TRANSPORT AND SAFETY
SAFETY

Safety distances for fires from leaking LPG hoses

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Abstract

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The radiant heat flux from 3 leakage scenarios of liquefied petroleum gas (LPG) was studied to determine safety distances when refilling LPG tanks from tank trucks. The three scenarios were 2 different leakage areas from a pipe and leakage from a textile reinforced rubber hose. Steady state tests with 5 minutes of burn time were performed as well as tests with 1 minute of burn time after which the emergency stop was activated. Measurements with water cooled heat flux meters and plate thermometers were used to determine heat flux levels. Measurements were designed to determine distances to heat fluxes of 12.5, 15 and 40 kW/m². Heat fluxes were measured both parallel and perpendicular to the flames at the same height as the leakage and 1 meter above the leakage.

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Content

Summary

This study was commissioned and financed by The Swedish Civil Contingencies Agency (MSB). The tests were performed in collaboration with Energigas Sverige, which provided equipment and liquified petroleum gas, and with south Älvsborgs rescue service association (SÄRF) which provided the testing site and supported in safety of the project.

Heat fluxs from burning liquified petroleum gas (LPG) leaking from hoses and pipes are measured via different leakage scenarios to provide data for safety distances when loading LPG from tanker to cistern. Three scenarios are divided into big and small leakages from a pipe and a large leakage from a textile reinforced rubber hose. One scenario with stationary conditions is tested for all three cases plus one scenario where the emergency stop is activated after one minute for the large leakage and for the textile reinforced rubber hose. The heat flux is measured with water cooled heat flux meters and with plate thermometers (PT) elements. The measurements are performed in the direction of, and perpendicular to, the leakage on distances adjusted to capture heat flux of 12.5 kW/m². The measurements are taken both level with (0.85 m)- and one meter above (1.85 m) the leakage. In addition to heat flux meters, thermal cameras and image processing were used to calculate the height and width of the flames. The results for heat fluxes at 12.5 kW/m² and the flame length are shown in Table 1. Distances to 15 and 40 kW/m² can be found in the conclusion section of this report.

Table 1. Summary of results showing distances from leakage for heat flux levels of 12.5 kW/m² and the flame size. Direction A is parallel to the flame, in line with the leakage.

	Test piece Nr 1 Pipe, large leakage	Test piece Nr 2 Hose, large leakage	Test piece Nr 3 Pipe, small leakage
Heat flux for stationary leakage: 12.5 kW/m²			
A-direction. Height: In level with leakage	6 meters	8 meters	<2 meter
A- direction. Height: 1 meter above leakage	7 meters	9 meters*	<2 meter
Flame size during stationary leakage			
Length	Mean: 3.72 meter Deviation: 0.18 meter	Mean: 5.58 meter Deviation: 0.19 meter	Mean: 1.61 meter Deviation: 0.13 meter
Height	Mean: 3.67 meter Deviation: 0.13 meter	Mean: 3.79 meter Deviation: 0.08 meter	Mean: 1.21 meter Deviation: 0.14 meter

* Calculated conservative for conditions between 0.85 and 1.85 meters with the assumption that $\dot{q}''_{inc} = Qr^{-\alpha}$ for large distances. Se section 5 for further details.

1 Background

The layout of cistern facilities for LPG is based on safety distances designed from various accidents. In Sweden, there exists a need to establish appropriate safety distances when unloading to cisterns in the event of fire from a leaking hose. As a basis, validated assessments of thermal impact from leaks are needed.

The purpose with this study is to measure the heat flux at different distances from a leakage. The simulated case is that between a tanker and cistern where the operator aborts the unloading with an emergency stop after 60 seconds and a case where the emergency stop is not used, i.e. steady-state conditions. Three leakage scenarios were tested, 2 on a two-inch steel pipe (one with a large slit formed hole and one with a small hole) and one leakage from a textile reinforced rubber hose with of 6 small holes. The different leakage scenarios are listed, together with the test matrix, for a total of 5 tests in Table 2.

Table 2. Test matrix

	Test piece nr 1: Steel pipe 2" with (sawn) slits 1.2 x 28 mm around the perimeter Total area: 34 mm^2.	Test piece nr 2: Reinforced rubber hose 2", with six holes à 2.5 mm in diameter. Total area: 29 mm^2.	Test piece nr 3: Steel pipe 3", with hole of 1.5 mm in diameter. Total area: 1.8 mm^2.
Steady-state conditions (ca 5 minutes)	Test 1	Test 3	Test 5
60 seconds to activated emergency stop, after which the flames burn out	Test 2	Test 4	

2 Equipment and measurements

The main purpose of this study was to measure heat flux at different distances from the leakage. The heat flux was measured using water cooled heat flux meters and special made plate thermometers (PT). In addition to heat flux, the pressure and temperature in the pipes were measured. The tests were performed Wednesday the 4 of September 2019 at Guttasjöns fire drill site in collaboration with SÄRF. The weather during the tests were, for the most part, windless and rain free.

2.1 Heat flux

Incoming heat flux contributes to an increase in temperature on objects close to the flame and can cause combustion if the heat flux is high enough. If the object is within the flame, convective heat transfer is a strong contributor to heating and flammable material is easily ignited. Outside the flame convective heat transfer is instead cooling the object a moderate amount. To determine a suitable safety distance, the incoming heat flux is measured using heat flux meters and PT elements.

2.1.1 Heat flux meters

Three heat flux meters of model Medtherm 64-2, calibrated for heat fluxes between 0-20 kW/m², were used to measure both the total heat flux on a cooled surface and to validate the calculated heat flux on the PT elements. The cooled surface results in a minimal convective cooling and that the heat flux meter, in theory, only measure the incoming heat flux if kept outside the flame. Medtherm 64-2 is a water-cooled heat flux meter which has a blackbody painted measuring spot with a high emissivity.

The circulating cooling water for the heat flux meters was kept at 25 °C ±0.1 °C with a Julabo F25 circulating cooling unit.

2.1.2 Special manufactured plate thermometers

The PT elements consists of a larger plate that reacts to both heat flux and the convective heat transfer. PT elements are more robust than heat flux meters and have in an earlier test[1] been used to calculate the incoming heat flux on the surface. The PT elements for this test consist of a 5 mm thick steel frame with dimensions of 100 x 100 x 30 mm. The exposed surface consists of a 0.4 mm thick Inconel 600 sheet which is welded on the steel frame. The Inconel sheet is painted with a high emissivity, LabIR-paint: HERP-HT-MWIR-BK-11. The paint has a high temperature resistivity and tabulated values for the emissivity as a function of temperature. On the backside of the Inconel sheet a type K thermocouple is welded and covered with a 30 mm thick ceramic insulation, which is shown in Figure 1.

[1] For example on earlier use of these PT elements se J. Sjöström et al (2015), Thermal exposure from large scale ethanol fuel pool fires, Fire Safety Journal, vol. 78, pp 229-237

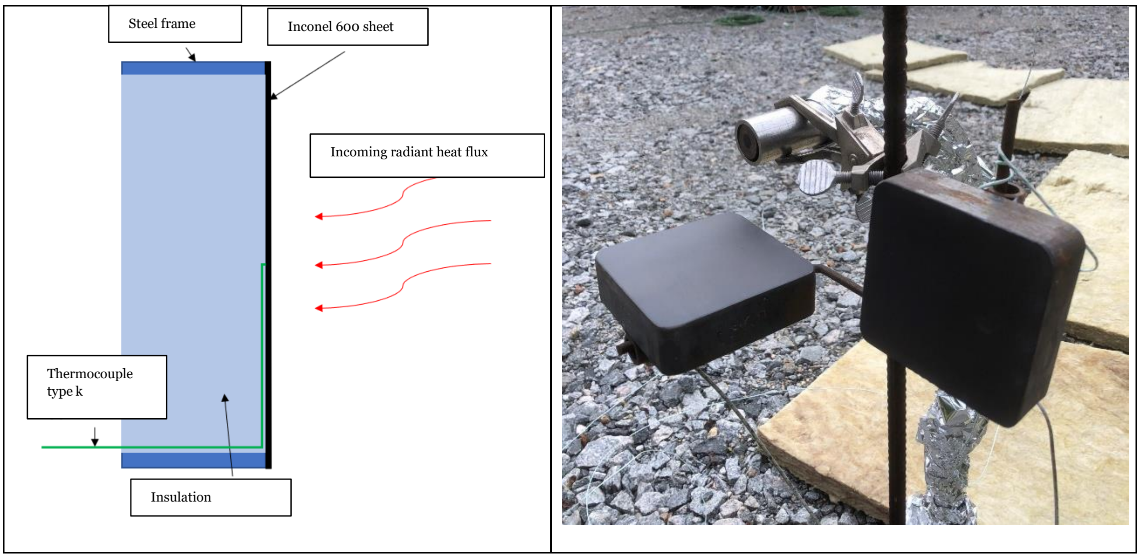

Figure 1. Special manufactured plate thermocouple

Temperature measurement with PT element is well documented as the basis for calculation of incoming heat flux in the normal direction of the surface with the relationship[2]:

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

Where h is the convective heat transfer coefficient between the exposed surface and air. T_{PT} and T_{amb} is the PT-element and the surrounding air temperature, ε_{PT} is the exposed surface emissivity and σ is Stefan-Boltzmann´s constant. K_{PT} and C_{PT} are correlation constants for heat loss and heat transfer in the PT element. K_{PT} and C_{PT} are chosen so that the calculated incoming heat flux (q''_{inc}) curve match the measure heat flux using the water-cooled heat flux meters. For these PT elements, K_{PT} = 5 W/m²K and C_{PT} = 2800 J/m²K. With these constants the calculated heat flux is close to the measured heat flux for all PT elements used for this test.

2.2 Pressure and temperature

Measurement of pressure are done with a DMU 03 device and temperature is measured with a PT-100 supplied by Energigas Sverige. Temperature and pressure were measured inside the pipe between the leakage and tanker 5 meters before the leakage.

2.3 Pipe, hose and leakage

Three different leakage scenarios were to be simulated where each one imitates a certain type of damage. The first is damage on a pipe, the second is leakage by the flanges and the third is leakage from a hose. The chosen scenarios were designed and determined by MSB and Energigas Sverige. All three leakages were in an outward radial direction with flowing LNG in both a liquid and gas phase.

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[2] For description of concept, se H. Ingason & U. Wickström (2007), Measuring incident radiant heat flux using the plate thermometer, Fire Safety Journal, vol. 42, pp 161-166.

Outside the leakage the liquid phase will quickly evaporate, and the jet consists of a liquid-gas mixture. The test was performed with a nominal pressure of 8 bar in the feeding tanker plus a differential pressure of ca 2 bar to be able to load to a secondary cistern.

2.3.1 Test piece 1

Test piece 1 was a 1.5-meter-long steel pipe with a diameter of 60.3 mm and a thickness of 2 mm. The hole was 1.2 mm wide and 28 mm around the circumference which equals an area of 34 mm², the hole is shown in Figure 2. The piece 1 is used to imitate a big leakage due to damage pipe.

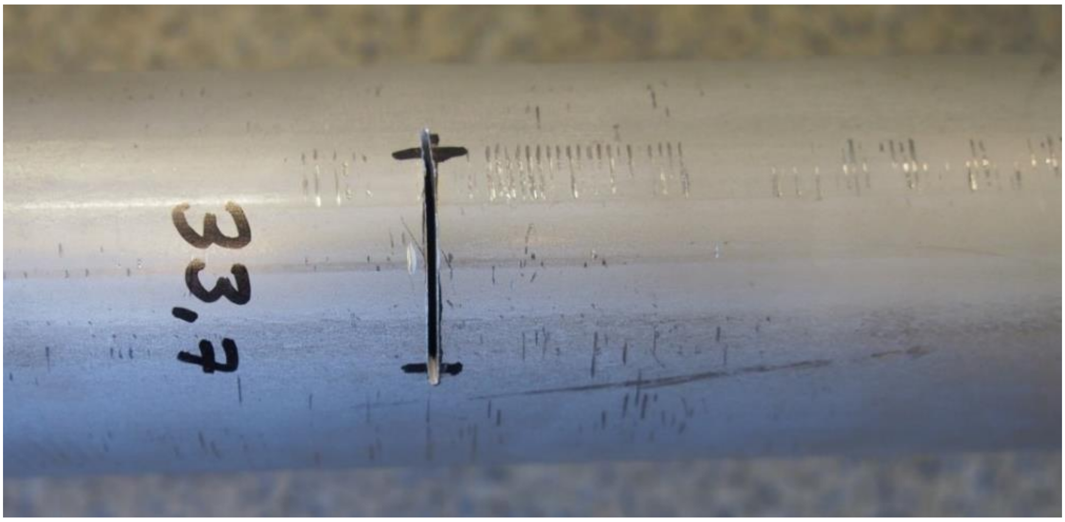

Figure 2. Test piece 1. Pipe with sawn slit

2.3.2 Test piece 2

Test piece 2 consists of a 1.5-meter-long textile reinforced hose. The hose has six 2.5 mm holes with a total area of 29 mm² shown in Figure 3.

Figure 3. Test piece 2. Textile reinforced hose.

2.3.3 Test piece 3

Test piece 3 consists of the same type of pipe as test piece 1 but with only one hole of an area of 1.77 mm² and designed to imitate a small leakage by the flanges. Test piece 3 is shown in Figure 4.

Figure 4. Test piece 3. Pipe with a drilled hole.

3 Test setup

All equipment related to the LPG was supplied, mounted and maintained by Energigas Sverige. The instrumentation was setup to measure the incoming heat flux parallel and perpendicular towards the flame. The distance from ground to leakage was 0.85 meters shown in Figure 5. The heat flux was measured perpendicular towards the flame on distances A1, A2, A3 and A4. In position A1, A2 and A3 the incoming heat flux was measured using both heat flux meters and PT element. At 0.85 meter the PT elements were oriented vertical and horizontal towards the flame and at 1.85 meters the PT was oriented only vertical towards the flame. Position B1 and B2 have 2 PTs, both vertical towards the flame. The heights are1.1 and 1.85 meters for B1 and 0.85 and 1.85 meters for B2. The entire test setup is shown graphically in Figure 5 and the distances are tabulated in Table 3.

Each test is filmed with a video camera as well as with an IR camera.

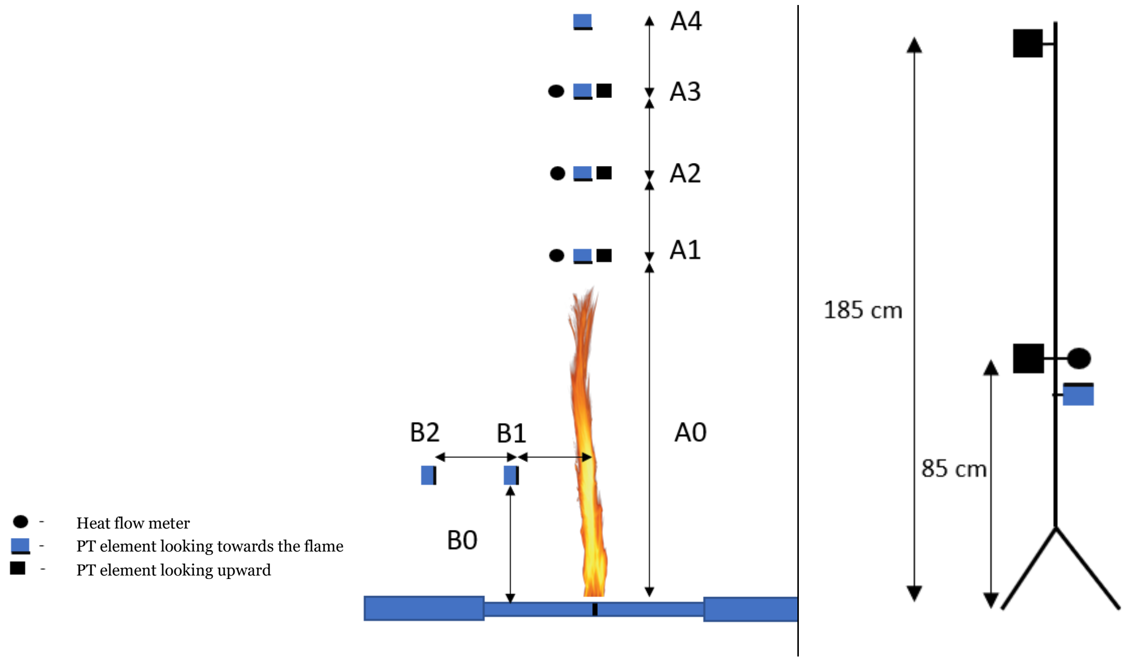

Figure 5. Instrumentation schematics. Left: Test setup seen from above. Right: Instrument in profile

Test 1,2,3 and 4 used the same distances in the test setup. For test 5, with a smaller leakage from a steel pipe, the measurement distances were reduced as the expected flame size was smaller. The distances were chosen so that the incoming heat flux are ~25 kW/m².

Table 3. Distances between measurement device and leakage for each test in meters.

	Test 1	Test 2	Test 3	Test 4	Test 5
A0	5	5	5	5	3.1
A1	5	5	5	5	3.1
A2	6	6	6	6	4
A3	7	7	7	7	5.3
A4	8	8	8	8	2
B0	3	3	3	3	2
B1	1.1	1.1	1.1	1.1	1.1
B2	2.2	2.2	2.2	2.2	2.2

4 Results

Results for the individual tests show the flame size and heat flux for each scenario. While all results are summarized in Table 4.

4.1 Test 1

Test 1 was a big leakage, from a pipe with a hole of 34 mm², which produced both a flame length and height of > 4 meters. Test 1 simulated steady-state conditions and had a total leakage time of 5 minutes. The operative pressure, i.e measured pressure in the pipe ca 5 meters from the leakage, was 8 bars with a maximal peak during ignition at 10 bar. The pipe temperature increased during the test from 11 °C to 17 °C which is shown in Figure 9. The characteristic flame for test 1 is shown, in RGB format, in Figure 6 and with thermal imaging in Figure 7. The flame height and length for the whole test is shown in Figure 8.

Figure 6. Characteristic flame for test 1

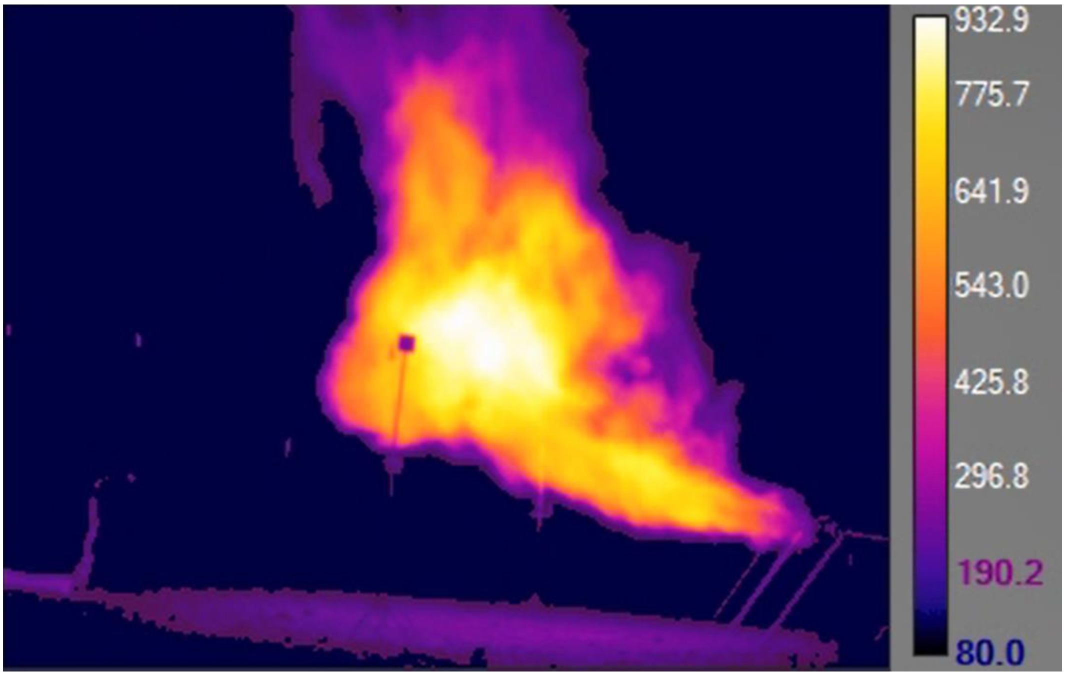

Figure 7. Thermal imaging for test 1. The scale to the right shows the flame temperature based on the incoming EM radiation to the IR-camera.

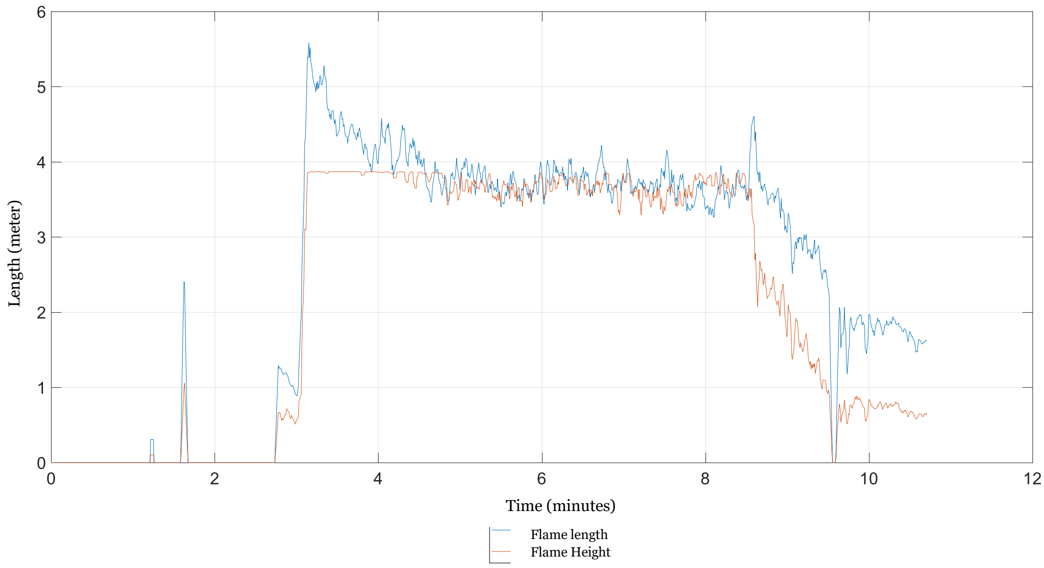

Figure 8. Flame length and height for test 1. The flame height is limited by the cameras field of view to 3.9 meter. The spikes in the beginning of the graph is leaking LPG that ignites before a continuous flame has formed.

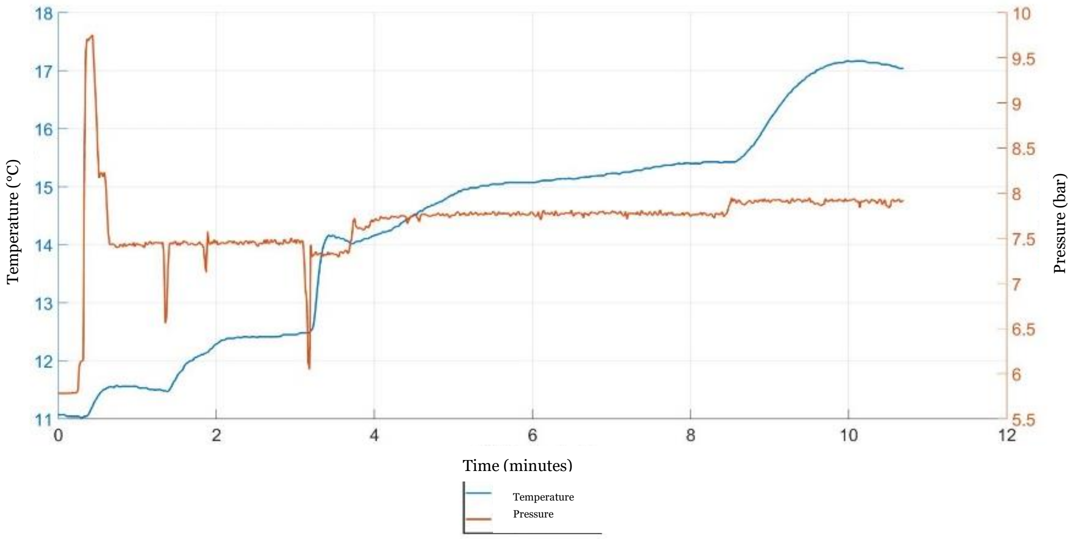

Figure 9. Pressure and temperature inside the pipe for test 1.

4.1.1 Test 1 Heat flux

The highest recorded heat flux during test 1 was at location A1, closest to the leakage. At the beginning of the test, when the pressure spiked at 9.5 bar, the heat flux reached 24 kW/m² but decreased to 20 kW/m² during steady-state conditions. The heat flux decreased to 20 kW/m² at 5 meters, 12 kW/m² at a distance of 6 meters and was below 10 kW/m² after 6.5 meters as shown in FIG.

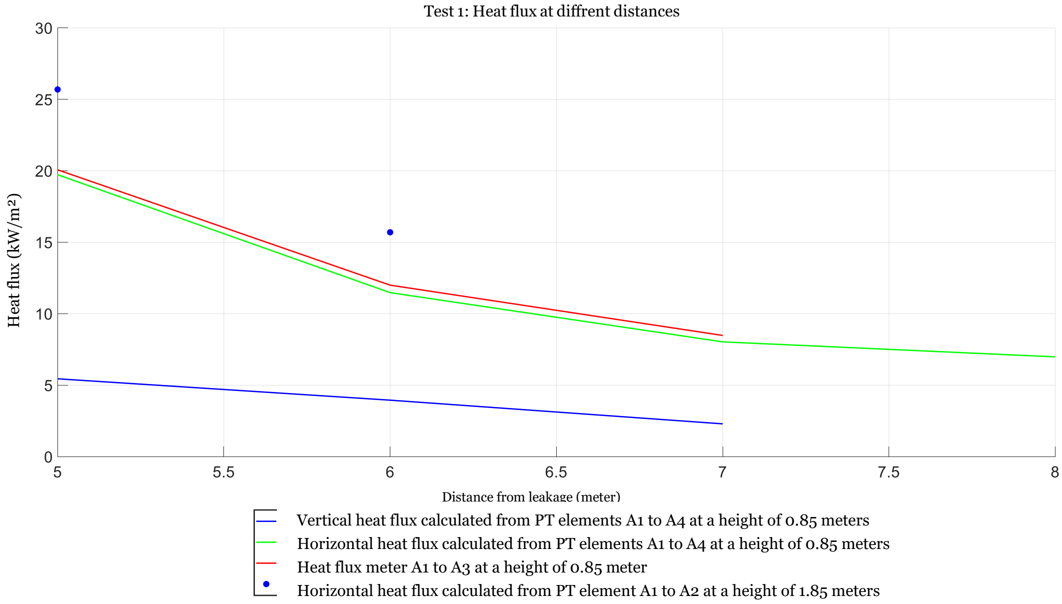

Figure 10. Test 1, heat flux at position A1 to A4 after 1.5 minutes of testing time. Distances are as follows: A1 = 5 meters, A2 = 5 meters, A3 = 7 meters and A8 = 8 meters

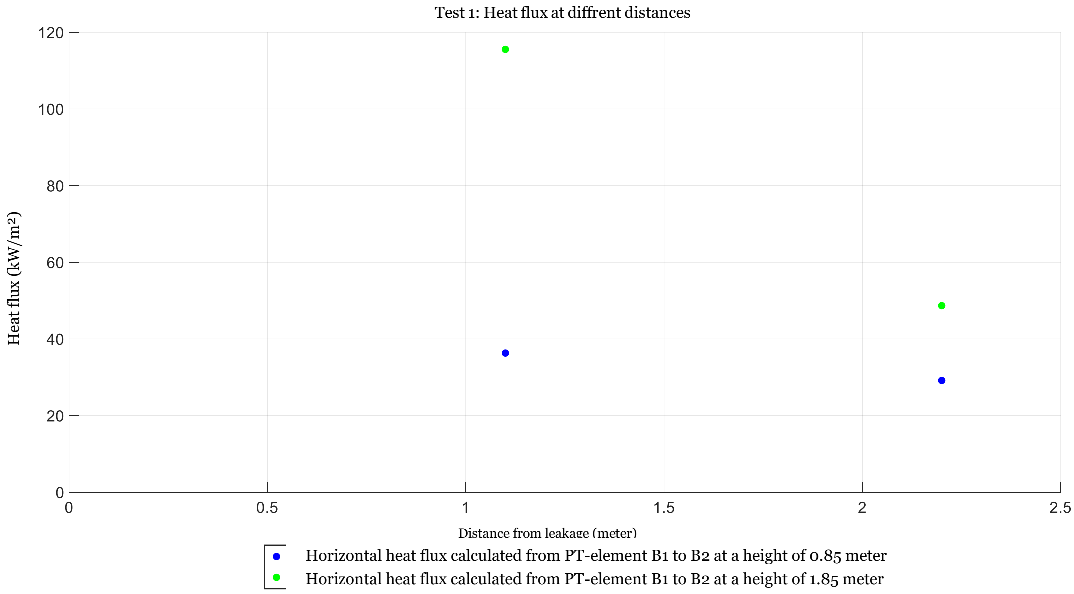

Figure 11. Test 1, heat flux at position B1 and B2 after 1.5 minutes. Distances are as follows: B1 = 1.1 meters and B2 = 2.2 meters.

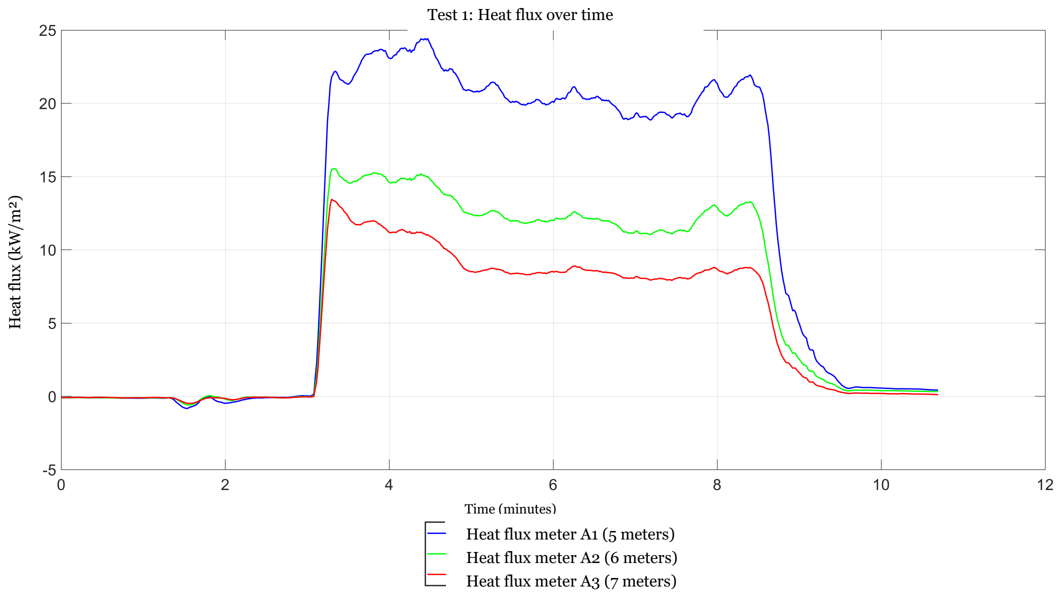

Figure 12. Test 1, measured heat flux levels with heat flux meters at position A1 - A3.

4.2 Test 2

Test 2 was, as test 1, a so-called big leakage using the same test piece as test 1 (with a hole of 34 mm²). Test 2 had a flame length and height of just above 4 meters before the emergency stop was activated after 60 seconds and the pressure decreased. After activating the emergency stop the flame size decreased until it eventually went out. This resulted in a total leakage time of 6 minutes. The operative pressure was around 8 bar until the emergency stop was activated after which the pressure decreased continuously down to 2 bar. The temperature of the pipe increased from 15 °C to 15.5 °C before the emergency stop was activated after which the lowest temperature was 7 °C. Pressure and temperature for test 2 is shown in Figure 16. The characteristic flame for test 2 is shown, in RGB format, in Figure 13 and with thermal imaging in Figure 14. The flame length and height for all of test 2 is shown in Figure 15.

Figure 13. Characteristic flame for test 2

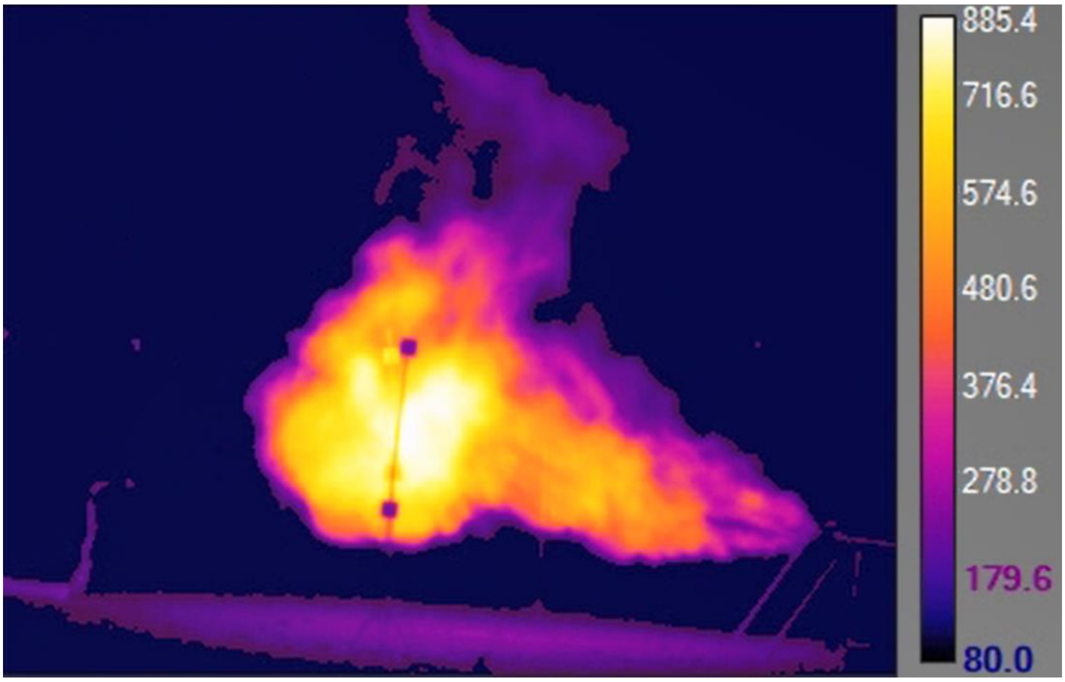

Figure 14. Thermal image for test 2. The scale to the right shows the flame temperature based on the incoming EM radiation to the IR-camera.

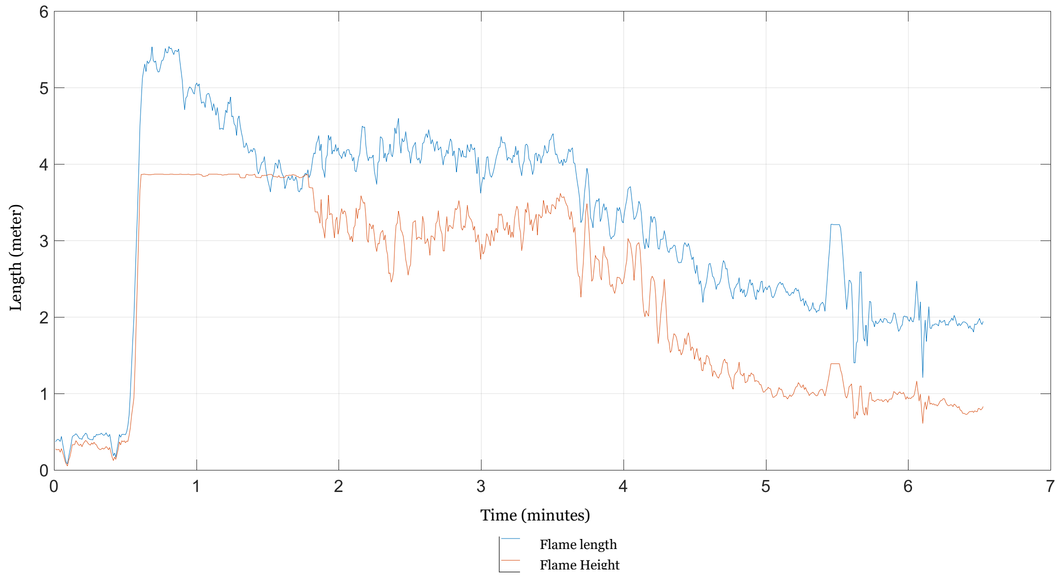

Figure 15. Flame length and height for test 2. Flame height is limited by the field of view of the camera to 3.9 meters. The emergency stop is activated after 1.85 minutes.

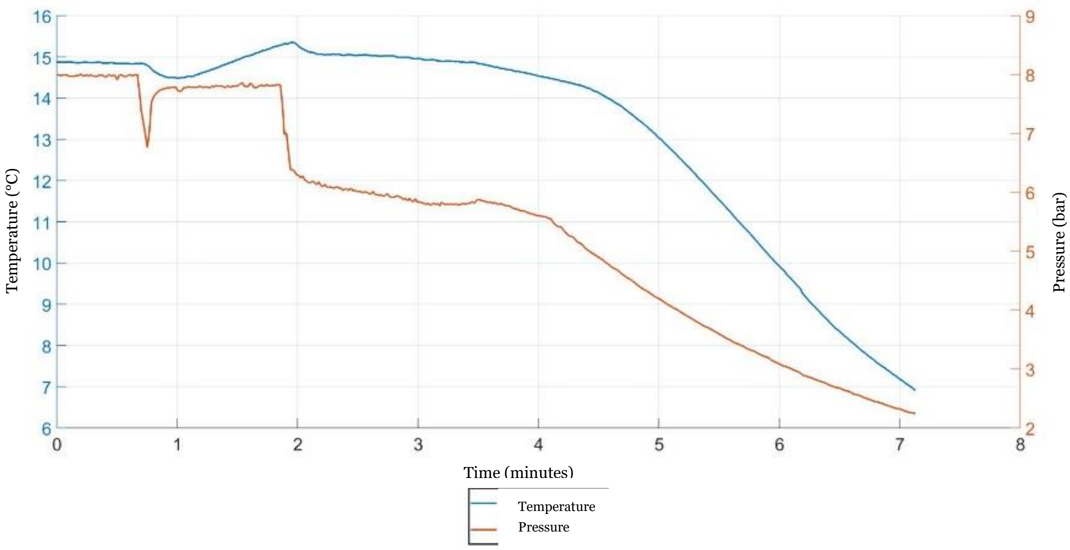

Figure 16. Pressure and temperature inside the pipe for test 2. Emergency stop activated after 1.85 minutes.

4.2.1 Test 2 heat flux

The highest heat flux during test 2 was at position A1 at 1.85 meters (except PT at position B1 at 1.85 meter which was engulfed in flames several times). The highest recorded heat flux was 50 kW/m² which is shown in Figure 17. The heat flux measurements at B positions were closer the leakage which is why the decrease in heat flow is not as significant as for position A, as shown in Figure 18. Heat flux over time, measured with heat flux metes, are shown in Figure 19.

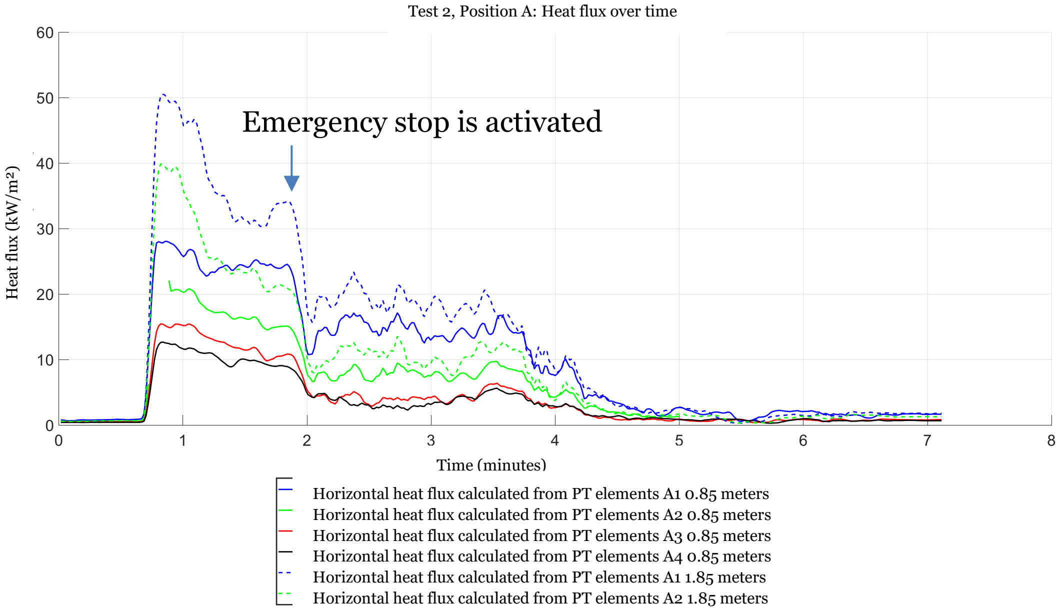

Figure 17. Test 2, heat flux calculated from all vertical PT in position A1-A4 (measures horizontal heat flux). Distances are as follows: A1 = 5 meters, A2 = 6 meters, A3 = 7 meters and A8 = 8 meters.

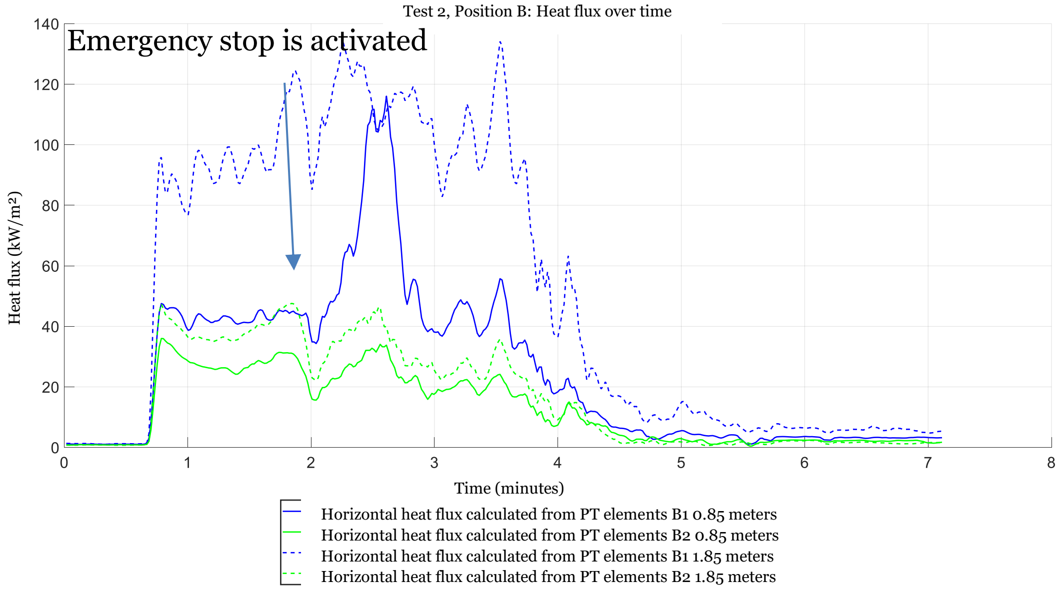

Figure 18. Test 2, heat flux for all vertical PT elements in position B1-B2 (measures horizontal heat flux). Distances are as follow: B1 = 1.1 meter and B2 = 2.2 meter.

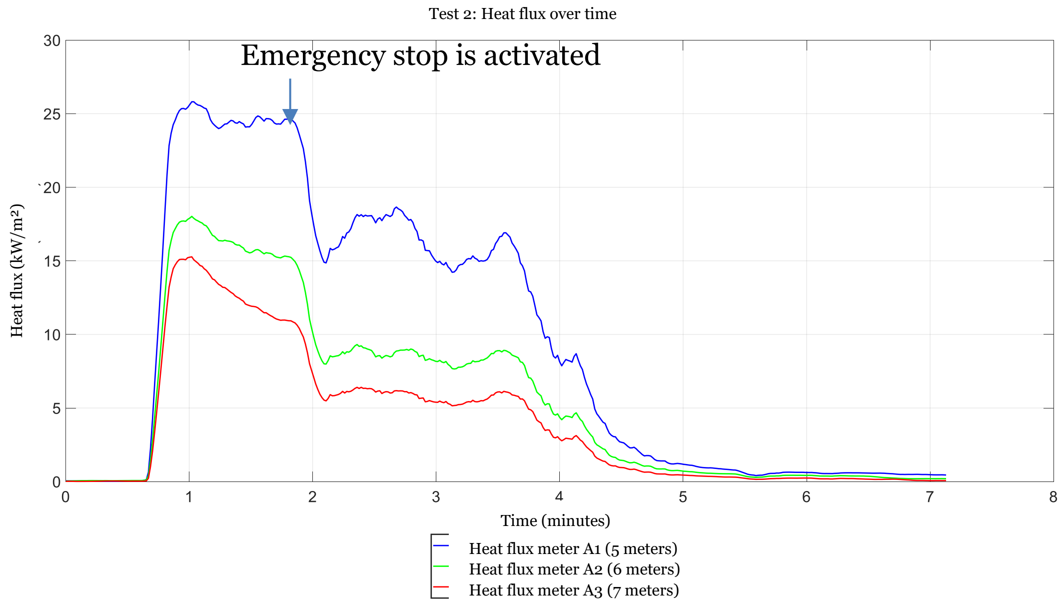

Figure 19. Test 2, measured heat flux levels with heat flux meters at position A1 - A3 at 0.85 meters height.

4.3 Test 3

Test 3 was a leakage from the textile armed rubber hose with 6 circular holes and a total area of 29 mm². The flame length was between 5.5 – 6 meters with a height above 4 meters. Test 3 was to reach steady-state conditions and had a total leakage time of 5 minutes. The operative pressure was at 8 bar, the temperature peaks at 21 °C and stabilizes at 16 °C, pressure and temperature for test 3 are shown in Figure 23. The characteristic flame, shown in RGB format in Figure 20 and from the thermal camera in Figure 21, was longer than for test 1 and 2 but with roughly the same height. This difference is also shown in the recorded heat flux. The flame height and length for test 3 is shown in Figure 22.

Figure 20. Characteristic flame for test 3.

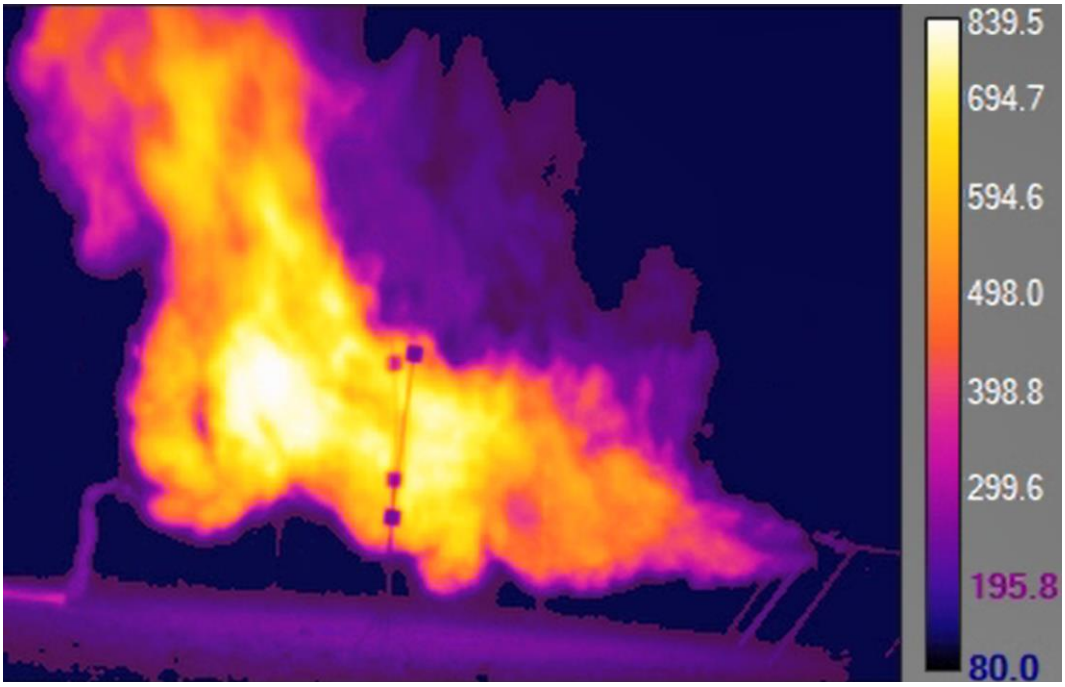

Figure 21. Thermal image for test 3. The scale to the right shows the flame temperature based on the incoming EM radiation to the IR-camera.

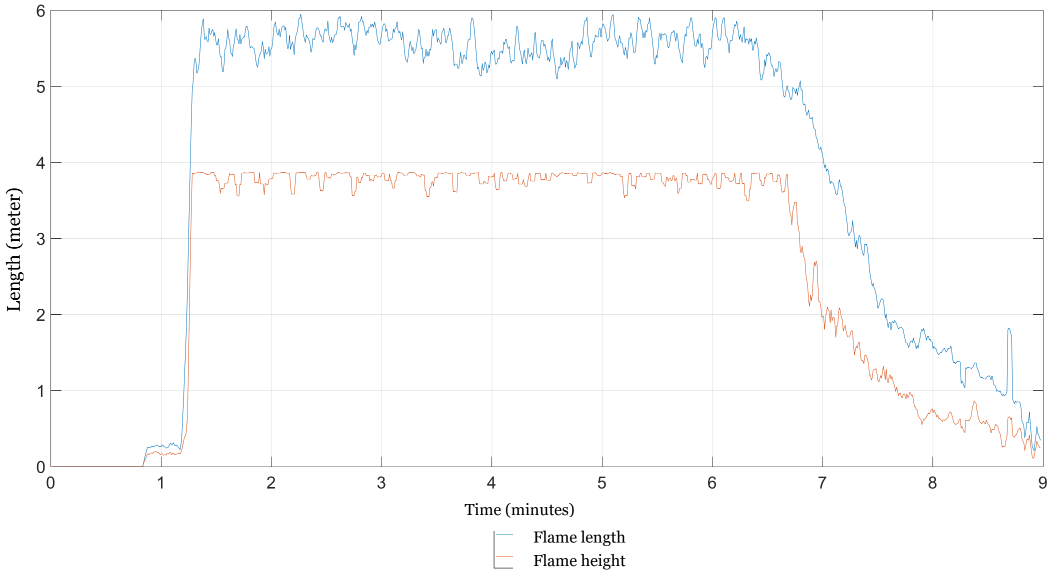

Figure 22. Flame length and height for test 3. The flame height is limited by the cameras field of view to 3.9 meters.

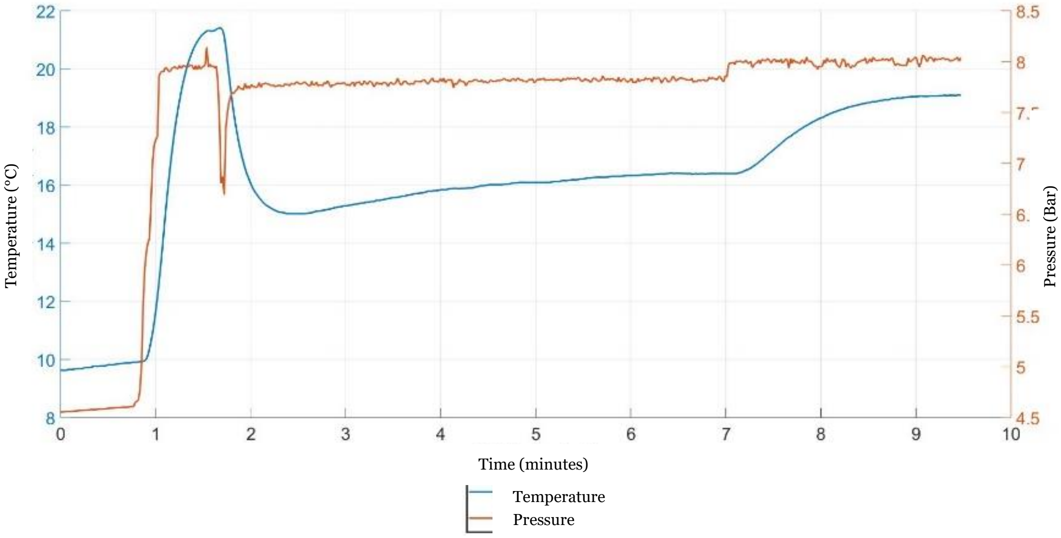

Figure 23. Pressure and temperature inside the pipe for test 3.

4.3.1 Test 3 heat flux

The highest heat flux during test 3 was 95 kW/m² at position B1 at 1.85 meters. The heat flux at position A1, closest to the leakage, at 1.85 meter during stationary conditions was 45 kW/m² with an increase to 60 kW/m² towards the end of the test. The incoming heat flux decreased from 45 kW/m° at 5 meters to 25 kW/m° at 6 meters and was just below 20 kW/m² after 6.5 meters which is shown in Figure 24. The calculated heat flux for PTs at B1 at 1.1 and 1.85 meter as well as B2 at 0.85 and 1.85 meter is shown in Figure 25. Heat flux levels measured with heat flux meters are shown in Figure 26.

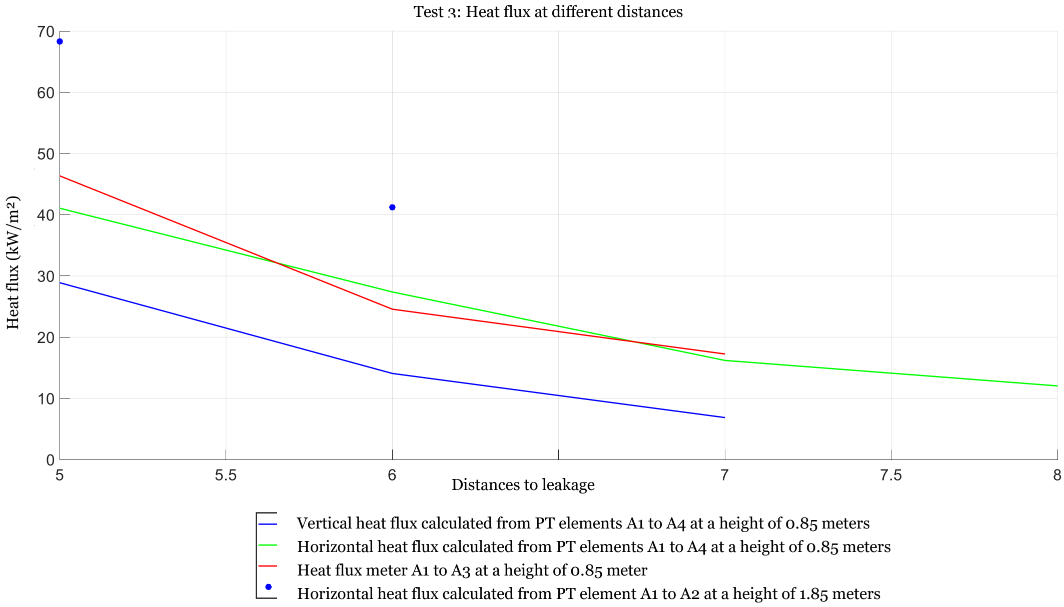

Figure 24. Test 3, Heat flux at position A1 to A4 after 2 minutes. Distances are as follows: A1 = 5 meters, A2 = 6 meters, A3 = 7 meters and A8 = 8 meters.

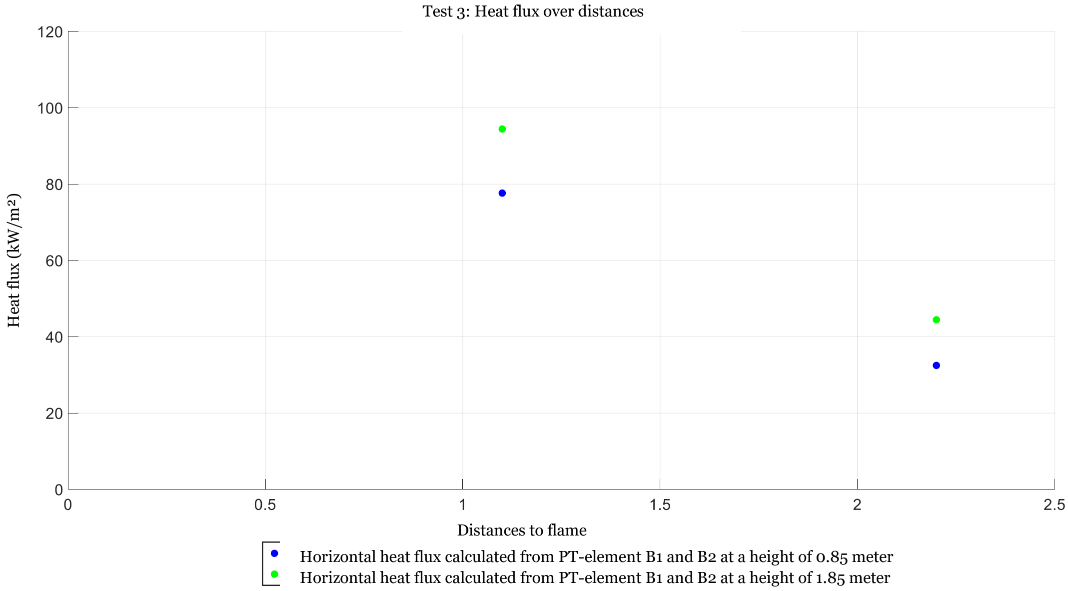

Figure 25. Test 3, heat flux at position B1 and B2 after 2 minutes. Distances are as follow: B1 = 1.1 meters and B2 = 2.2 meters.

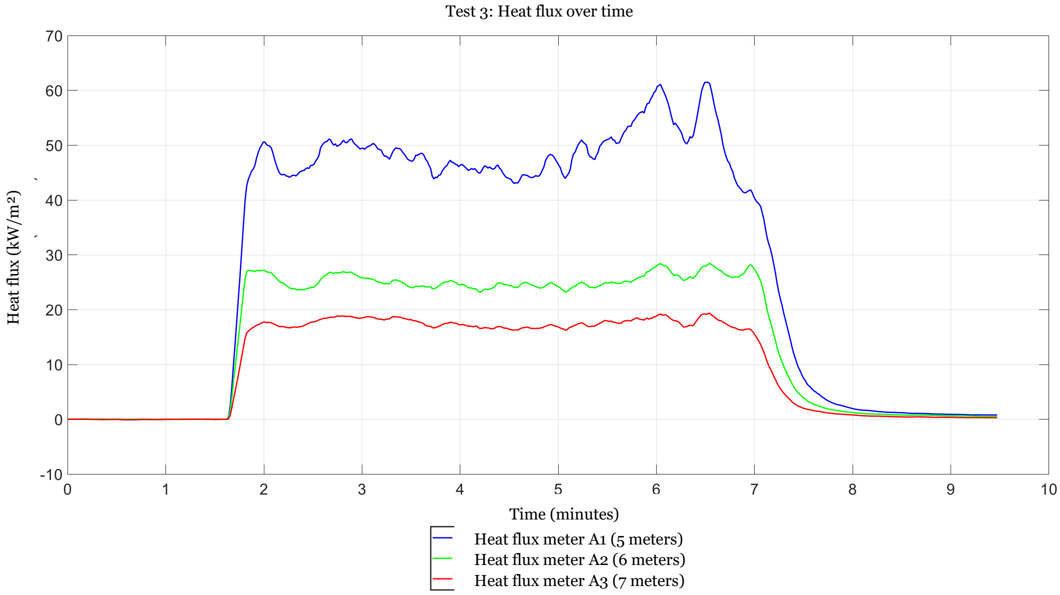

Figure 26. Test 3, measured heat flux with heat flux meter at position A1 - A3 at the height of 0.85 meter.

4.4 Test 4

Test 4 was a leakage from the same textile reinforced hose as in test 3, with 6 circular hole and a total area of 29 mm². The largest flame length was 5.5 – 6 meters with a flame height above 4 meters before the emergency stop was activated. Test 4 had a leakage time of 60 seconds before the emergency stop was activated after which the flame burned out. The operative pressure was 8 bar until activation of emergency stop after which the pressure decreased to 3 bar. The start temperature was 18 °C which decreased and stabilized at 16 °C before activation of the emergency stop and decreased to 9 °C after. Pressure and temperature for test 4 are shown in Figure 30. The characteristic flame for test 4 before activation of the emergency stop is shown, in RGB format, in Figure 27and thermal imaging in Figure 28. The flame length and height for test 4 is shown in Figure 29. The holes in the hose was unchanged after test 3 and 4.

Figure 27. Characteristic flame for test 4.

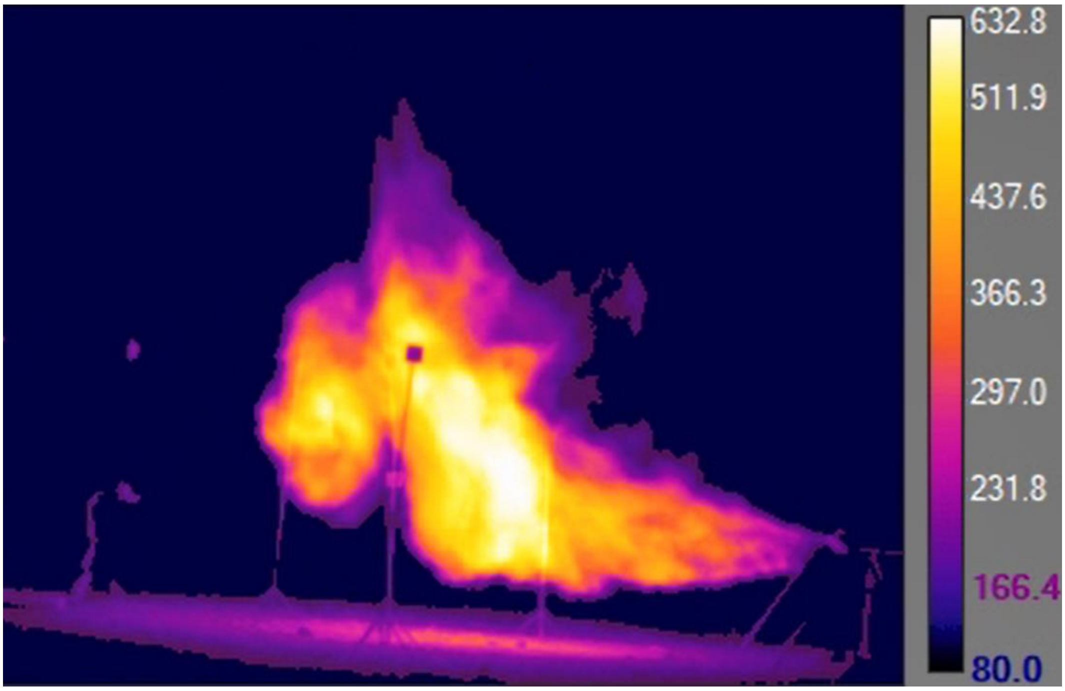

Figure 28. Thermal imaging for test 4. The scale to the right shows the flame temperature based on the incoming EM radiation to the IR-camera.

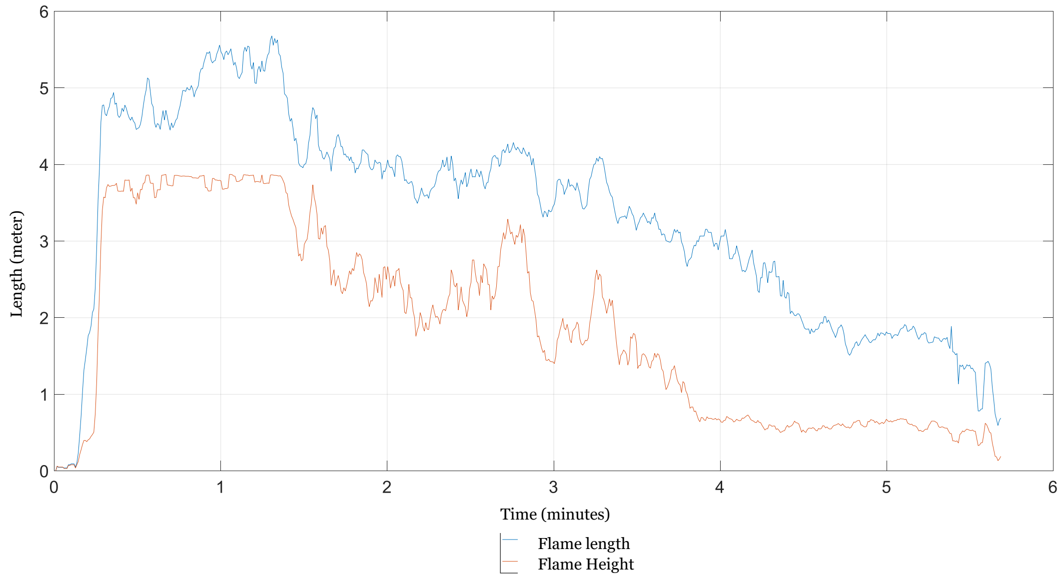

Figure 29. Flame length and height for test 4. The flame height is limited by the cameras field of view to 3.9 meter. The emergency stop is activated after 1.55 minutes.

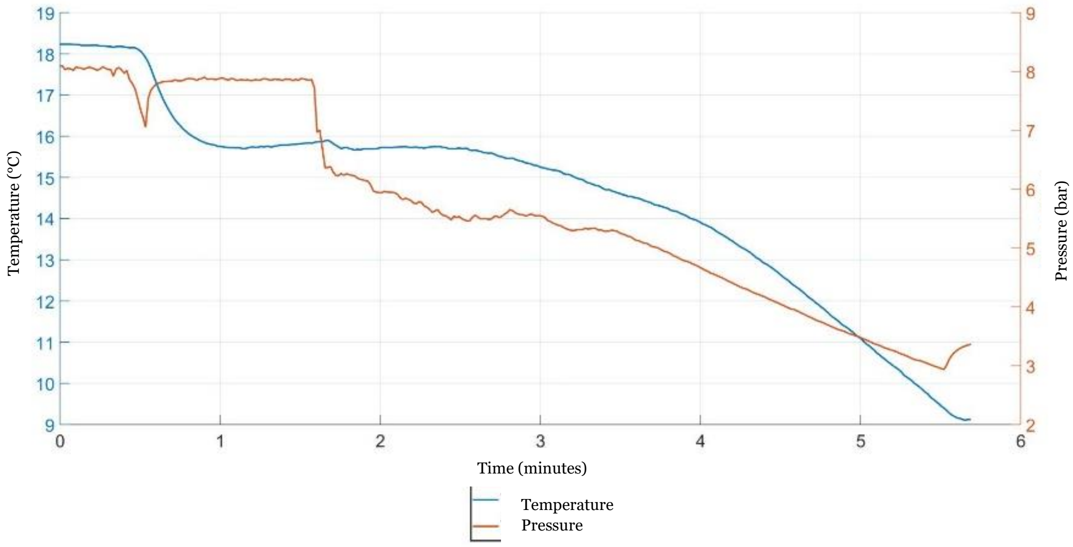

Figure 30. Pressure and temperature for test 4

4.4.1 Test 4 heat flux

The highest heat flux during test 4 was around 50 kW/m² at position A1 at a height of 1.85 meters. PT elements at position A1 and B1 recorded a higher temperature at a height of 1.85 meters but was within the flame several times. There was a significant decrease in heat flux at all locations when the emergency stop was activated. For example, at A1 at a height of 0.85 meters, the heat flux decreased form 40 kW/m² to 20 kW/m² the moment the emergency stop was activated which is shown in Figure 31. The decrease in heat flux at B positions, which were closer to the leakage, was not as significant as for position A but still noticeable, which is shown in Figure 32. Heat flux over time with heat flux meters are shown in Figure 33.

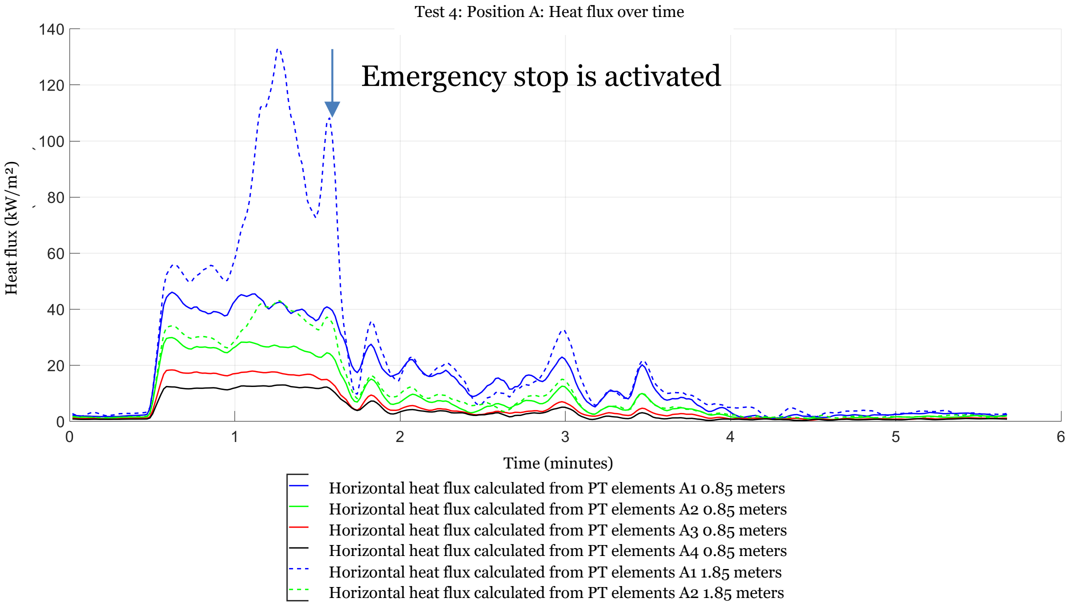

Figure 31. Test 4, heat fluxed calculated from all vertical (measuring horizontal heat flux) PT i position A1-A4. Distances is as follow: A1 = 5 meters, A2 = 6 meters, A3 = 7 meters and A8 = 8 meters.

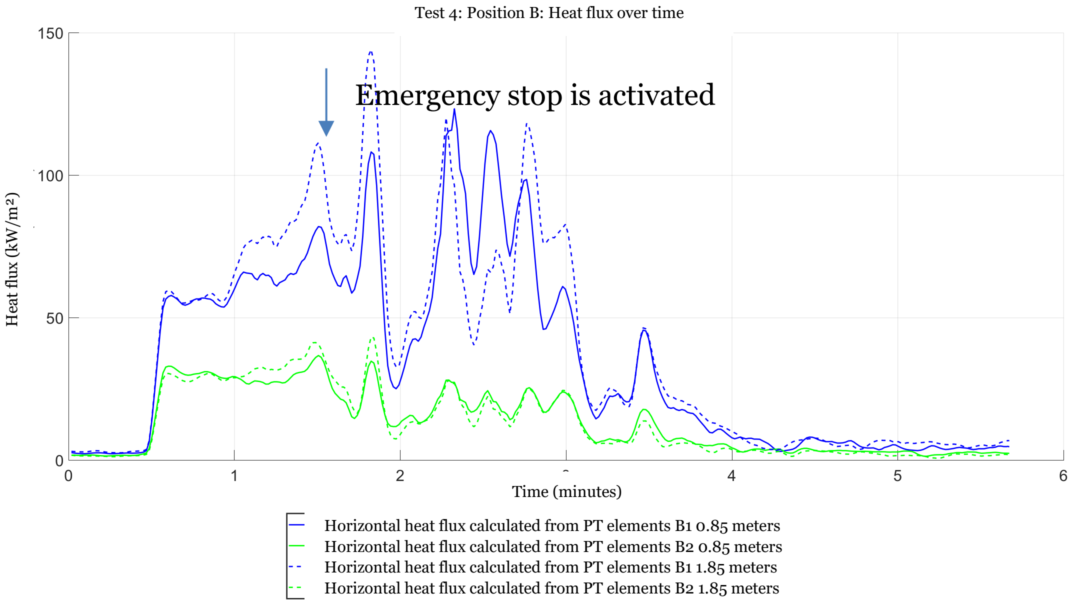

Figure 32. Test 4, heat flux calculated from all PT in position B1-B2. Distance is as follow: B1 - 1.1 meter, B2 - 2.2 meters.

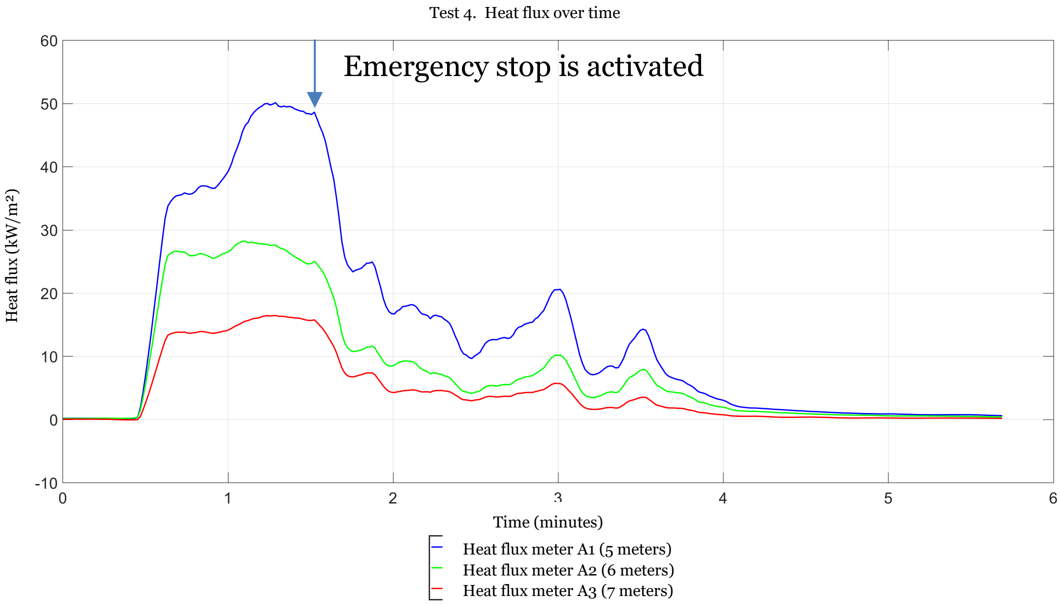

Figure 33. Test 4, measured heat flux with heat flux meter at position A1 - A3 at a height of 0.85 meters.

4.5 Test 5

Test 5 was a small leakage from a circular hole in a pipe with an area of 1.77 mm². The flame length was 1.75 meters and the flame height 1.25 meters. Test 5 simulated steady-state conditions and hade a total leakage time of over 5 minutes. The operative pressure was at 8 bars and the temperature spiked at 22 °C before stabilizing at 15 °C for 5 minutes, pressure and temperature for test 5 are shown in Figure 37. The characteristic flame, shown in RBG in Figure 34 and thermal imaging in Figure 35. The flame length and height are shown in Figure 36 and was smallest in test 5 compared to the other tests.

Figure 34. Characteristic flame for test 5.

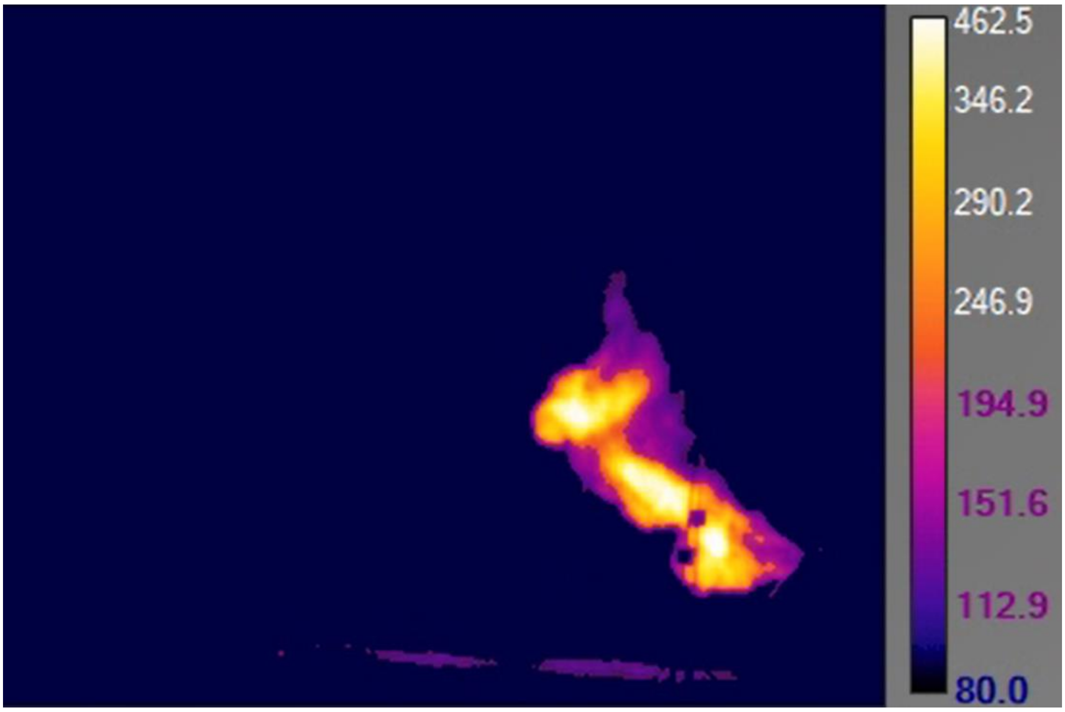

Figure 35. Thermal image for test 5.

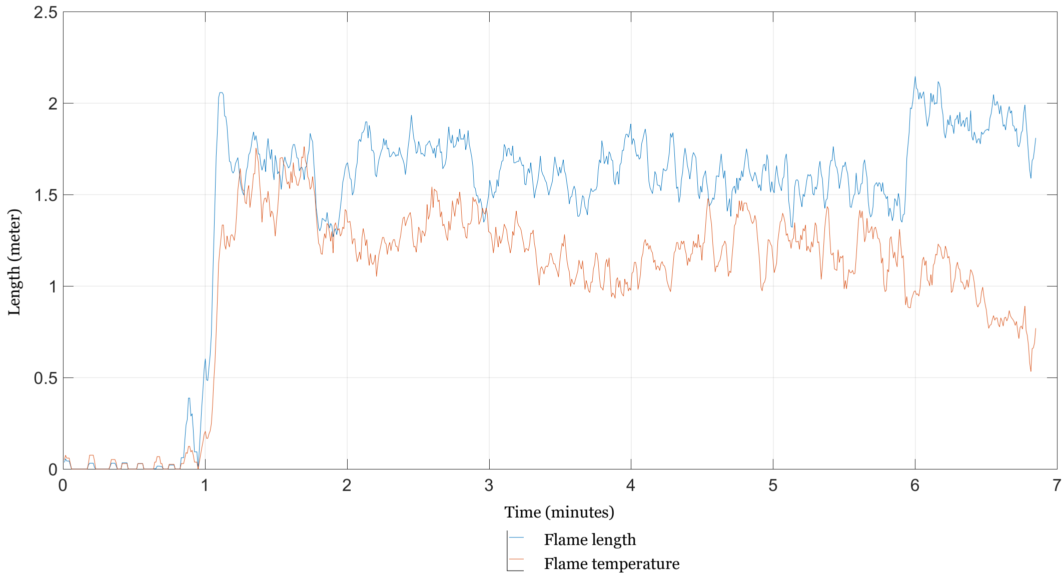

Figure 36. Flame length and height for test 5.

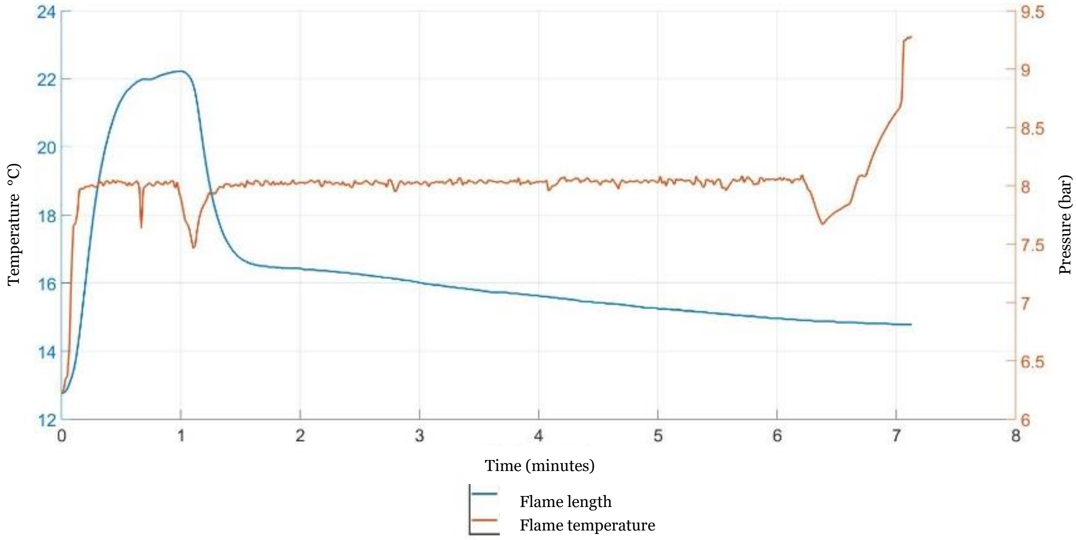

Figure 37. Pressure and temperature inside the pipe for test 5.

4.5.1 Test 5 heat flux

Test 5 was a small leakage and all measuring positions were moved closer according to Table 3. The highest heat flux during test 5 was at position A1, closest to the leakage at a height of 0.85 meters. During steady-state conditions the heat flux was between 7.5 and 10 kW/m² with a spike on 15 kW/m² in the beginning of the test. The heat flux decreased from 7.5 – 10 kW/m² at 2 meters, to 2.5 kW/m² at 3.1 meters, shown in Figure 38. The calculated heat flux from PT at B1 at 1.1 meter and 1.85 meter as well as B2 at 0.85 and 1.85 meters is shown in Figure 39. Heat flux over time, measured with heat flux meters are shown in Figure 40 and all calculated heat fluxes at position A is shown in Figure 41.

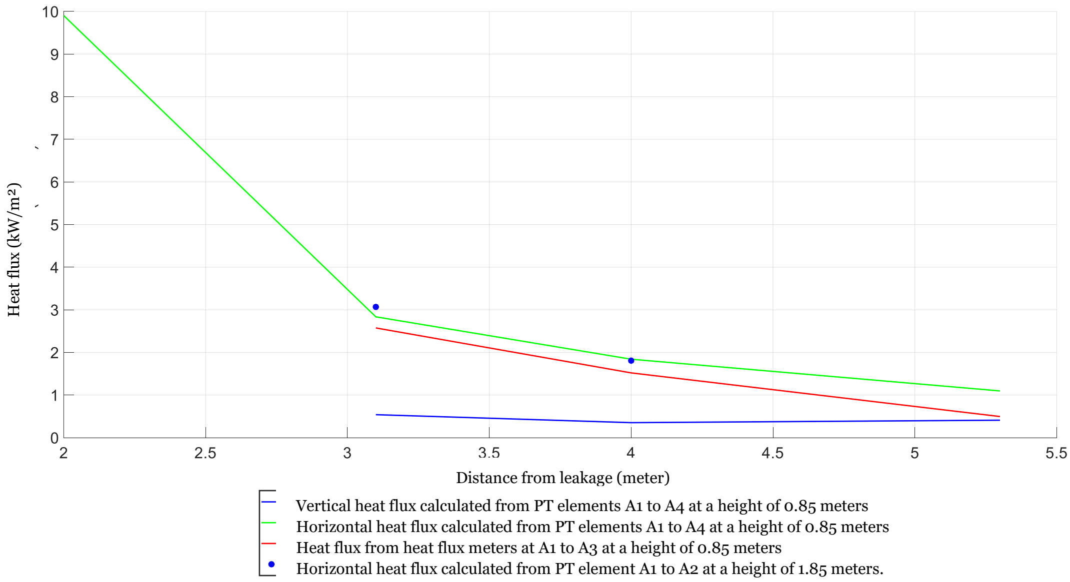

Figure 38. Test 5, heat flux at position A-A4 after 3 minutes. Distances are as follows: A1 = 2 meter, A2 = 3.1 meters, A3 = 4 meters and A4 = 5.3 meters.

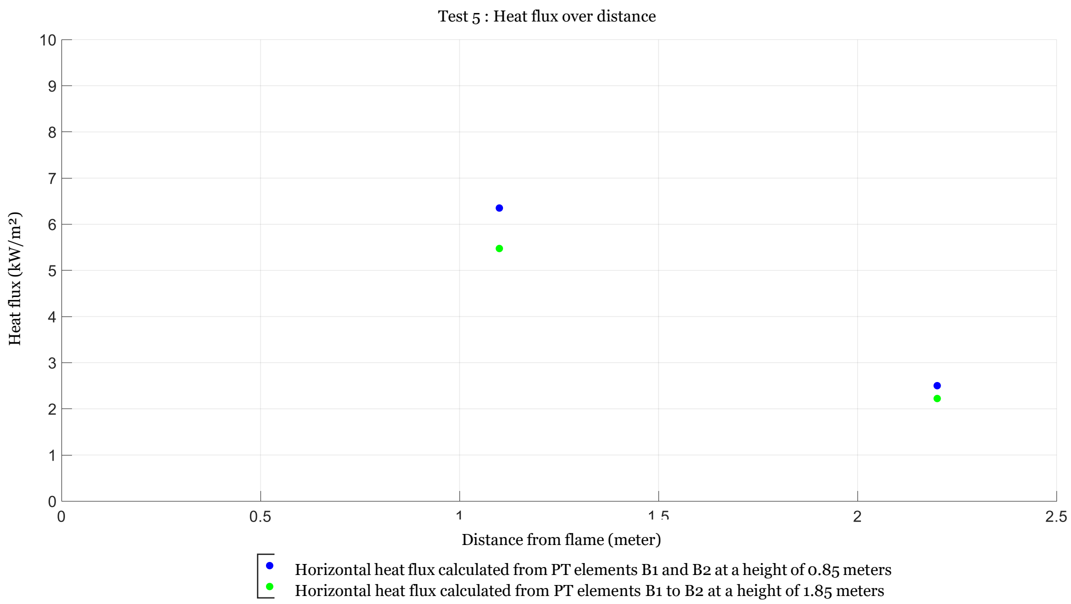

Figure 39. Test 5, heat flux at position B1 to B2 after 3 minutes. Distances are as follows: B1 = 1.1 meters and B2 = 2.2 meters.

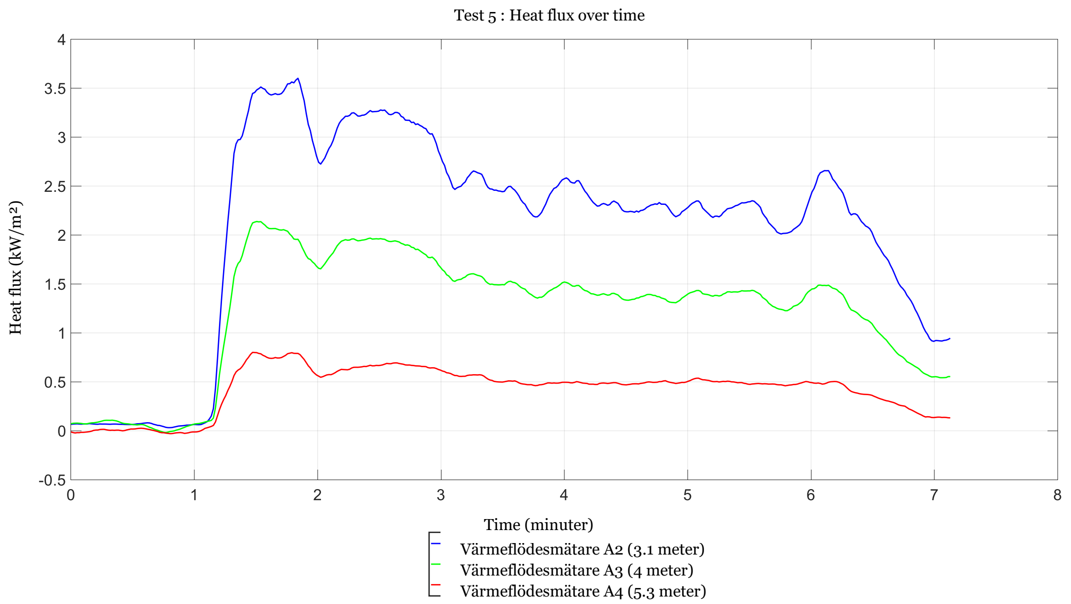

Figure 40. Test 4, measured heat flux values with heat flux meters at position A1-A3 at a height of 0.85 meters.

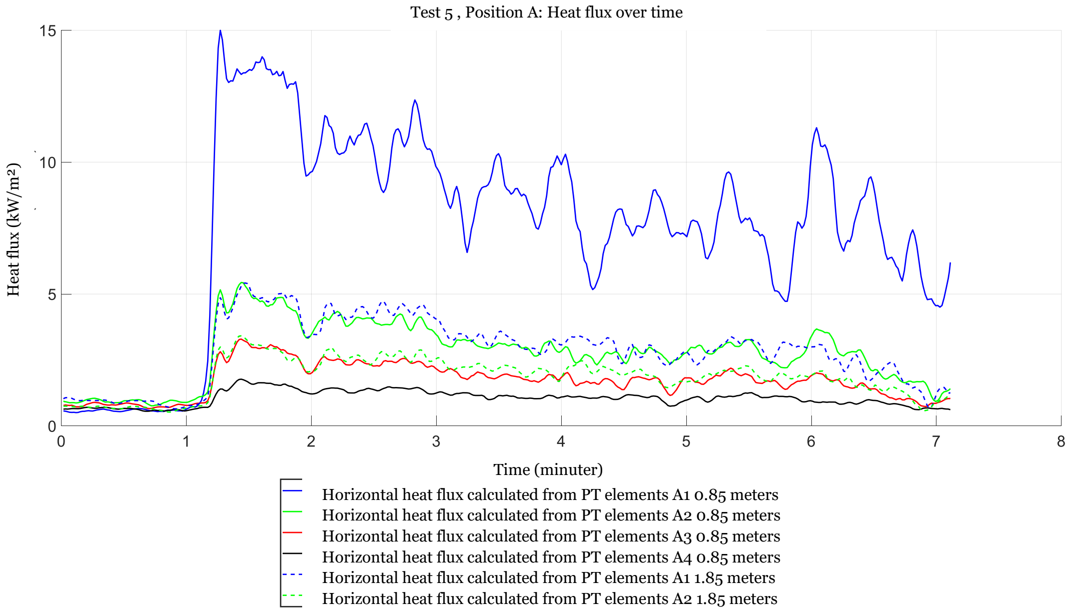

Figure 41. Test 5, calculated heat fluxes with PT elements at position A1 - A4 at a height of 0.85 meters. Distances are as follows: A1 = 2 meters, A2 = 3.1 meters, A3 = 4 meters and A4 = 5.3 meters.

5 Discussion and conclusion

Where the measurements contained 3 or more measurement devices a polynomial curve in the form of $\dot{q}_{inc}^{''} = Qr^{-\alpha}$ is fitted to the points. If an object is far away from a radiant heat flux source, or if the source can be approximated as a point, the incoming heat flux decreases with $\sim r^{-2}$. In this case the measurements are performed relatively close to the heat source and the heat flux decreases with an exponent somewhat different to 2. For example, in test 1, the heat flux in the same level as the leakage is fitted with $\dot{q}_{inc}^{''} = 1600r^{-2.7256}$. The curve fit is used to calculate distances corresponding to 12.5, 15 and 40 kW/m². In cases where there are only 2 measurement points a range where heat flux levels 12.5, 15 and 40 kW/m² should exist are presented.

Test piece 1, pipe with a slit-hole with a length of 28 mm and an area of 34 mm² resulted in a distance of 6 meters at a height of 0.85 and 7 meters at a height of 1.85 meters to avoid heat flux levels above 12.5 kW/m² in direction of the flame.

Test piece 2, textile reinforced rubber hose consisting of 6 holes with an area 29 mm² resulted in a distance of 8 meter at a height of 0.85 meters and 9 meters at a height of 1.85 meters to avoid heat fluxes above 1.25 kW/m² in the direction of the flame.

Test piece 3, pipe with a hole of 1.77 m² resulted in a distance of < 2 meter for a height of 0.85 and 1.85 meters above ground to avoid heat fluxes of 12.5 kW/m² in the direction of the flame.

5.1 Compiled data

Full results for the calculated critical distances are presented in Table 4 and directions used are visualised in Figure 42.

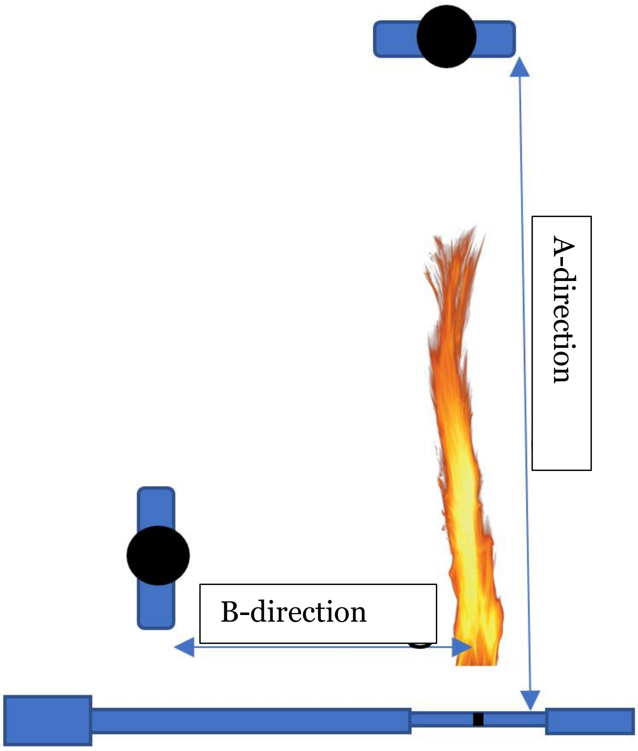

Figure 42. Visualisation of A- and B- distances

Table 4 Complied data, distances for heat flux levels 12.5, 15 and 40 kW/m². A and B distances shown in Figure 42

Heat flux for stationary leakage	Test piece Nr 1 Pipe, big leakage	Test piece Nr 2 Hose, big leakage	Test piece Nr 3 Pipe, small leakage
12.5 kW/m²			
A-direction. Height: Same as leakage	6 meters	8 meters	<2 meter
A- direction. Height: One meter above leakage	7 meters	9 meters[1, 3]	<2 meter
B- direction. Height: Same as leakage	(-)[2]	(-)[2]	<1 meter
B- direction. Height: One meter above leakage	(-)[2]	(-)[2]	<1 meter
15 kW/m²			
A-direction. Height: Same as leakage	6 meters	7.5 meters	<2 meter
A- direction. Height: One meter above leakage	6.5 meters	9 meters[1, 3]	<2 meter
B- direction. Height: Same as leakage	(-)[2]	(-)[2]	<1 meter
B- direction. Height: One meter above leakage	(-)[2]	(-)[2]	<1 meter
40 kW/m²			
A-direction. Height: Same as leakage	<4 meters[1]	5.5 meters[1]	<2 meter
A- direction. Height: One meter above leakage	<5 meters[1]	6.1 meters[1]	<2 meter
B- direction. Height: Same as leakage	1 meter	<2.2 meter	<1.1 meter
B- direction. Height: One meter above leakage	3 meters	<3 meter	<1.1 meter
Flame size during stationary conditions			
Length	Mean: 3.72 meter Spread: 0.18 meter	Mean: 5.58 meter Spread: 0.19 meter	Mean: 1.61 meter Spread: 0.13 meter
Height	Mean: 3.67 meter Spread: 0.13 meter	Mean: 3.79 meter Spread: 0.08 meter	Mean: 1.21 meter Spread: 0.14 meter

[1]Calculated with curve-fit $\dot{q}''_{inc} = Qr^{-\alpha}$ from measurement points A1-A4. For test 1: vid 0 m above leakage and for test 3: $\dot{q}''_{inc} = 5045r^{-2.9753}$.
[2] Is outside the limits of two measurements points.
[3] Calculated conservative estimate from conditions between 0.85 and 1.85 meter.

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