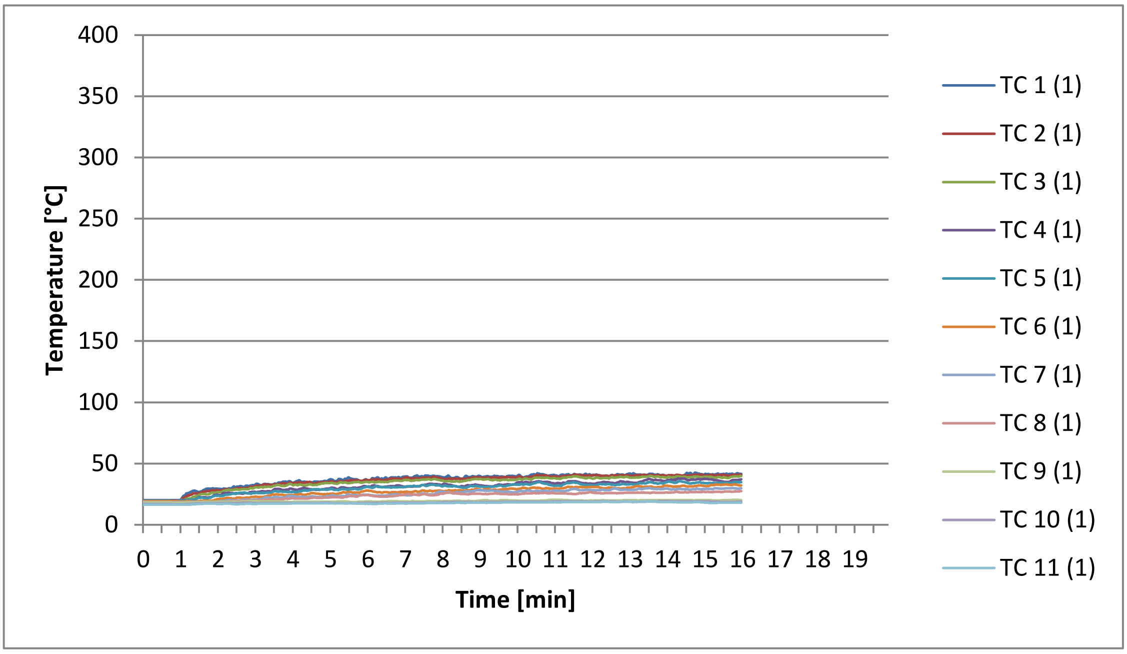

Figure 1- 64. Temperatures from thermocouple tree 1 during test denominated as BM-WS-f⁻.

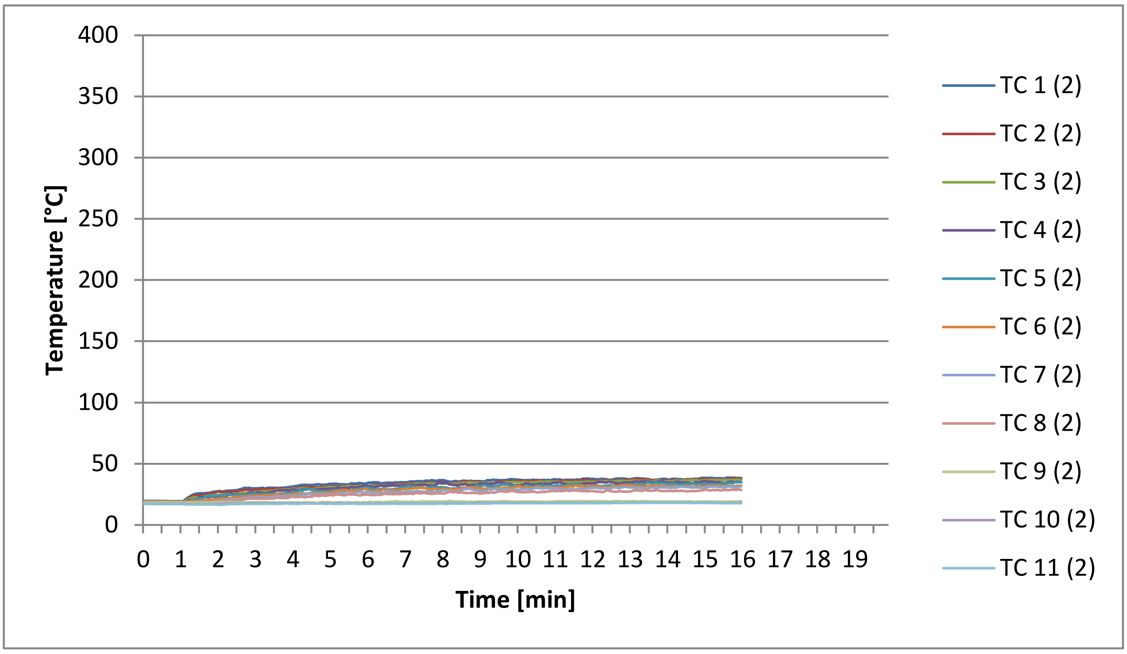

Figure 1- 65. Temperatures from thermocouple tree 2 during test denominated as BM-WS-f⁻.

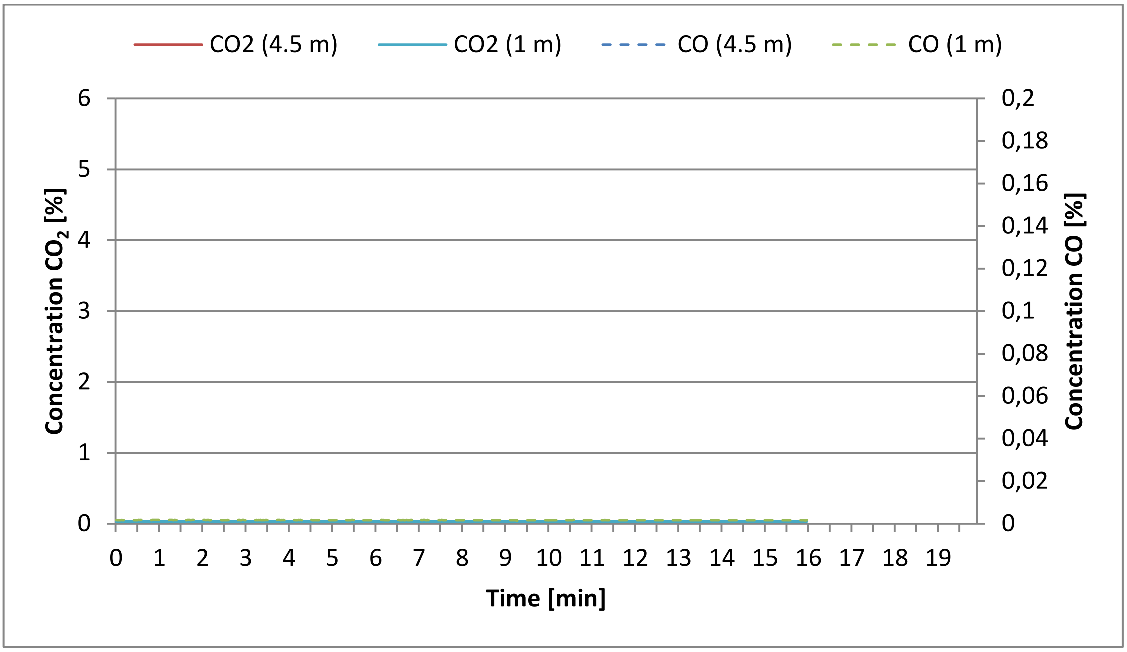

Figure 1- 66. CO and CO_2 measurements during test denominated as BM-WS-f⁻.

Appendix 1

BM-WMl-f

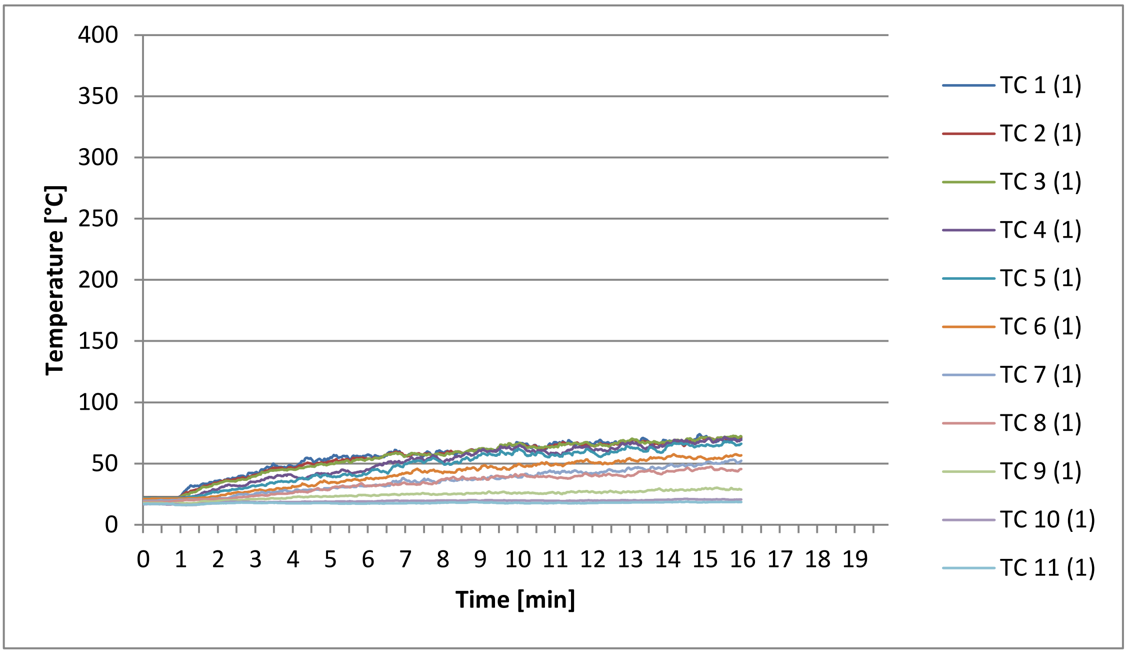

Figure 1- 67. Temperatures from thermocouple tree 1 during test denominated as BM-WMl-f.

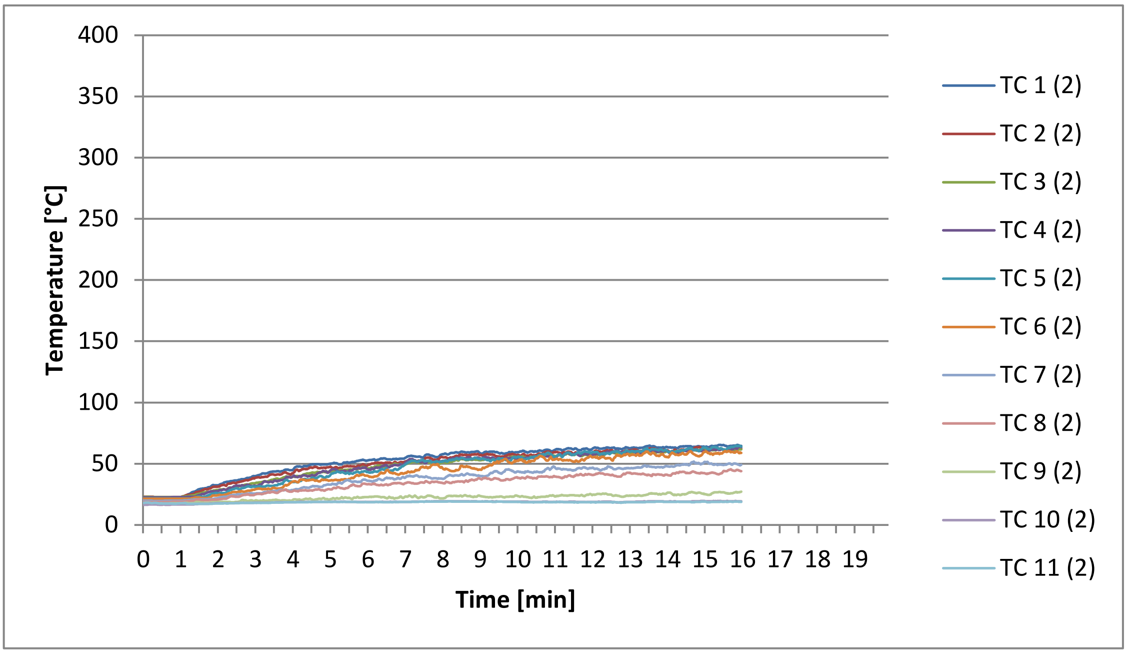

Figure 1- 68. Temperatures from thermocouple tree 2 during test denominated as BM-WMl-f.

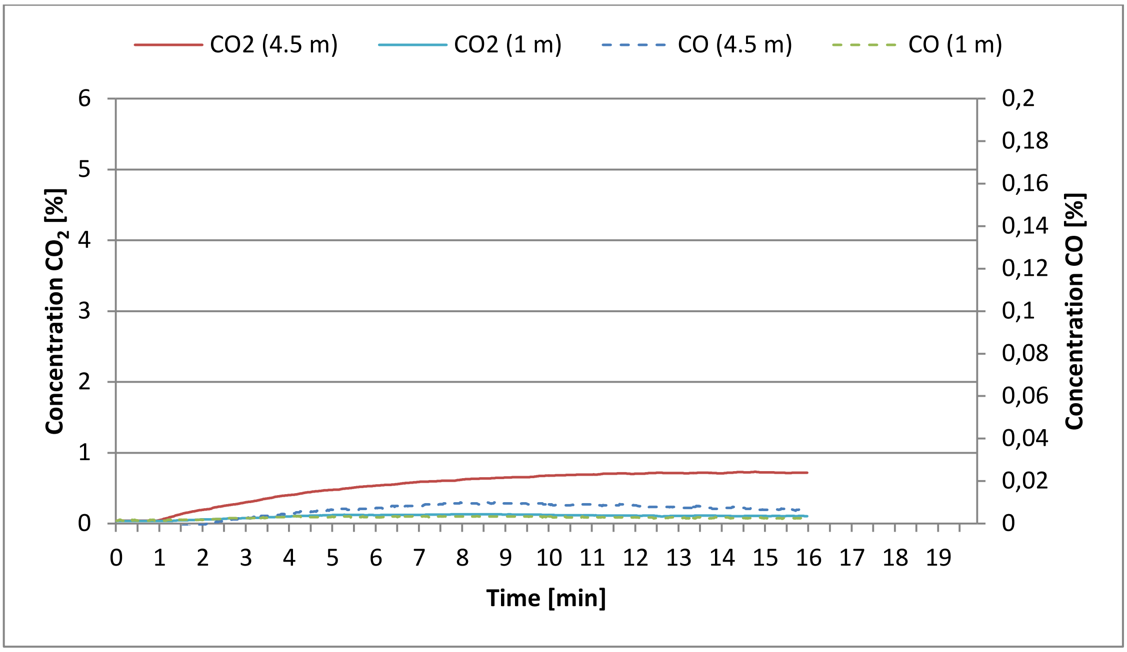

Figure 1- 69. CO and CO_2 measurements during test denominated as BM-WMl-f.

D0.5-WS

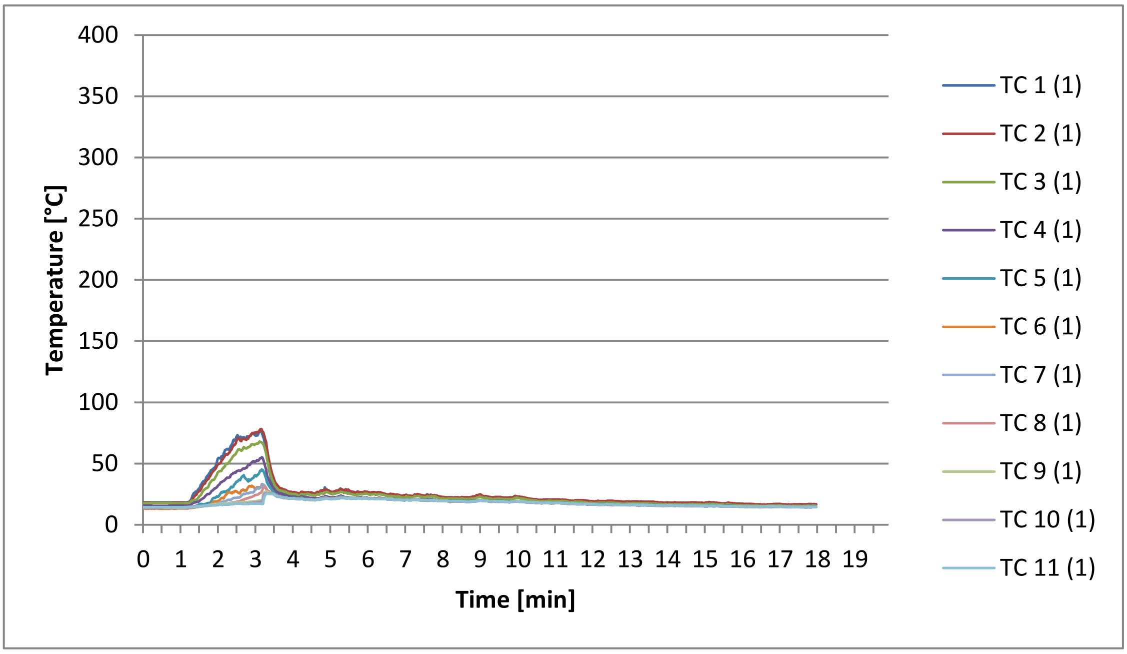

Figure 1- 70. Temperatures from thermocouple tree 1 during test denominated as D0.5-WS.

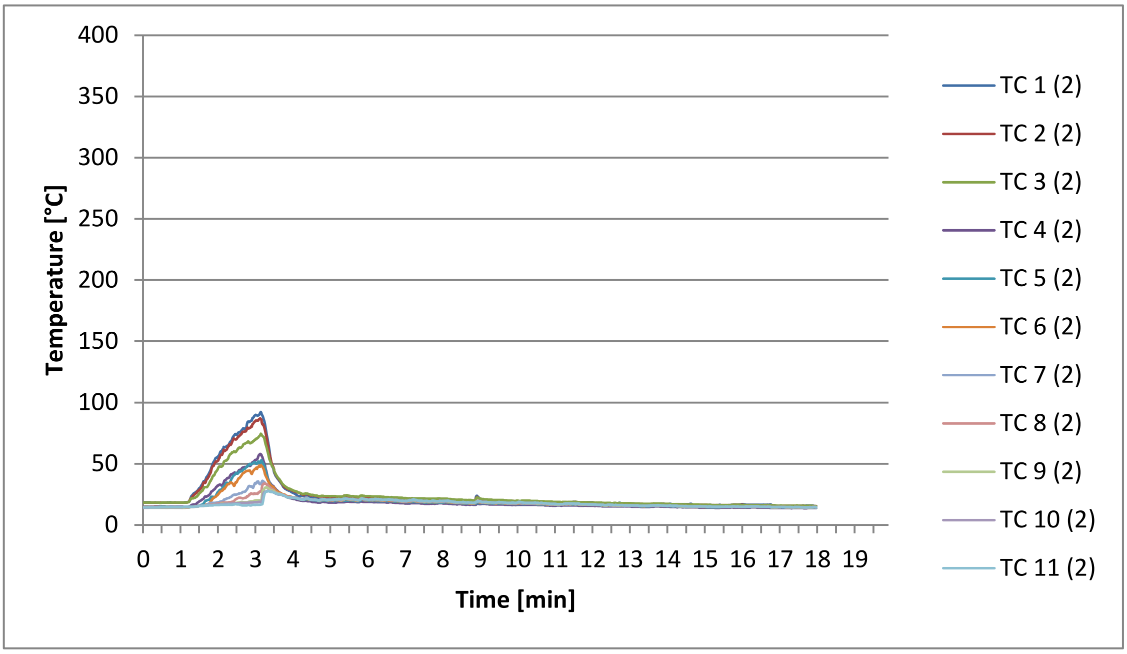

Figure 1- 71. Temperatures from thermocouple tree 2 during test denominated as D0.5-WS.

Appendix 1

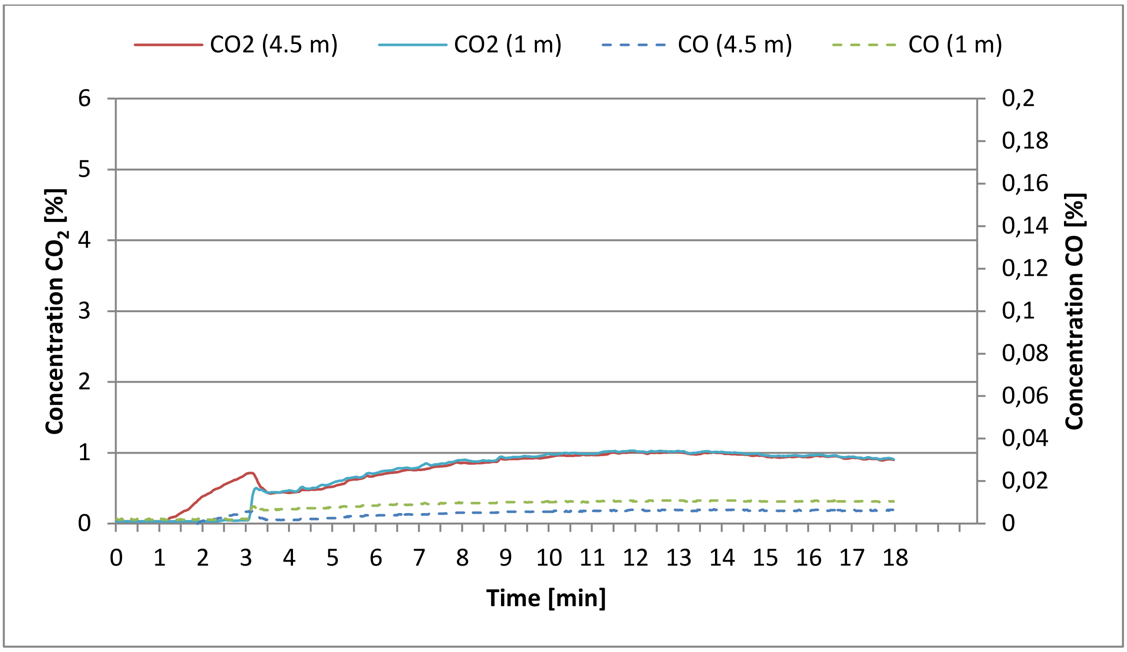

Figure 1- 72. CO and CO_2 measurements during test denominated as D0.5-WS.

D0.5-WMl

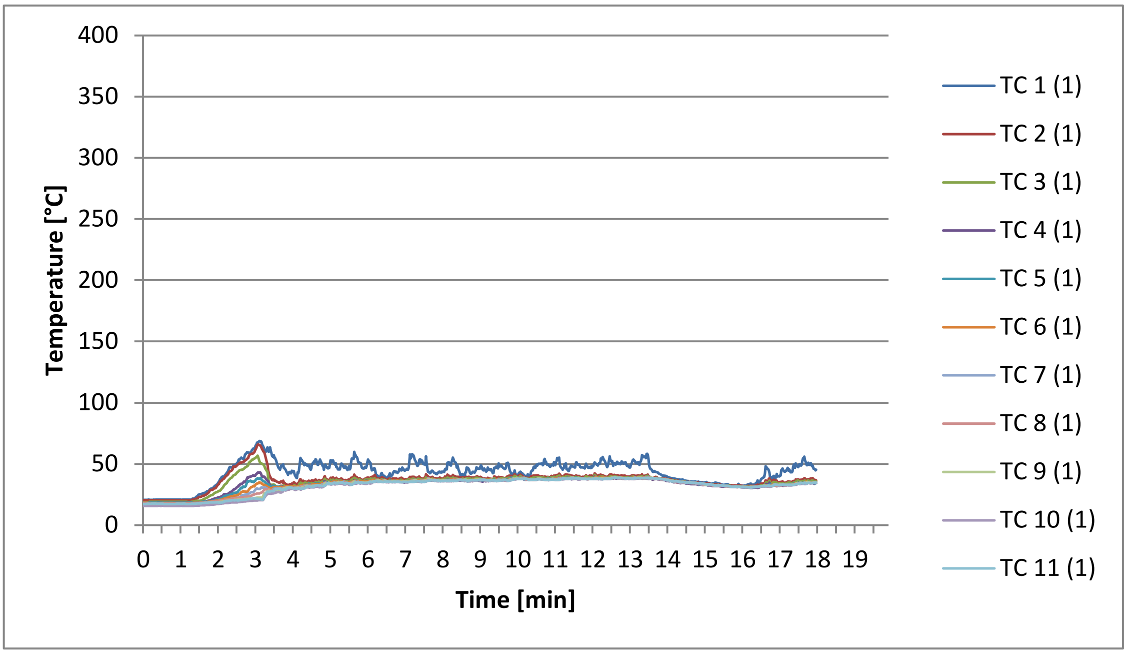

Figure 1- 73. Temperatures from thermocouple tree 1 during test denominated as D0.5-WMl.

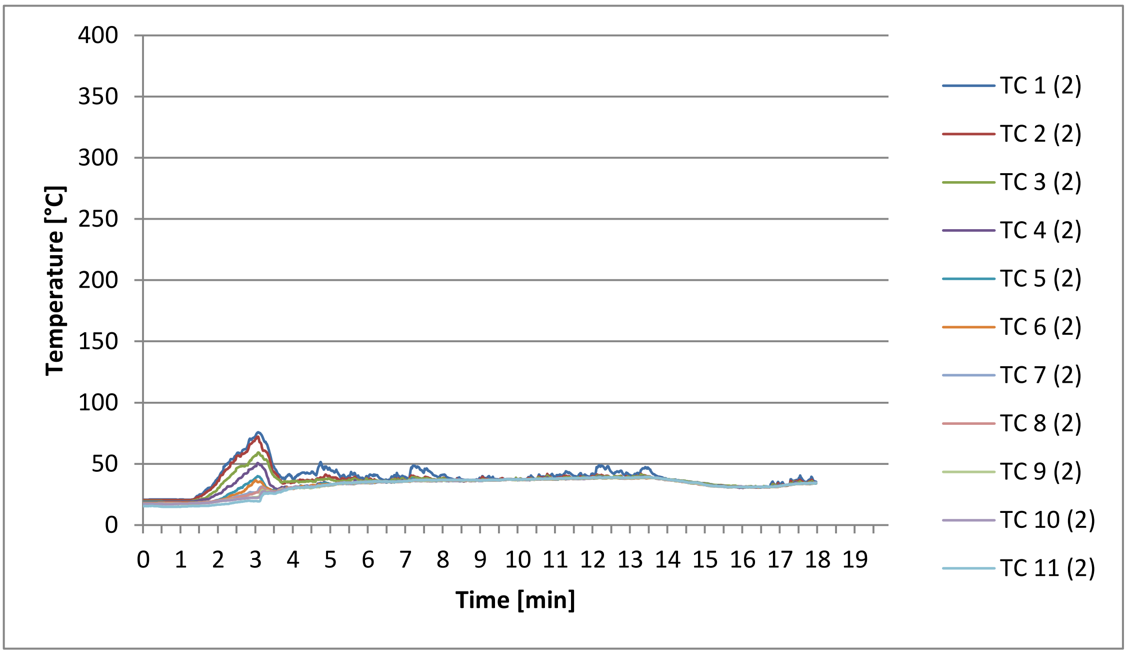

Figure 1- 74. Temperatures from thermocouple tree 2 during test denominated as D0.5-WMl.

Appendix 1

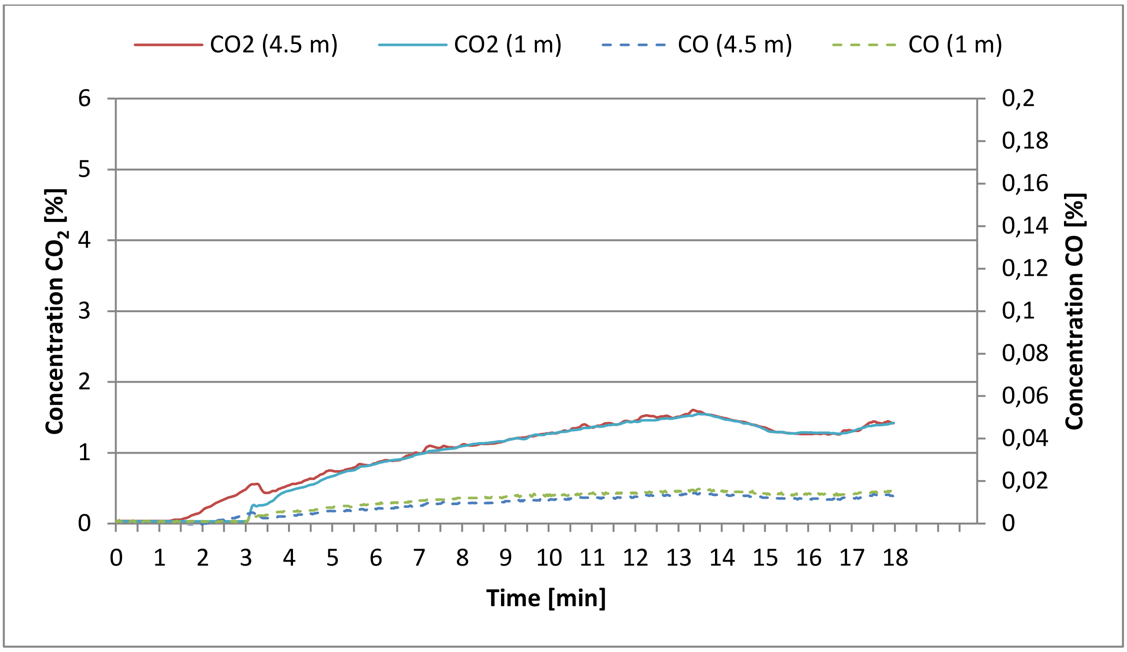

Figure 1- 75. CO and CO_2 measurements during test denominated as D0.5-WMl.

M0.5-WS-f

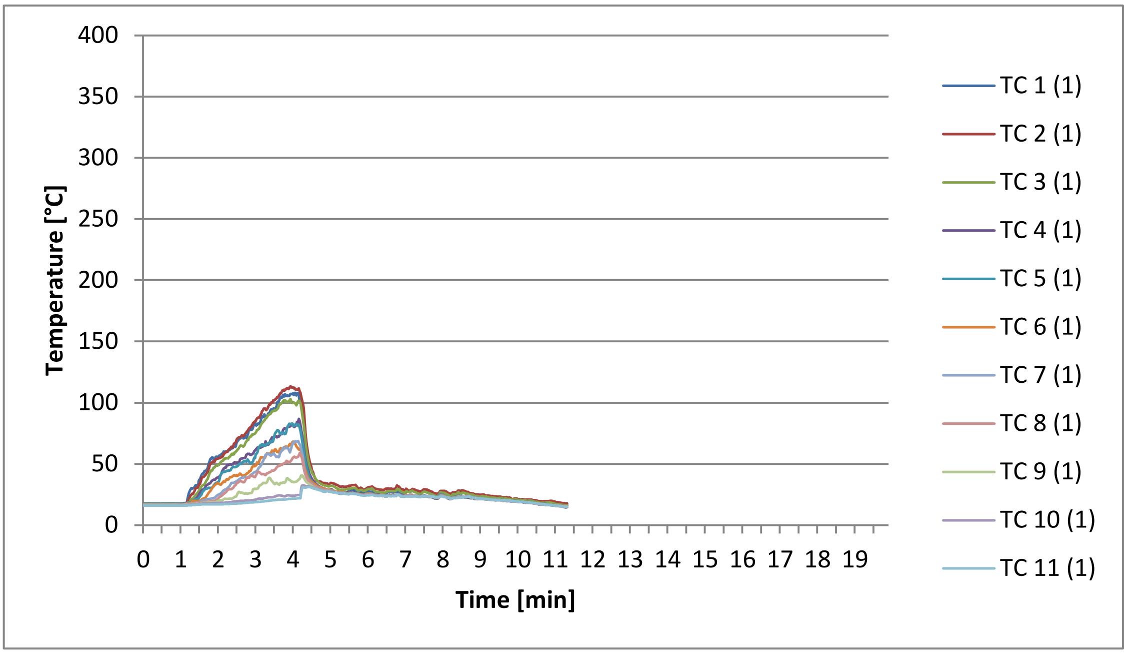

Figure 1- 76. Temperatures from thermocouple tree 1 during test denominated as M0.5-WS-f.

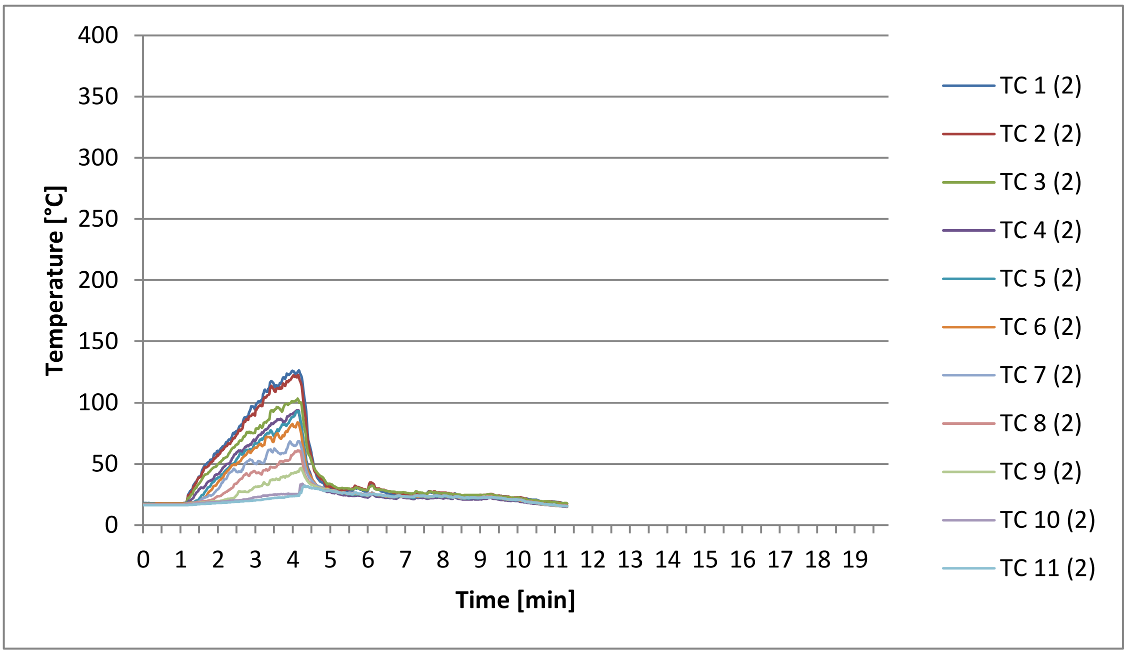

Figure 1- 77. Temperatures from thermocouple tree 2 during test denominated as M0.5-WS-f.

Appendix 1

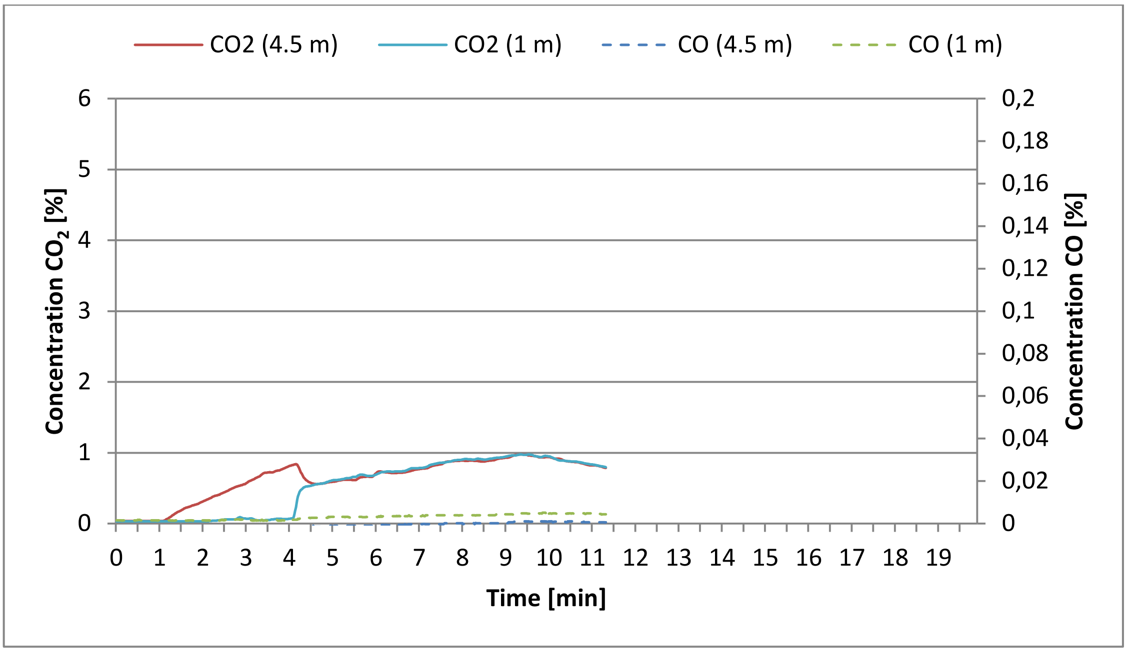

Figure 1- 78. CO and CO_2 measurements during test denominated as M0.5-WS-f.

M0.5-WMl-f

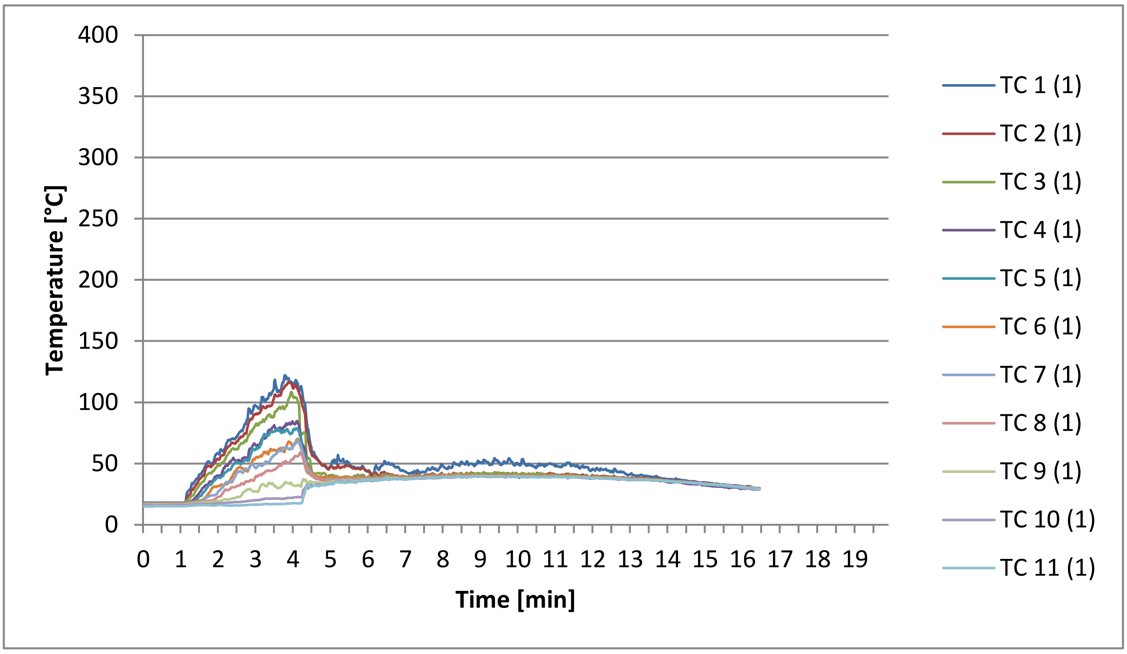

Figure 1- 79. Temperatures from thermocouple tree 1 during test denominated as M0.5-WMl-f.

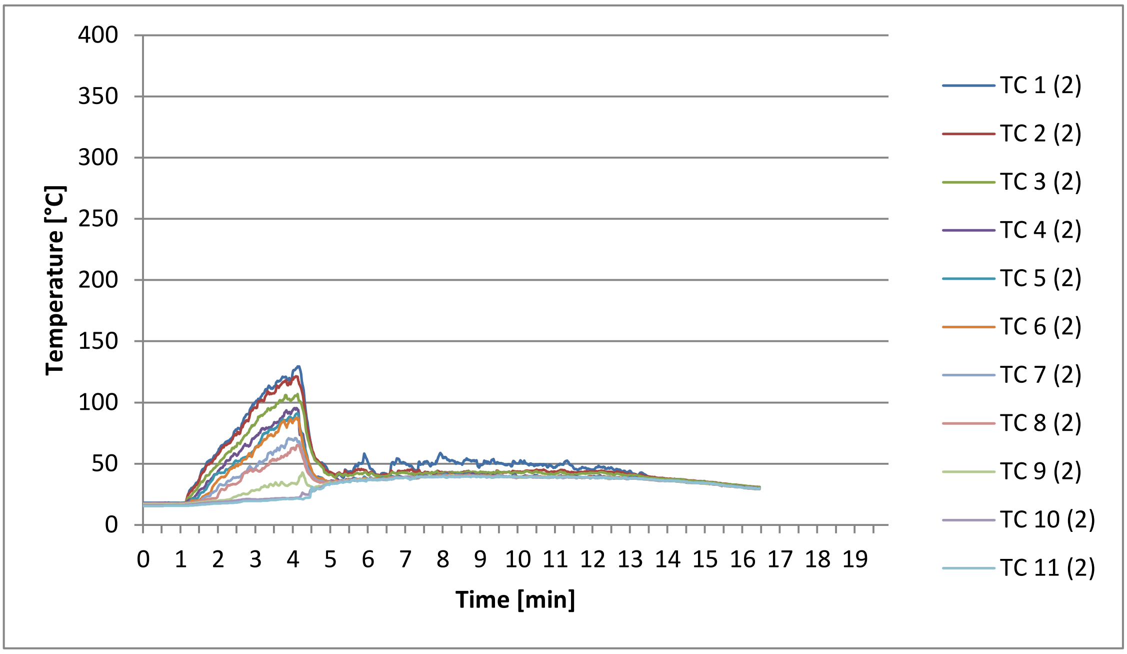

Figure 1- 80. Temperatures from thermocouple tree 2 during test denominated as M0.5-WMl-f.

Appendix 1

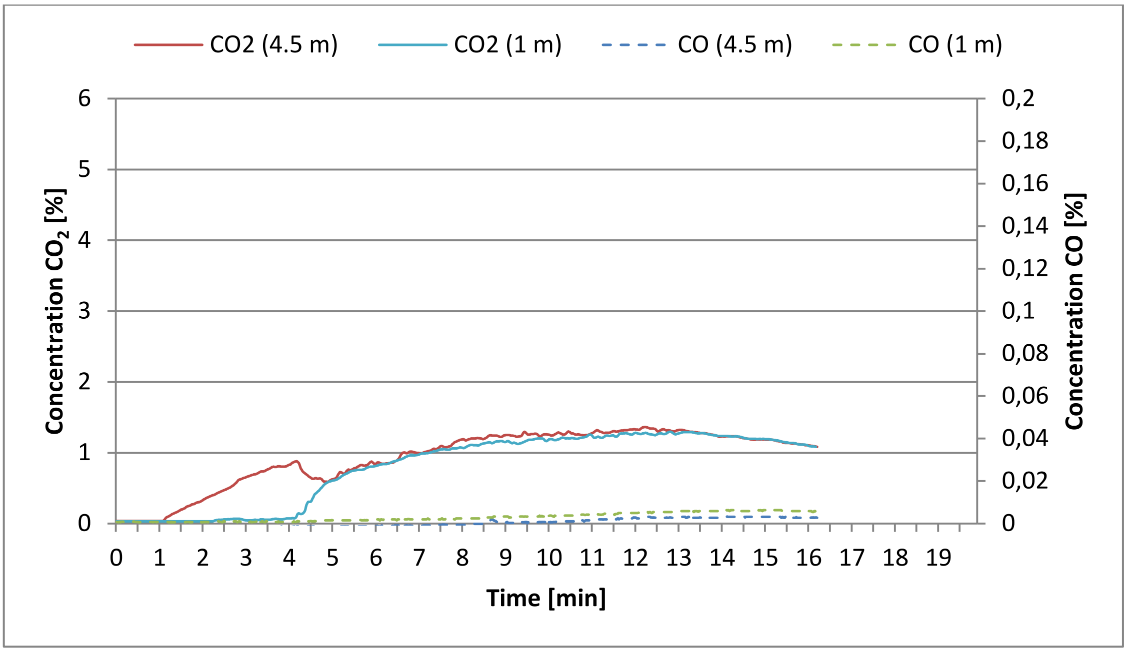

Figure 1- 81. CO and CO_2 measurements during test denominated as M0.5-WMI-f.

M0.5-WMh-f

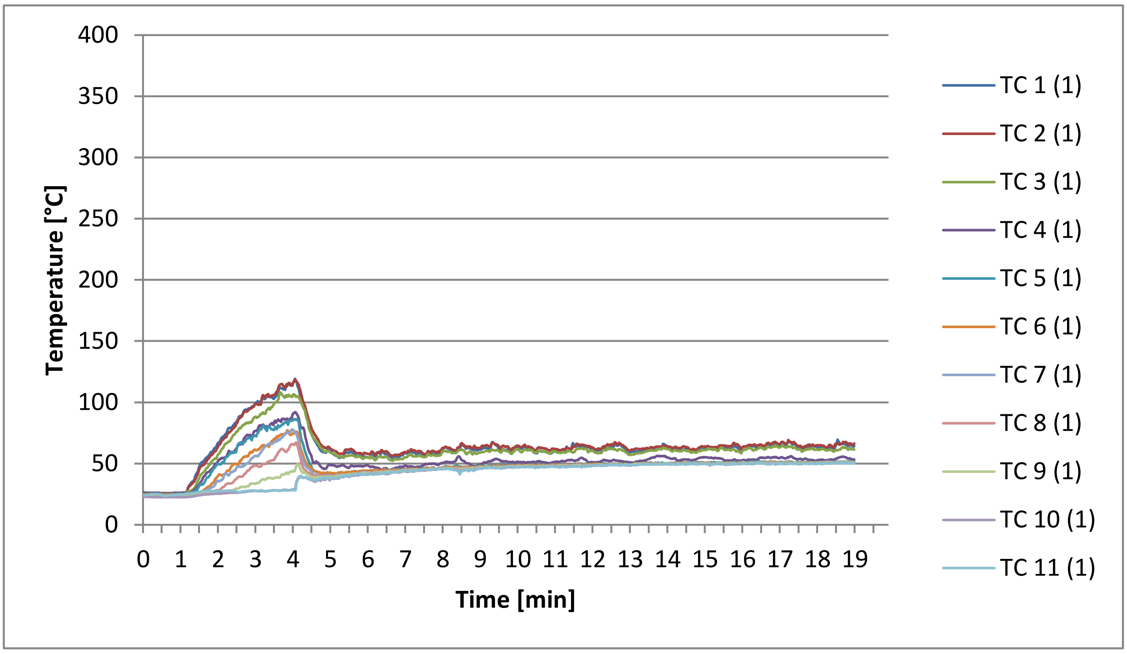

Figure 1- 82. Temperatures from thermocouple tree 1 during test denominated as M0.5-WMh-f.

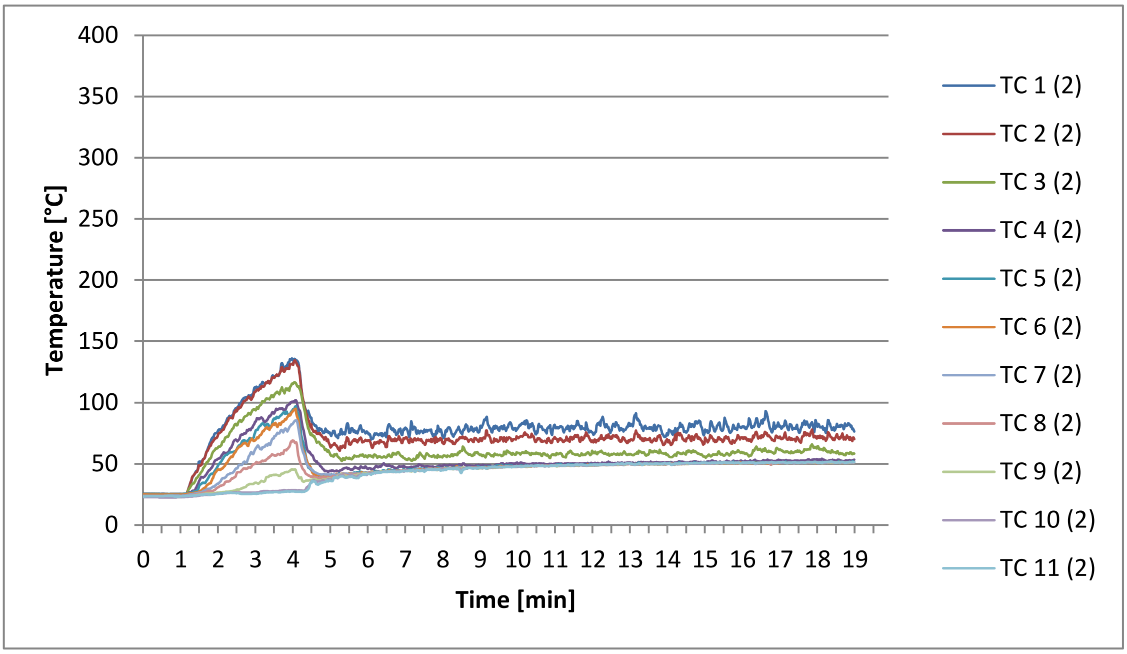

Figure 1- 83. Temperatures from thermocouple tree 2 during test denominated as M0.5-WMh-f.

Appendix 1

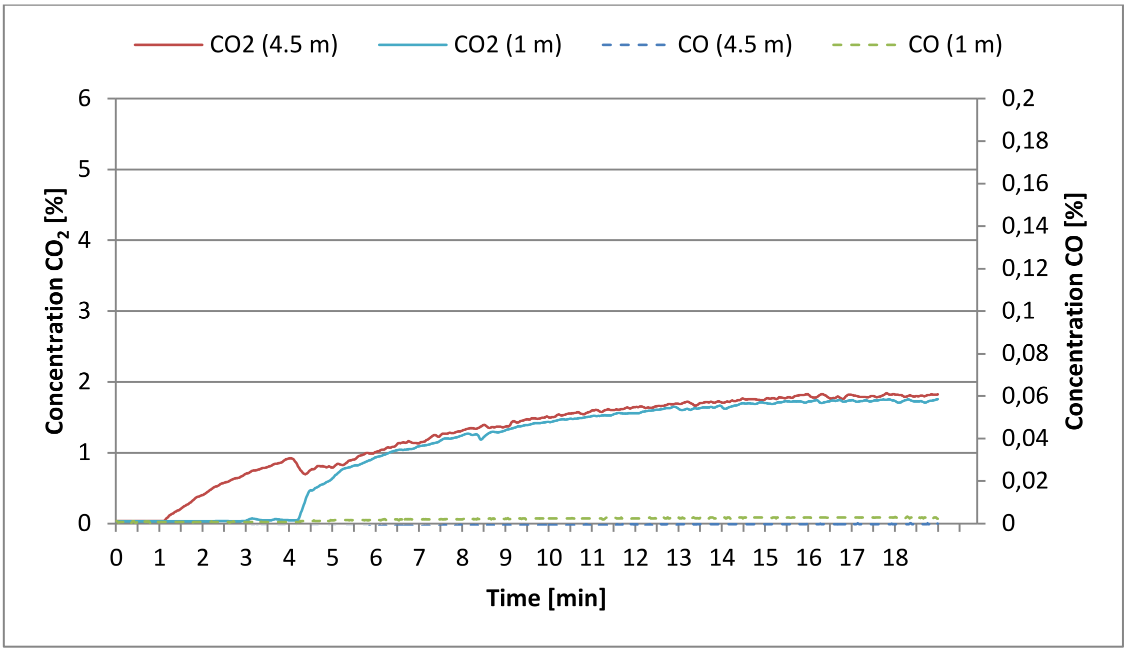

Figure 1- 84. CO and CO_2 measurements during test denominated as M0.5-WMh-f.

D1.0-WS

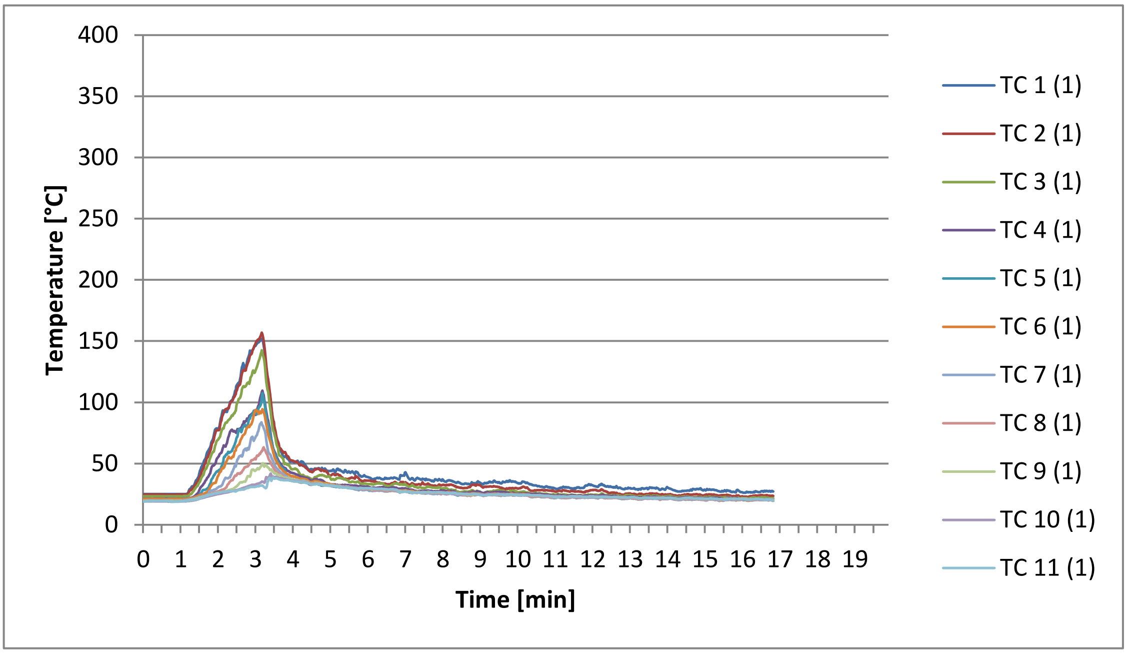

Figure 1- 85. Temperatures from thermocouple tree 1 during test denominated as D1.0-WS.

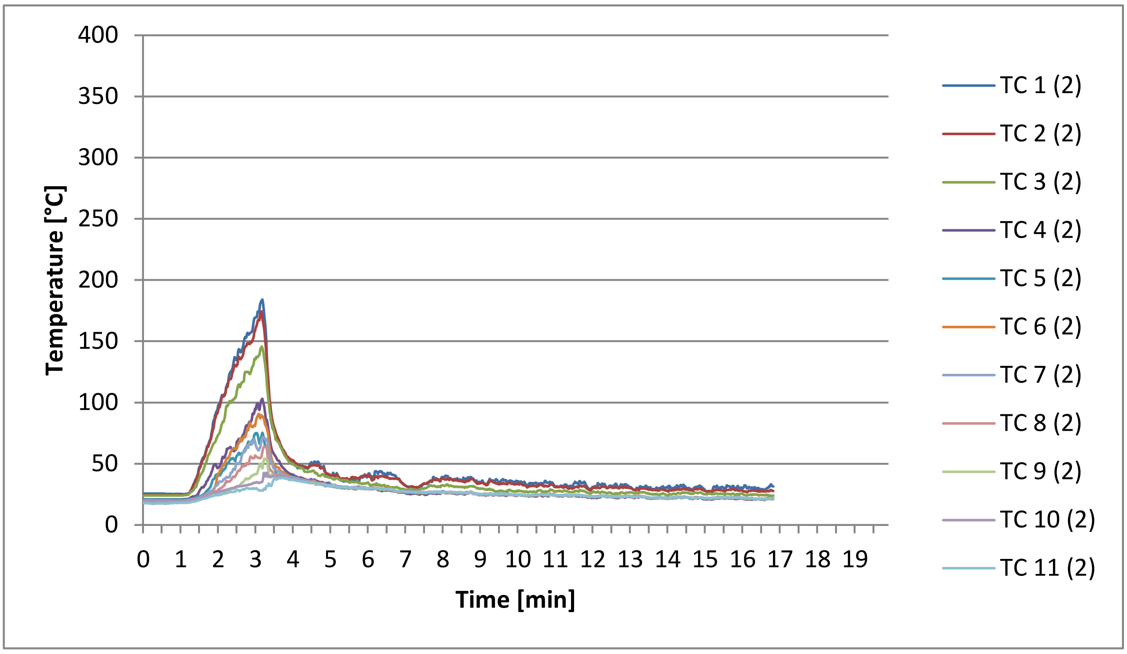

Figure 1- 86. Temperatures from thermocouple tree 2 during test denominated as D1.0-WS.

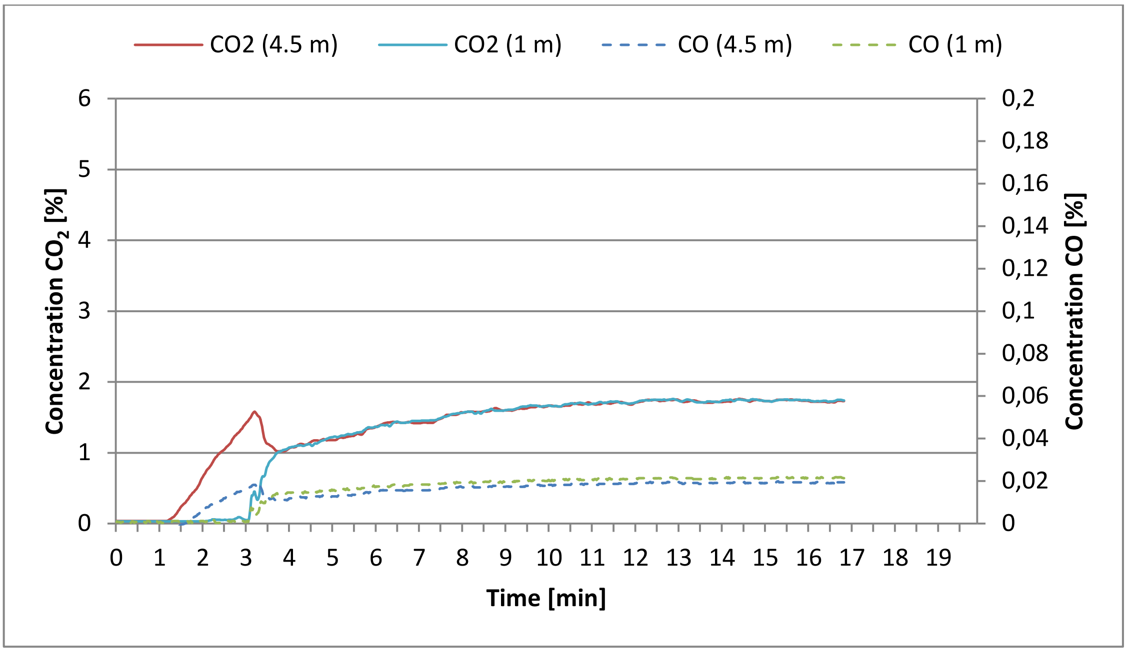

Figure 1- 87. CO and CO_2 measurements during test denominated as D1.0-WS.

D1.0-WMl

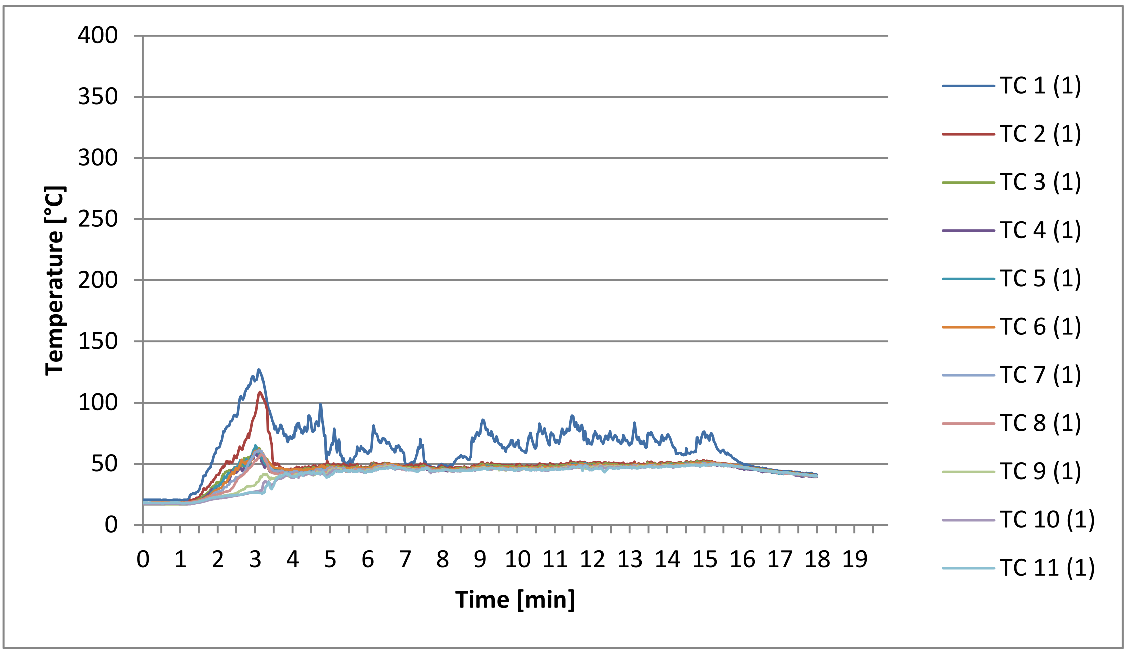

Figure 1- 88. Temperatures from thermocouple tree 1 during test denominated as D1.0-WMl.

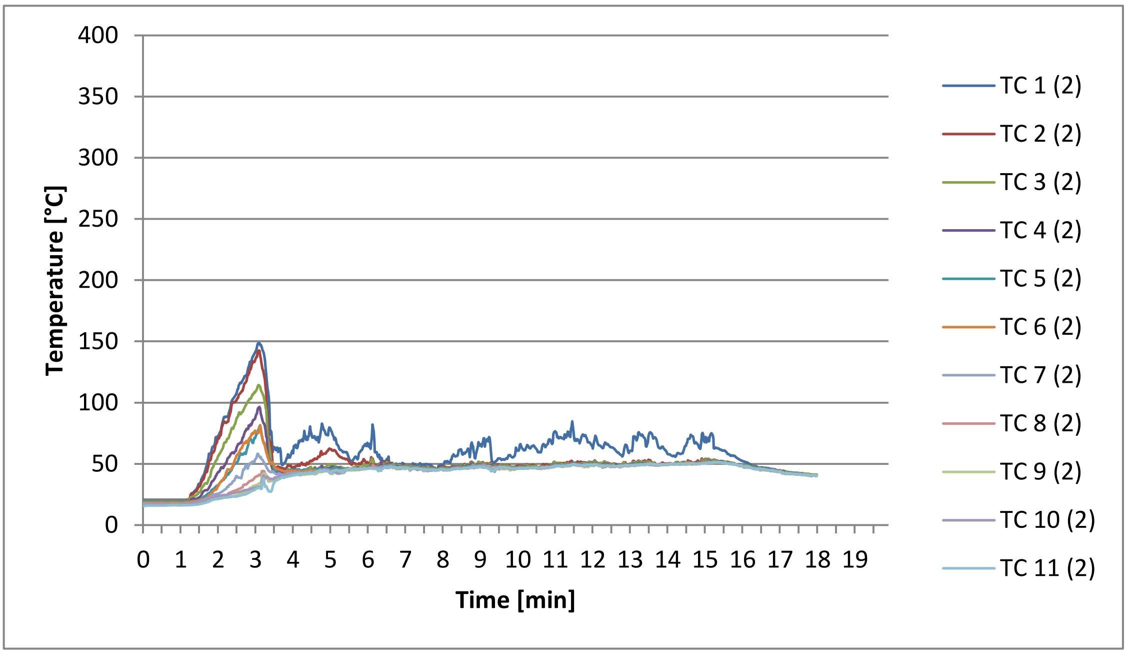

Figure 1- 89. Temperatures from thermocouple tree 2 during test denominated as D1.0-WMl.

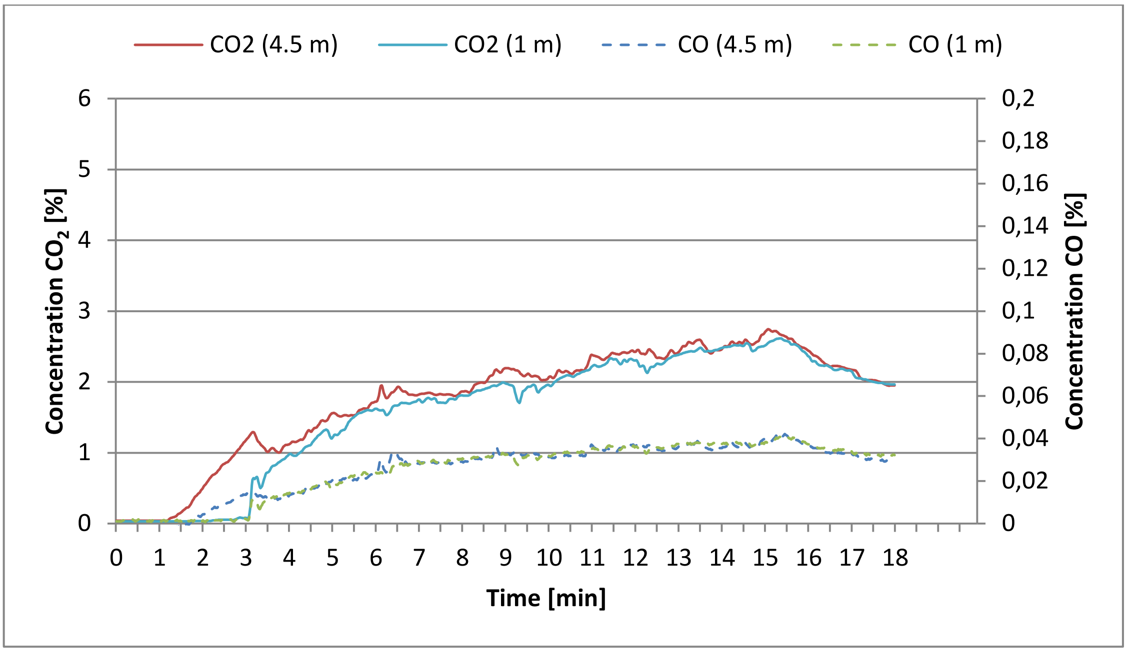

Figure 1- 90. CO and CO_2 measurements during test denominated as D1.0-WMl.

D1.0-WMh

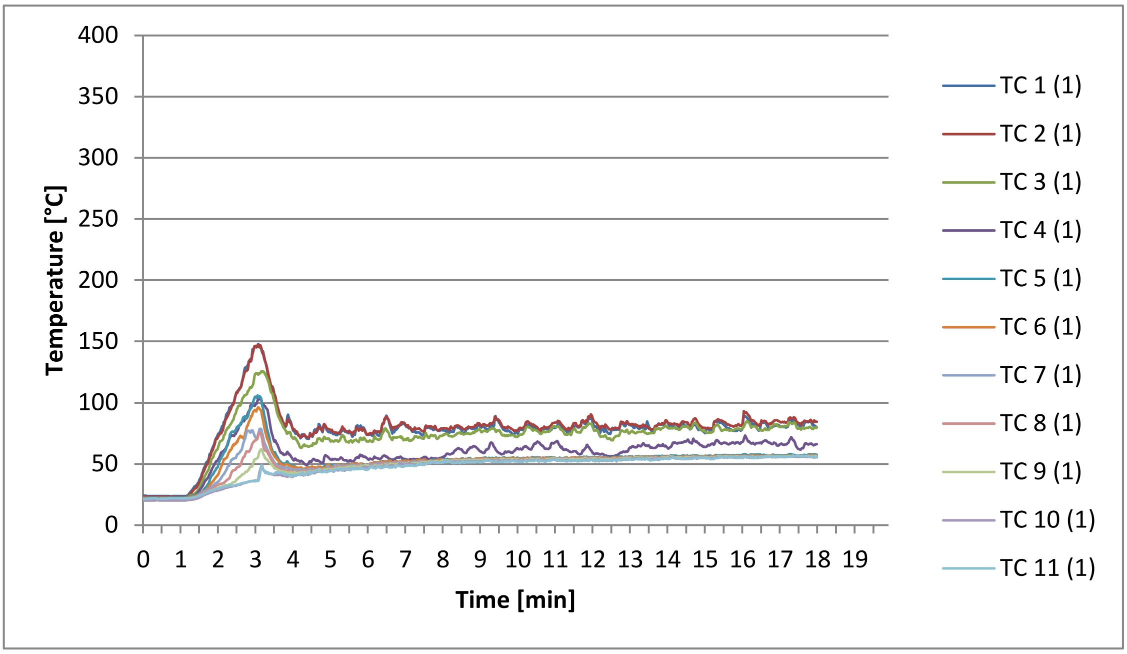

Figure 1- 91. Temperatures from thermocouple tree 1 during test denominated as D1.0-WMh.

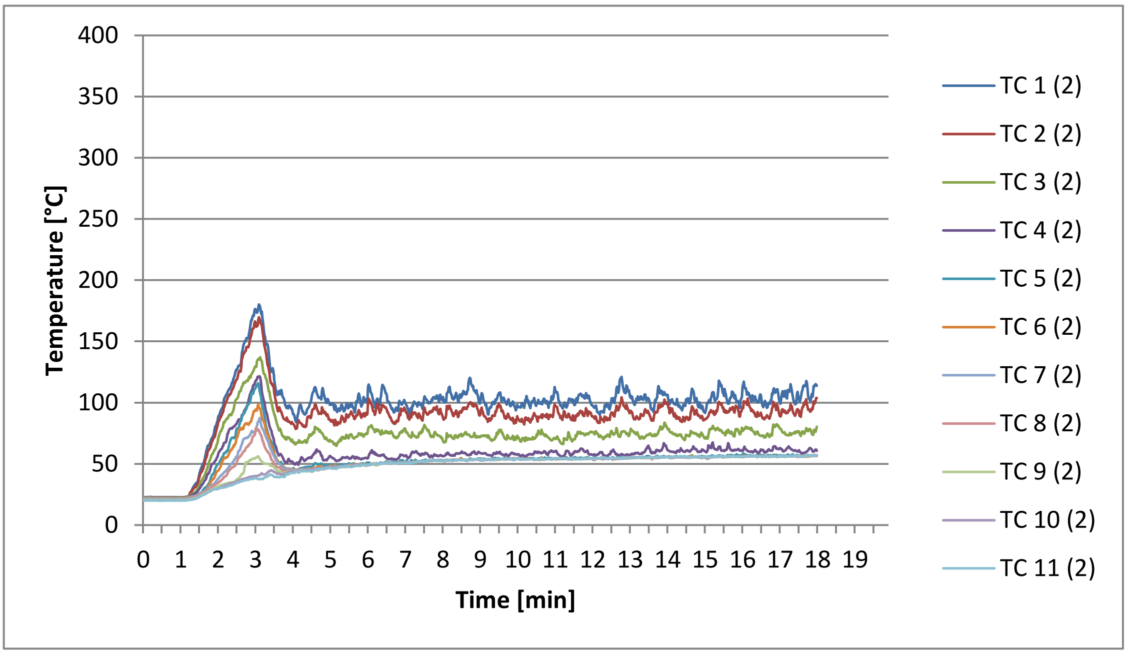

Figure 1- 92. Temperatures from thermocouple tree 2 during test denominated as D1.0-WMh.

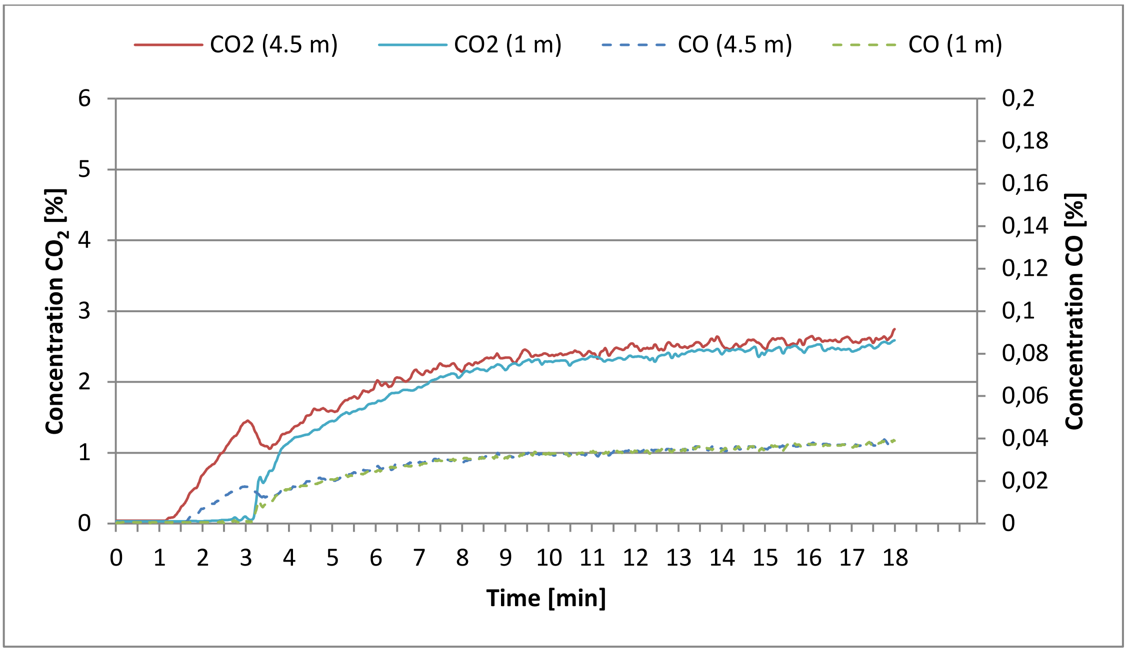

Figure 1- 93. CO and CO_2 measurements during test denominated as D1.0-WMh.

M1.0-WS-f

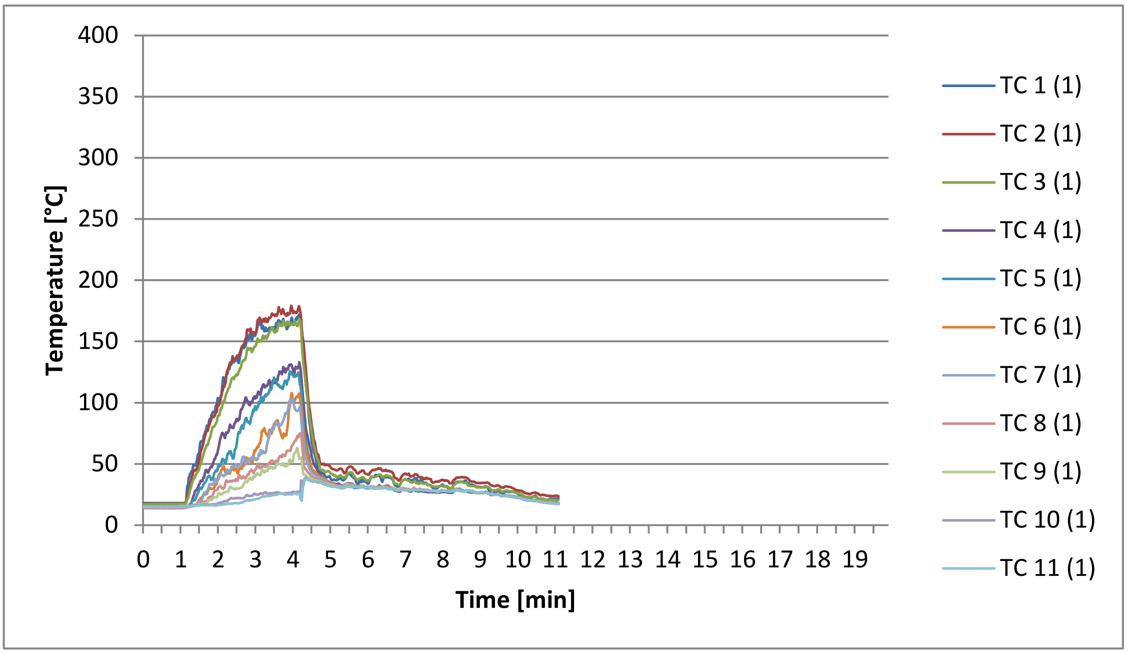

Figure 1- 94. Temperatures from thermocouple tree 1 during test denominated as M1.0-WS-f.

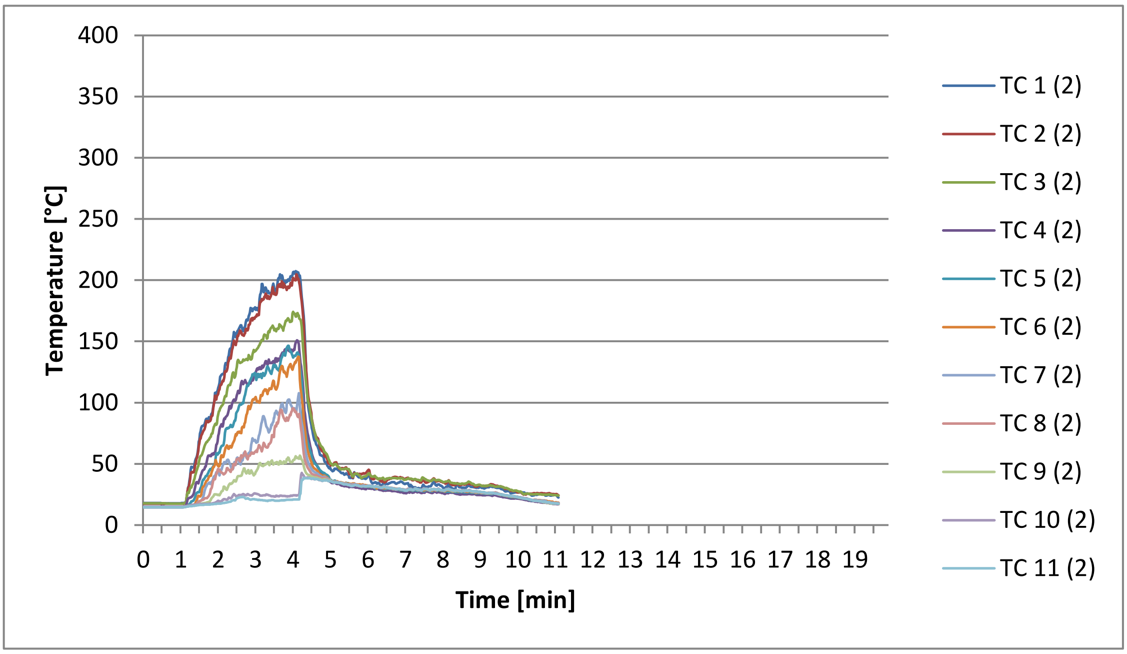

Figure 1- 95. Temperatures from thermocouple tree 2 during test denominated as M1.0-WS-f.

Appendix 1

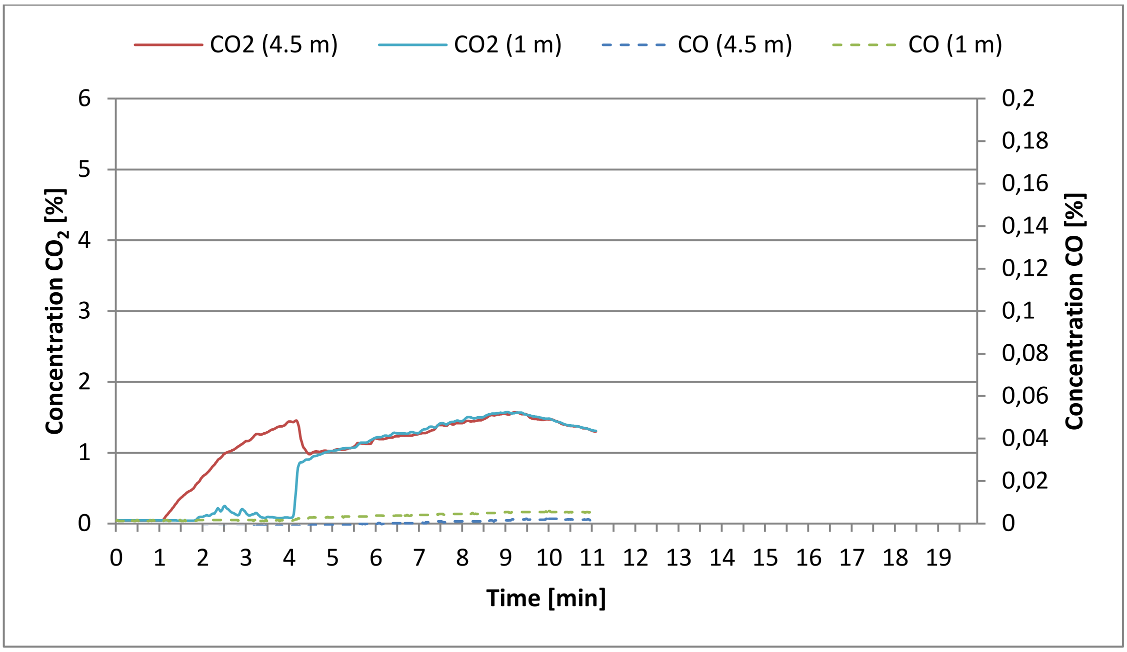

Figure 1- 96. CO and CO_2 measurements during test denominated as M1.0-WS-f.

M1.0-WS-f3

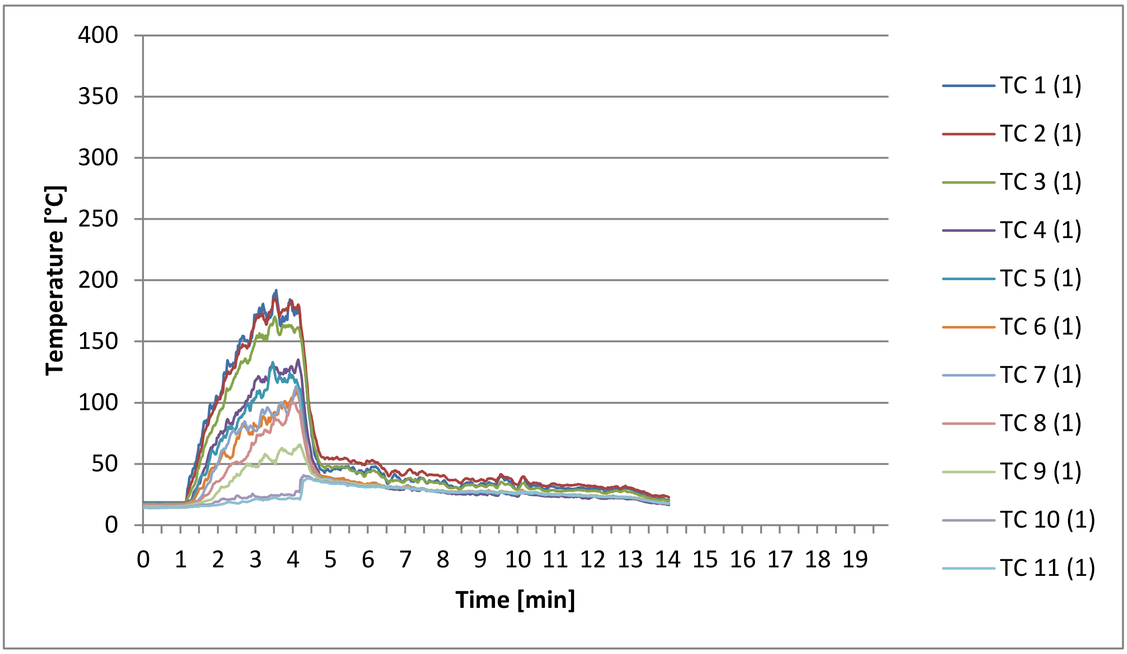

Figure 1- 97. Temperatures from thermocouple tree 1 during test denominated as M1.0-WS-f3.

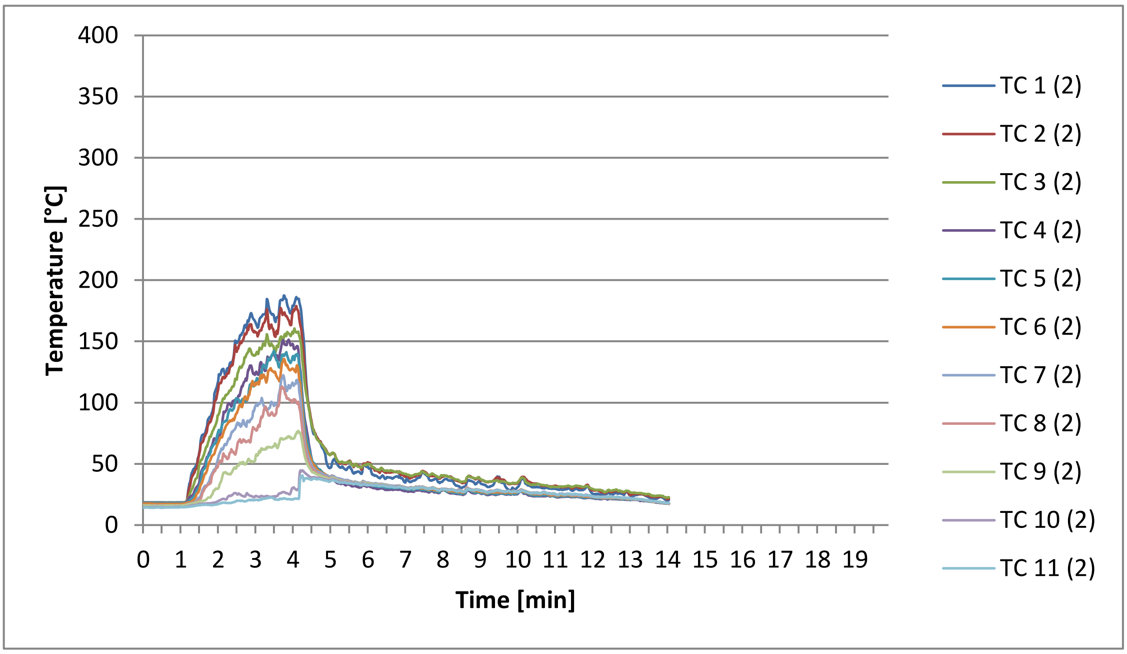

Figure 1- 98. Temperatures from thermocouple tree 2 during test denominated as M1.0-WS-f3.

Appendix 1

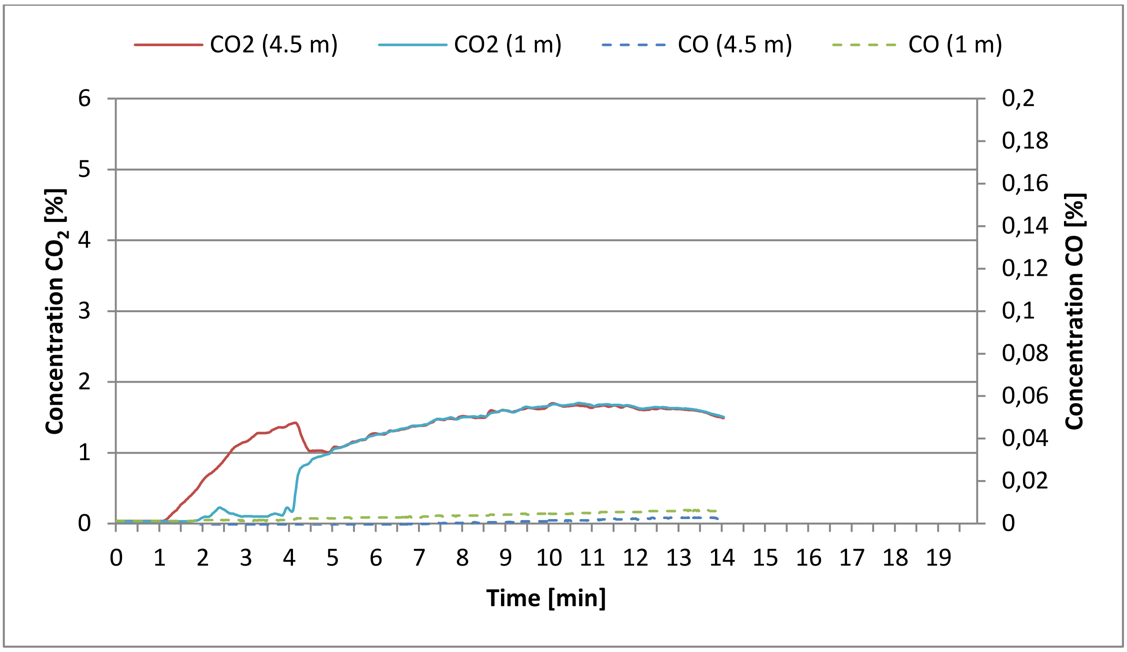

Figure 1- 99. CO and CO_2 measurements during test denominated as M1.0-WS-f3.

Appendix 1

M1.0-WS-fef

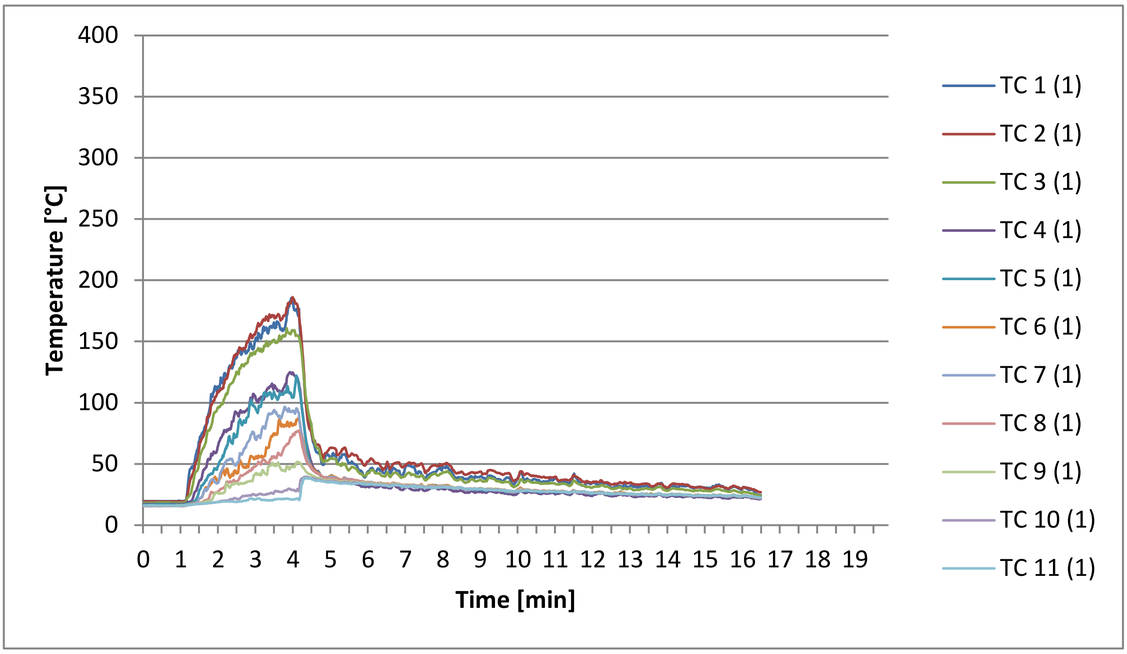

Figure 1- 100. Temperatures from thermocouple tree 1 during test denominated as M1.0-WS-fef.

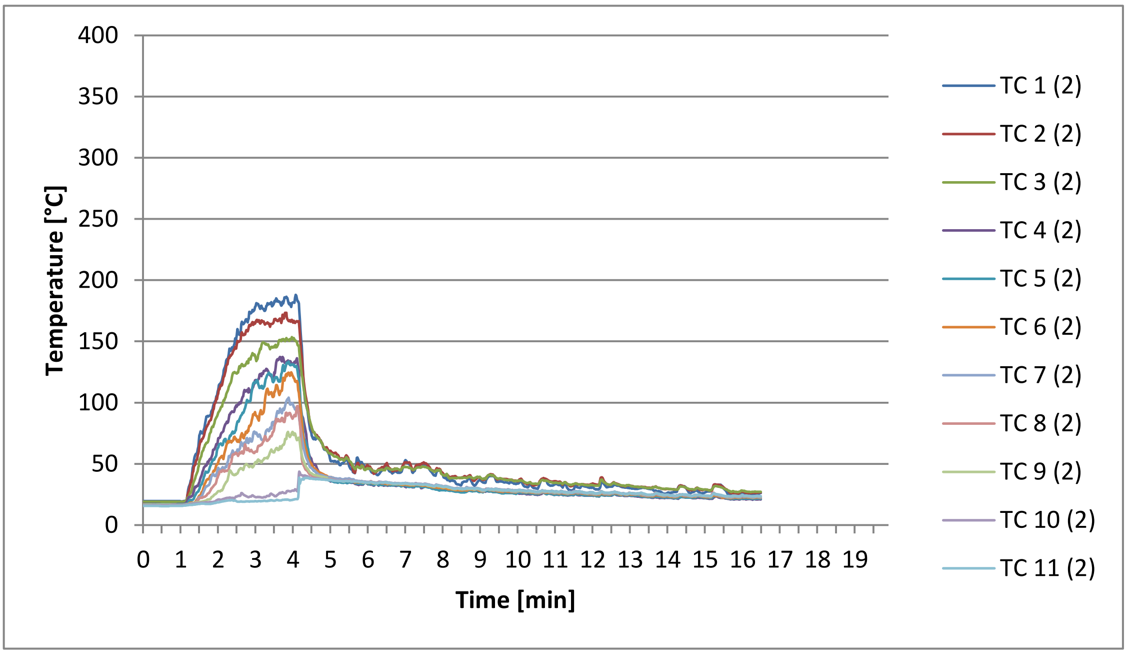

Figure 1- 101. Temperatures from thermocouple tree 1 during test denominated as M1.0-WS-fef.

Appendix 1

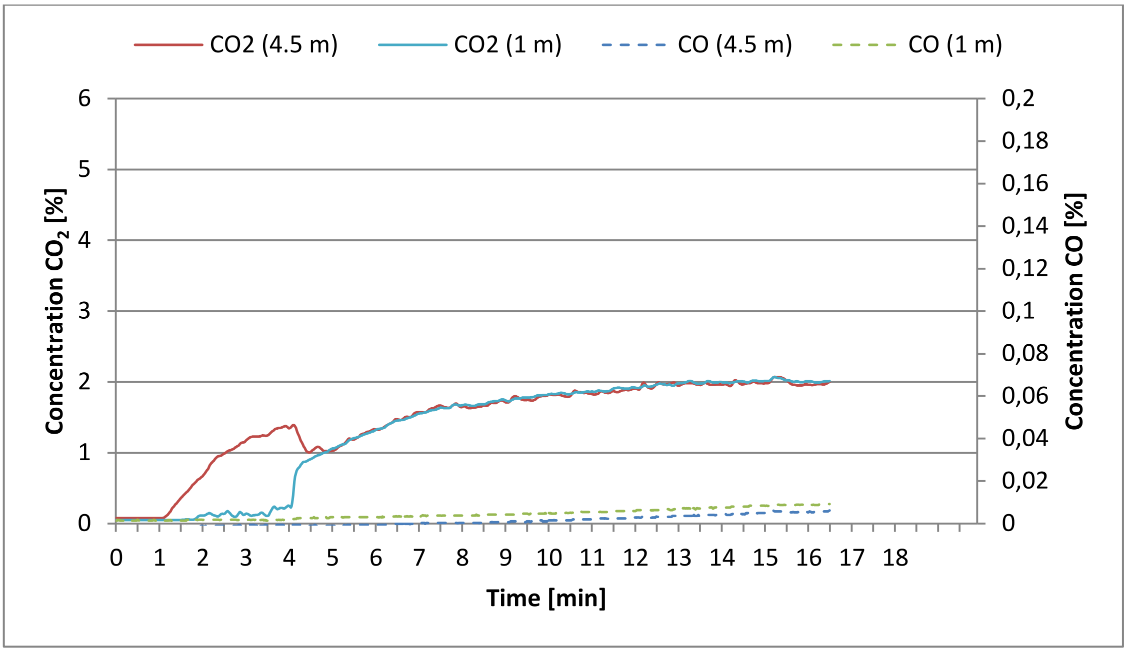

Figure 1- 102. CO and CO_2 measurements during test denominated as M1.0-WS-fef.

M1.0-WMl-f

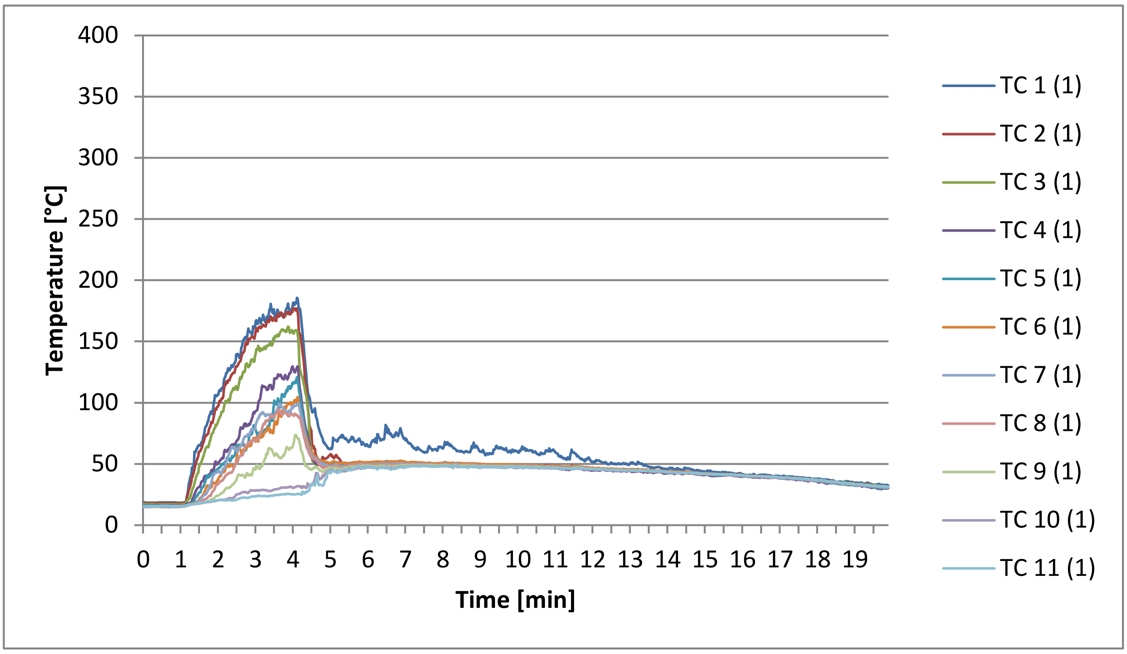

Figure 1- 103. Temperatures from thermocouple tree 1 during test denominated as M1.0-WMl-f.

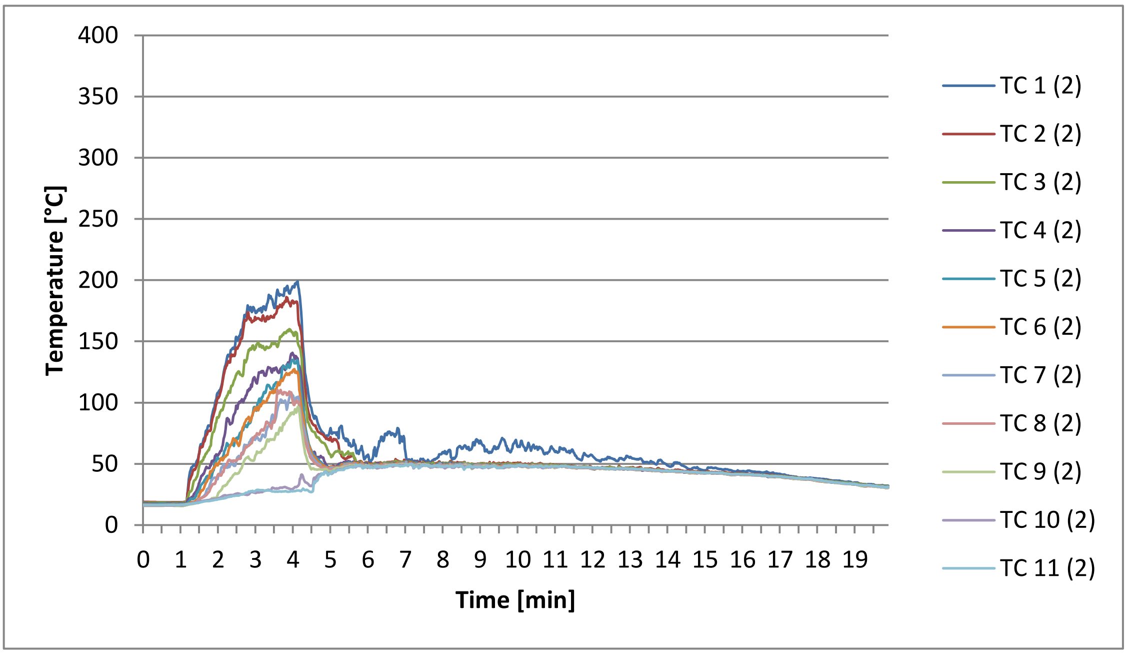

Figure 1- 104. Temperatures from thermocouple tree 2 during test denominated as M1.0-WMl-f.

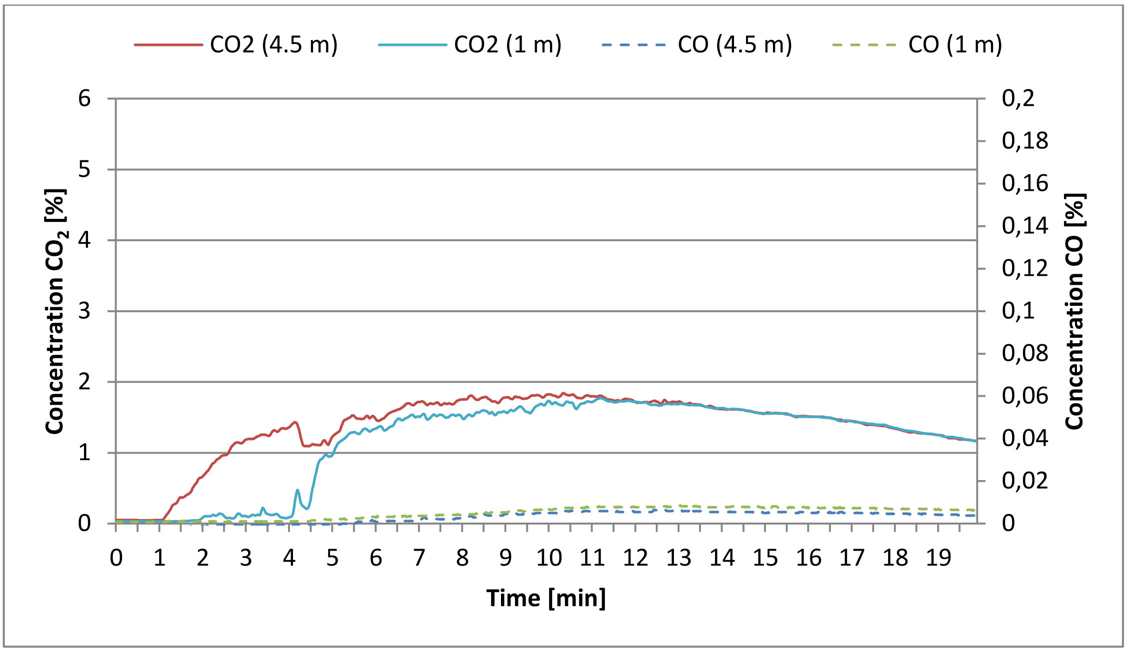

Figure 1- 105. CO and CO_2 measurements during test denominated as M1.0-WMl-f.

M1.0-WMh-f

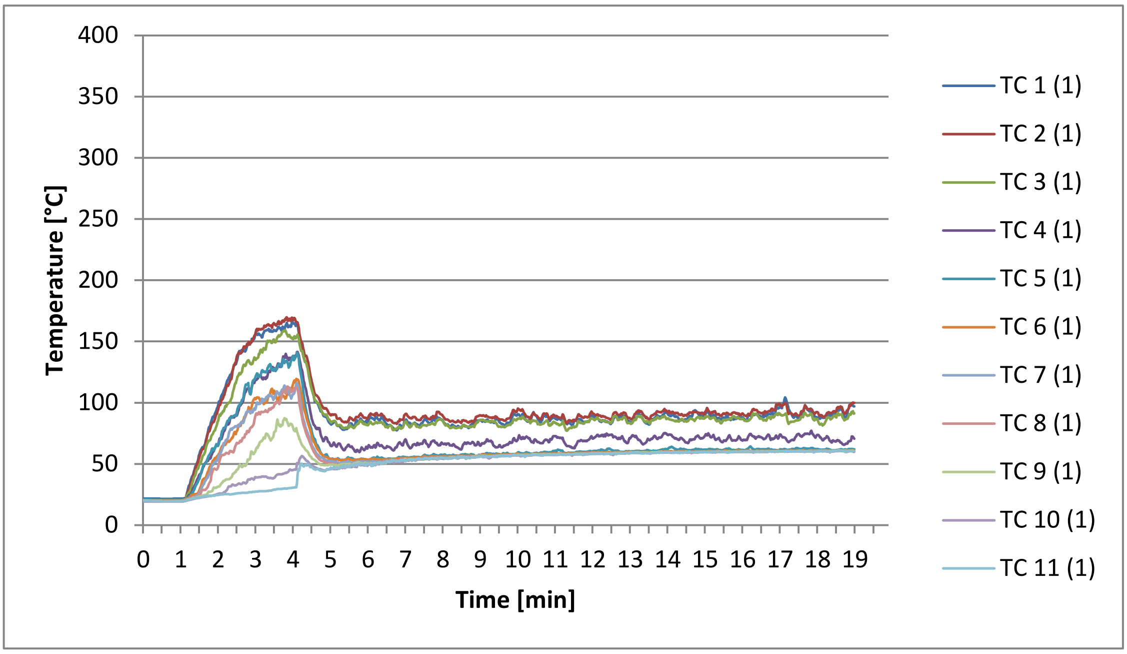

Figure 1- 106. Temperatures from thermocouple tree 1 during test denominated as M1.0-WMh-f.

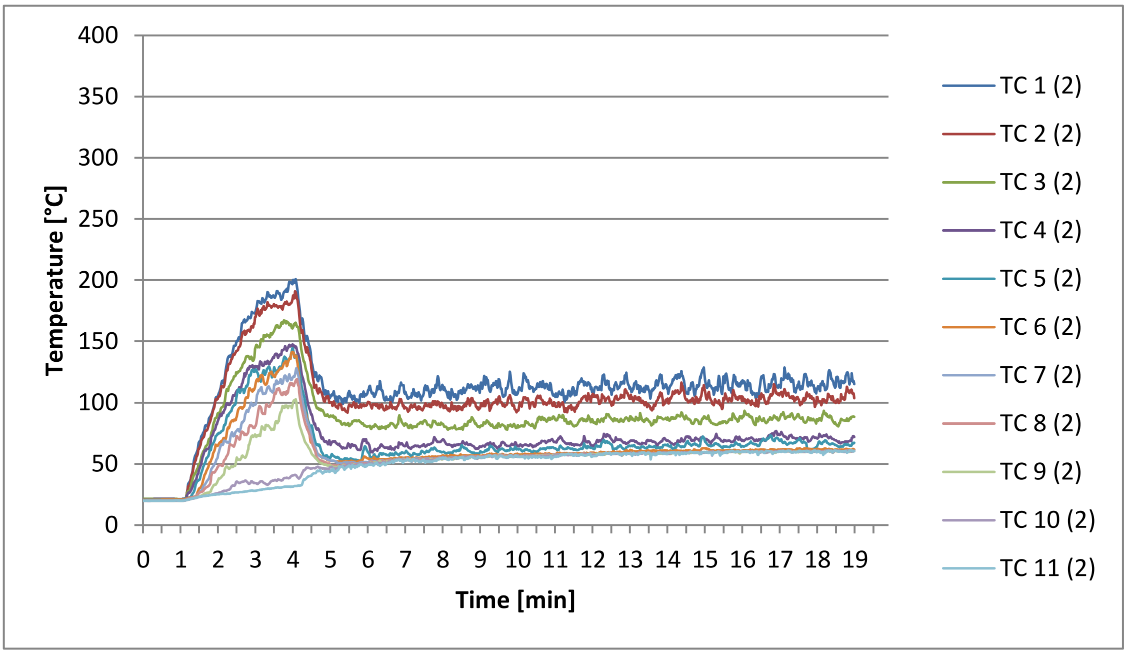

Figure 1- 107. Temperatures from thermocouple tree 2 during test denominated as M1.0-WMh-f.

Appendix 1

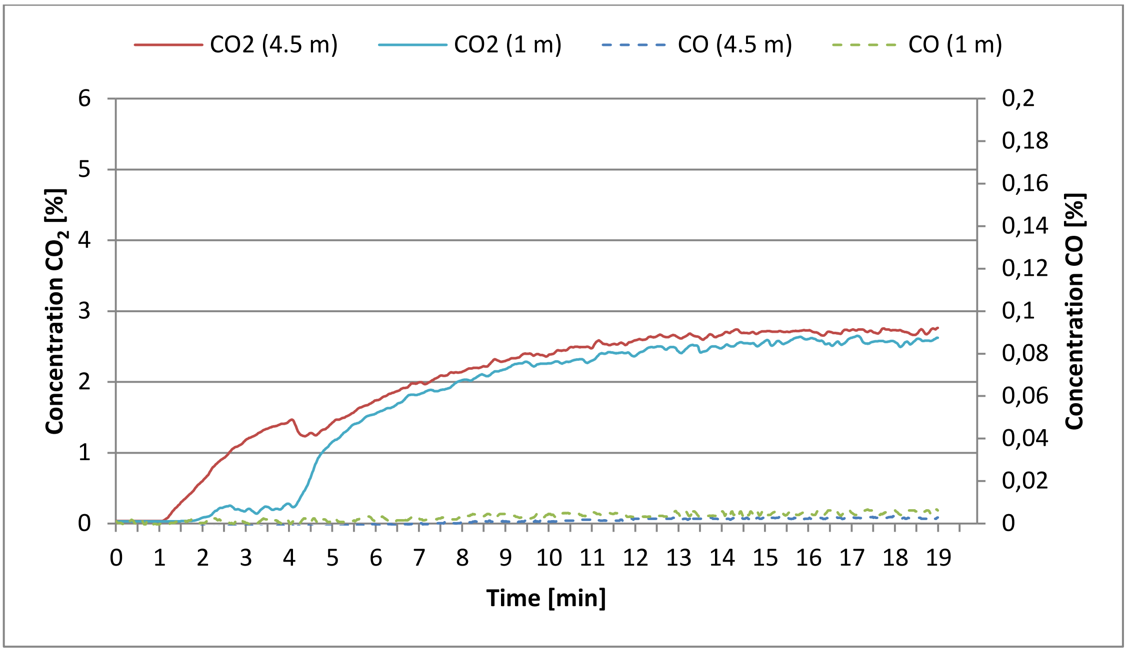

Figure 1- 108. CO and CO_2 measurements during test denominated as M1.0-WMh-f.

D2.0-WMl

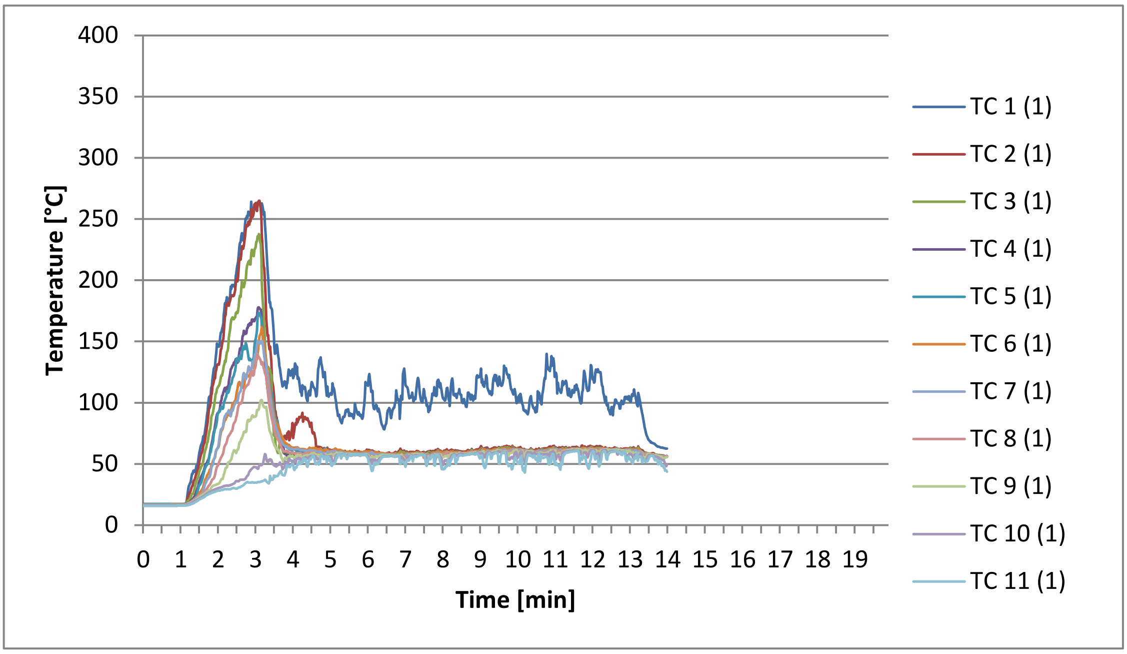

Figure 1- 109. Temperatures from thermocouple tree 1 during test denominated as D2.0-WMl.

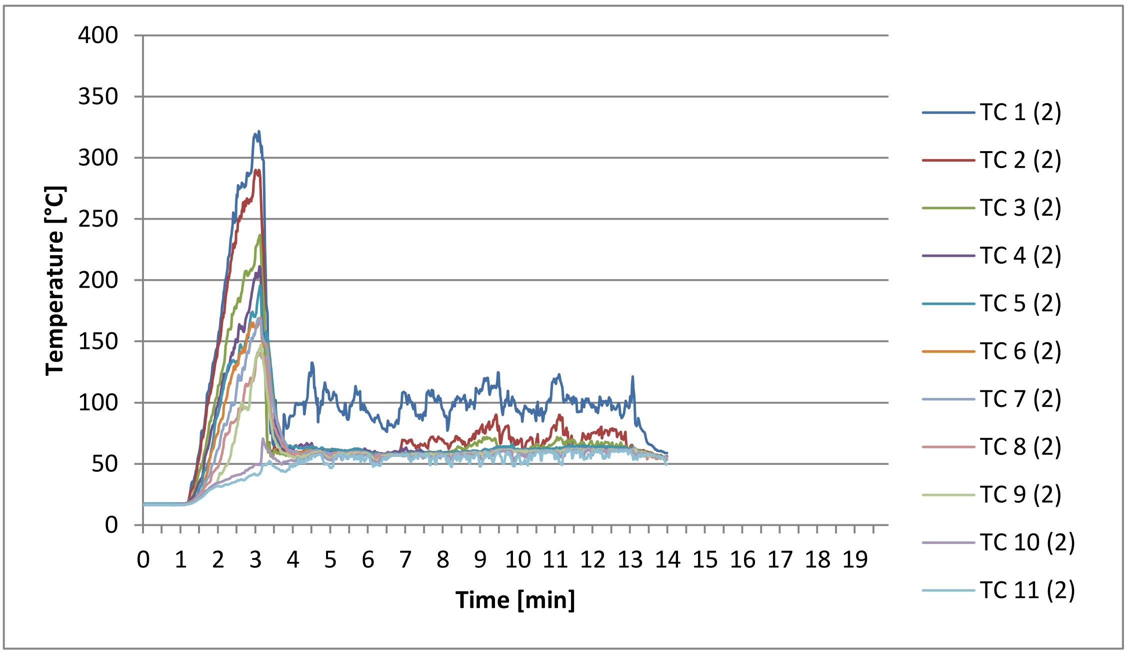

Figure 1- 110. Temperatures from thermocouple tree 2 during test denominated as D2.0-WMl.

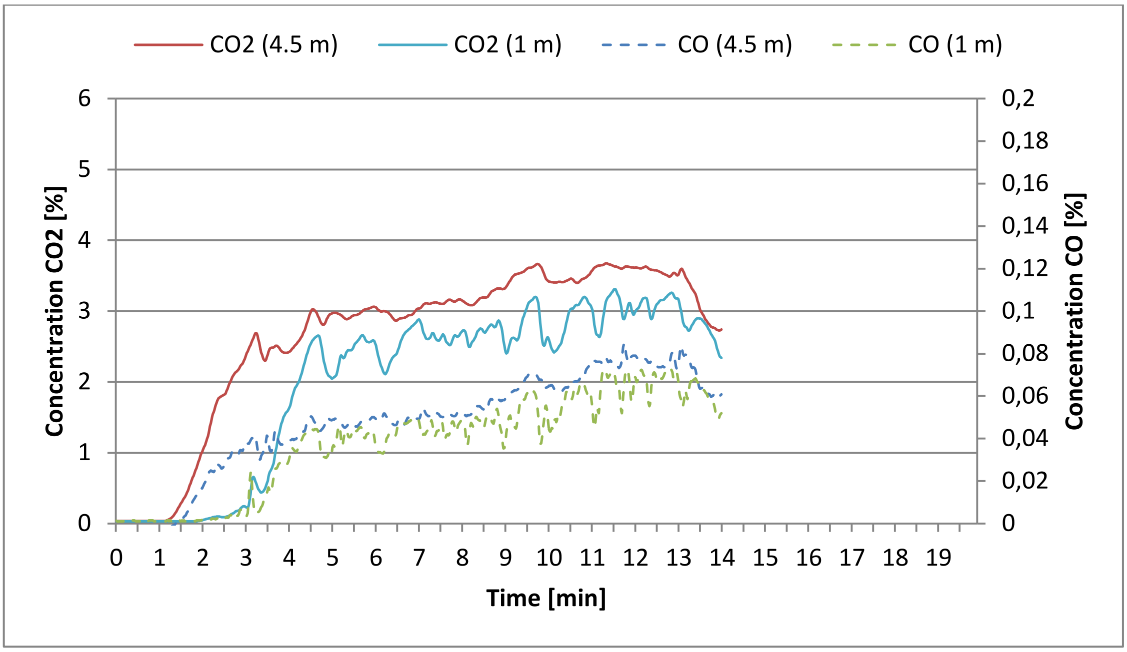

Figure 1- 111. CO and CO_2 measurements during test denominated as D2.0-WMl.

D2.0-WMh

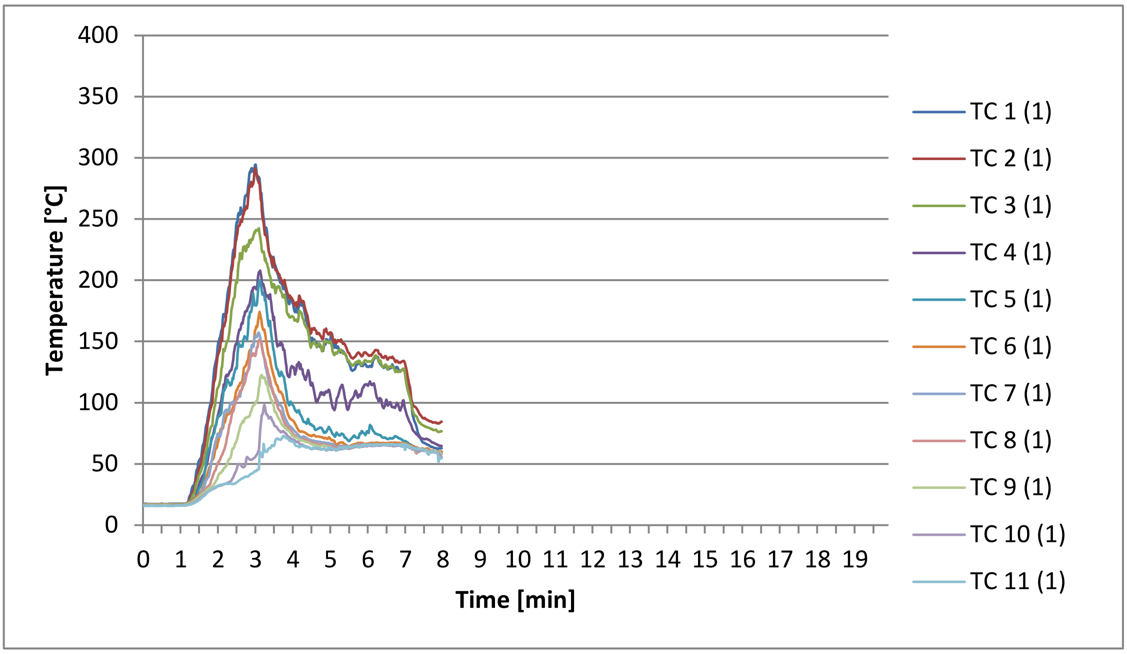

Figure 1- 112. Temperatures from thermocouple tree 1 during test denominated as D2.0-WMh.

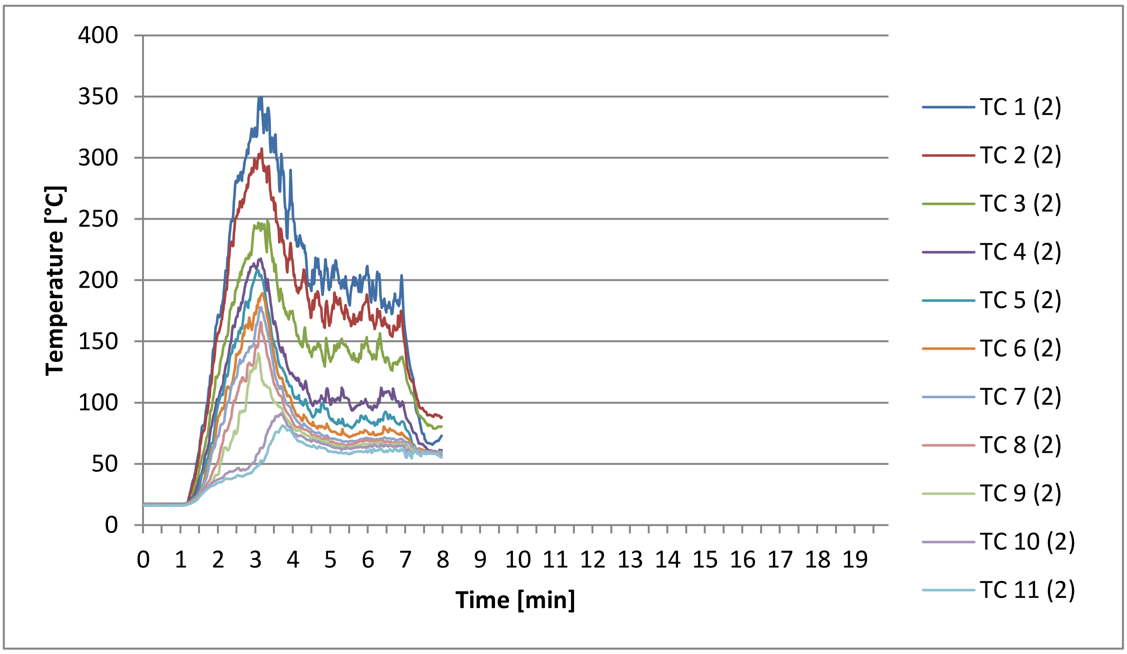

Figure 1- 113. Temperatures from thermocouple tree 2 during test denominated as D2.0-WMh.

Appendix 1

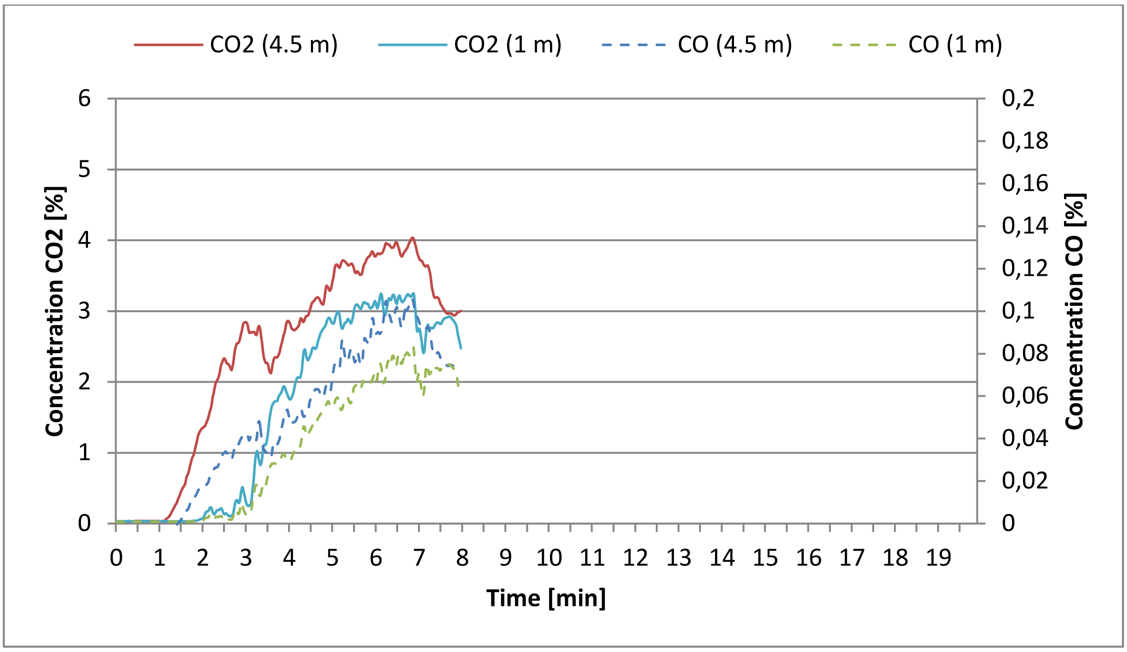

Figure 1- 114. CO and CO_2 measurements during test denominated as D2.0-WMh.

M2.0-WMl-f

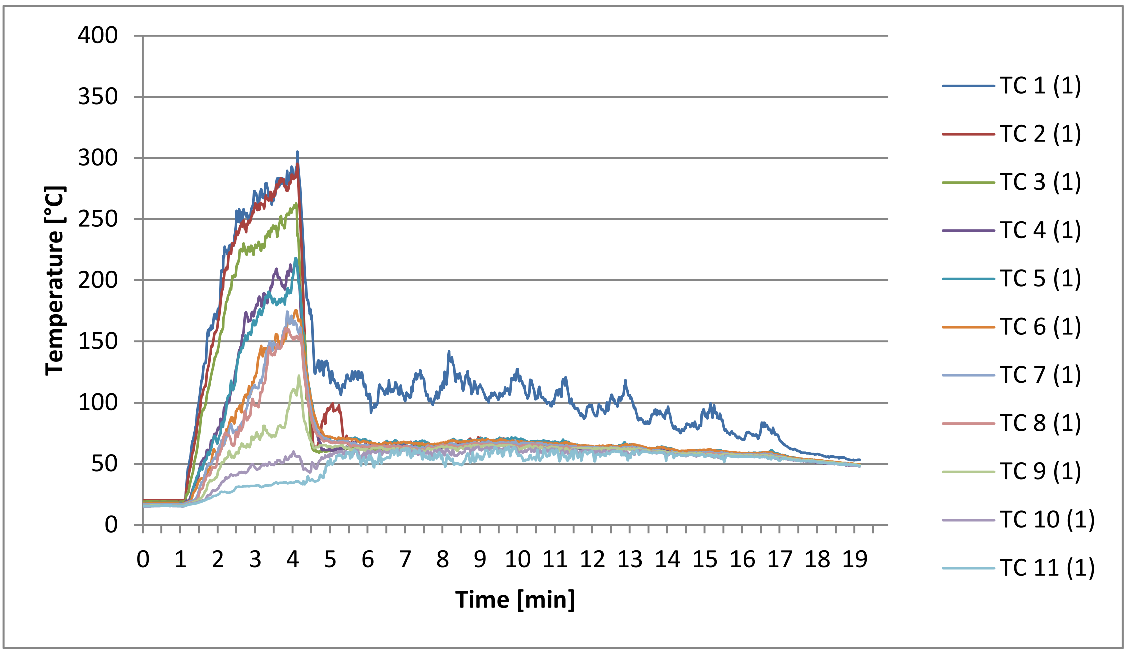

Figure 1- 115. Temperatures from thermocouple tree 1 during test denominated as M2.0-WMl-f.

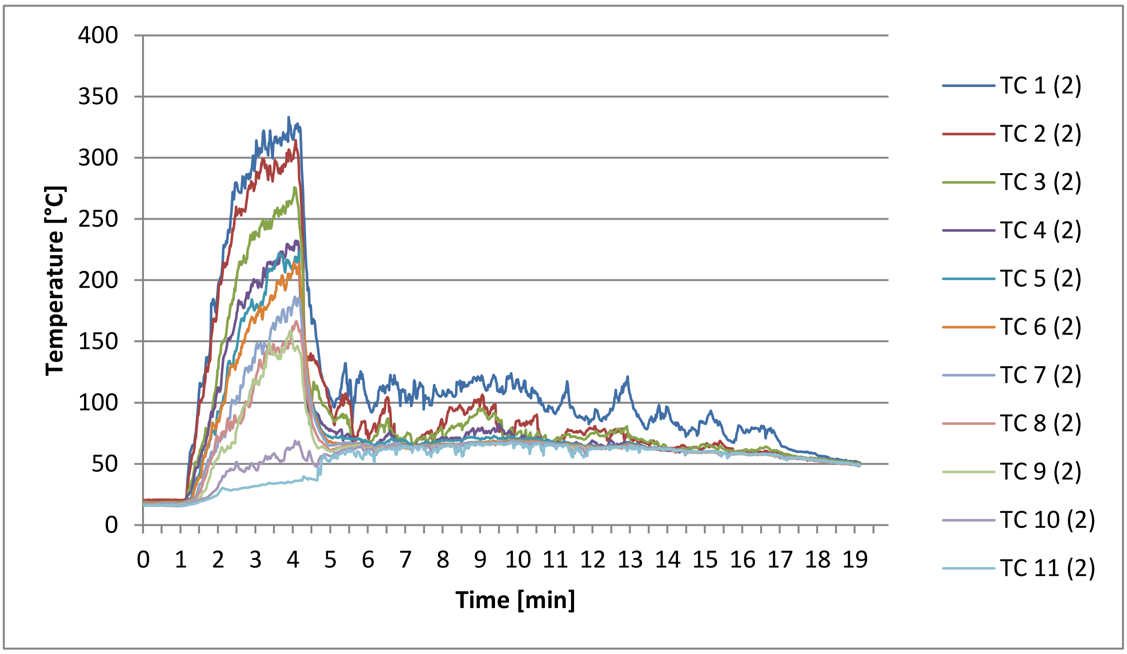

Figure 1- 116. Temperatures from thermocouple tree 2 during test denominated as M2.0-WMl-f.

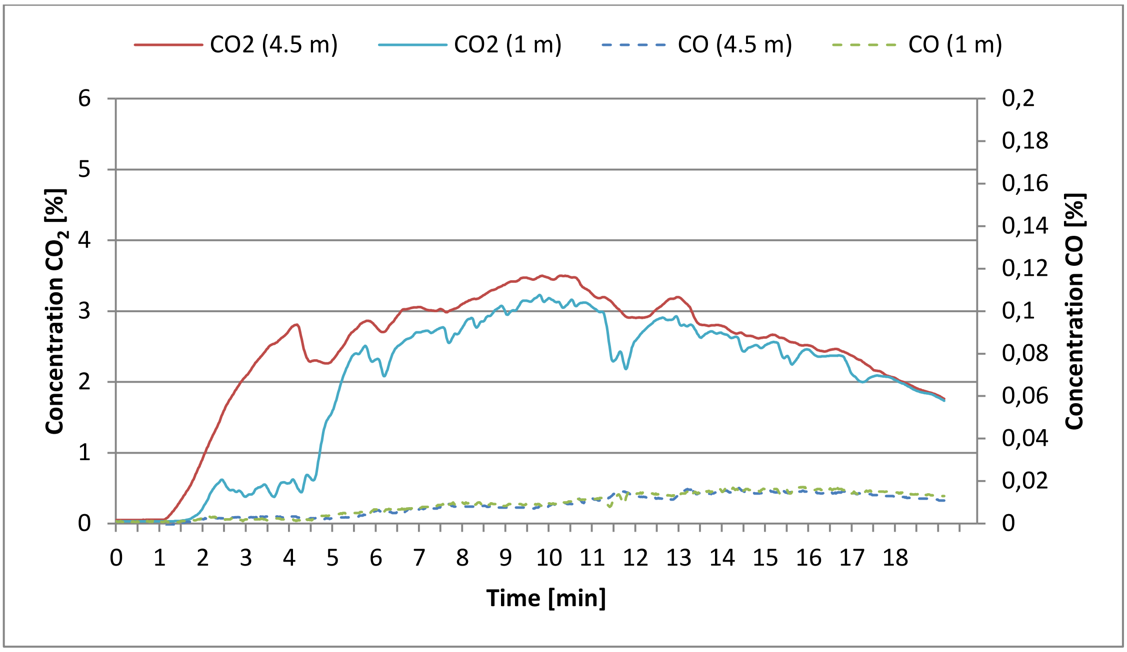

Figure 1- 117. CO and CO_2 measurements during test denominated as M2.0-WMI-f.

M2.0-WMh-f

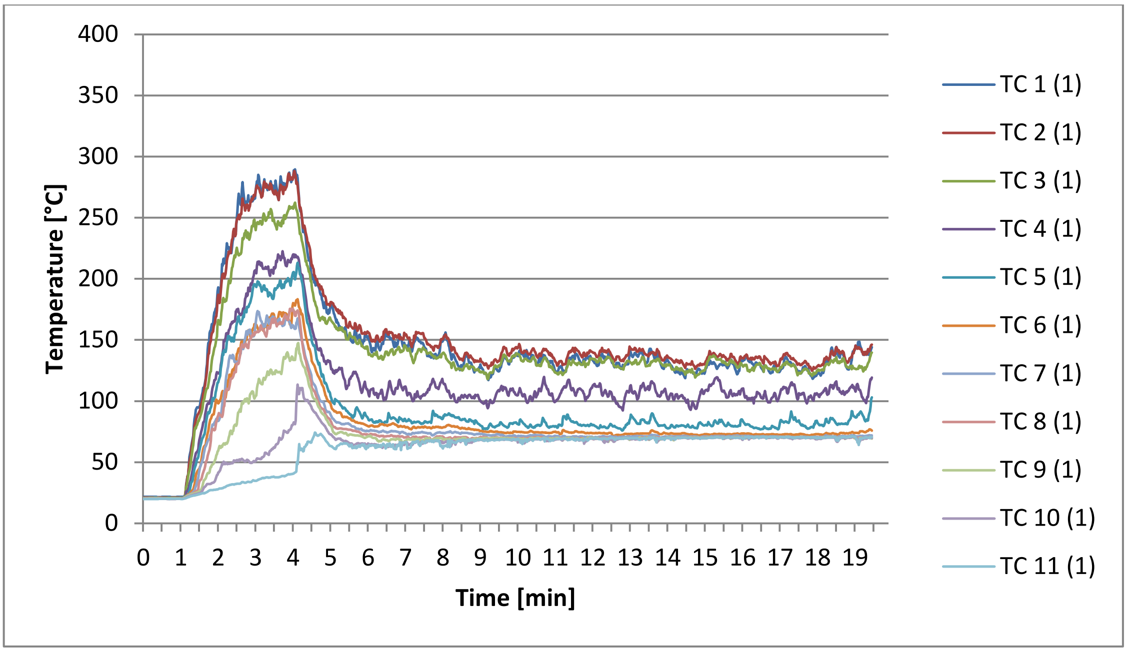

Figure 1- 118. Temperatures from thermocouple tree 1 during test denominated as M2.0-WMh-f.

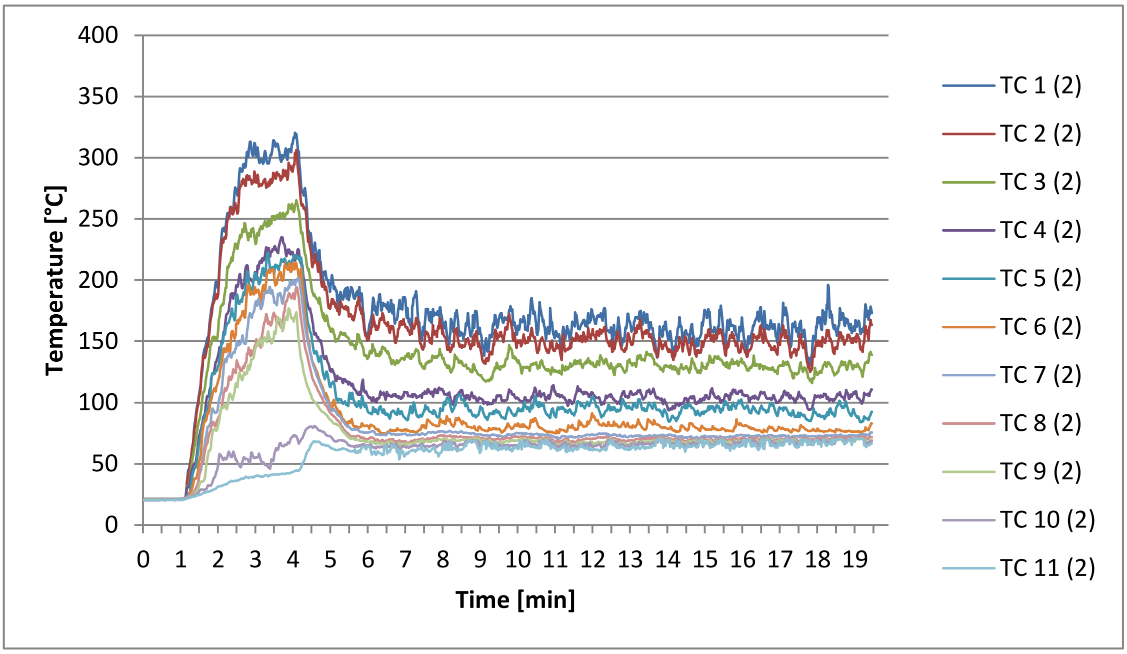

Figure 1- 119. Temperatures from thermocouple tree 2 during test denominated as M2.0-WMh-f.

Appendix 1

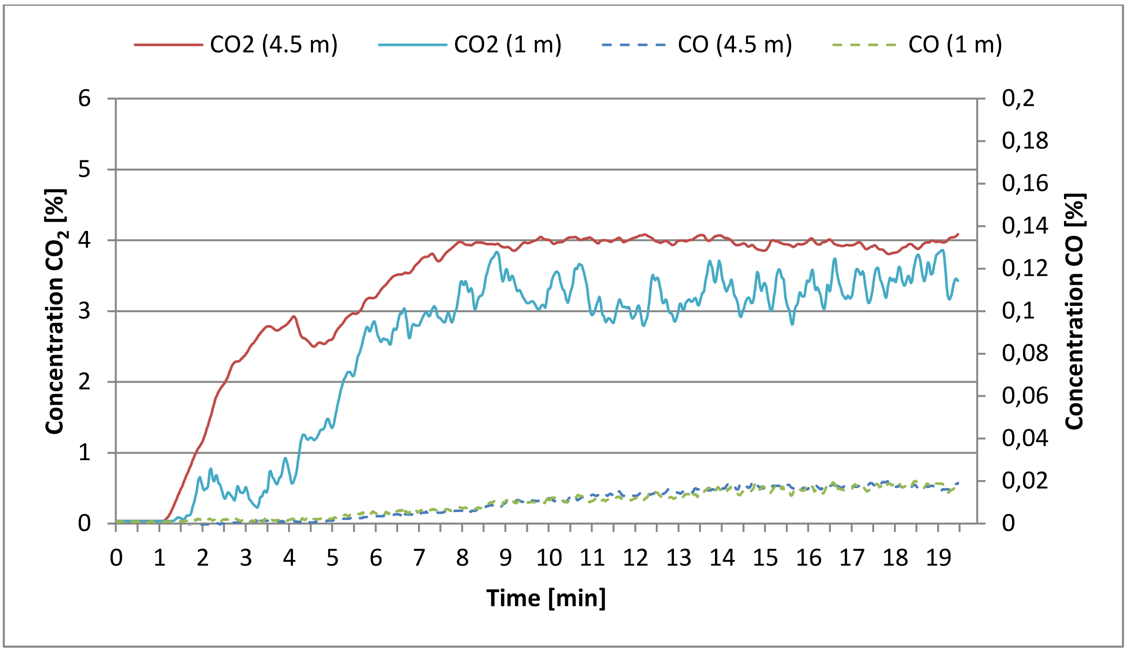

Figure 1- 120. CO and CO_2 measurements during test denominated as M2.0-WMh-f.

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2017-04-10

Reference
Brd6081-04

Part of the proFLASH research project

Spectral radiation measurements of open pool fires of methanol and other liquid fuels

Introduction

The stricter regulations for sulphur content in bunker fuel have stimulated use of alternative fuels such as LNG and methanol, which differ from traditional bunker fuels in many ways. One important difference is their low flashpoint, which increases the probability of ignition in case of leakage. There are also other differences which increase fire risks, not least properties which affect the possibilities for fire detection and extinguishment. Methanol flames can for example be difficult to see and oxygen is bound to the molecule. LNG has a very low boiling point and is difficult to extinguish with water.

The purpose of the proFLASH project was to increase knowledge and to influence regulations regarding fire detection and fire extinguishment of low-flashpoint fuels, in particular LNG and methanol. The project consisted of a preliminary study and large-scale fire test phase, evaluating the suitability of relevant detection and extinguishing system solutions. It was decided to focus the experimental part of the project on methanol.

Background

The stricter regulations for sulphur content in bunker fuels have stimulated the use of alternative fuels, such as alcohols and gaseous fuels. Differences in the flashpoint and flame emissivity of alternative fuels, such as methanol, in comparison to traditional bunker fuel oils, can modify the fire risks. It is possible that the low flashpoint of alcohols may increase the risk of a fire in case of a leakage and the differences in flame emissivity may affect the possibilities for fire detection and extinguishment. The combustion of methanol gives a flame with low emissivity in the visible spectrum. Firefighting non-sooting flames might result arduous since these can be difficult to discern from the surroundings.

This report documents one of the test series in the proFLASH project, investigating the spectrally resolved radiation from methanol fires in comparison with other liquid fuels. This was done to evaluate potential effects on flame detection.

Experimental setup and procedure

The radiation from five different liquid fuels burning in different trays was spectrally characterised. Diesel, ethanol *90 % (Eth90)*, heptane, methanol *(Meoh)* and T-sprit (methylated spirit) were burned in a small square tray. Methanol was also burned in three larger circular trays of different sizes.

The radiation from the aforementioned pool fires was characterised using a modular FTIR spectrometer coupled to a DTGS detector with a responsivity range comprehended between *6,000 to 350* cm^{-1}. The radiation emitted from the studied flames was imaged into the spectrometer by the aid of an optical tube with a longitude of *1 130 mm*, coated in its interior with a non-reflective film.

A sketch of the experimental setup is depicted in Figure 1, showing parameters relevant to the placement of the equipment during the measurements. h_1 is the distance between the optical line of symmetry and the common ground, h_2 is the distance from the ground to the rim of the used tray, l_a is the optical path between the iris and the detector, l_b is the optical path from the opening to the detector and l_c is the distance between the optical opening and the centre of the used tray, Φ_a and Φ_b are the diameters of the optical cross sections of the aperture of the spectrometer and the tube, respectively, and Φ_c is the diameter of the imaged section. D_p is the characteristic dimension of the tray (diameter or length). Spectral data was acquired using a resolution of *64* cm^{-1}. For each measurement a total of one hundred single shots were averaged. The opening Φ_b was kept constant throughout all the experiments and equal to *40 mm*.

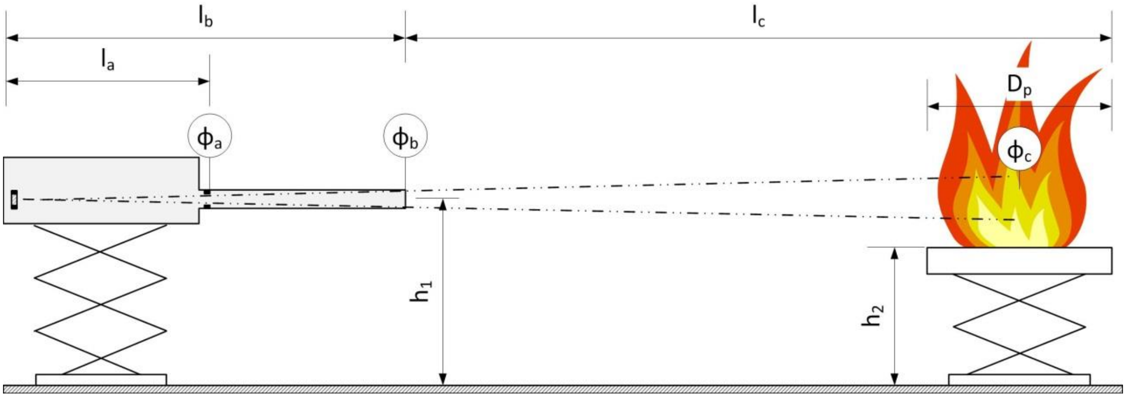

Figure 1. Experimental set-up for the spectrally resolved radiation measurements.

The cross section of the imaged portion of the flame which radiation is captured can be calculated according to Equation 1.

$$\emptyset_c = \emptyset_b \left(\frac{l_b + l_c}{l_b}\right) \quad (1)$$

Table 1 shows the parameters of the tests: optical path between the spectrometer and centre of the flame, l_c, optical cross section ratio, Φ_c / Φ_b, vertical distance from the tray's rim to the optical axis of the spectrometer, h_2-h_1, and characteristic length of the tray, D_p.

Table 1. Geometrical parameters for each experiment.

Tests ID	l_c [mm]	Φ_c/Φ_b	h_1-h_2 [mm]	D_p [mm]
F1440-Meoh	6400	6.52	530	1400[1]
F2400-Meoh	7400	8.2	1120	2400[1]
F3000-Meoh	7400	8.2	1640	3000[1]
S0500-Diesel	3500	3.85	100	500[2]
S0500-Eth90	3500	3.85	100	500[2]
S0500-Heptane	3500	3.85	100	500[2]
S0500-Meoh	3500	3.85	100	500[2]
S0500-Tsprit	3500	3.85	100	500[2]

[1] Circular tray (D_p = diameter).
[2] Square tray (D_p = side length).

Results

Figure 2 to Figure 10 show the spectrally resolved measurements of the radiation emitted from the combustion of the studied fuels in open trays at one position and at different times after the Start of Ignition (SOI).

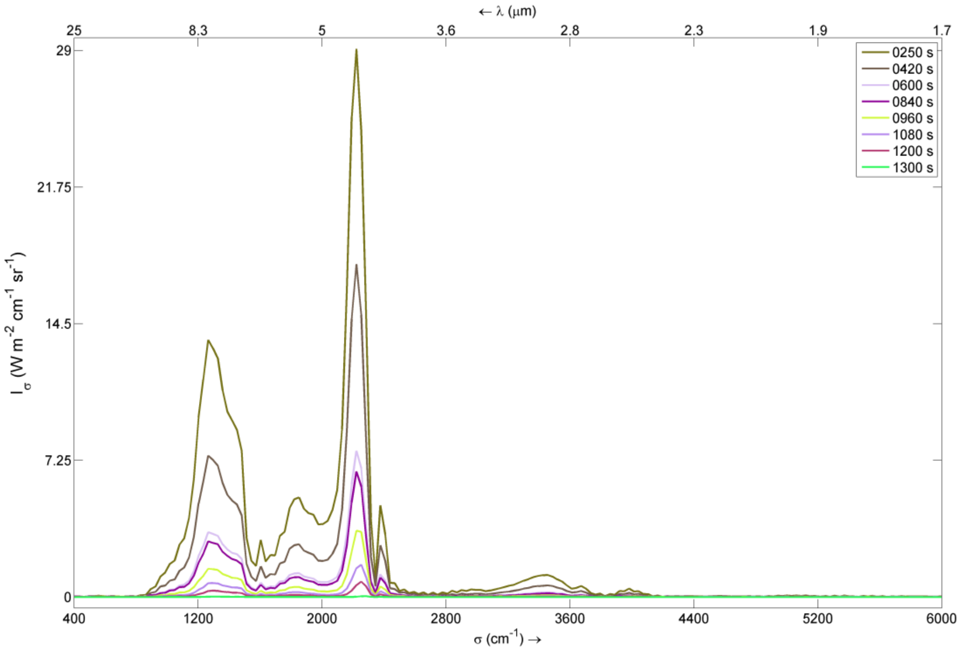

Figure 2. Spectrally resolved radiation from F1440-Meoh.

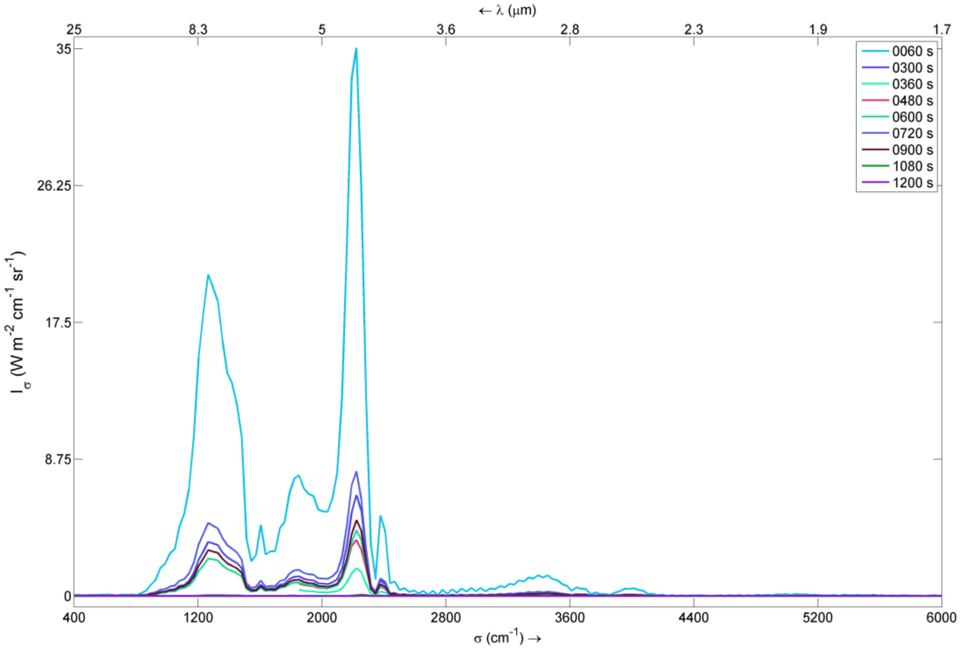

Figure 3. Spectrally resolved radiation from F2400-Meoh.

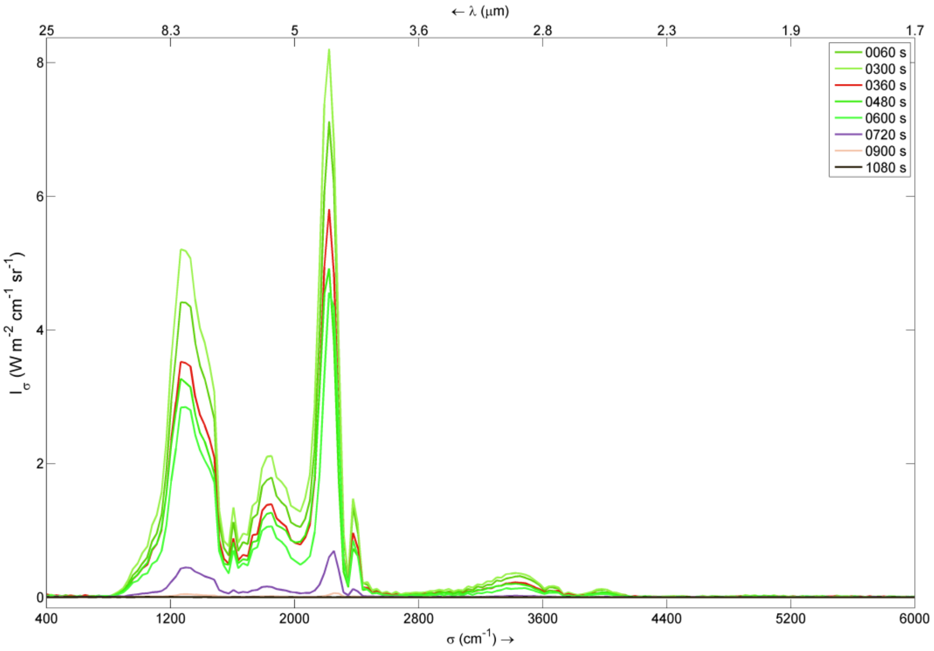

Figure 4. Spectrally resolved radiation from F3000-Meoh.

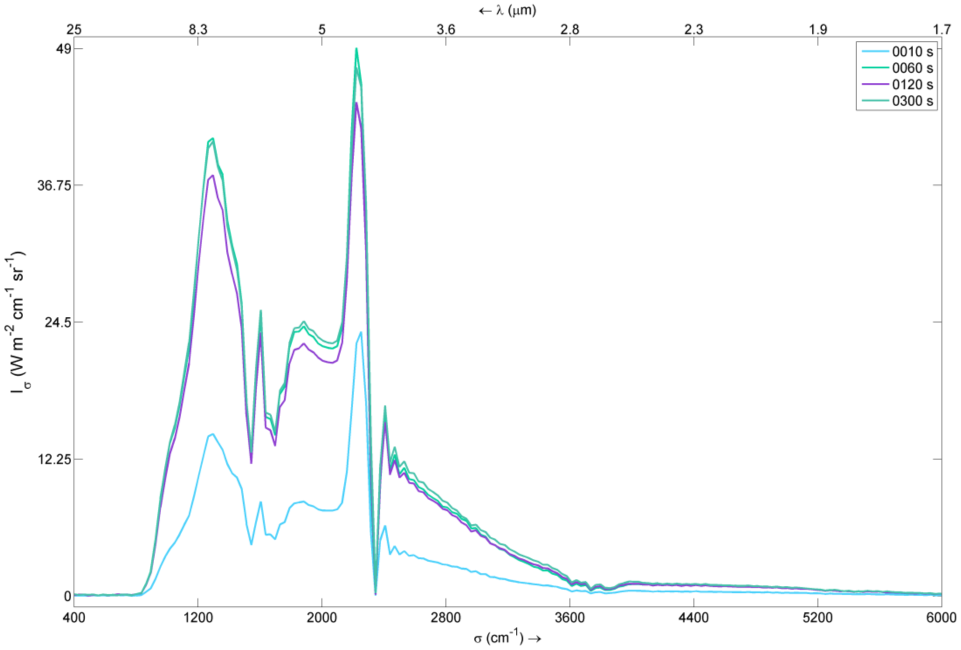

Figure 5. Spectrally resolved radiation from S0500-Diesel.

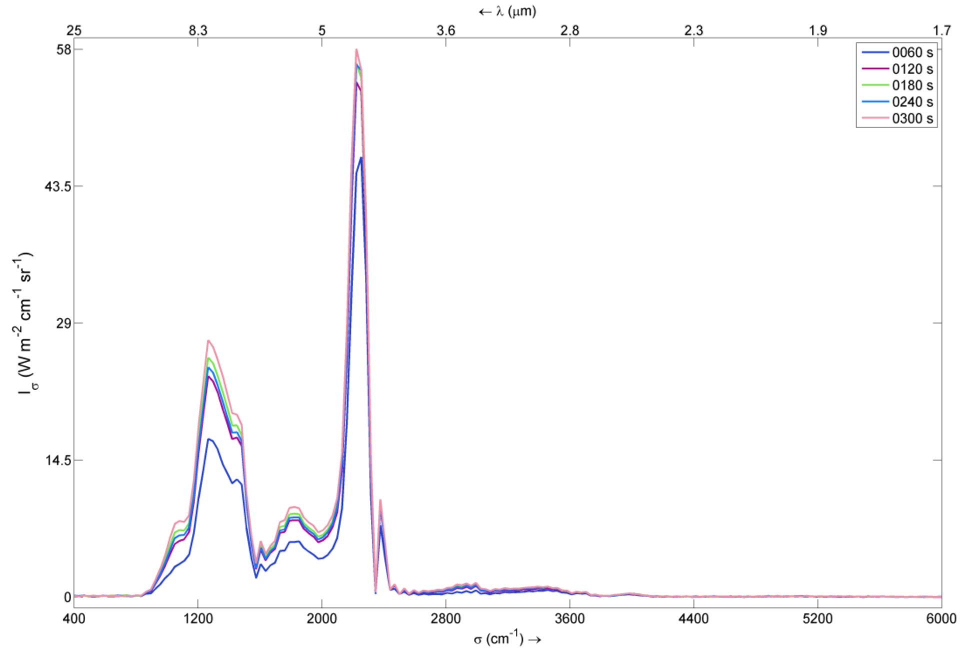

Figure 6. Spectrally resolved radiation from S0500-Eth90.

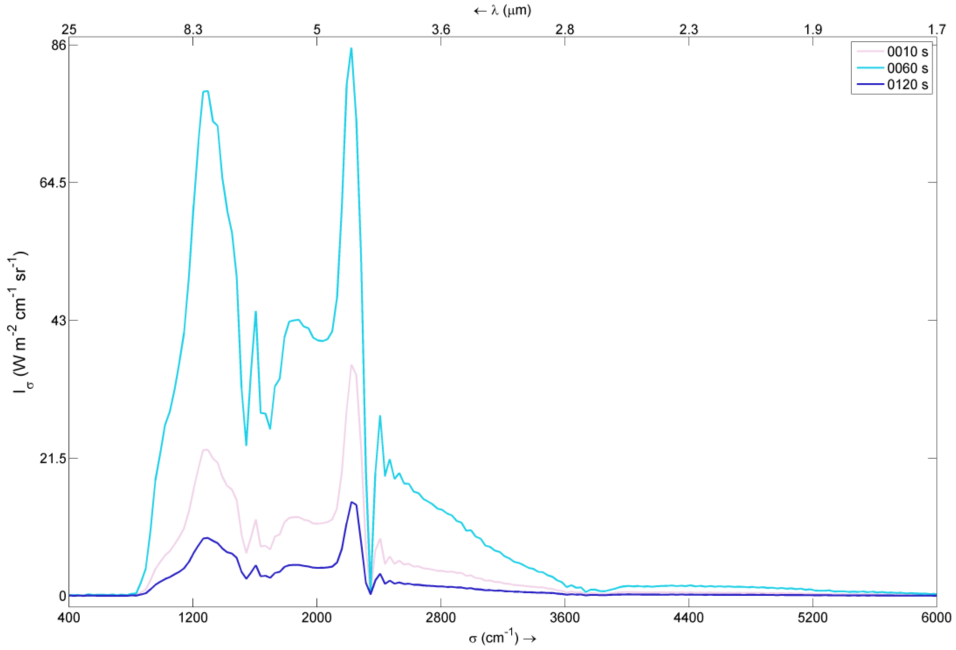

Figure 7. Spectrally resolved radiation from S0500-Heptane.

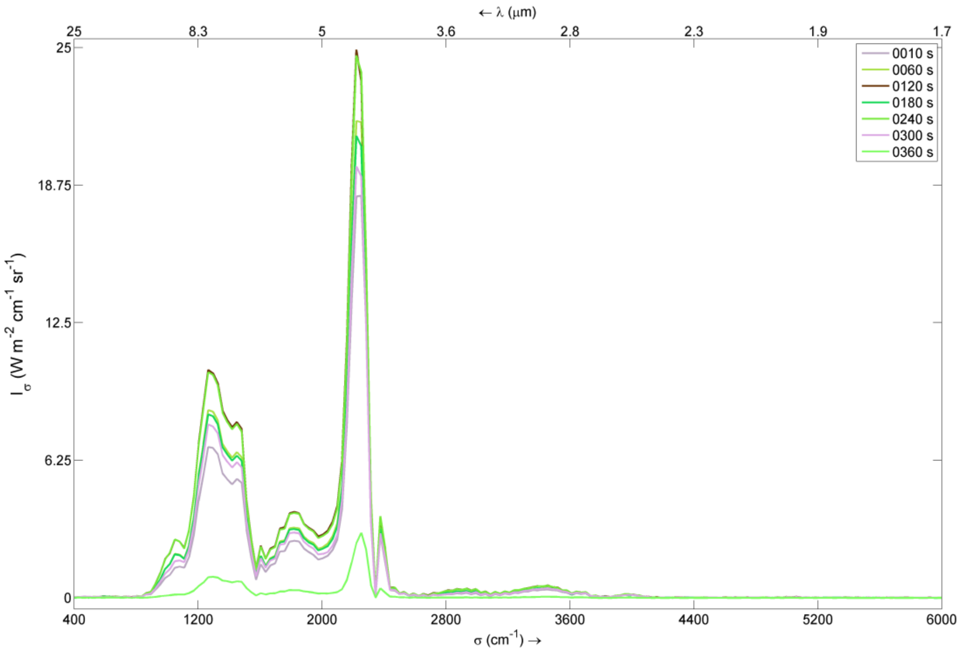

Figure 8. Spectrally resolved radiation from S0500-Meoh.

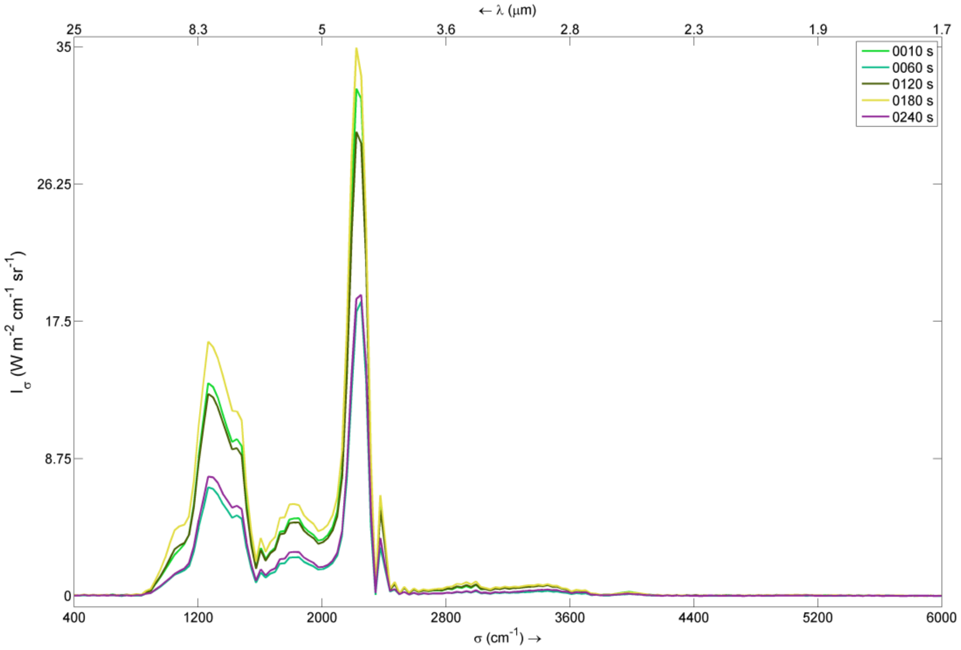

Figure 9. Spectrally resolved radiation from S0500-Tsprit.

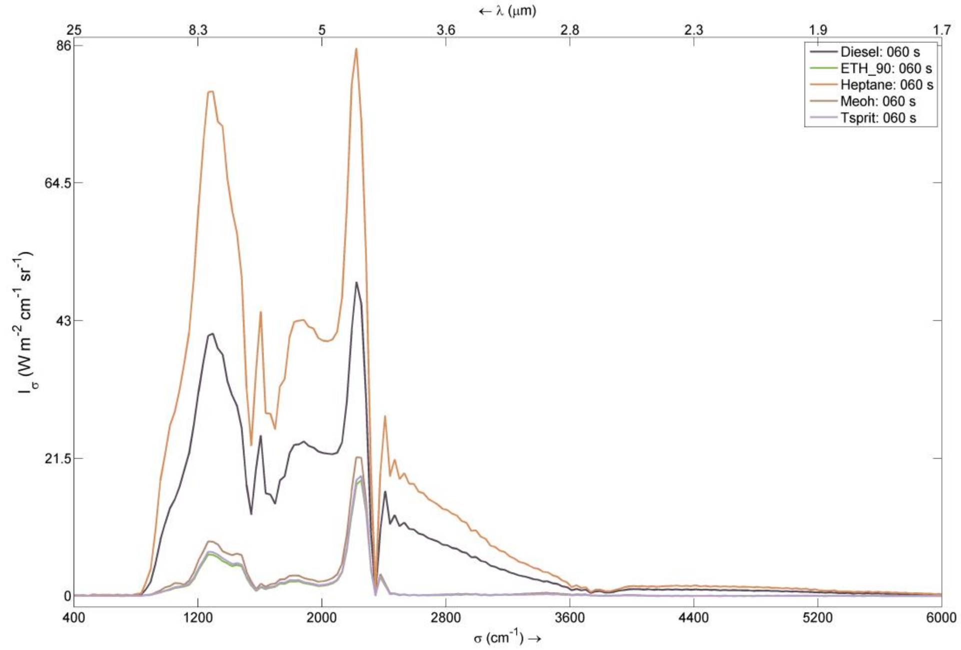

Figure 10. Comparison of spectrally resolved radiation from S0500 for all the studied fuels, 120 s after SOI.

Discussion

Comparing Figure 2 and Figure 3 shows that the radiation for methanol (Meoh) is higher in magnitude for the larger tray. The results plotted in Figure 4 correspond to measurements done at a different height and therefore are difficult to compare to the former ones. The latter is the cause of a lower radiation intensity in Figure 4 (for F3000-Meoh) than in Figure 3 (for F2400-Meoh).

Comparing the plots in Figure 10 shows that the radiation emitted from fires of alcohols has little blackbody radiation when placed in contrast against hydrocarbon fuel fires.

Implications to fire detection

Flame detectors operate by observing changes in radiation at certain narrow spectral bands, like OH at 309 nm, H_2O around 2.8 µm or CO_2 between 2.9 and 4.3 µm. More detailed information regarding radiation and absorption from fires and gas plumes can be found elsewhere[1],[2]. Since the emission from burning methanol, ethanol and T-spirit is similar in the IR region, triple-band detectors tested with these fuels will probably also be suitable to detect burning methanol. In this regard, it is important that a flame detector for methanol applications analyses the bands corresponding CO_2 and H_2O. In Figure 10 it can be observed that non-sooty methanol flames emit radiation in the CO_2 and H_2O bands and that sooty flames, such as a diesel fire, radiate in CO_2 and H_2O bands but also emit blackbody radiation.

Conclusions

The radiation from five different liquid fuels burning in a trays was spectrally characterised using a modular FTIR spectrometer. The spectral characterisation of alcohol fires exhibit similarities in the IR region. The emission from burning alcohols, including methanol, has radiation in the CO_2 and H_2O bands but little blackbody radiation when placed in contrast against open fires from hydrocarbon fuels. It is believed that triple-band IR flame detectors successfully tested on alcohols other than methanol are suitable to detect methanol fires.

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Safety - Fire Research, Fire Dynamics

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[1] Försth M. and Roos A., Absorptivity and its dependence on heat source temperature and degree of thermal breakdown, Fire and Materials, **35:** 285-301, (2011).
[2] Försth M., and Möller K., Enhanced absorption of fire induced heat radiation in liquid droplets, Fire Safety Journal **55**:182–196, (2013).

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Part of the proFLASH research project

Methanol flame detection tests

1 Background

The stricter regulations for Sulphur content in bunker fuel have stimulated use of alternative fuels such as LNG and methanol, which differ from traditional bunker fuels in many ways. One important difference is their low flashpoint, which increases the probability of ignition in case of leakage. There are also other differences which increase fire risks, not least properties which affect the possibilities for fire detection and extinguishment. Methanol flames can for example be invisible and oxygen is bound to the molecule. LNG has a very low boiling point and is difficult to extinguish with water.

The purpose of the proFLASH project was to increase knowledge and to influence regulations regarding fire detection and fire extinguishment of low-flashpoint fuels, in particular LNG and methanol. The project consisted of a preliminary study and large-scale fire test phase, evaluating the suitability of relevant detection and extinguishing system solutions. It was decided to focus the experimental part of the project on methanol.

This report documents one of the test series performed in the proFLASH project. It evaluated detection of methanol with different types of detectors and with different obstructions. Furthermore, flame detectors are typically tested against fire in n-heptane and methylated spirit (mainly ethanol), based on EN 54-10, 5.5 Fire sensitivity. The test series therefore included comparison between detection of fire in those fuels and methanol.

2 Experimental setup and procedure

Ten different flame detectors were provided by four different detection system suppliers: Consilium, Tyco, Dräger, and Autronica. IR-detectors were used in the tests since they are very common and used for most applications where hydrocarbon fires are expected. UV/IR and visual detectors were also included in the tests for comparison. The visual detector cannot detect invisible flames (methanol fire) and results are therefore only presented for detection of n-heptane and methylated spirit fires. The detectors tested are listed in Table 1.

The type of detection technology used in the detectors is indicated in Table 1 under *Sensors*, where IR3 means that detection is determined by analysis of signals at three different infrared wavelength bands, IR2 implies that two different infrared wavelength bands are analyzed, UV/IR means that detection is determined by analysis of signals at both ultraviolet and infrared wavelengths, and visual means that detection is determined from signals in the visual spectrum or close to the visual spectrum (wavelengths up to about 1.1 µm). The reason why flame detectors normally include several sensors sensitive to different wavelength bands is to avoid false alarms.

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Table 1. Detectors tested

Detector	*Sensor/s*	*Sensitivity setting (used/available)*	*Range (for used settings) for a 1 ft² n-Heptane pan fire (m), according to specification*
FlameVision FV411f	IR3	2/4	15
Salwico AC-IR-3Fq	IR3	3/3 “class 1”	27
Salwico EVC-IR	IR2	1/1 “class 1”	25
AutroFlame BG-21	IR2	2/2 “class 1”	25
AutroFlame X33AF	IR3	3/3 “very high”	81
AutroFlame X52AF	UV/IR	3/3 “high”	26
SharpEye 40/40I	IR3	2/4	30
Dräger Flame 2570	IR3	2/4	40
CD-F-300	Visual	1/1	60
CD-F-301	Visual	1/1	44

There can be many sources radiating light in the infrared, visual, and ultraviolet spectra, but a fire can in most situations be distinguished by comparing the radiation at different wavelengths. For hydrocarbon fires it is most common to detect the radiation emitted from production of carbon dioxide, in the narrow spectral band around 4.3 µm. Especially non-sooty fires such as a methanol fire will have the most significant radiation in the “carbon dioxide range”. Comparison to other wavelengths makes it easy (with the right setting) to distinguish that combustion is taking place. Sooty fires, such as a diesel fire, also produce carbon dioxide but in addition they emit a lot of blackbody radiation from the soot particles. This makes radiation from carbon dioxide relatively less significant in comparison and the soot particles also absorb some of the radiation from the carbon dioxide. In this case, the fire radiates in a larger spectrum and the radiation at different wavelengths can still be compared to identify a fire.

Most detectors have several different sensitivity settings and noted in Table 1 are the settings used in the tests (determined by the supplier). The numbers represent the used sensitivity setting out of the available sensitivity settings (a higher number implies a more sensitive setting), as well as a note on the standard range for a 1 ft² n-Heptane pan fire. Furthermore, detectors can have different alarm delay settings and filters such as “anti-flare”, which of course affect the response times of the detectors.

The test scenarios are presented in Table 2. The first four scenarios are related to EN54-10 chapter 5.5 Fire sensitivity. EN 54 is the European standard for approval of fire detection systems and part 10 deals with flame detectors. In chapter 5.5, the detectors are tested against both a sooty n-heptane fire and a non-sooty methylated spirit (mainly ethanol) fire. A methanol fire is characteristically different from fire in methylated spirit since the latter gives off clear yellow flames (but little/no smoke). The first four scenarios were therefore set up to compare detection of methanol and diluted methanol with detection of the fuels used in the test standard. It was thereby evaluated whether methanol and diluted methanol could be detected by the detectors approved in accordance with EN54-10. The diluted methanol was watered down by 50%.

Table 2. Test scenarios

Test name	*Distance (m)*	*Fuel*	*Comments*	*Fig.*
n-Hep (12)	12	n-Heptane		2
Eth (12)	12	Methylated spirit	Ethanol 75-95%, isopropanol	2
Meth (12)	12	Methanol		2
D Meth (12)	12	Diluted methanol	50% methanol and 50% water	2
n-Hep (6)	6	n-Heptane		2
Eth (6)	6	Methylated spirit	Ethanol 75-95%, isopropanol	2
Meth (6)	6	Methanol		2
D Meth (6)	6	Diluted methanol	50% methanol and 50% water	2
Perf. sheet	6	Methanol	Perforated sheet in front of fire	3
Sheet 25	6	Methanol	25 cm steel sheet in front of fire	4
Sheet 50	6	Methanol	50 cm steel sheet in front of fire	5
Sheet 75	6	Methanol	75 cm steel sheet in front of fire	6
Sheet 100	6	Methanol	100 cm steel sheet in front of fire	7
Meth behind	2	Methanol	Fire positioned behind detectors	8
Meth behind, with reflector	2	Methanol	Large reflector in front of detectors (fire behind detectors)	8
Hot surf /Meth	6	Methanol	Hot surface (~400°C) in front of fire	9
Hot surf/ Sheet 75/Meth	6	Diluted methanol	Hot surface (~400°C) and 75 cm steel sheet in front of fire	10

The test setup was based on the specifications in EN54-10. However, instead of using a pre-burn time of at least 1 min, the tests were started directly upon ignition of the fire, which was thought to be a more realistic scenario. The installation height of the detectors also differed slightly from the specified 1.5 m in EN54-10, as seen in Figure 1. The fuel trays are specified in EN54-10 to be 0.33×0.33 m^2 for n-heptane and 0.5×0.5 m^2 for methylated spirit. The different burning areas of the different fuels generate approximately the same heat release rate. The larger tray was chosen for the methanol and diluted methanol fire scenarios and was used throughout the whole test series.

The shortest distance between the fire and the detectors is 12 meters according to EN54-10. The first four scenarios (with the four different fuels) were also repeated at a distance of 6 meters to the fire, which was thought to be a more realistic distance in a machinery space or pump room on a ship.

In addition to the tests based on EN54-10, a number of other test scenarios were performed with different types of obstructions and disturbing signals (e.g. hot surface). These tests are also listed in Table 2, with reference to illustrating figures below.

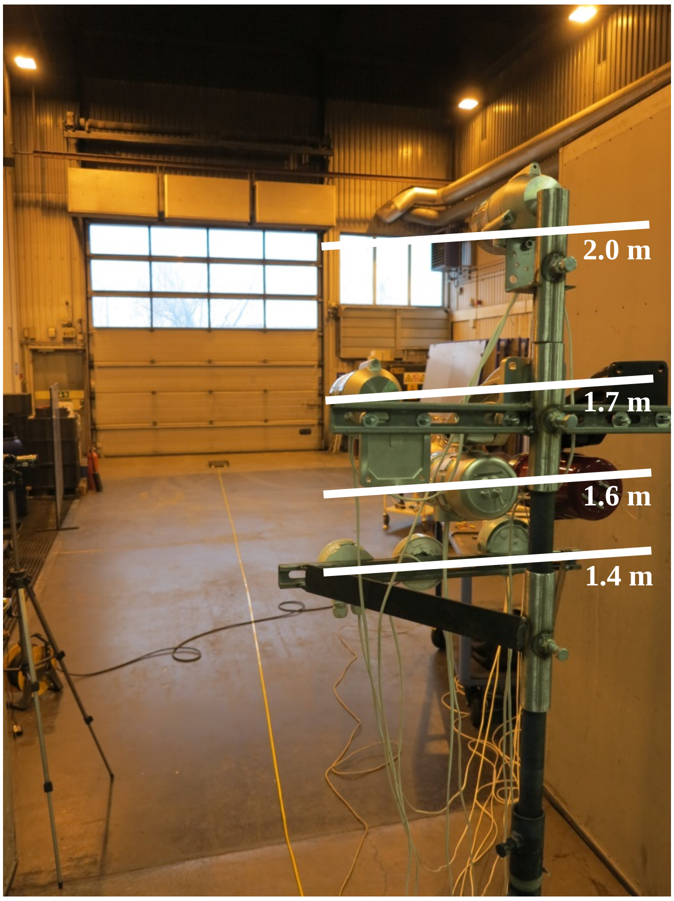

Figure 1. Detectors mounted at different heights; 7 detectors are seen in the photo directed towards the fuel tray at a distance of 12 m, 3 detectors were tested separately and were mounted at a height of 1.7 m.

Figure 2. From left to right: n-heptane, methylated spirit, methanol and diluted methanol (50% water).

Figure 3. Perforated sheet in front of methanol fire.

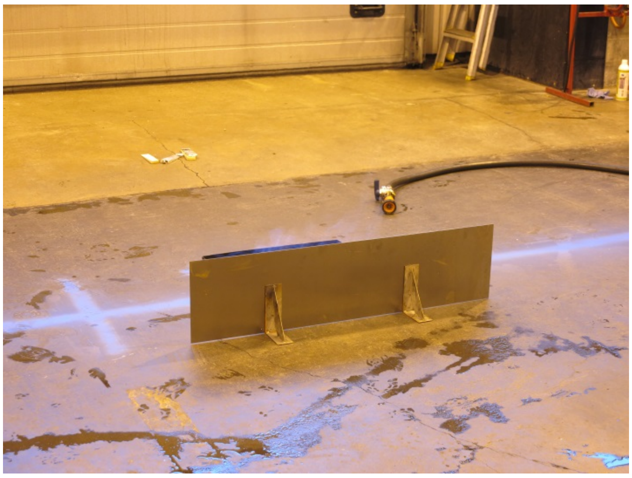

Figure 4. 25 cm steel sheet in front of fire.

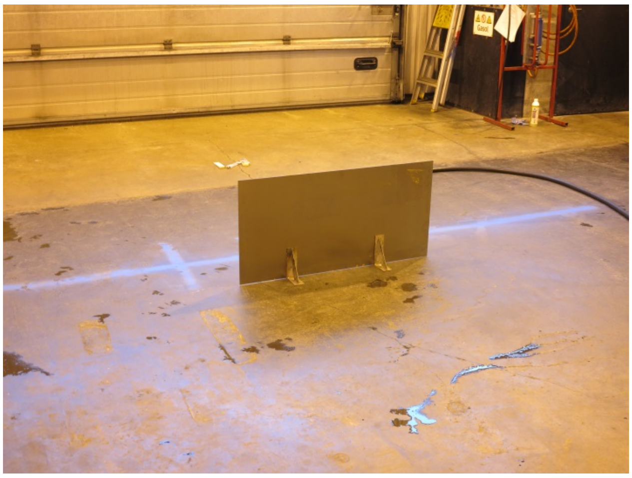

Figure 5. 50 cm steel sheet in front of fire.

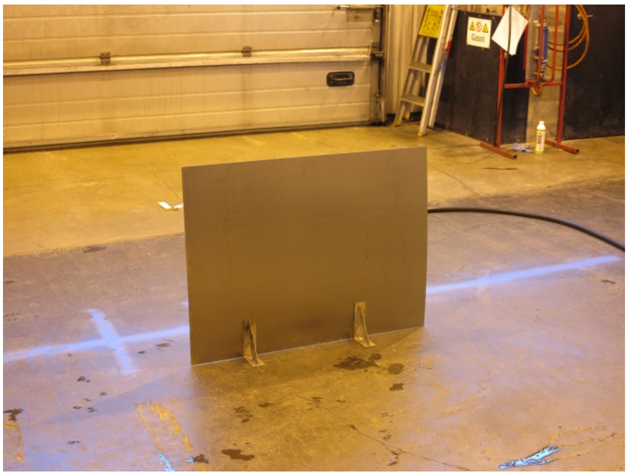

Figure 6. 75 cm steel sheet in front of fire.

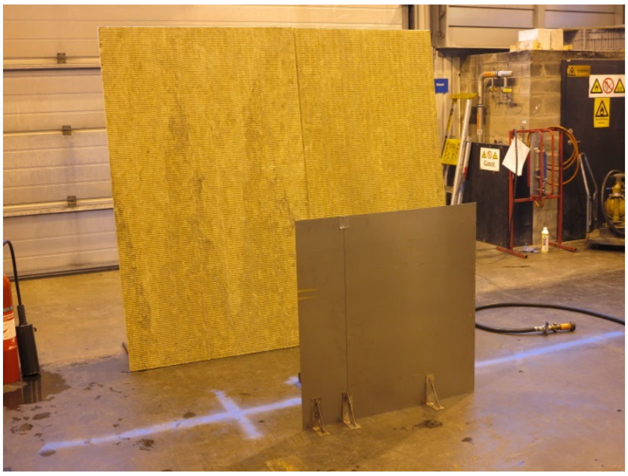

Figure 7. 100 cm steel sheet in front of fire. Insulation board positioned behind fire to reduce reflections.

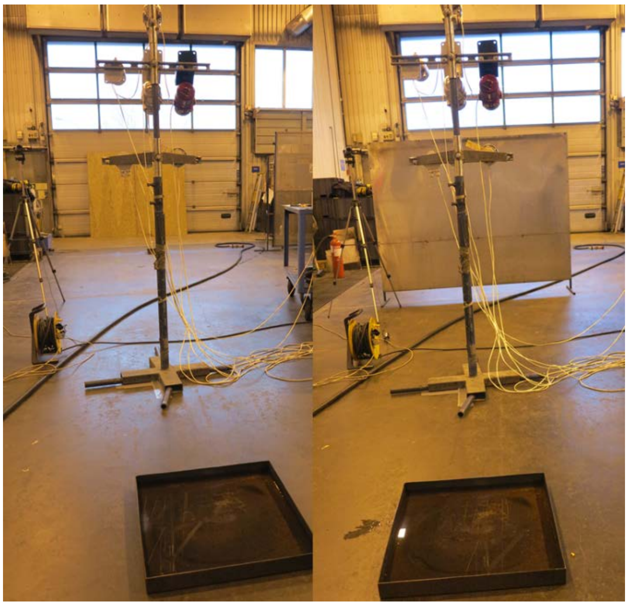

Figure 8. Fire positioned behind detectors, with (right) and without (left) large reflector in front of detectors.

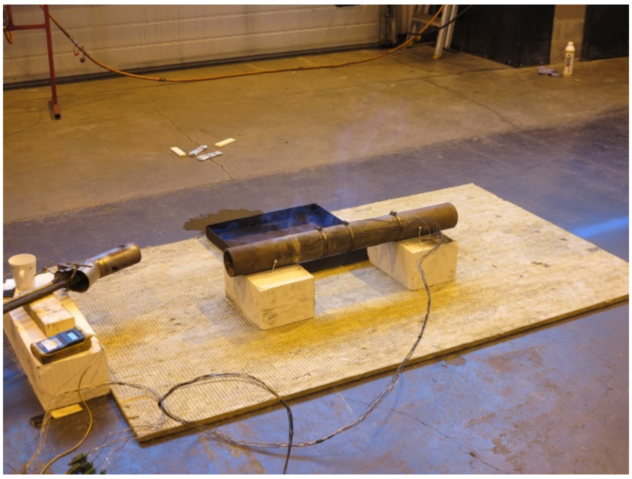

Figure 9. Hot surface in front of fire.

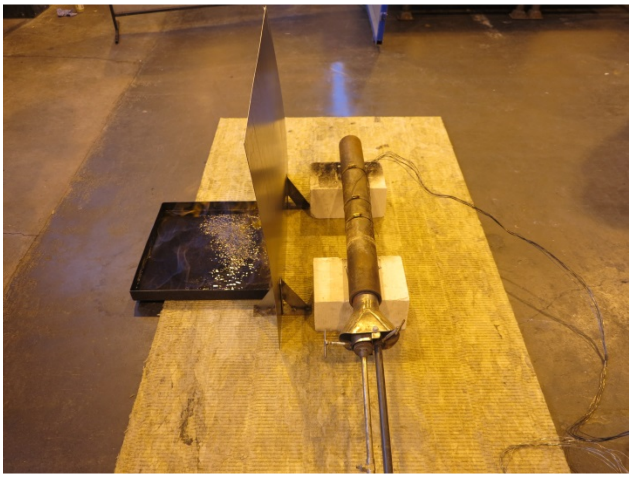

Figure 10. Hot surface and 75 cm steel sheet in front of fire.

3 Results

The response times of the detectors are presented in Table 3. The results are approximate, based on video recordings of the detector's alarm indicators. The detector called Dräger Flame 2570 often detected the fire in less than 1 s, but all results are rounded to full seconds. Some scenarios were repeated and the results in Table 3 then represent averages values. The UV/IR detector (X52AF) indicated alarm for the UV sensor in less than 1 s for most scenarios, except when the fire was obstructed. In the scenarios where this detector did not indicate an alarm, the reason was lack of detection by the UV sensor. The IR sensor detected fire in all scenarios.

Table 3. Detector response times for used sensitivity settings (Table 1), from ignition of the fires (s)

Detector / *Test*	*FV 411f*	*AC-IR -3Fq*	*EVC-IR*	*BG-21*	*X33 AF*	*X52 AF*	*40/40I*	*2570*	*CD-F-300*	*CD-F-301*
n-Hep (12)	4		3	8	2	6	4	1	5	9
Eth (12)	5		5	5	2	6	6	1	8	9
Meth (12)	5		4	4	2	4	4	1		
D Meth (12)	-		6	6	4	8	9	4		
n-Hep (6)	3		5	11	3	2	3	1	5	5
Eth (6)	3	7	4	4	3	4	4	1	8	
Meth (6)	3	8	4	4	1	4	2	1		
D Meth (6)		8	6	5	4	6	10	2		
Perforated sheet	4	7	4	5	1	5	4	1	5(H)	5(H)
Sheet 25	4	8	3	5	1	5	4	1	5(H)	5(H)
Sheet 50	4	6	6	4	3	7	5	1	5(H)	5(H)
Sheet 75	7	6	3	4	1	10	4	1	39(H)	38(H)
Sheet 100	15	6	4	4	2	-	4	1	-(H)	-(H)
Meth behind	-	32	12	12	3	-	19	1		
Meth behind with reflector	4	5	6	5	1	8	3	1		
Hot surf /Meth	3	6	5	6	2	6	4	1	5(H)	5(H)
Hot surf/ Sheet 75/Meth	-	93	39	53	7	-	43	15	40(H)	47(H)

Empty space indicates that the detector was not tested.
- The detector did not initiate an alarm.
H n-heptane was used instead of methanol (for the visual flame detectors).

4 Discussions

There were very small differences in detection times for the detectors tested, when considering that the detectors can be configured with different delay settings, filters, and sensitivity settings. The largest differences can be seen for the highest obstructions and when the fire was located behind the detectors. In these scenarios, very little radiation from the fire reached the sensors and the sensitivity settings are quite crucial. However, there is always a balance between sensitivity and risk of false alarms. In addition to the tests listed above, it was noted that none of the detectors indicated (false) alarm for the hot surface set-up, unless modulations were generated. With modulations, generated randomly by waving with solid objects in front of the detectors, some of the detectors indicated an alarm.

No significant differences were noted between detection of methanol and detection of other fuels. Slightly longer response times were recorded for diluted methanol. It is possible that such effects on the response time could be relevant also for other fuels (e.g. methylated spirit), since dilution affects the magnitude of radiation.

It was also noted that higher background radiation (hot surface in combination with fire) did not affect the response times when the fire was unobstructed. However, for an obstructed fire and high background radiation, the response times are much longer (less radiation from the fire, in comparison to background radiation, reaches the detector).

5 Conclusions

The most important conclusions from this test series relating to methanol installations on ships are summarized below:

1. A methanol fire is typically easily detected by IR flame detectors.
2. There is no difference in response time when comparing detection of methanol fire to n-heptane fire with suitable detectors at short distances.
3. Approval according to EN54-10, where n-Heptane and methylated spirit is used for test fires, does not ensure suitability for detection of a methanol fire (e.g. visual flame detectors).
4. IR flame detectors can detect completely obstructed fires due to reflections from the fire, if it is located in a room with metal surfaces (typically the case in a machinery space on a ship).

Hot surfaces may generate false alarms for some detectors if the heat radiation is modulated, e.g. due to someone moving or working in between the detector and the hot surface (also depends on the detector sensitivity setting).

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