Preventing smoke gas ignition

Partial report: experiments with the desktop flashover cabinet

Publication details

BRANDWEER
Brandweeracademie

Abstract

Smoke ignition and smoke explosions are dangerous phenomena for firefighters, especially when performing an internal attack. In order to prevent the smoke igniting, smoke cooling techniques are applied. According to literature, cooling the smoke prevents ignition when cooled down lower than the self-ignition temperature. Furthermore, cooling reduces the radiation to which firefighters are exposed. Another phenomenon described in literature is that the steam formed during cooling makes the smoke inert. This is important, because it is well known that, in the right composition with air, cold smoke can still ignite. However, a literature study done by the Dutch Fire Service Academy showed that there is no convincing scientific evidence to the extent of the inertising, and that different terms are used in the literature. Furthermore, there is a discussion globally about the most easy and effective technique to cool and inertise smoke.

The Dutch Fire Service Academy therefore started an investigation into smoke gas cooling. The research consists of three parts. One study addresses the effectiveness of different techniques to cool the smoke. Secondly, we investigate fires where smoke explosions are reported in order to find out the mechanism and the influencing factors. Thirdly, the present report studies the inertising effect of water and nitrogen in a smoke gas layer to prevent smoke gas ignition. For safety reasons, this has been done on laboratory scale by means of so-called desktop flashover cabinets.

The purpose of these experiments was to determine whether the existing smoke gas cooling technique can prevent smoke ignition (inertisation). Based on this objective, the following main question has been formulated:

Can the introduction of water (steam or mist) or nitrogen into a smoke layer prevent smoke gas ignition?

The experiments were carried out with a cold (20 degrees Celsius) gas mixture of propane and with a hot (approximately 220 degrees Celsius) gas mixture, also of propane, in a desktop flashover cabinet. Different amounts of water spray, steam and nitrogen (which was only used with the cold gas mixture) were added to these mixtures, after which it was examined as to whether they could be ignited.

The experiments with cold gas mixtures showed that only the addition of 34% or more by volume of nitrogen made the gas mixture inert. This was not possible with water spray or steam. The experiments with hot gas mixtures showed that water could make the gas mixture inert at a percentage by volume of approximately 42% or higher.

Management summary

If smoke fulfils certain conditions, it can ignite. This is one of the reasons why smoke is a risk if there are fire service personnel or any other people in the premises where there is a fire. In order to prevent this smoke gas ignition, the fire service employs a technique called 'smoke gas cooling'. The intention of using smoke gas cooling is to lower the temperature of the smoke to below the auto-ignition temperature. This makes it impossible for the smoke to self-ignite, and it will also reduce any radiation that fire service personnel may be exposed to in case of an indoor attack. This makes smoke gas cooling a good method to enable the seat of the fire to be approached safely if it cannot be reached directly. However, there is still some ambiguity as to the exact operation and the effect of that technique. For instance, we know that cold smoke can also ignite if it has the right composition with air. We already encountered these questions during a previous study by the Dutch Fire Service Academy in 2013 and a literature review into smoke gas cooling. The literature shows that the steam formed while cooling leads to inertisation. However, the literature does not explain the degree to which this phenomenon effectively prevents smoke explosions, and, furthermore, several different physical effects are intermixed. Besides this, there is a global discussion about the most effective, and preferably simplest, way to cool smoke gases.

This is why the Dutch Fire Service Academy started a study into smoke gas cooling. This report addresses the possible inertising effect of water and nitrogen in a smoke gas layer in order to prevent smoke gas ignition. For safety reasons, this was done on a laboratory scale by means of 'experiments in desktop flashover cabinets and vessels'. Another study looked into the easiest and most effective way of cooling smoke.

The goal of this study was to determine whether smoke gas ignition (inertisation) can be prevented by the fire service using the existing techniques for smoke gas cooling. The following main question was formulated based on this objective:

Can the introduction of water (steam or mist), or nitrogen into a smoke gas layer prevent smoke gas ignition (inertisation)?

A literature review was carried out to prepare for this study. This literature review looked for smoke gas cooling methods (in the Netherlands and abroad) and the information known about smoke gas cooling. This literature review revealed that there are still many ambiguities as regards smoke gas cooling. This report therefore gives a detailed description of the elements contained in smoke gases and the decisive characteristics regarding smoke gas ignition in order to be able to analyse the results of the experiments that were carried out. This analysis was based on three assessment criteria: flammability limits, the inert point, and the lower oxygen concentration.

The experiments were carried out with a cold (20 degrees Celsius) gas mixture (propane) in a desktop flashover cabinet and with a hot (approx. 220 degrees Celsius) gas mixture (propane) in a desktop flashover vessel. Different quantities of water mist, steam and

nitrogen (only with cold gas mixtures) were added to these mixtures after which attempts were made to ignite the mixture.

The experiments with cold gas mixtures showed that the gas mixture was only inertised if 34 vol% of nitrogen or more was added. This was not possible with water mist or steam. The experiments with hot gas mixtures revealed that it was possible to inertise the gas mixture by means of water. This occurred at a volume percentage of approx. 42% or higher.

Contents

Introduction

Background

In recent years, the fire service has paid increasing attention to the risk of smoke ignition. If smoke fulfils certain conditions, it can ignite. This is one of the reasons why smoke is a risk if there are fire service personnel or any other people in the premises where there is a fire. If the smoke suddenly ignites, fire service personnel may get injured or trapped (Dutch Fire Service Academy, 2017). Signs that indicate a risk of smoke gas ignition are hard to recognise. Several different past incidents have indicated the danger of smoke gas ignition. One of those incidents was the well-known fire in De Punt (2008) where three members of the fire service lost their lives while fighting the fire (Onderzoeksraad voor Veiligheid (Dutch Safety Board), 2009).

In order to prevent such smoke gas ignitions, the fire service employs a technique called 'smoke gas cooling'. The intention of using smoke gas cooling is to lower the temperature of the smoke to below the auto-ignition temperature. This makes it impossible for the smoke to self-ignite, and it will also lower any radiation that fire service personnel may be exposed to in case of an indoor attack. This makes smoke gas cooling a good method to enable the seat of the fire to be approached safely if it cannot be reached directly. However, there is still some ambiguity as to the exact operation and the effect of that technique. For instance, we know that cold smoke can also ignite if it has the right composition with air. We already encountered these questions during a previous study by the Dutch Fire Service Academy in 2013 and a literature review into smoke gas cooling. The literature shows that the steam formed while cooling leads to inertisation. However, the literature does not explain the degree to which this phenomenon effectively prevents smoke explosions, and, furthermore, several different physical effects are intermixed. Besides this, there is a global discussion about the most effective, and preferably simplest, way to cool smoke gases.

Is the technique as safe as it is assumed to be and how can hot or cold smoke gases be prevented from igniting? This report is part of the 'smoke gas cooling' project. The study into smoke gas cooling consists of three parts: firstly a study of which method is the easiest to apply whilst effectively cooling smoke, secondly, a study of real-life incidents in order to assess which factors play a role in cold smoke explosions, and thirdly, and that is what this report is actually about, we want to identify the extent to which inertisation plays a role in preventing smoke gas ignition, both with cold and with hot smoke. In preparation for the experiments that are described in this report, the Dutch Fire Service Academy conducted a literature review into smoke gas cooling (Dutch Fire Service Academy, 2017). This literature review considered several aspects, including smoke gas cooling methods (in the Netherlands and abroad) and study findings about smoke gas cooling.

This report addresses the possible inertising effect of water and nitrogen in a smoke gas layer. This was done by means of 'experiments in desktop flashover cabinets and vessels'.

Goal

The goal of this study is to determine whether smoke gas ignition (by inertisation) can be prevented by the fire service using the existing techniques for smoke gas cooling.

Main question

Based on the objective of this report, the following main question can be formulated:

Can the introduction of water (steam or mist), or nitrogen into a smoke gas layer prevent smoke gas ignition (inertisation)?

Demarcation

This study looks at the introduction of water and nitrogen into a smoke gas layer. No other inert gases are considered in the experiments.

The study is limited to small-scale experiments. The experiments were conducted using a 'desktop flashover cabinet' and/or a 'desktop flashover vessel'. The gas used was propane, but smoke gases can contain a variety of different gases. Due to safety considerations, it was decided to carry out small-scale experiments.

1 Theoretical framework

1.1 Literature review into smoke gas cooling

This literature review (Dutch Fire Service Academy 2017) considered several aspects, including smoke gas cooling methods (in the Netherlands and abroad) and study findings about smoke gas cooling.

In summary, the following findings have been arrived at concerning the current methods:
> An important share of the scientific and other publications is about the initial reduction of the temperature of a smoke gas layer. The aspects studied include how water is introduced into the smoke gas layer (e.g. which method is used, surface or 3D cooling, and the flow rate, pressure, drop size, ligand cone angle and spray angle).
> Less attention is paid in the literature to the question of how this decrease in temperature can be maintained (as long as the fire is not under control) and what the consequences of this decrease are for the flammability of the smoke gas layer and the probability of ignition.
> Some authors refer to 'inertising' a smoke gas layer. Not all authors indicate clearly what exactly they mean by this. Where a definition is given, it is not always clear whether there is a difference between inertising and diluting, and, if so, what this difference is. The definitions given have also been found to be different. Based on the fifth *SFPE Handbook* (SFPE, 2016) it can be asserted that inertising and diluting are two different things which will actually occur simultaneously in practice and which will lead to the same effect (i.e. lowering the probability of ignition).
> The feasibility of 3D techniques, commonly referred to by some authors, is a subject of debate. Although this is a promising technology in theory, some authors question the level of knowledge and skills required in order to correctly carry out this technology.
> Cooling a smoke gas layer can create steam which may unintentionally lead to a significant physical burden and cause burns for firefighters who are in the same room as the smoke gas layer they are trying to cool or inertise.

In order to be able to analyse the experiments described in this report, it is important that the theory of gas mixtures and the decisive characteristics regarding smoke gas ignition are addressed in more detail. The following sections go into this in more detail.

1.2 Flammability limits

Not all gas mixtures can ignite. The presence of fuel (fire gases), oxygen and energy, including ignition energy is important. The correct mixture (mixture ratio) of fire gases and oxygen must also be present. The mixture is flammable within certain limits; these limits are called the flammability limits. The limits per gas are usually indicated as a volume percentage in air. The flammability limits (*lower and upper flammability limit)*, lower temperature limit*,* and auto-ignition temperature of a number of relevant gases are shown in the table below (SFPE, 2016).

Table 1: Flammability limits, lower and upper flammability limit (LFL and respectively UFL), lower temperature limit (TL) and auto-ignition temperature (AIT)

Flammable gas	LFL [vol%]	UFL [vol%]	T_L [°C]	AIT [°C]
Methane	5	15	-187	540
Propane	2.1	9.5	-102	450
Carbon monoxide	12.5	74	-191	609
Styrene	1.1	6.1	31	490

Craig Beyler's contribution to the fifth edition of the *SFPE Handbook of Fire engineering* from 2016 includes an extensive list of the flammability limits of individual gases and vapours in air at atmospheric pressure and relatively low temperatures (SFPE, 2016).

The flammability limits are a function of the oxygen and inert gas concentrations, as are the temperature and the pressure of the mixture. If the concentration of inert gases is reduced and the oxygen concentration increases, the upper flammability limit will also increase, whereas the lower flammability limit will remain relatively unchanged (SFPE, 2016). This can be explained by the fact that the oxygen concentration does not play a role for the lower flammability limit, since sufficient oxygen is present. However, the oxygen added takes part in the combustion process for the upper flammability limit.

The lower flammability limit is also insensitive to pressure, except for pressures which are much lower than the atmospheric pressure. The upper flammability limit shares this insensitivity to sub-atmospheric pressures, but increases if supra-atmospheric pressures occur (SFPE, 2016).

The limits are extended as the temperature of the mixture increases. The lower flammability limit decreases and the upper flammability limit increases as the temperature increases. This is shown in figure 1 from (SFPE, 2016).

Figure 1: Flammability limits (SFPE, 2016)
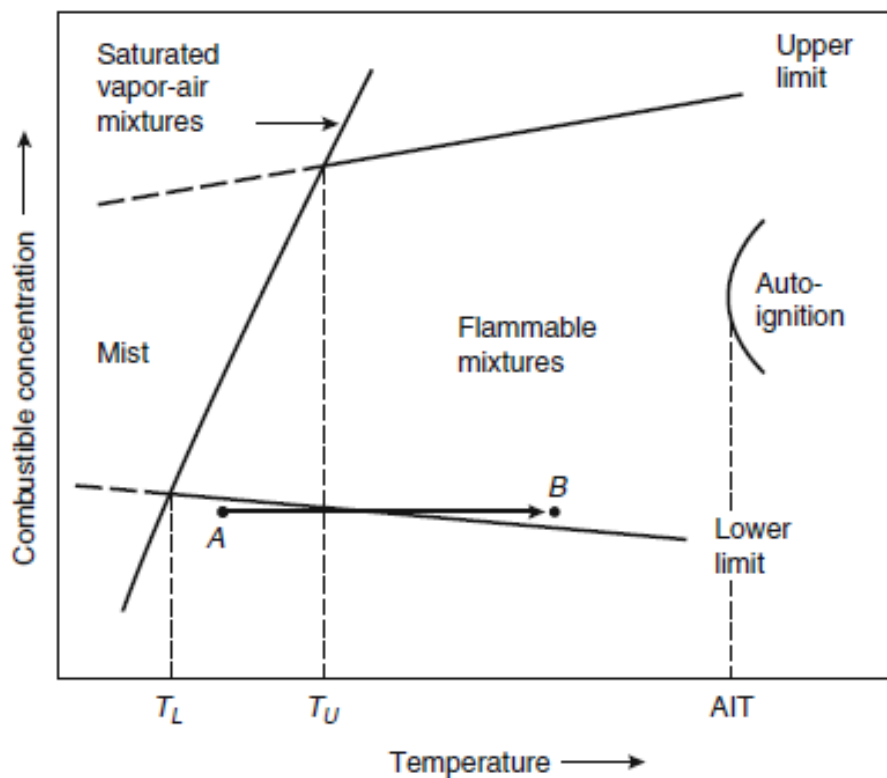
The lower temperature limit (Lower limit) in the figure equals the flashpoint of a liquid. However, as the figure shows, a mixture with a certain concentration of flammable gases (point A) can be brought to within the flammability limits (B) whilst the temperature increases and the concentration remains unchanged. Table 2 shows the lower flammability limit of a number of gases with different temperatures (SFPE, 2016).

Table 2: Table of lower flammability limits for gases with different temperatures

Flammable gas	LFL [vol %]					
	Start temp. [°C]	100 [°C]	150 [°C]	200 [°C]	250 [°C]	300 [°C]
Methane	5[a]	4.9	4.7	4.5	4.3	4.1
Propane	2.1[a]	2.0	2.0	1.9	1.8	1.7
Carbon monoxide	12.5[a]	12.1	11.5	10.8	10.1	9.5
Styrene	1.1[b]	1.0	1.0	1.0	0.9	0.9

[a] T = 70 °C
[b] T = 29 °C

Such a development can also be specified for the upper temperature limit (Upper limit), with the limit increasing if the temperature increases. This is based on the adjusted Burgess-

Wheeler law, which is explained in more detail in a study by Filip van den Schoor (Van den Schoor, 2007). Table 3 shows the upper flammability limits for propane as the temperature increases.

Table 3: Upper flammability limits for propane with different temperatures

Flammable gas	UFL [vol %]					
	Start temp. [°C]	100 [°C]	150 [°C]	200 [°C]	250 [°C]	300 [°C]
Propane	9.5[a]	10.0	10.6	11.3	12.0	12.6

[a] T = 70 °C

In practice, the smoke will not be one flammable gas, but it will consist of a combination of gases. If it is known which gas concentrations are present, 'Le Chaterlier's rule' can be used to determine the lower flammability limit of a mixture of fire gases (Fire Service Academy, 2017; SFPE, 2016).

The critical Adiabatic Flame Temperature (AFT) is another aspect that is important with regard to the lower flammability limit. The critical AFT can be defined as the threshold under which the heat losses exceed the speed of heat production within the flame. A consequence of this is that the flame cannot sustain itself. This concept can be used, for example, to determine the composition of a gas/air mixture and an added inert gas where no ignition can take place any longer. Based on the chemical equation of such gas/air mixtures, the AFT that goes with the lower flammability limit, i.e. the 'critical AFT', can be calculated. Annex 2 has determined the critical AFT based on the chemical equation for propane, methane and carbon monoxide.

Most fuels that consist of carbon, hydrogen and oxygen have the same critical AFT which is approximately 1600 K ($\pm$150 K). Exceptions are hydrogen (980 K), carbon monoxide (1300 K), and acetylene (1280 K). This AFT is an indication of the reactivity of the fuel: the lower this temperature, the higher the reactivity of the fuel (SFPE, 2016).

Table 4 lists the calculated AFT at the lower flammability limits for several hydrocarbons.

Table 4: AFT of hydrocarbon/air mixtures at the lower flammability limits

Gas	AFT at lower flammability limits (K)
Methane	1446
Ethane	1502
Propane	1554
n-Butane	1612
n-Pentane	1564
n-Heptane	1692
n-Octane	1632

However, the use of the concept of the critical AFT at the lower flammability limit goes beyond merely knowing the reactivity of the fuel. Section 1.4 goes into this in more detail.

1.3 Minimum oxygen concentration (LOC)

In a general sense, the flammability limits of fuel, oxygen and inert mixtures can be shown more effectively in flammability diagrams. Two examples of flammability diagrams of methane are shown in figure 2 (SFPE, 2016). Please note that these graphs concern ambient temperatures.
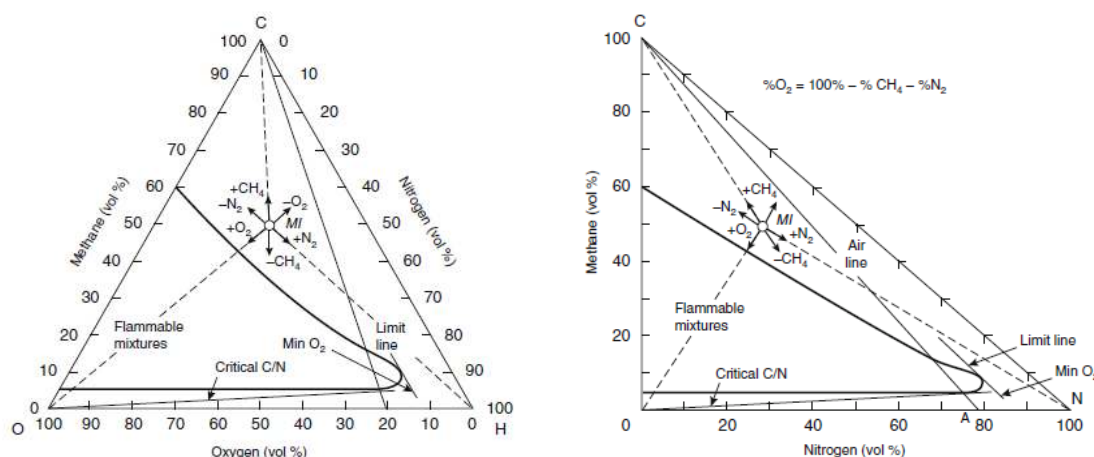
Figure 2: Flammability diagrams

These diagrams are based on an extensive series of tests with a series of different compositions of mixtures. The air line and the limit line are important for a mixture in ambient air. The limit line represents a series of mixtures with a fixed oxygen/nitrogen ratio that touch the non-flammable area. Every oxygen/nitrogen mixture with an oxygen/nitrogen ratio below

the limit will not support any combustion when mixed with an amount of methane. This condition is known as the 'limiting oxygen concentration' (LOC) (SFPE, 2016).
This LOC plays an important role in inertisation. If the oxygen concentration can be kept below the LOC, the ignition of gases can be prevented.

Table 5 indicates the LOC values of several gases for nitrogen and carbon dioxide as inert dilution gases at ambient temperature and ambient pressure (SFPE, 2016).

Table 5: LOC (limiting oxygen concentration) values with ambient temperature and pressure

Flammable gas	LOC N_2/air [vol%]	LOC CO_2/air [vol%]
Propane	11.5	14.5
Hexane	12	14.5
Carbon monoxide	5.5	5.5
Hydrogen	5	5.2

The extensive list in the SFPE Handbook shows that the LOC value with nitrogen as the dilution gas is generally between 10-12%. Only carbon monoxide and hydrogen have lower LOC values. If carbon dioxide is the dilution gas, the LOC value is approximately 2 to 3% higher (SFPE, 2016) compared to that of nitrogen.

No LOC values have been included in the SFPE Handbook for water vapour as the dilution gas. The LOC values included in table 6A can be found in a study by Giurcan (Giurcan, 2013), based on existing sources such as those of the American Bureau of Mines (Zabetakis, 1965) and the German database of safety characteristics of explosion safety (CHEMSAFE, 2009).

Table 6: LOC (limiting oxygen concentration) values for different temperatures and ambient pressures

Flammable gas	LOC N_2/air [vol%]	LOC H_2O/air [vol%]	LOC CO_2/air [vol%]
Propane 298 K	11.6 [1]	-	14.3 [1]
Propane 373 K	9.2 [2]	12.5 [2]	-
Propane 473 K	-	11.5 [2]	-
Propane 523 K	7.2 [2]	-	11.1 [2]

[1]   (Zabetakis, 1965)
[2]   (CHEMSAFE, 2009)

Although the LOC value for water vapour in air at ambient temperatures is not known, this value is expected to be between that of carbon dioxide (11.5 – 11.6%) and nitrogen (14.3 – 14.5%).

1.4   Inert point (IP)

As well as the LOC value and the ATF, the inert point is also important. The inert point of a fuel/oxygen mixture is the point with the highest concentration of inert gas where combustion is still possible. In a general sense, this point is indicated as the inert point (IP) for every inert gas. For example, if nitrogen is present as an inert gas, this point will be indicated as the nitrogen point (NP). If the concentration of the inert dilution gas exceeds the IP, no fuel/oxygen mixture will ignite, regardless of the source of ignition (SFPE, 2016).

As indicated in section 1.2, the critical AFT can be defined as the threshold under which the heat losses exceed the speed of heat production within the flame. If sufficient inert gas is added to a flammable mixture, the critical AFT cannot be reached. This means that the heat production of the flame is lower than the heat losses for heating inert gases. As a result, the flame will not be able to sustain itself and no ignition will take place. In other words: the IP for inert gases can be determined based on the critical AFT.

Table 7 shows the IPs (volume percentage) of water vapour and nitrogen where no ignition can take place for propane, methane and carbon monoxide, determined on the basis of the critical AFT. Annex 2 provides a further explanation based on the chemical equations of these substances.

Table 7: IP of water vapour and nitrogen with different gases based on the AFT

Gas	Water vapour [%]	Nitrogen [%]
Propane	41	47
Methane	42	48
Carbon monoxide	56	61

Lower values are found for the inert point in some experiments. This is partly because the AFT concept assumes adiabatic conditions. This does not mean that no heat is exchanged with the surroundings. However, this is the case in real-life situations.

Figure 3 shows another representation of the flammability limits of methane if diluted by inert gases. This figure is an enlarged version of the right-hand part next to the air limit line from the flammability diagram (in figure 2).

Figure 3 also includes the stoichiometric line (C_{st}). The point where the stoichiometric line intersects with the flammability area is the stoichiometric limit (SL). The SL is the most highly diluted stoichiometric mixture that can still ignite (SFPE, 2016). If water vapour is used for dilution, this point is found at a volume percentage of methane of around 7%, a volume percentage of water vapour of 27%, and a volume percentage of air of 66%.

Figure 3: Flammability limits of methane if diluted by inert gases (SFPE, 2016)
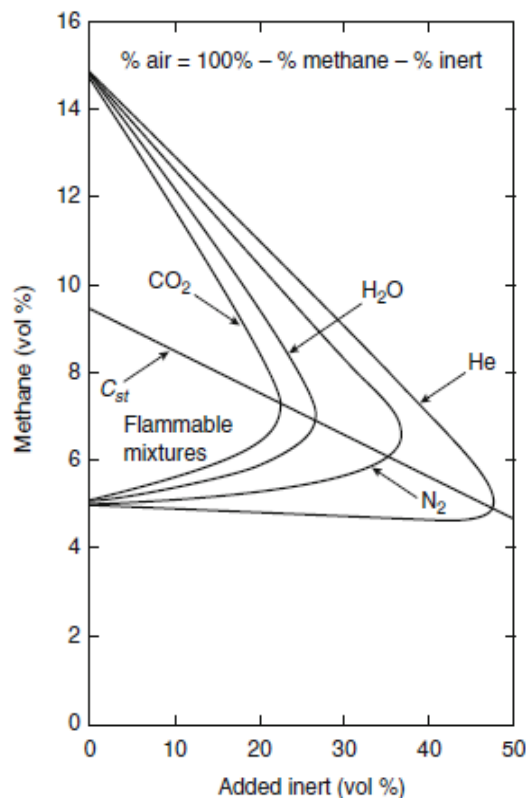
As indicated by the concept of the critical Adiabatic Flame Temperature, the lower flammability limit is increased in proportion to the heat capacity of the dilution gas.

The SFPE handbook (SFPE, 2016) does not feature any flammability diagrams for propane. A study by Saito and Liao (Saito, 2004) mentions a volume percentage of 35-40% as the IP for water vapour as an inert gas for propane. A study by Abdelkhalik (Abdelkhalik, 2016) shows flammability diagrams of several different hydrocarbons with different inert gases. Water vapour has not been included in that study as an inert gas, whereas nitrogen and carbon dioxide have.

Figure 4: Flammability limits of propane and acetone if diluted by inert gases (Abdelkhalik, 2016)

A. Abdelkhalik et al. / Journal of Loss Prevention in the Process Industries 43 (2016) 669–675
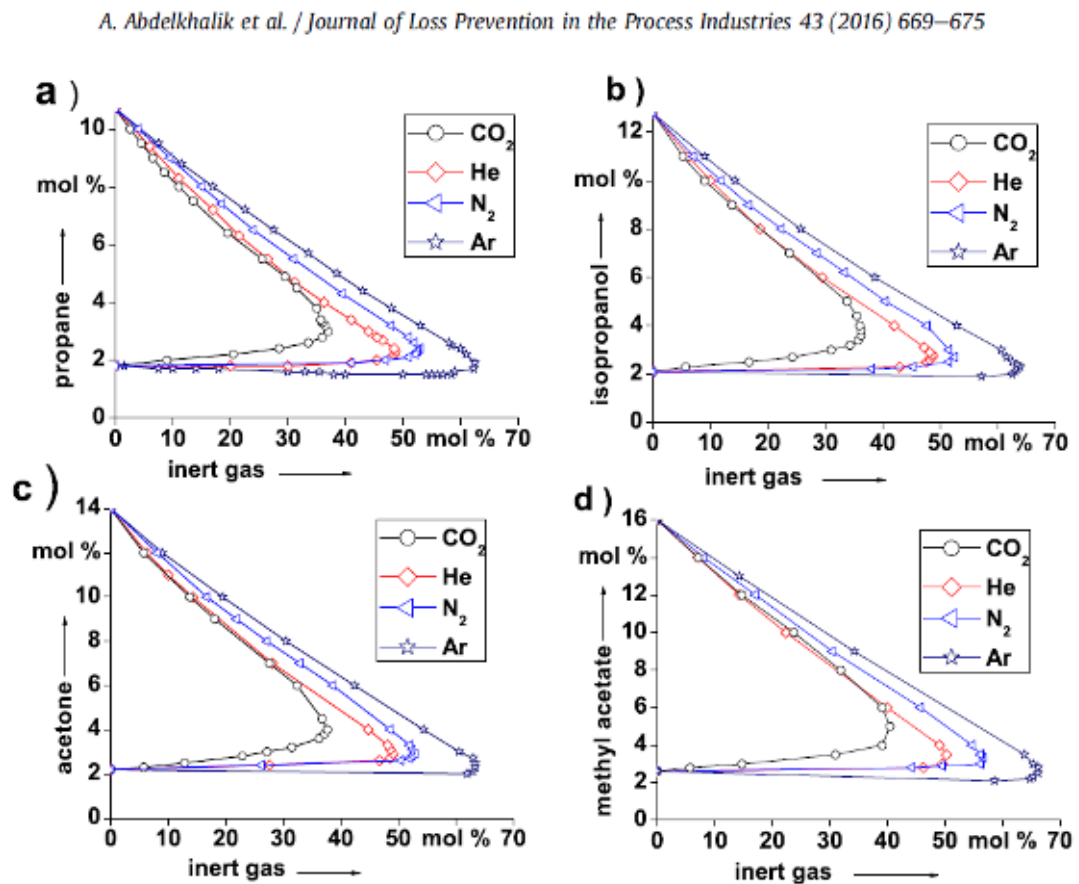
Figure 3 shows that the volume percentage of added water vapour is between those of carbon dioxide and nitrogen. Assuming this, and based on figure 4, the IP for water vapour where ignition is no longer possible will in theory be between 37% and 53%.

Based on a study by Giurcan (Giurcan, 2013), the following flammability diagrams can be derived for propane:

Figure 5: Flammability diagram for propane 298 K

Brandbaarheidsdiagram Propaan 298 K
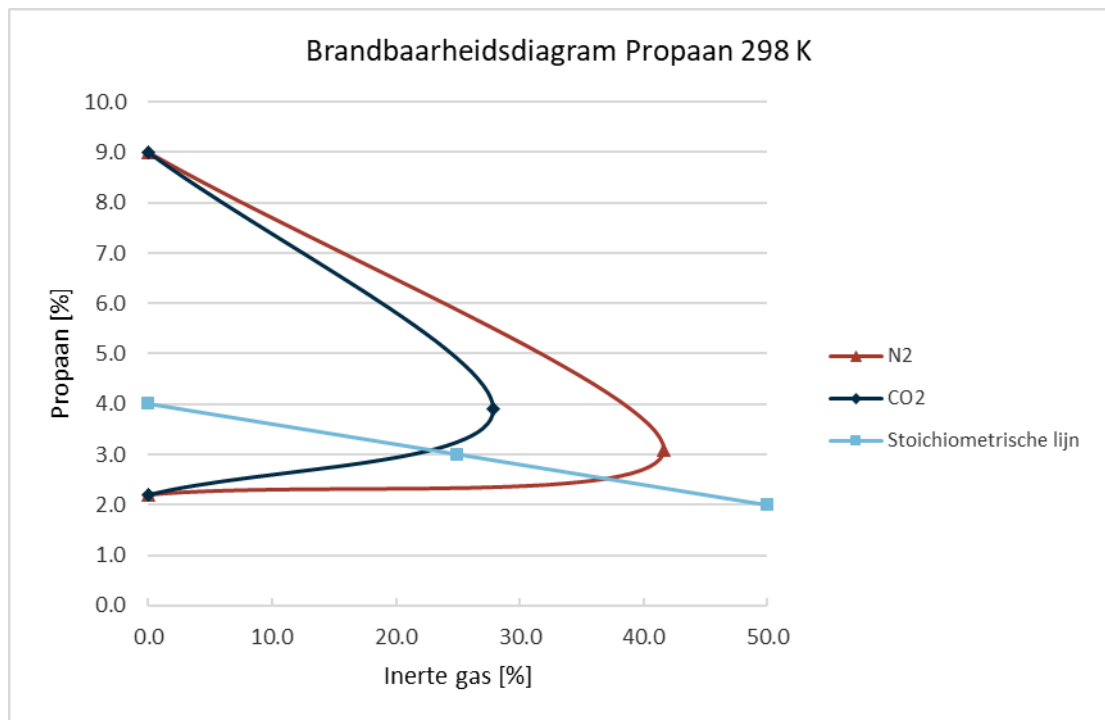
With an ambient temperature and atmospheric pressure, this leads to an IP for water vapour of between 28% and 42% (volume percentages).

Figure 6: Flammability diagram for propane 373 K

Brandbaarheidsdiagram propaan 373 K
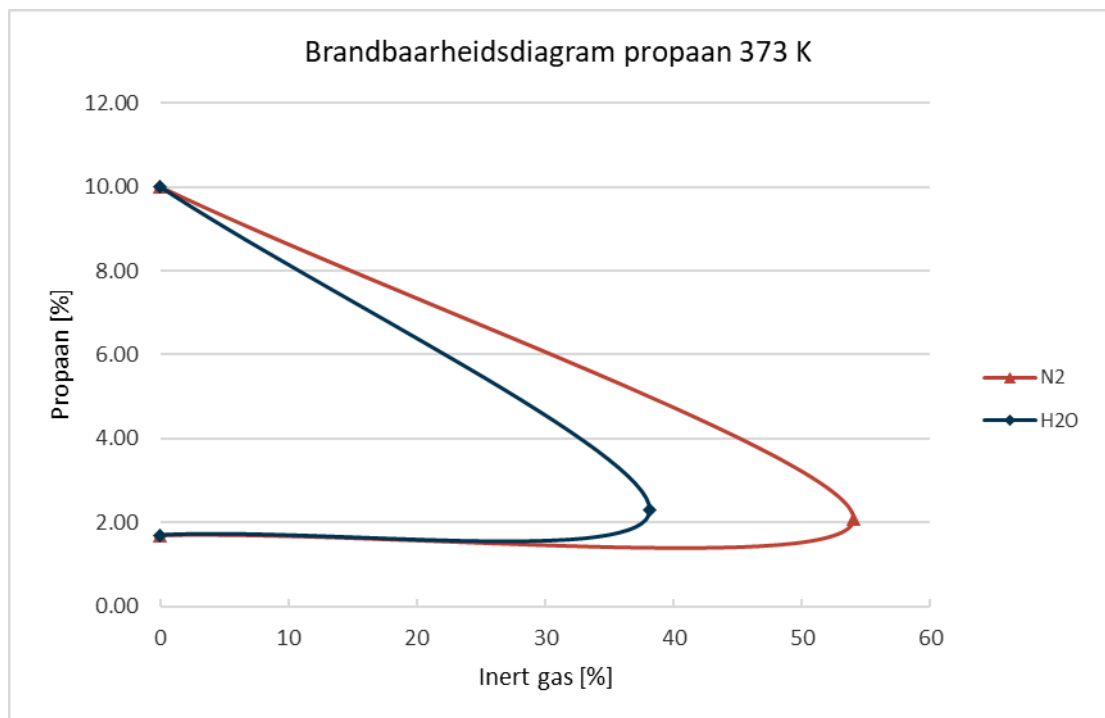
With a temperature of 100 °C and atmospheric pressure, this leads to an IP for water vapour of approx. 38% (volume percentage).

Figure 7: Flammability diagram for 473 K
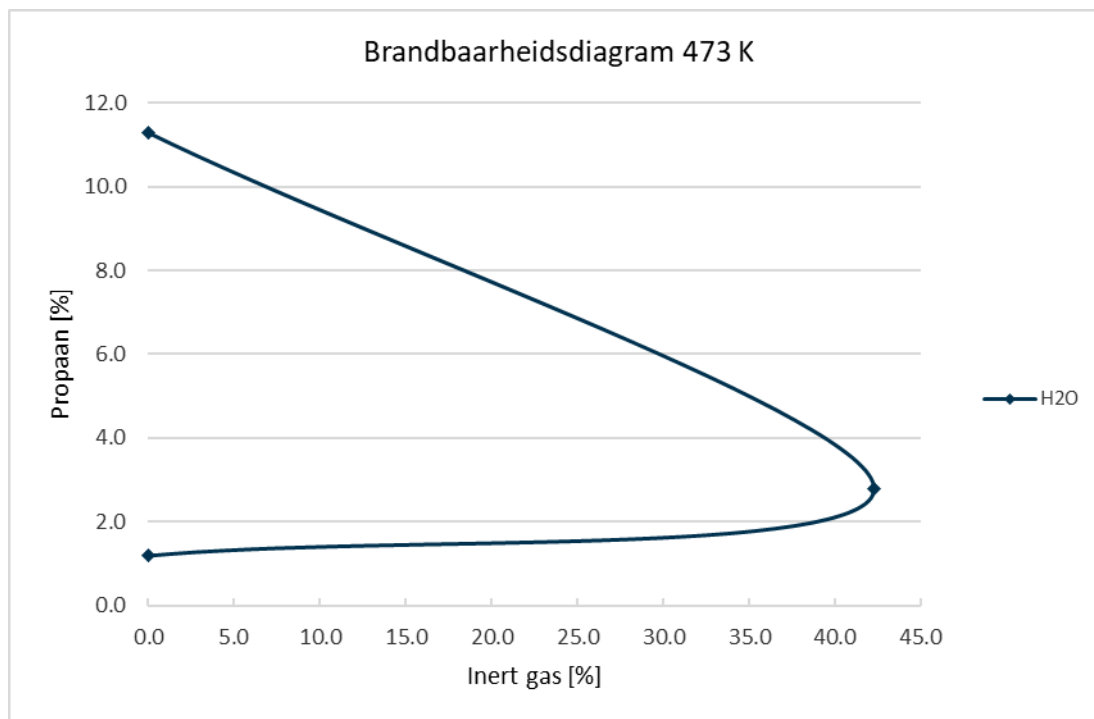
With a temperature of approx. 200 °C and atmospheric pressure, this leads to an IP for water vapour of approx. 42% (volume percentage).

Here, it should be noted that these diagrams are based on three measurement points taken from various available data (Giurcan, 2013). This means that the limits of these diagrams are not exactly fixed, but have been derived. This means that there is a certain margin of error.

1.5 Humidity

As indicated above, the flammability limits depend on temperature. This applies to every fuel/oxygen mixture with inert gases. However, if water vapour is the inert gas, the amount of water vapour in air also depends on temperature. This can be explained in more detail based on humidity.

Humidity is the amount of water vapour present in air. Water vapour in gaseous form is not visible to the human eye. Humidity is a measure, e.g. to indicate where there is a probability of dew or fog. Air can become saturated due to which the amount of water vapour in that air cannot increase anymore. The point where the air becomes saturated is called the saturation point or the dew point. The amount of water vapour that air can contain depends on temperature until the boiling point of water is reached. If the temperature decreases and the vapour pressure remains unchanged, the excess water vapour will condensate.

Humidity is often expressed in terms of absolute or relative humidity. Absolute humidity is the amount of water vapour in air indicated in grams per cubic metre or grams per kilogram. Relative humidity is the absolute humidity relative to the maximum humidity at a certain temperature, indicated as a percentage.

At temperatures below boiling point, gas mixtures such as air can contain a limited amount of water vapour. This amount depends on temperature (and pressure). In fire situations, there often are differences in pressure (often dozens of Pascals), but these have no, or hardly any, effect on the amount of water vapour in gas mixtures compared to the atmospheric pressure (1013000 Pascal or 1.013 bar).

For temperatures in excess of the boiling point of water, a gas mixture can contain large amounts (up to 100%) of water vapour without condensation occurring.

Figure 8 indicates that, in theory, a gas mixture can be inertised at ambient temperature. The theoretical inert point (IP) of water vapour for a gas mixture of propane is between 28 and 42%. In practice, such a volume percentage of water vapour in a gas mixture of propane can be reached if the boiling point of water is exceeded. However, at temperatures below the boiling point, this is not always possible in practice. Figure 8 shows the maximum volume percentage of water vapour (vertical axis) in air depending on temperature (horizontal axis) with a relative humidity of 100%.

Figure 8: Maximum volume percentage of water vapour
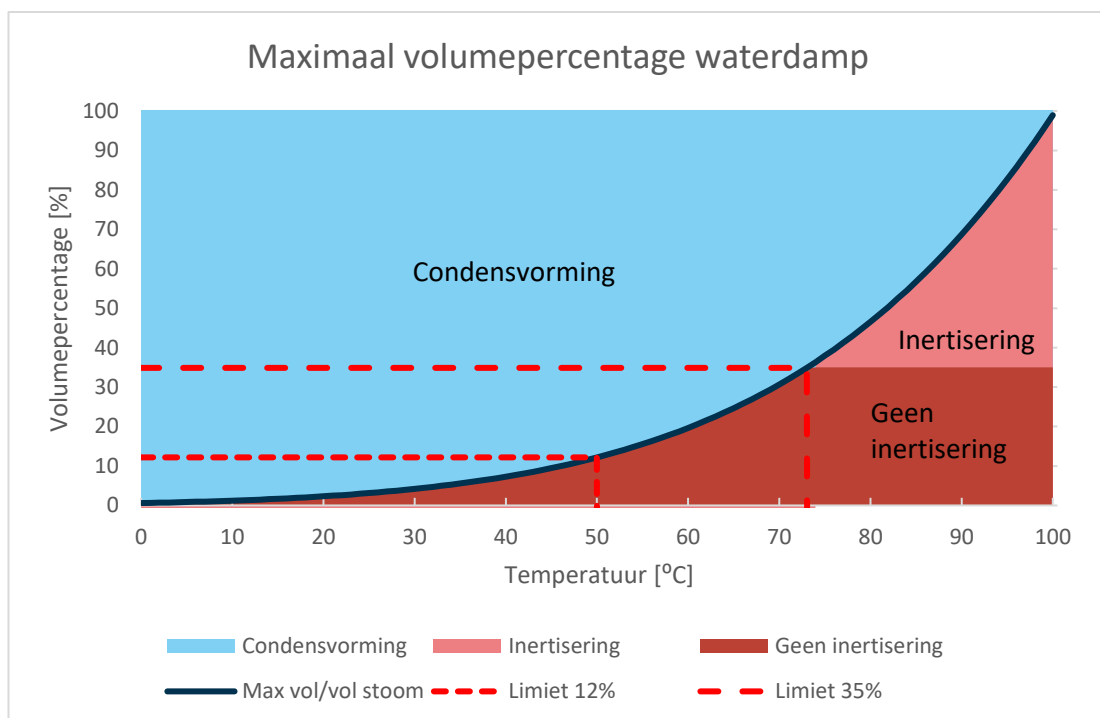
The graph shows that, at temperatures of above 73 °C, a gas mixture can contain more than 35 volume percent of water vapour. This means that if this temperature is exceeded, inertisation by means of water vapour is theoretically possible for a gas mixture of propane. This is not possible at a lower temperature.

1.6 Assessment criteria

The assessment criteria listed below were derived from the previous sections. These criteria can be used to analyse the experiments conducted for the purpose of this study into smoke gas explosions.

1.6.1 Flammability limits
The flammability limits are the first criterion. As indicated above, the flammability limits depend on temperature. They also change as more inert gases are added.

The assumptions for the flammability limits can be based on figure 5 for the cold experiments and on figure 7 for the hot experiments.
The flammability limits can be assessed in combination with the inert point (the third criterion, see below). This is because the UFL and LFL are basically at the same point for a concentration of inert gas.

1.6.2 Minimum oxygen concentration (LOC)
The second criterion is the LOC value. This value represents the minimum oxygen concentration where ignition can still take place. The mixture cannot ignite at values below this value. If nitrogen is the inert gas, the LOC value for propane is 11.6% (ambient temperature), see table 7. The LOC value for propane with water vapour as the inert gas is 11.5% (at 200 ºC).

1.6.3 Inert point (IP)
The third criterion is the inert point (IP) where total inertness of the fuel mixture is reached, regardless of fuel or oxygen percentages. This minimum inert concentration can be indicated as a volume percentage of inert gas. If sufficient inert gas is added to a flammable mixture, the critical AFT cannot be achieved. This means that the heat production of the flame is lower than the heat losses for heating inert gases. As a result, the flame will not be able to sustain itself and no ignition will take place. The exact inert point of different inert gases is not known for propane. The publication by Giurcan (Giurcan, 2013) suggests that the following volume percentages can be assumed, see also figures 5 to 7.

Table 8: Volume percentages

Inert gas	Volume percentage [%]
Water vapour (373 K)	38.1 [1]
Water vapour (473 K)	42.3 [2]
Nitrogen (298 K)	41.6 [2]

[1]   (Zabetakis, 1965)
[2]   (CHEMSAFE, 2009)

2 Research method

2.1 General description

The research method chosen is an experiment. Two experiments are distinguished here:
> experiments with cold gases in a 'desktop flashover cabinet'
> experiments with hot gases in a self-built desktop flashover vessel.

2.1.1 Experiment with cold gases

Desktop flashover cabinets are used in firefighter training courses in order to simulate phenomena such as smoke gas ignition. The desktop flashover cabinet is easy to operate and suitable for creating a similar situation several times. The results are reproducible.

The experiments used the desktop flashover cabinet shown in illustration 1. Its operation is as follows: a flammable gas mixture is introduced into the cabinet. Next, water mist, steam or nitrogen are added for a certain number of seconds. The fan is running throughout the experiment ensuring that the gases in the cabinet are well mixed. The cabinet has a remotely operated ignition mechanism. After a pre-determined amount of water mist, steam or nitrogen has been added, the mixture is ignited. If the concentration of the mixture is still within the flammability limits, there will be an ignition. If the composition of the flammable gases has changed to such an extent that the concentrations are beyond the flammability limits, there will not be any ignition. There is a door on one side of the desktop flashover cabinet that enables water mist, steam or nitrogen to be introduced into the cabinet.

Illustration 1: The desktop flashover cabinet

The cubic capacity of the desktop flashover cabinet used is 116 litres.

2.1.2 Experiments with hot gases

A desktop flashover vessel was designed for the experiments with hot gases. This desktop flashover vessel resembles the desktop flashover cabinet that was used in the experiments with cold gases, but contrary to the cabinet, the vessel enables the gas mixture to be heated (see illustration 2).

Illustration 2: Desktop flashover vessel with the burner in the right-hand bottom corner

As in the experiments with the cold gases, a flammable gas mixture is introduced first. This mixture is then heated to the desired temperature of approx. 225 °C using a burner in the lower part of the vessel. Next, water mist or steam is added for a certain number of seconds. The fan is running throughout the experiment ensuring that the gases in the cabinet are mixed well. The cabinet has a remotely operated ignition mechanism. The mixture is ignited after adding a pre-determined amount of water mist or steam. If the concentration of the mixture is still within the flammability limits, there will be an ignition. If the composition of the flammable gases has changed to such an extent that the concentrations are beyond the flammability limits, there will not be any ignition. The cubic capacity of the desktop flashover vessel used is 343 litres.

2.2   Justification of the study method chosen

The conditions were varied during the experiments by adding water mist, steam and nitrogen to the desktop flashover cabinet with the cold gases, and by adding water mist and steam to the desktop flashover vessel with the hot gases.

Water mist was chosen as this is one of the resources used by the fire service as part of its fire suppression techniques. Water can be sprayed into the layer of smoke gases as a mist to thus make optimum use of the cooling effect of water. The droplet size of the water mist is 3-8 micrometres. The smaller the droplet size, the greater the contact surface with the smoke gases and therefore the cooling capacity.

Steam was chosen for the fact that adding finely distributed droplets of water to smoke gases creates steam. At the same time, firefighters learn to limit the creation of steam since this may lead to undesired effects, such as burns, inconvenience and poor view. The amounts of water mist and steam were determined by weighing, using high-precision scales.

Finally, nitrogen, an inert gas, was chosen for the experiments with cold gases. This substance does not cool the smoke gases, but dilutes (inertises) them (Dutch Fire Service

Academy, 2017). Using nitrogen for inertisation is most commonly put into practice in the form of 'emergency inertisation systems', safety systems used in companies to prevent fire and explosions.

Propane was used as a flammable gas for both experiments. The propane gas was stored in a tank and was introduced into the desktop flashover cabinet at a pressure of 29 millibar. The tank features a 'flow meter' that enables the amount added per minute to be regulated.

Illustration 3: The propane gas tank with a flow meter

The water mist was produced using the equipment shown in illustration 4. The mist droplet size used was 3 to 8 micrometres.

Illustration 4: Water mist control box

The steam was produced using a Kärcher SC 3.

Illustration 5: The Kärcher SC 3

The amounts of water mist and steam were determined by weighing, using high-precision scales.

The nitrogen (N_2) was stored in the cylinder shown in illustration 6. The amount of nitrogen added can be controlled.

Illustration 6: Cylinder of nitrogen

2.3 Parameters

2.3.1 Temperature

Thermocouples were used for the temperature measurements. Two thermocouples were used for the experiments with cold gases: one at the top of the cabinet and one at the bottom. Four thermocouples were used for the hot experiments, spread throughout the vessel. Thermocouple 3 was used as the reference thermocouple.
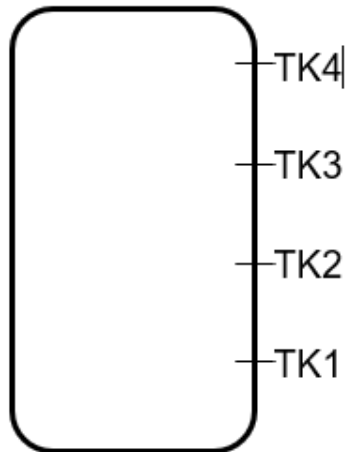
Illustration 7: Schematic presentation of the thermocouple positioning

2.3.2 Oxygen

The oxygen measurements were carried out using 'Testos'. The Testo is an emission analyser. The analysis box features six gas sensors for CO, NO, NO_2, SO_2, H_2S, C_xH_y and CO_2. The oxygen (O_2) content is specifically relevant for this experiment. Both setups, i.e. with the desktop flashover cabinet and the desktop flashover vessel, featured an opening, enabling a lance to be introduced into the cabinet or the vessel. This lance drew in the gas/air mixture which was then passed along a sensor. Figure 8 shows the Testo with a lance.

Illustration 8: Testo with a lance

2.4 Test protocol

Baseline measurements were first carried out in order to determine the amount of propane gas needed to produce an ideal (stoichiometric) gas mixture in the desktop flashover cabinet and the desktop flashover vessel. The flammability limits of propane are between 2 and 10 vol%. The baseline measurement was carried out five times. The ideal gas mixture was used in all experiments. After this, the leak tightness of both test setups was determined. For this

purpose, the gas mixture was introduced into the test setup. Then, after a five-minute waiting time, the Testos were used to continually measure the composition of the mixture.

To determine the amount of water mist or steam that was added per time unit, this was collected and measured by filling a layer of water into a plastic cup and determining its weight. Next, the hose used to introduce the water mist or steam into the vessel was placed in the bottle for 10 seconds, after which the weight was determined again. The increase in weight should then represent the amount of water mist or steam introduced into the test setup per 10-second time unit. This measurement was carried out five times after which the average value of the values measured was determined. This average value was used to determine the amount of water mist added per time unit.

The flow meter was set to 20 litres per minute for the experiments with nitrogen (only for the experiments with cold gases). The temperature of the water mist was equal to room temperature and the steam temperature was approx. 120 °C.

The experiments with the cold gases were prepared by first introducing the necessary amount of propane into the test setup, after which different amounts of water mist, steam or nitrogen were added. This sequence was also followed with the later experiments with the hot gases, but for the purpose of heating the gas, there was a 10-second waiting time here before adding the different amounts of water mist or steam. Attempts to ignite the mixture thus created were undertaken whenever a substance had been added. All experiments were carried out twice.

The experiments with hot gases required the gas mixture to be heated to approx. 225 °C before adding the different amounts of water mist or steam.

The following schedule was used for the experiments:

> adding water mist/steam or nitrogen for 10 seconds
> adding water mist/steam or nitrogen for 20 seconds
> adding water mist/steam or nitrogen for 30 seconds
> adding water mist/steam or nitrogen for 60 seconds
> adding water mist/steam or nitrogen for 120 seconds
> adding water mist/steam or nitrogen for 180 seconds
> adding water mist/steam or nitrogen for 240 seconds
> adding water mist/steam or nitrogen for 300 seconds

The temperature and oxygen contents were measured during the experiments.

Experiments with cold gases:
Based on the baseline measurement, it was determined that gas had to be added for 15 seconds for every experiment. The amount of propane gas added with every experiment was 32 litres per minute for 15 seconds, i.e. 8 litres of propane gas. These 8 litres of propane gas represented a 4.81 volume percentage relative to the desktop flashover cabinet with its cubic capacity of 166.44 litres (8/166.44 = 4.81) and it was therefore within the flammability limits (2 vol% - 9.5 vol%).

Experiments with hot gases:

Based on the baseline measurement, it was determined that gas had to be added for 50 seconds for every experiment. The amount of propane gas added was 31 litres/minute for 50 seconds, i.e. 25.8 litres of propane gas. The 25.8 litres of propane gas expressed as the volume percentage relative to the 343-litre desktop flashover vessel is 7.52 (25.8/343 x 100 = 7.52 vol%). This amount of propane gas is within the flammability limits (2% - 9%).

2.5 Quality of the study

2.5.1 Reliability
The baseline measurements to determine the right amount of gas were carried out five times. The actual experiments were carried out twice. The temperatures of the gas mixture with the hot gases varied between 200 and 250 °C.

2.5.2 Generalisability
The experiments used propane as a model for smoke gases. Since very many different flammable smoke gases occur in real-life situations, the results from the tests cannot be automatically translated into real-life situations. This will be addressed in more detail in the discussion.

3 Results

The sections below present the results of the experiments. A distinction is made here between the 'cold' and hot experiments. Given the large number of experiments conducted, and with an eye to the legibility of this report, it was decided to not present the extensive results here, but to provide tables of summaries. Annexes 2 and 3 show the extensive results of all experiments.

3.1 Cold situation experiments

3.1.1 Baseline measurement

Propane gas

The amount of propane is a function of time. How long the gas had to be added for a flammable mixture to be created in the desktop flashover cabinet was determined in advance. 8 litres of propane gas were used in these experiments, equalling a 4.81 volume percentage which is within the flammability limits (2 vol% - 9.5 vol%).

Inert gases

Some baseline measurements were carried out in order to be able to determine the amounts of inert gases added. Five measurements were carried out, both for water mist and steam, in the form of weighing to determine the decrease in mass during a 10-second time unit. The average value of these five measurements was assumed as the average mass decrease per second. The table below features the measurement results and the average. The rest of this report is based on these averages.

Table 9: Measurement results for the amount of water mist/steam per 10-second time unit

	Test 1 [gr]	Test 2 [gr]	Test 3 [gr]	Test 4 [gr]	Test 5 [gr]	Average [gr/s]
Water mist	15	13	14	14	14	1.4
Steam	9	7	9	9	9	0.86

Nitrogen was added through a cylinder that could be set to a specific flow rate; here 20 l/minute.

3.1.2 Experiments conducted

TableTable 10: Inert substances/gases added per time unit' shows a summary of the experiments conducted and the inert gases added.

Table 10: Inert substances/gases added per time unit

Time [s]	Steam [gr]	Water mist [gr]	Nitrogen [l]
10	8.6	14	3.3
20	17.2	28	6.6
30	25.8	42	10
60	51.6	84	20
120	103.2	168	40
180	X	252	60
210	X	X	70
240	X	X	80
300	258	420	X

The sections below summarise the results of the experiments with steam, mist and nitrogen. The extensive results of all experiments can be found in annex 3.

Both when steam and when nitrogen were added, the volume percentages of the gases present in the desktop flashover cabinet were determined on the basis of a volume balance. Further explanations of the volume balance, preconditions and assumptions are given in annex 5.

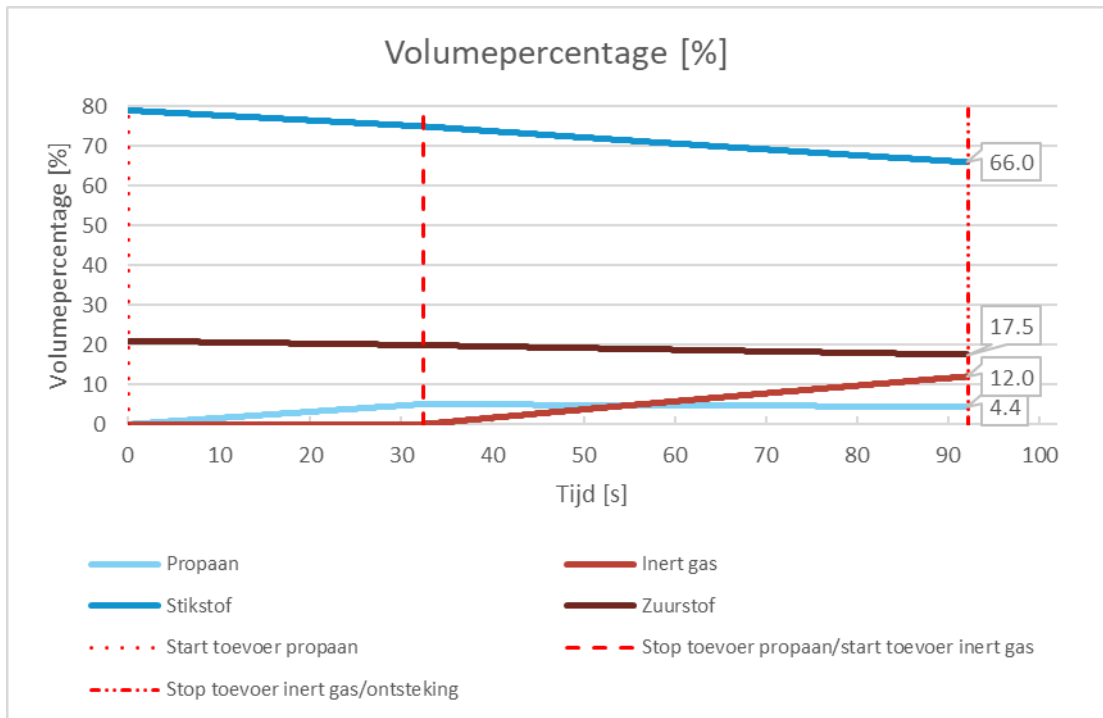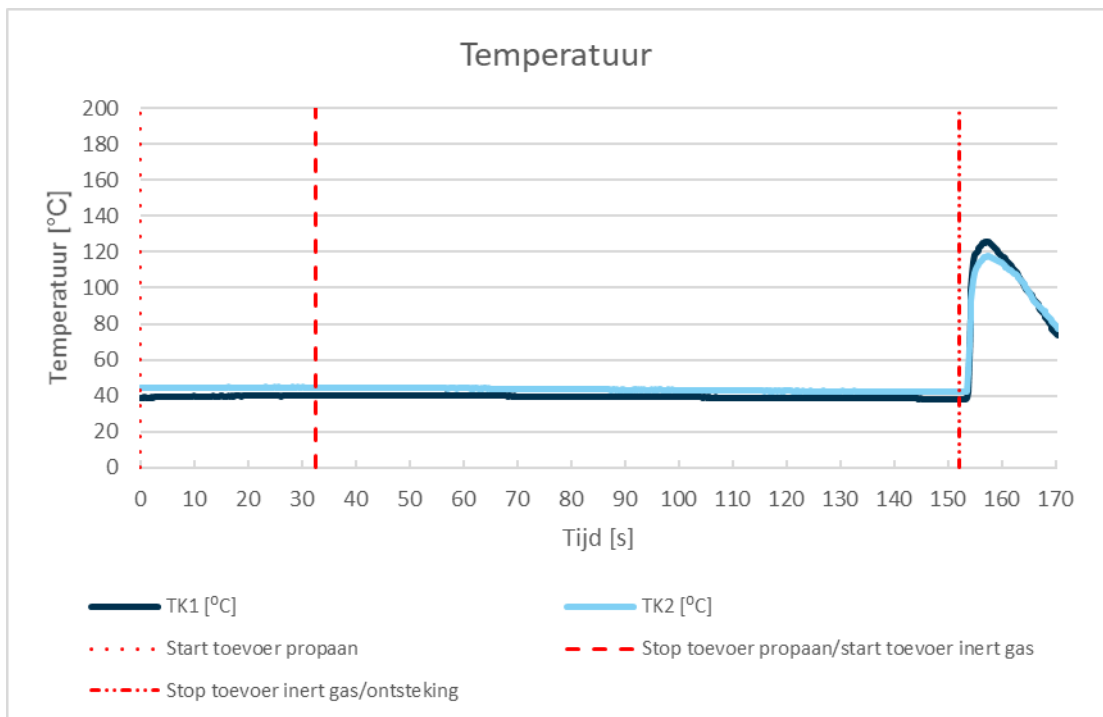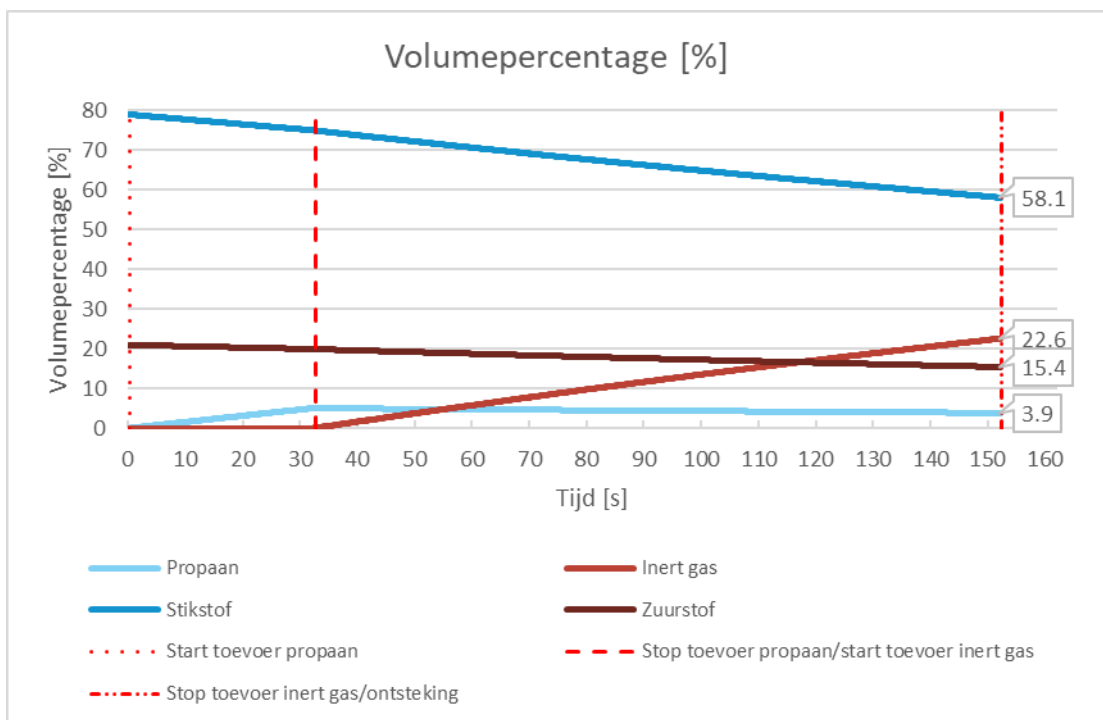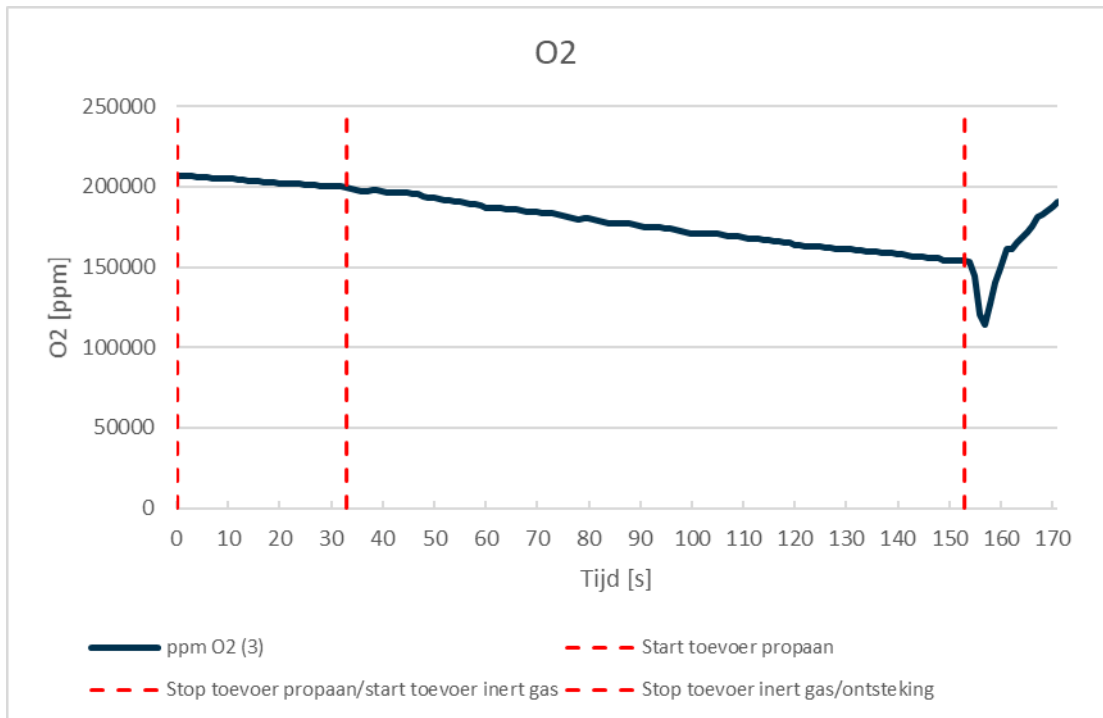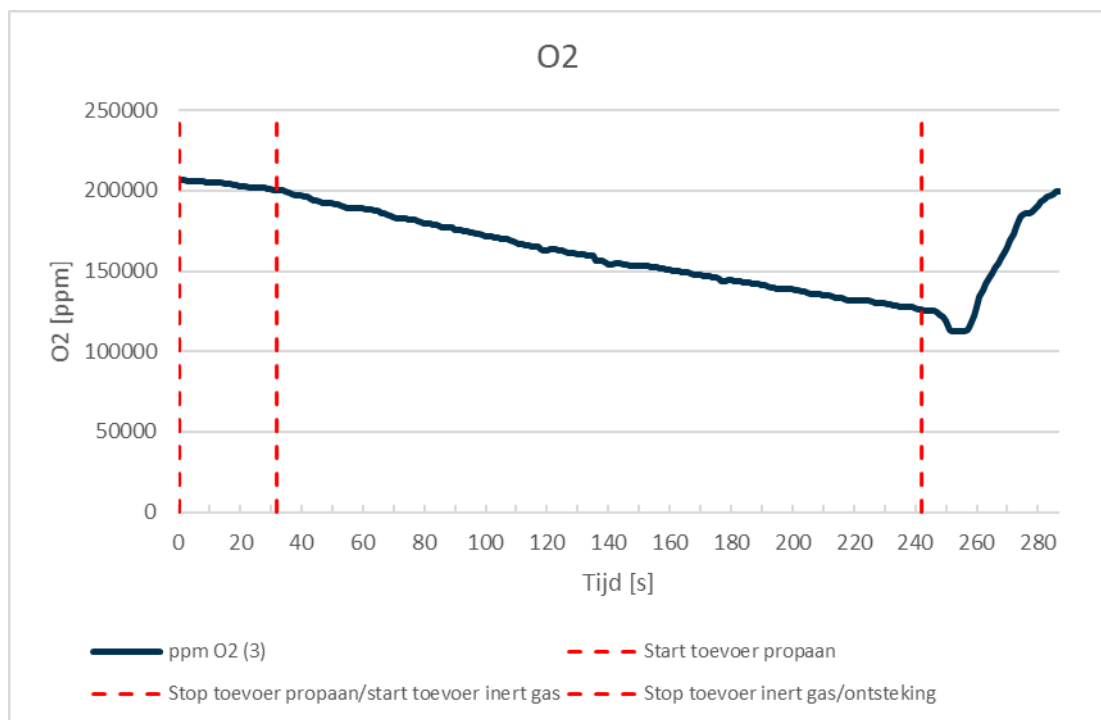### 3.1.3 Summary of the results for steam

Figure 9: Added for 60 seconds

Temperatuur
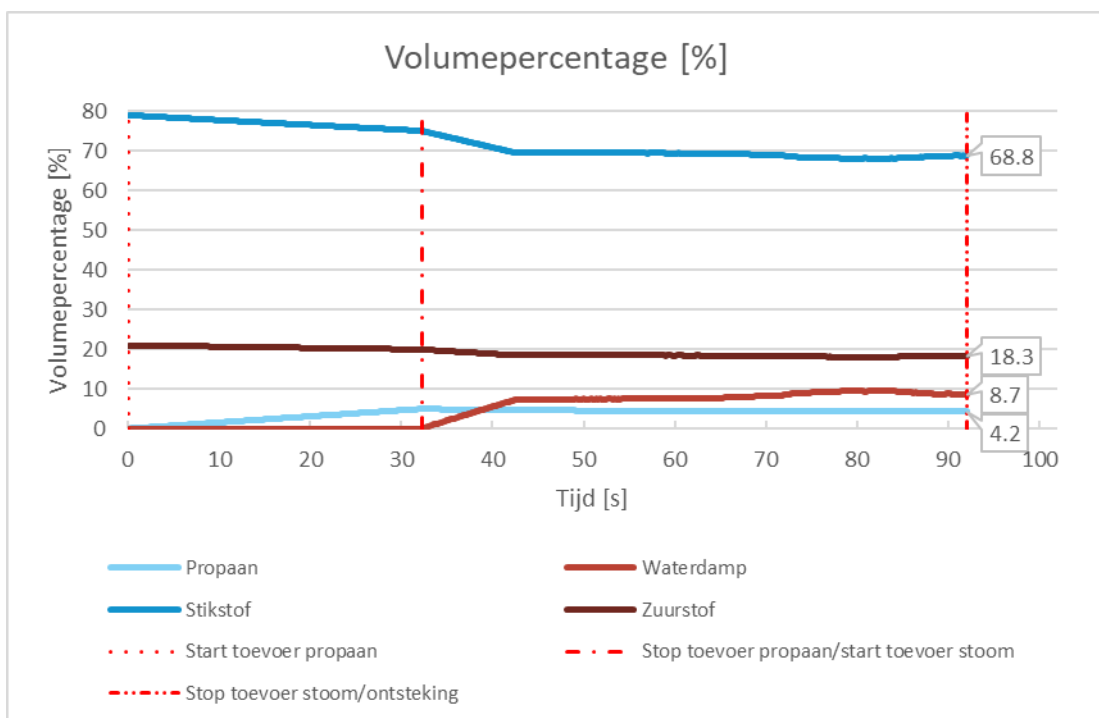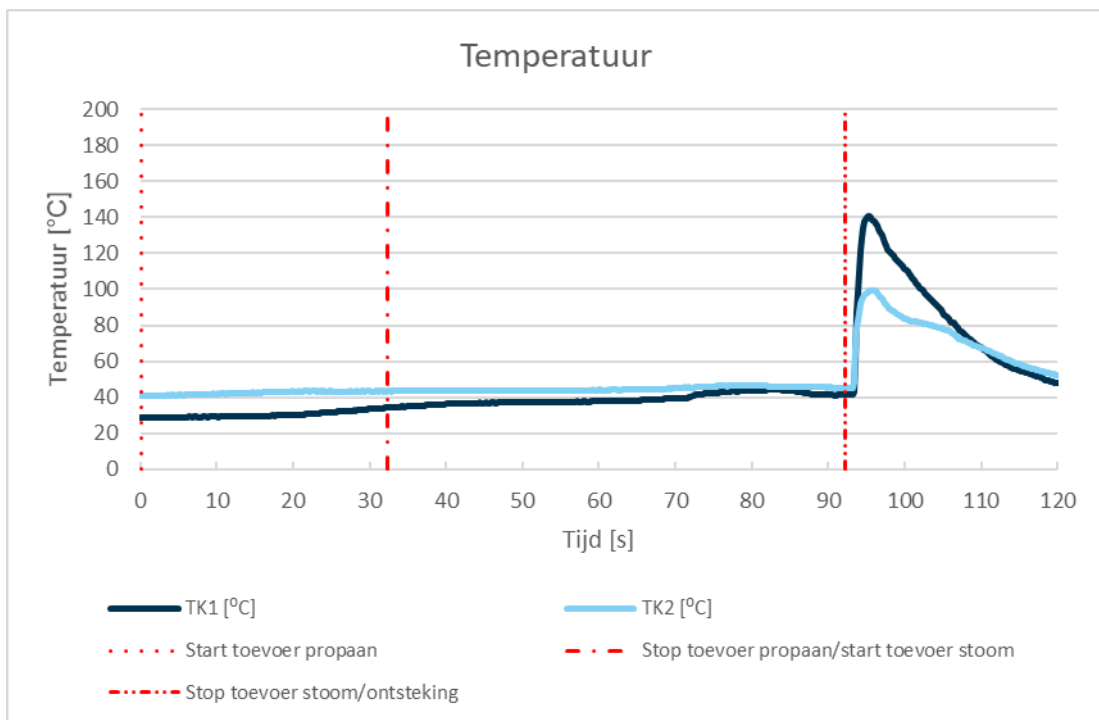
Volumepercentage [%]

Figure 10: Added for 120 seconds
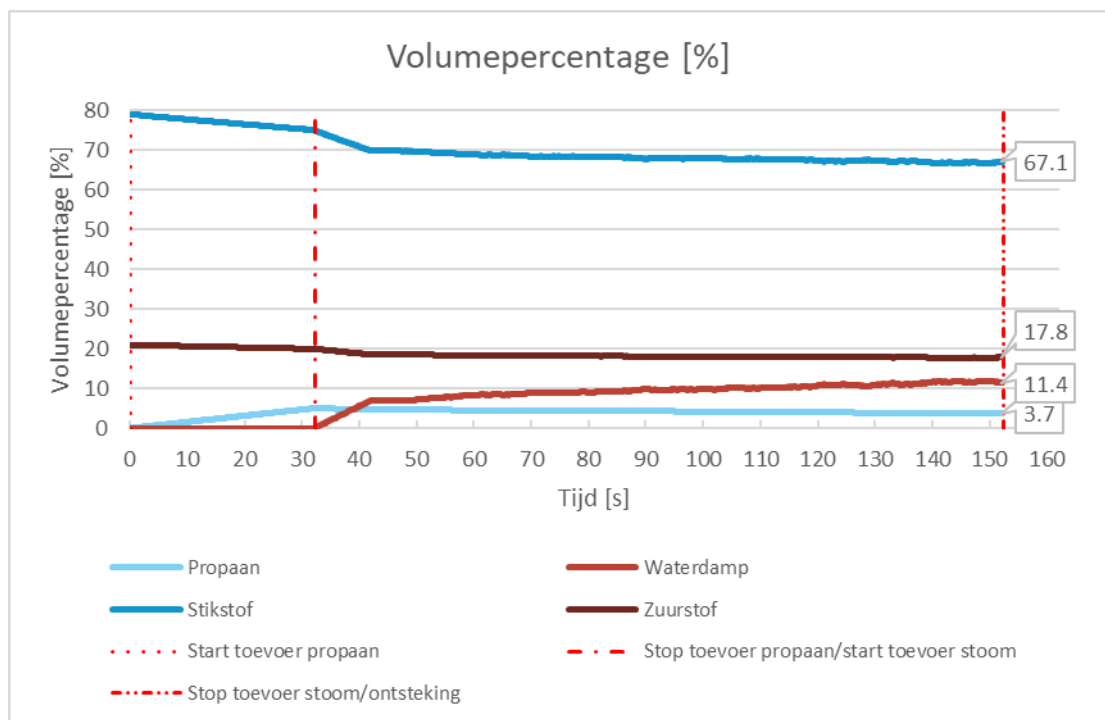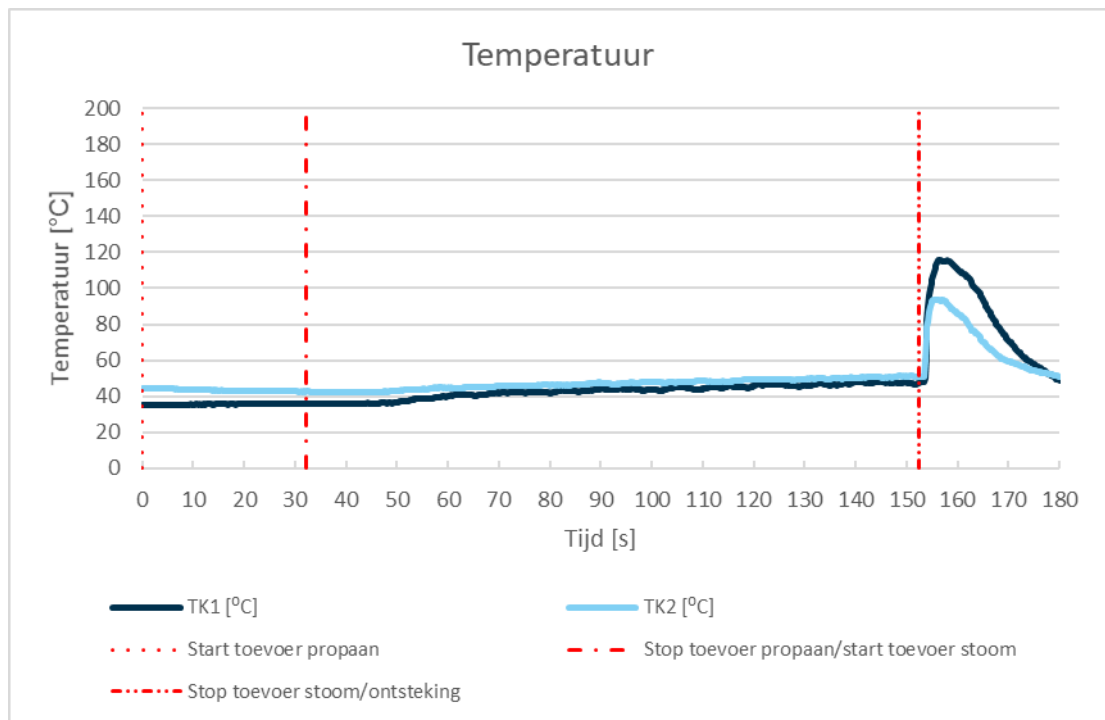
Figure 11: Added for 300 seconds

Temperatuur
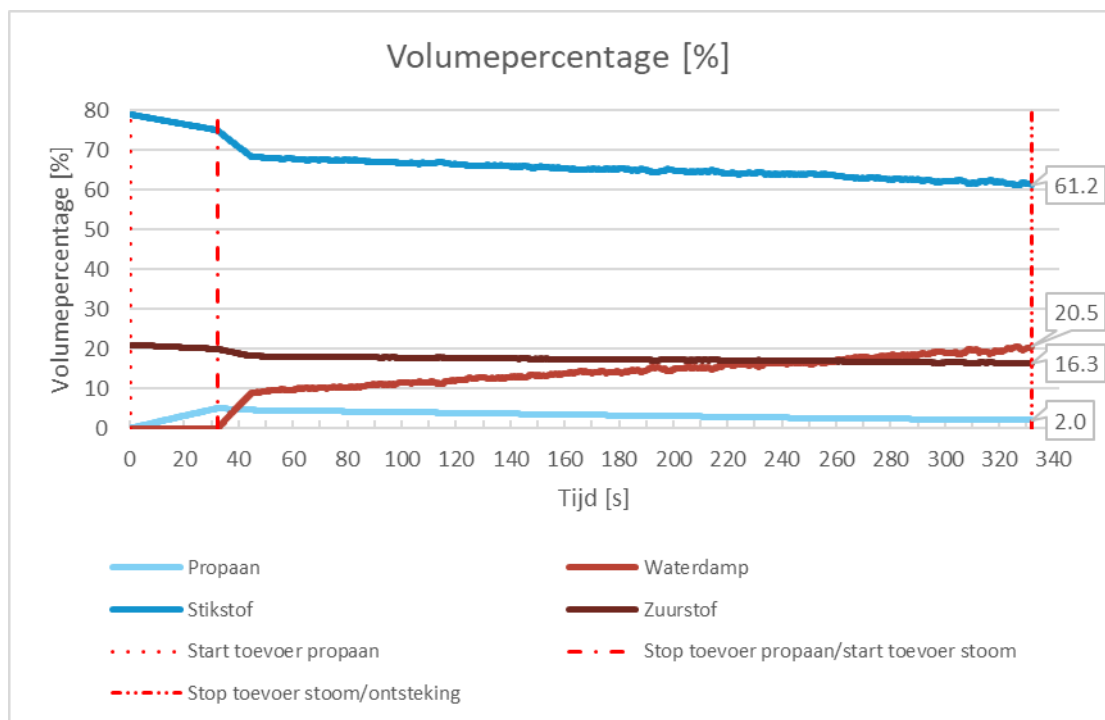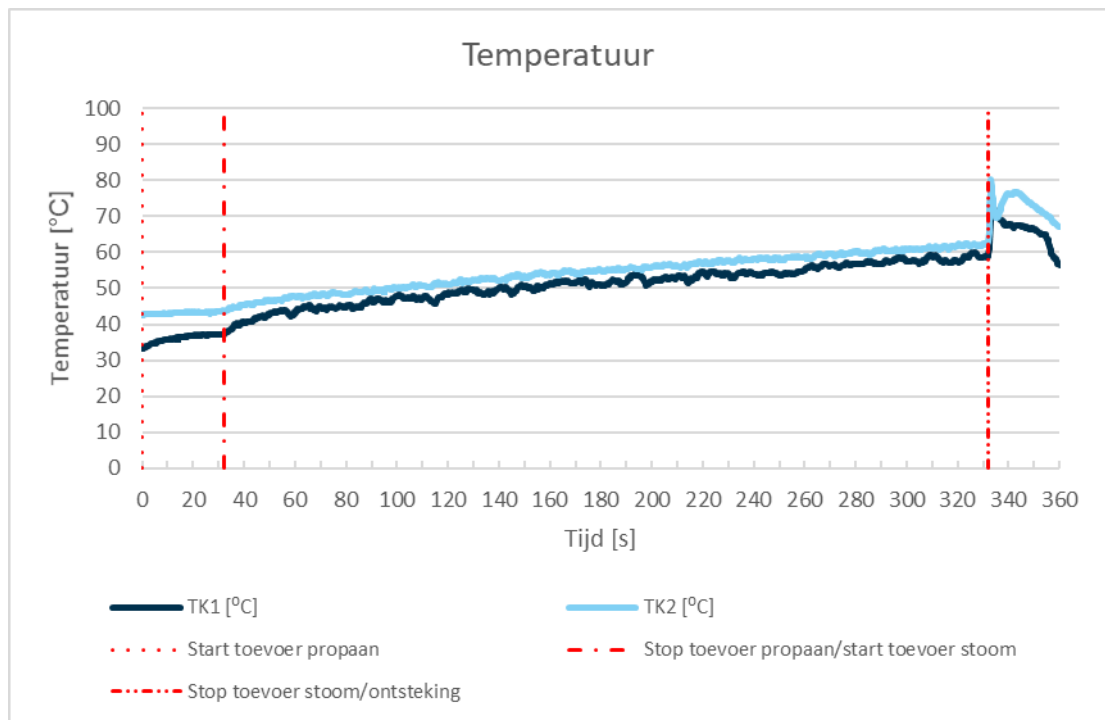
Volumepercentage [%]

Overview

Table 11: Summary of the measurement results for steam with cold gases

Supply time [s]	Volume percentage [%]			Ignition [-]	Temperature [ºC] [2]	
	Oxygen	Water vapour	Propane		Max. after explosion	Difference
0	20	0	4.8	-	-	-
10	19.3	3.5	4.6	Yes	144	120
20	18.7	6.2	4.6	Yes	149	115
30 [1]	18.4	7.9	4.5	Yes	150	110
60	18.3	8.7	4.2	Yes	145	102
120 [1]	17.6	12.5	3.6	Yes	122	74
300 [1]	16.4	19.7	2.3	Yes	78	20

[1] Due to a measuring error, the volume balance could only be determined in one case of these experiments.

[2] The maximum temperature and the temperature difference were determined on the basis of thermocouple 1.

Figure 12: Average volume percentages (%)

Gemiddelde temperatuur
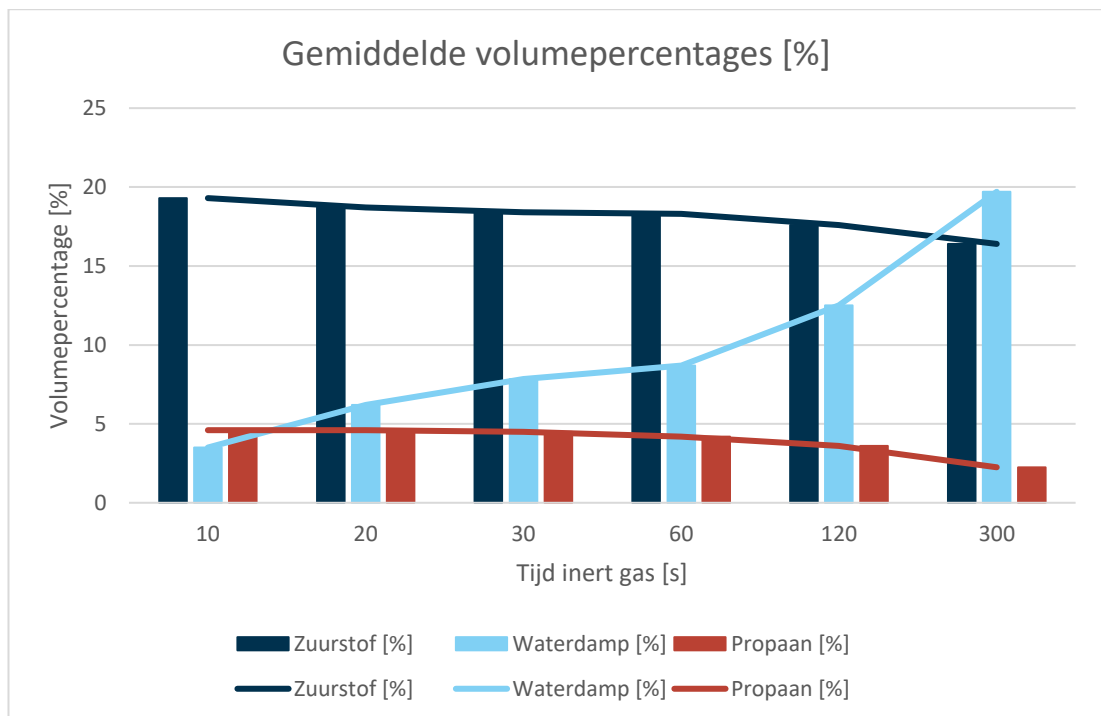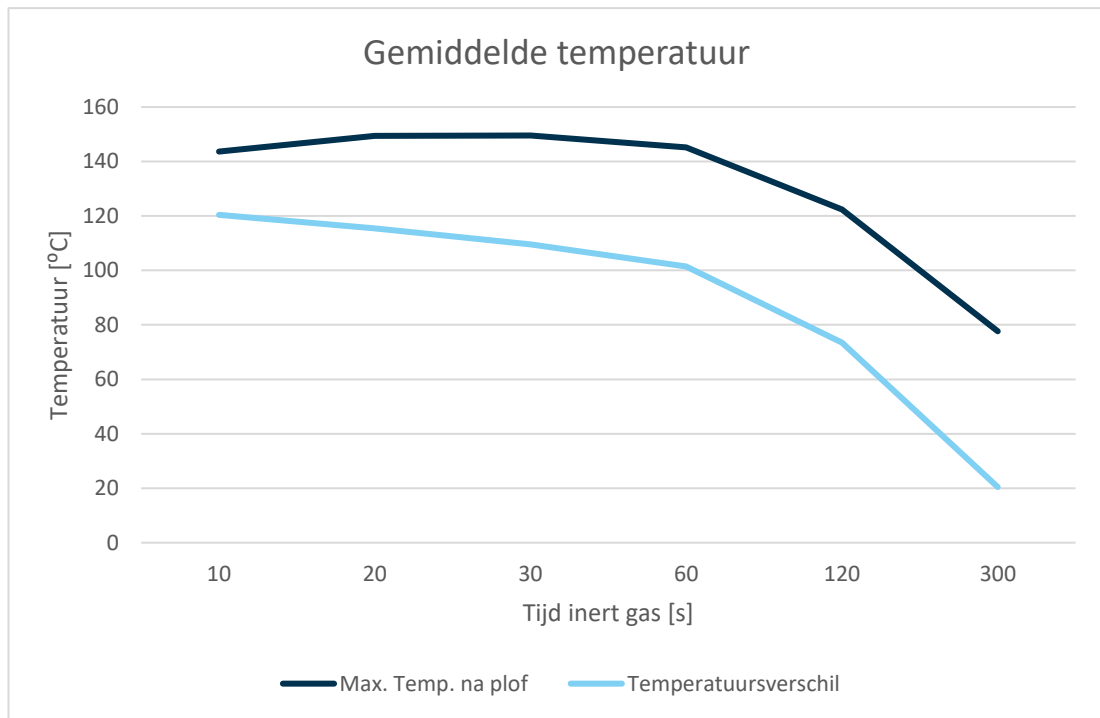
The results showed the following:

> There was ignition in all experiments.
> The volume percentage of propane gas was 4.8% before adding steam and it was at least approximately 2.0% (after adding steam for 300 seconds).
> The volume percentage of oxygen was 20% before adding steam and was at least approximately 16.4% (after adding steam for 300 seconds).
> The maximum volume percentage of water vapour was 19.7% (adding steam for 300 seconds).
> The maximum temperature after ignition was virtually equal for the first experiments (steam added for 10 to 60 seconds), i.e. between 140 ºC to 150 ºC. When steam was added for 120 seconds and for 300 seconds, the maximum temperature after ignition was lower (between 122 ºC and 78 ºC).
> The temperature difference between the values before and during the ignition decreased as more steam was added, from 120 ºC to a minimum value of 20 ºC.

Furthermore, the theory from chapter 1 indicates that the amount of water vapour present is mainly determined by the saturation point of water vapour in the air, since the temperature is below the boiling point of water.

3.1.4 Summary of mist results

Figure 13: Added for 60 seconds
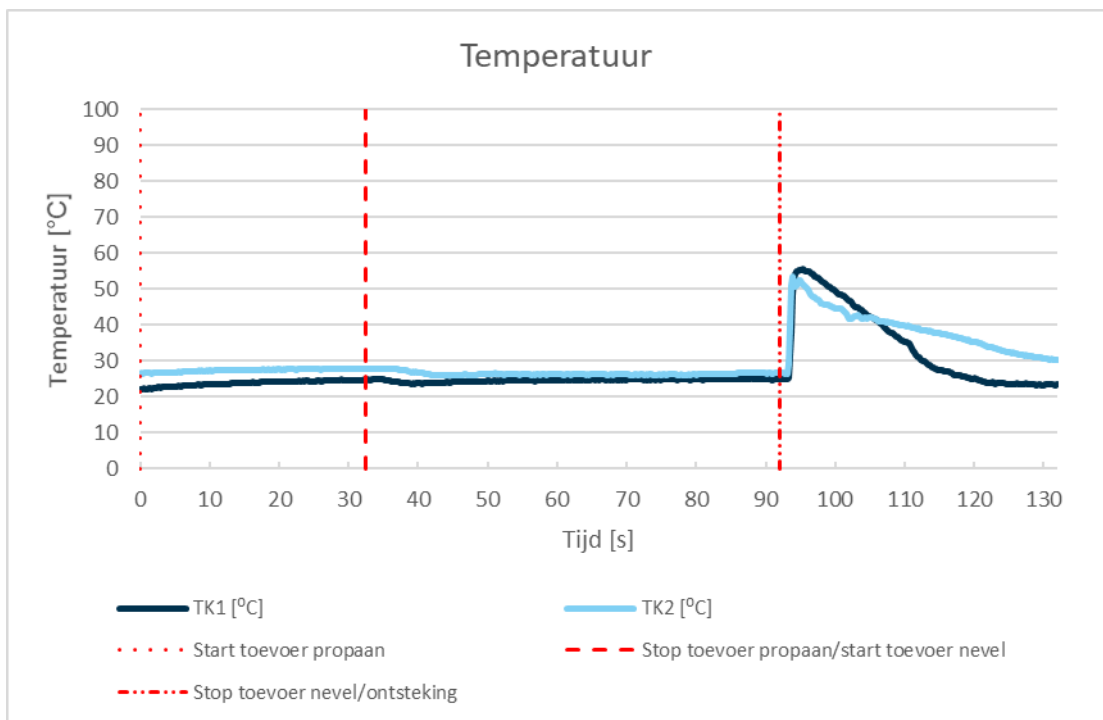
Figure 14: Added for 120 seconds
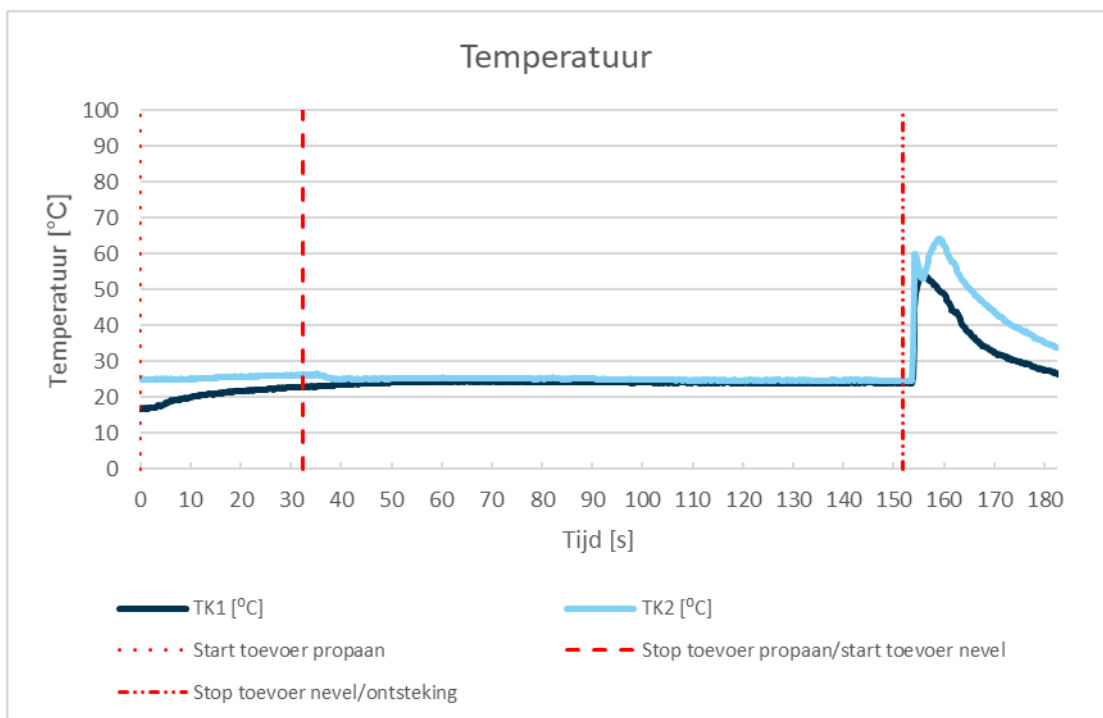
Figure 15: Added for 300 seconds
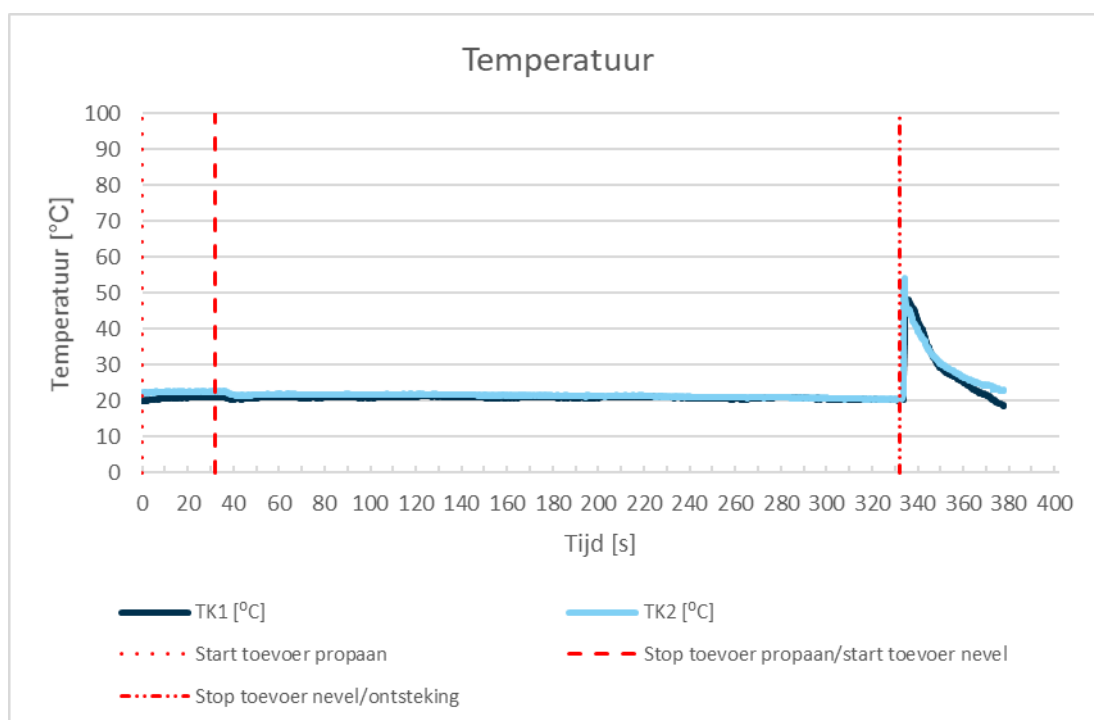
Overview

Table 12: Summary of the measurement results for water mist with cold gases

Supply time [s]	Volume percentage [%] [1)]			Ignition [-]	Temperature [ºC] [2)]	
	Oxygen	Water vapour	Propane		Max. after explosion	Difference
10	-	4.0	-	Yes	118	90
20	-	4.4	-	Yes	81	51
30	-	3.7	-	Yes	80	53
60	-	3.4	-	Yes	57	31
120	-	3.1	-	Yes	54	29
300	-	2.5	-	Yes	49	28

[1] The volume balance could not be determined exactly, as it was not clear how much water mist was actually converted into water vapour. The volume percentages of water vapour included here were determined on the basis of the saturation point.

[2] The maximum temperature and the temperature difference were determined on the basis of thermocouple 1.

Figure 16: Average temperature
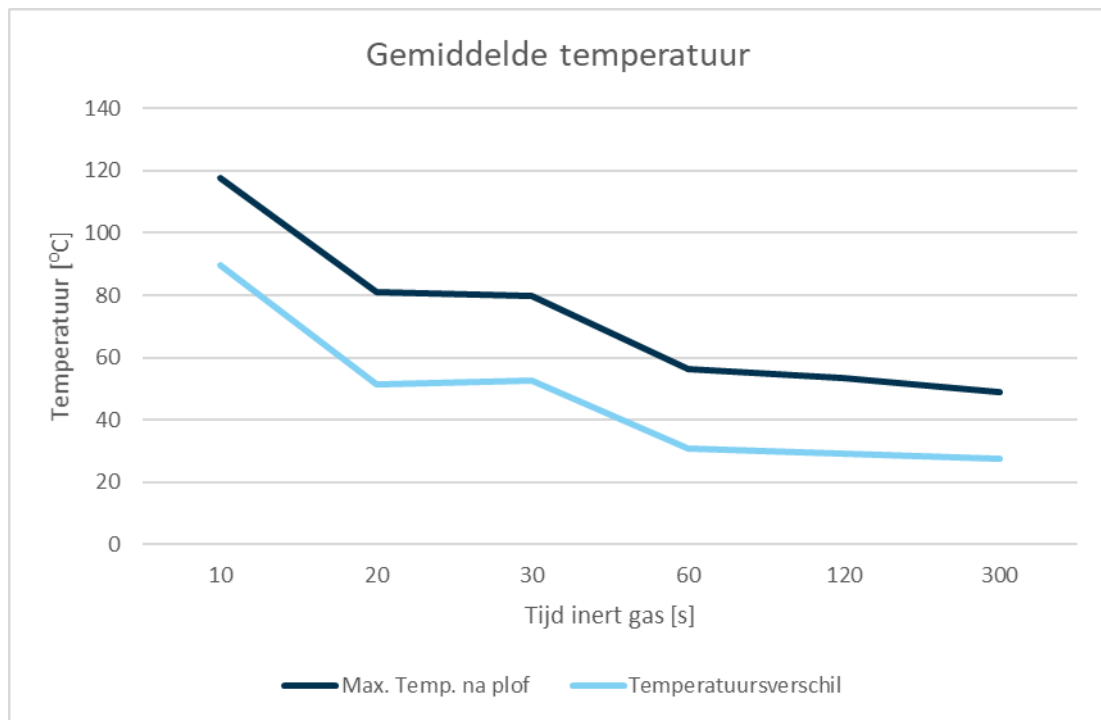
The results show the following:
> There was ignition in all experiments.
> As the temperature was below the boiling point of water, the amount of water vapour present was determined by the saturation point of water vapour in the air.
> The maximum volume percentage of water vapour was 4.4% (adding mist for 20 seconds) and the minimum volume percentage was 2.5% (adding mist for 300 seconds).
> The volume percentages of propane and oxygen were not known since it was not clear how much mist was converted into water vapour. However, based on the volume percentage of water vapour (saturation point) and the ignition, the volume percentages of propane and oxygen were expected to be between 3 to 5% and 19 to 20% respectively.
> The maximum temperature after ignition decreased as more mist was added from approximately 118 ºC to a minimum value of 49 ºC.
> The temperature difference between the values before and during the ignition decreased as more steam was added, from approx. 90 ºC to a minimum value of 28 ºC.

3.1.5 Summary of the results for nitrogen

Figure 17: Added for 60 seconds
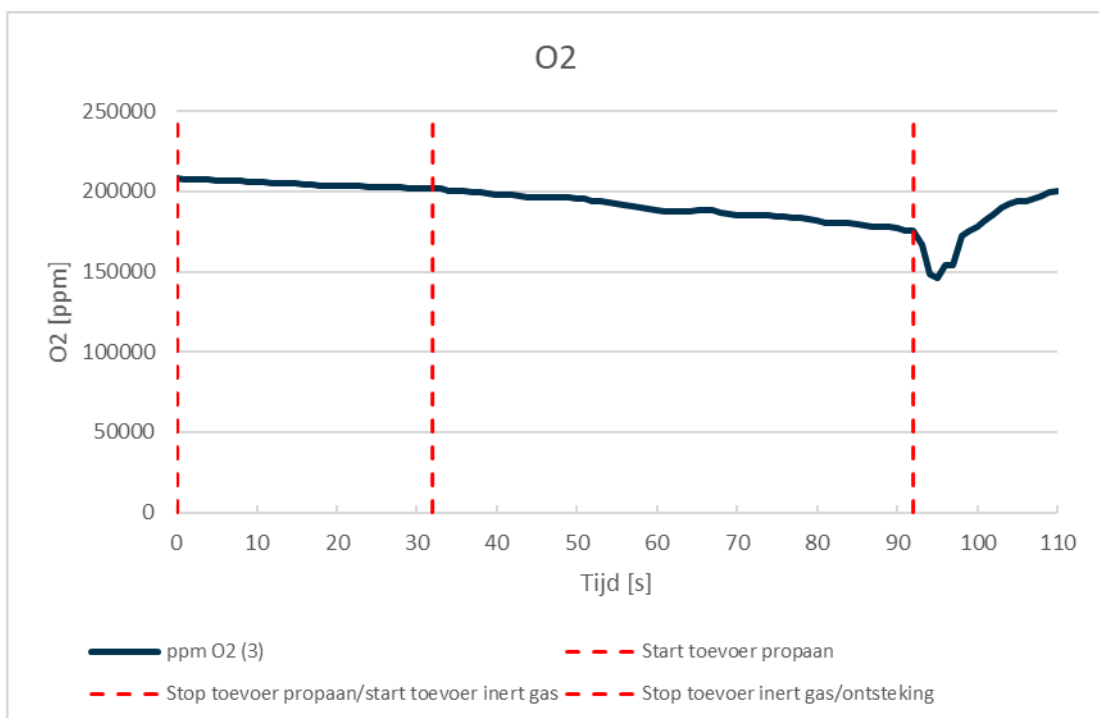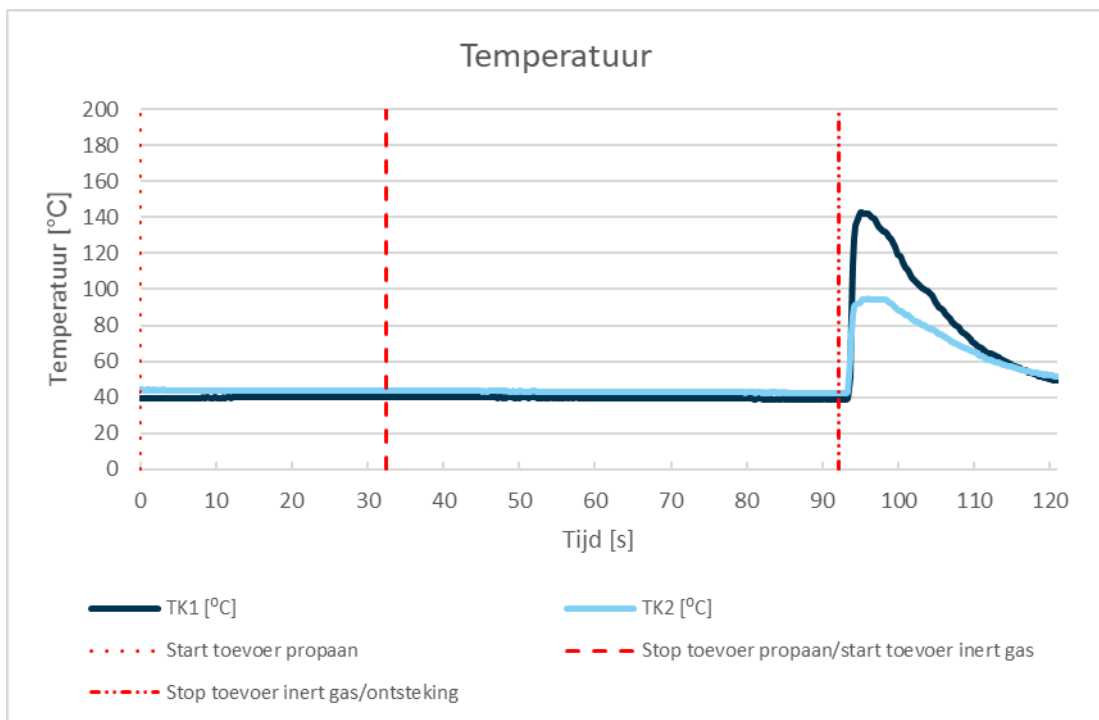
Figure 18: Added for 120 seconds

O2

Volumepercentage [%]

Figure 19: Added for 210 seconds

Temperatuur

O2
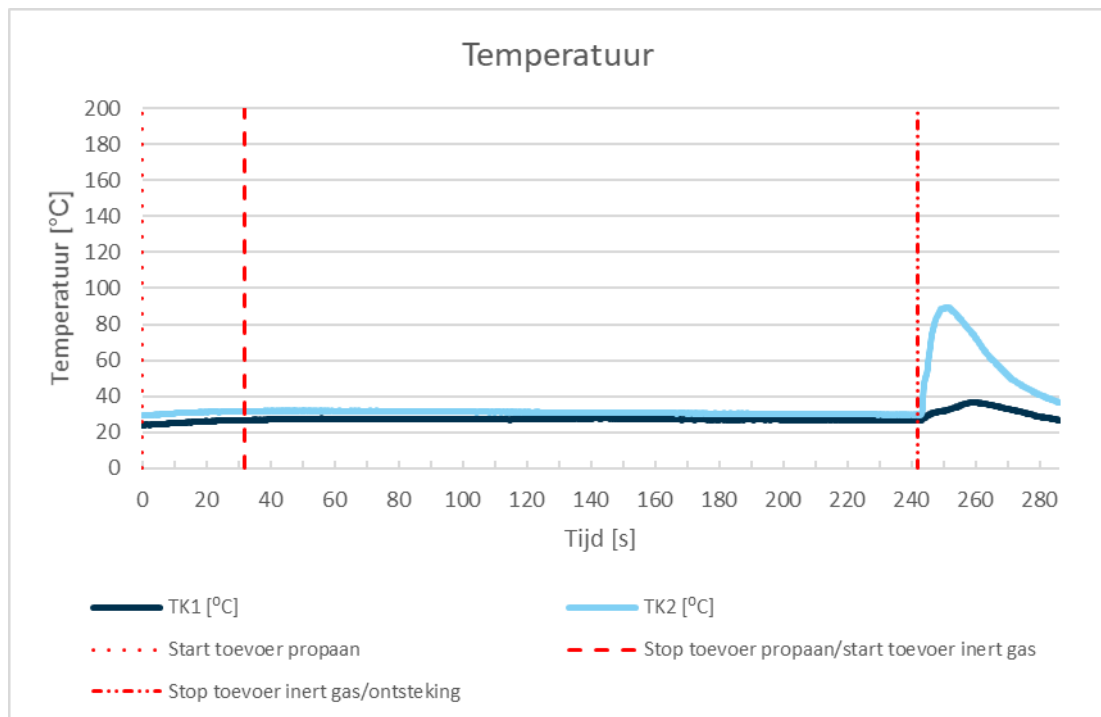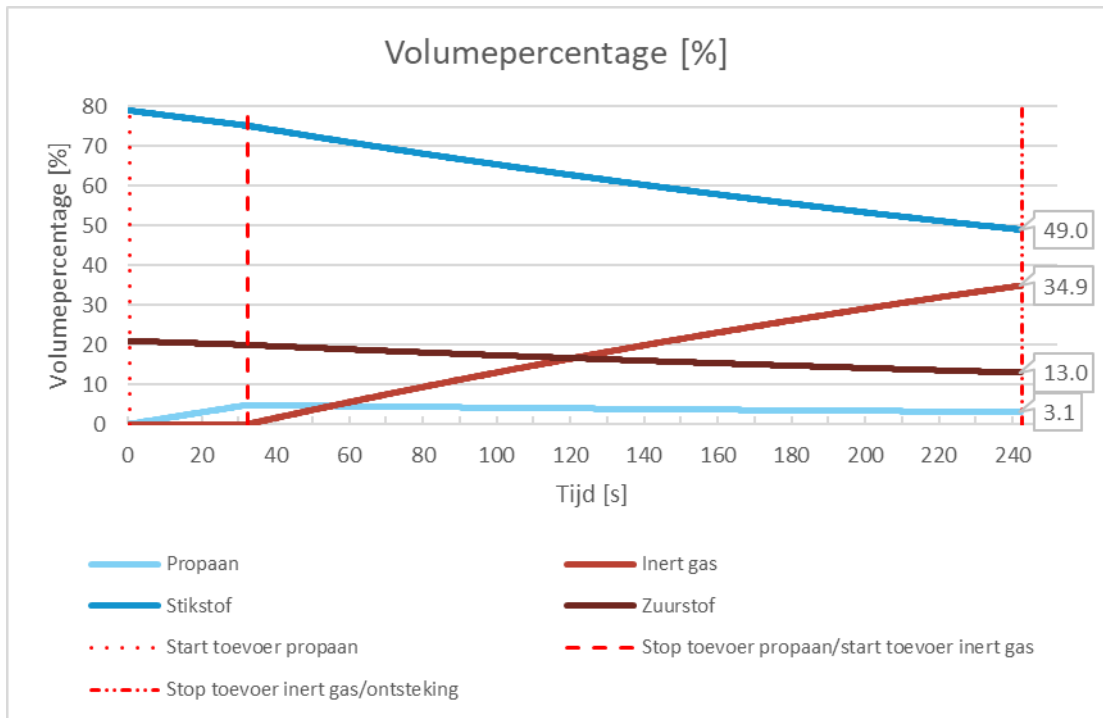
Figure 20: Added for 240 seconds

O2
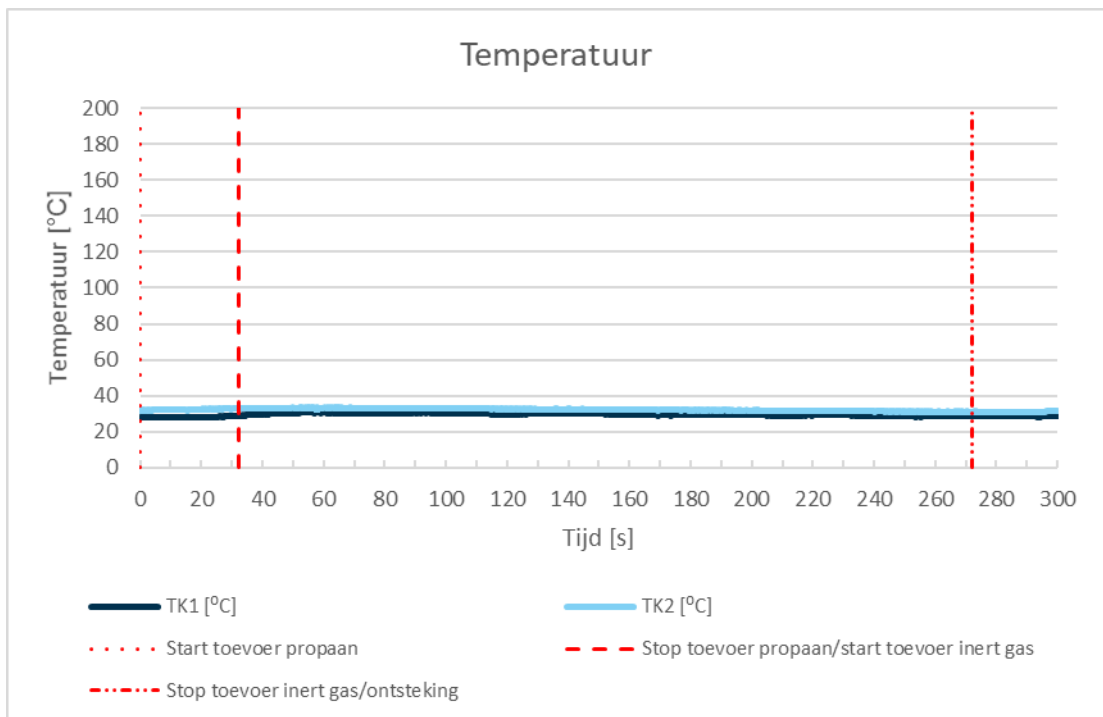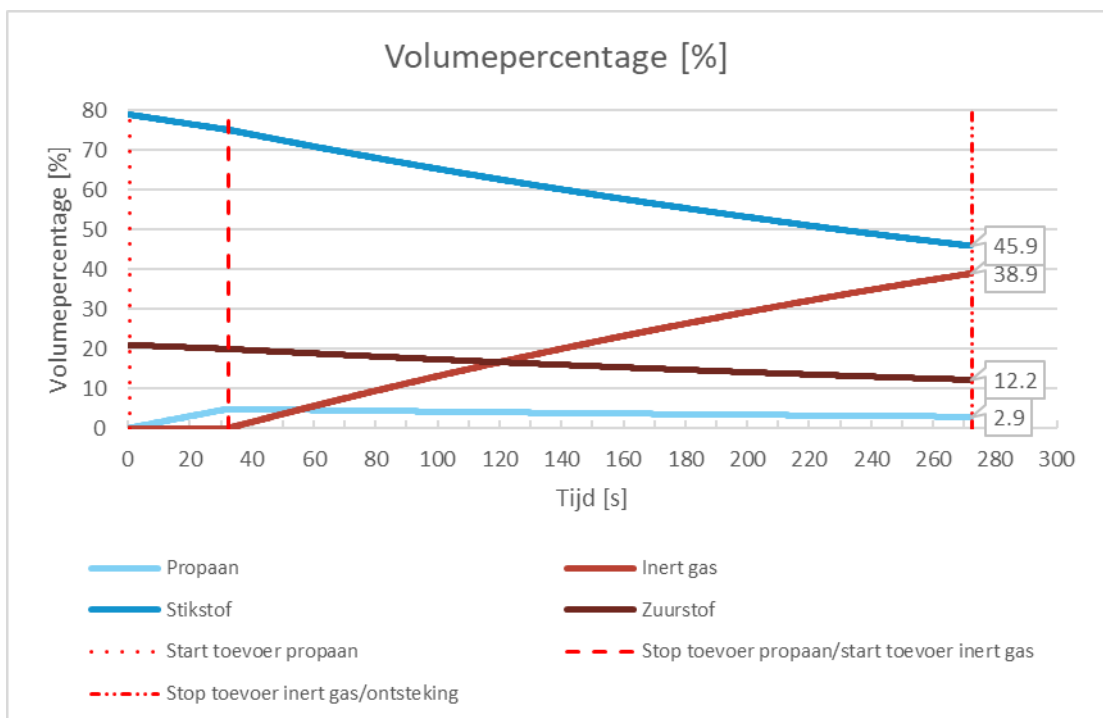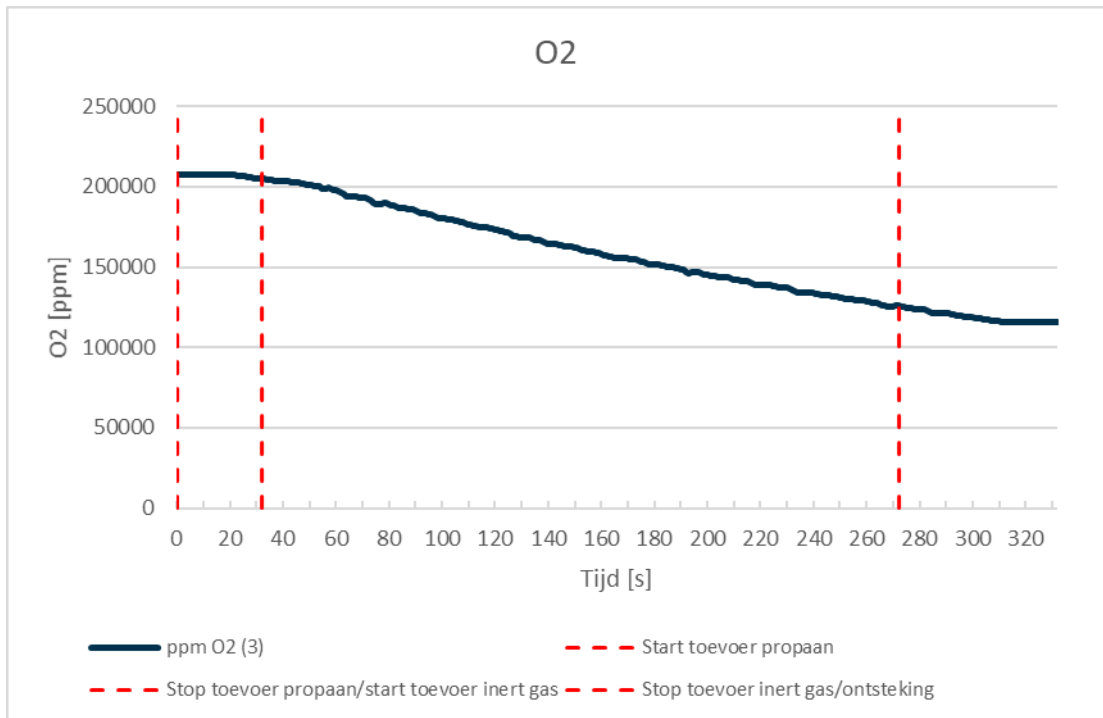
Volumepercentage [%]

Overview

Table 13: Summary of the results for nitrogen with cold experiments

Supply time [s]	Volume percentage [%]			Ignition [-]	Temperature [ºC] [2]	
	Oxygen	Nitrogen	Propane		Max. after explosion	Difference
10	19.6	2	4.8	Yes	145	115
20 [1]	19.1	4.1	4.8	Yes	140	105
30 [1]	18.7	6.1	4.7	Yes	147	110
60 [1]	17.5	12	4.4	Yes	131	91
120 [1]	15.4	22.6	3.9	Yes	134	94
180 [1]	13.6	32	3.4	Yes	149	107
210 [1]	13	34.9	3.1	Yes	36	8
240 [1]	12.2	38.9	2.9	No	-	-

[1] For these experiments, the volume balances could only be determined for one of the two experiments.

[2] The maximum temperature and the temperature difference were determined on the basis of thermocouple 1.

Figure 21: Average volume percentage (%)

Gemiddelde temperatuur
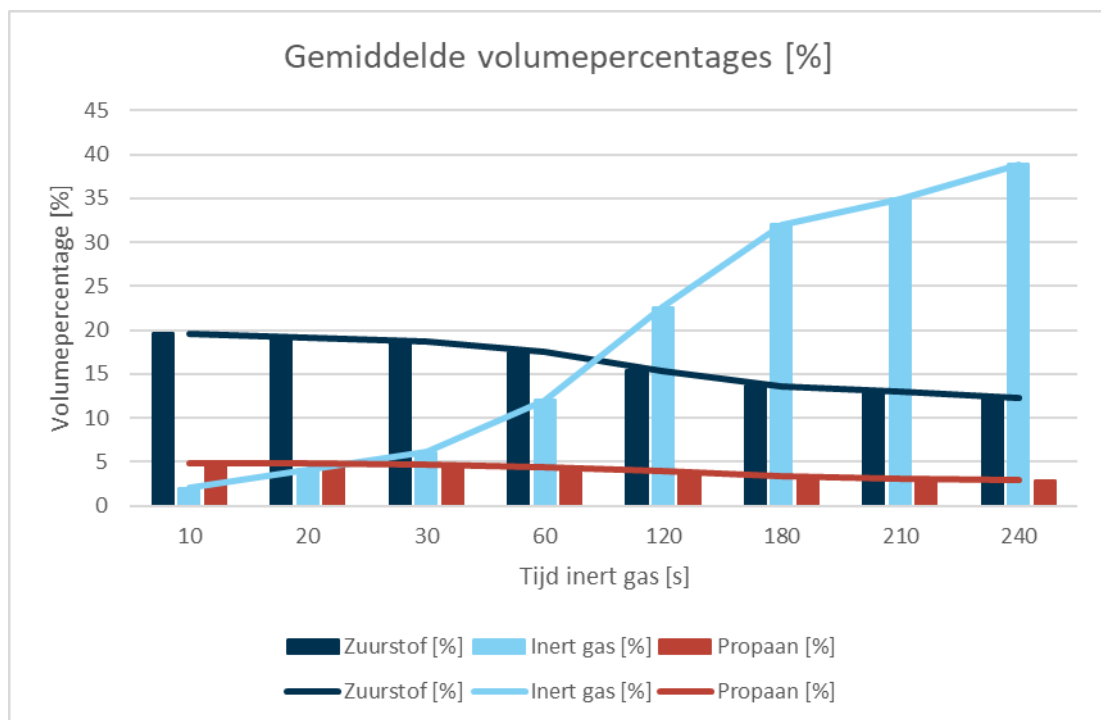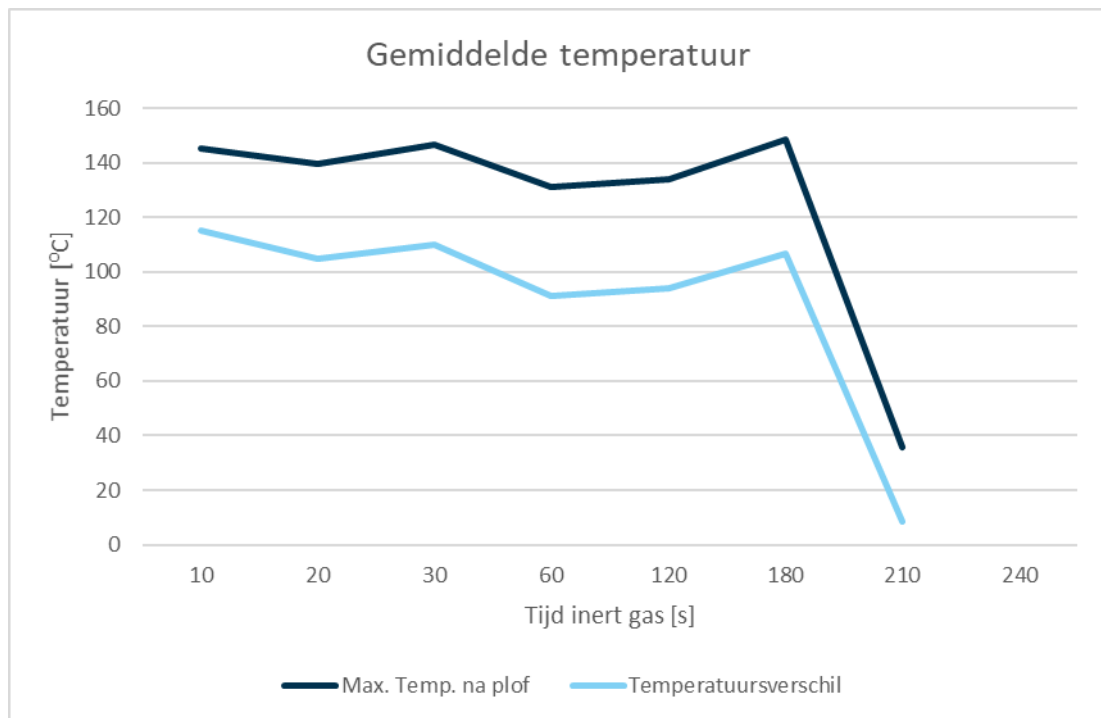
The results show the following:

> No ignition took place if nitrogen was added for 240 seconds. There was ignition in all other experiments.
> The volume percentage of propane gas was 4.8% before adding steam and was at least approximately 2.9% (after adding nitrogen for 240 seconds).
> The volume percentage of oxygen was 20% before adding steam and was at least approximately 12.2% (after adding nitrogen for 240 seconds).
> The maximum volume percentage of nitrogen was 38.9% (after adding nitrogen for 240 seconds).
> The maximum temperature after ignition was virtually equal for the first experiments (nitrogen added for 10 to 180 seconds), i.e. between 130 ºC to 150 ºC. When nitrogen was added for 210 seconds, the maximum temperature after ignition was lower (36 ºC).
> The same applies to the temperature difference. The temperature difference in the first experiments was between 90 ºC and 110 ºC. When nitrogen was added for 210 seconds, the temperature difference was approximately 8 ºC.

3.1.6 Summary of the results of experiments with the cold situation

Table 14: Summary of results for experiments with the cold situation

Time [s]	Volume percentage [%]					
	Steam	Explosion	Mist	Explosion	Nitrogen	Explosion
10	3.5	Yes	4	Yes	2	Yes
20	6.2	Yes	4.4	Yes	4.1	Yes
30	7.9	Yes	3.7	Yes	6.1	Yes
60	8.7	Yes	3.4	Yes	12	Yes
120	12.5	Yes	3.1	Yes	22.6	Yes
180	-	-	-	-	32	Yes
210	-	-	-	-	34.9	Yes
240	-	-	-	-	38.9	No
300	19.7	Yes	2.5	Yes	-	-

The results show the following:
> An ignition occurred in all experiments where steam was added.
> An ignition occurred in all experiments where mist was added.
> In the experiments with nitrogen, ignition was prevented when nitrogen was added for 240 seconds (volume percentage of approx. 39%).

3.2 Hot situation experiments

3.2.1 Baseline measurement

Propane gas
Five measurements were conducted to determine the right amount of propane gas. It was important that there was still enough gas in the desktop flashover vessel after 300 seconds so that an ignition could be caused.

Table 15: Number of seconds of supplying propane

	Number of seconds of gas	Time of ignition	Explosion/no explosion
0-1-10	35	After 10 seconds	Yes
0-2-300	35	After 300 seconds	No
-	50	After 10 seconds	Yes
-	50	After 300 seconds	Yes
-	60	After 10 seconds	Yes

Inert gases

The assumptions included in section 3.1.1. were also applied to the addition of inert gases. This means a steam supply of 0.86 gr/s and a mist supply of 1.4 gr/s.

3.2.2 Experiments conducted

Table 16: Experiments conducted

Time [s]	Steam [gr]	Water mist [gr]
10	8.6	14
20	17.2	28
30	25.8	42
40	-	56
50	-	70
60	51.6	-
90	77.4	-
100	86	-
120	103.2	-

The sections below summarise the results of the experiments with steam and mist. The extensive results of all experiments can be found in annex 4.
Both when steam and when mist were added, the volume percentages of the gases present in the desktop flashover cabinet were determined on the basis of a volume balance. Further explanations of the volume balance, preconditions and assumptions are given in annex 5.

3.2.3 Summary of the results for steam

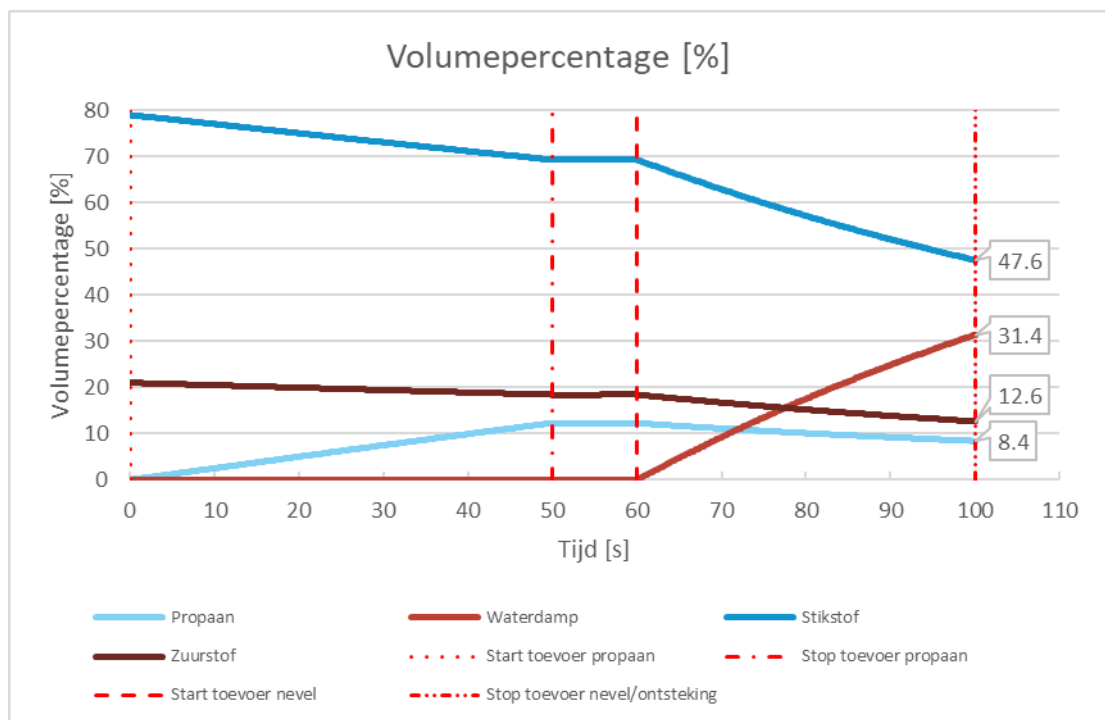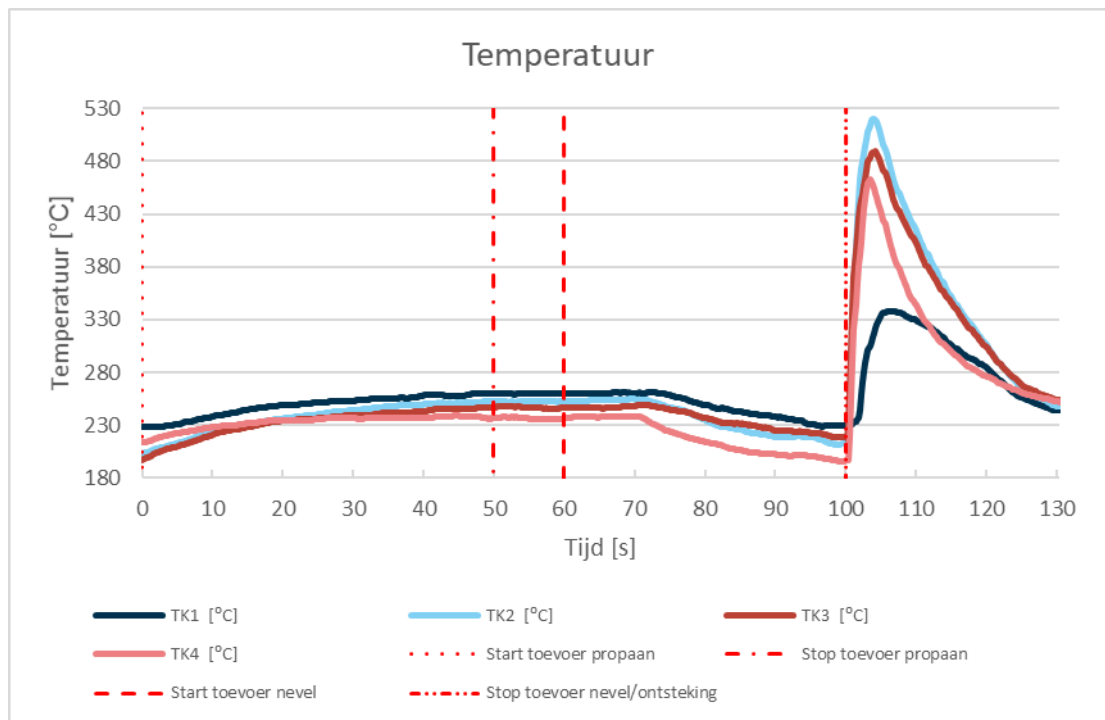**Figure 22: Test 8, 60-second supply**
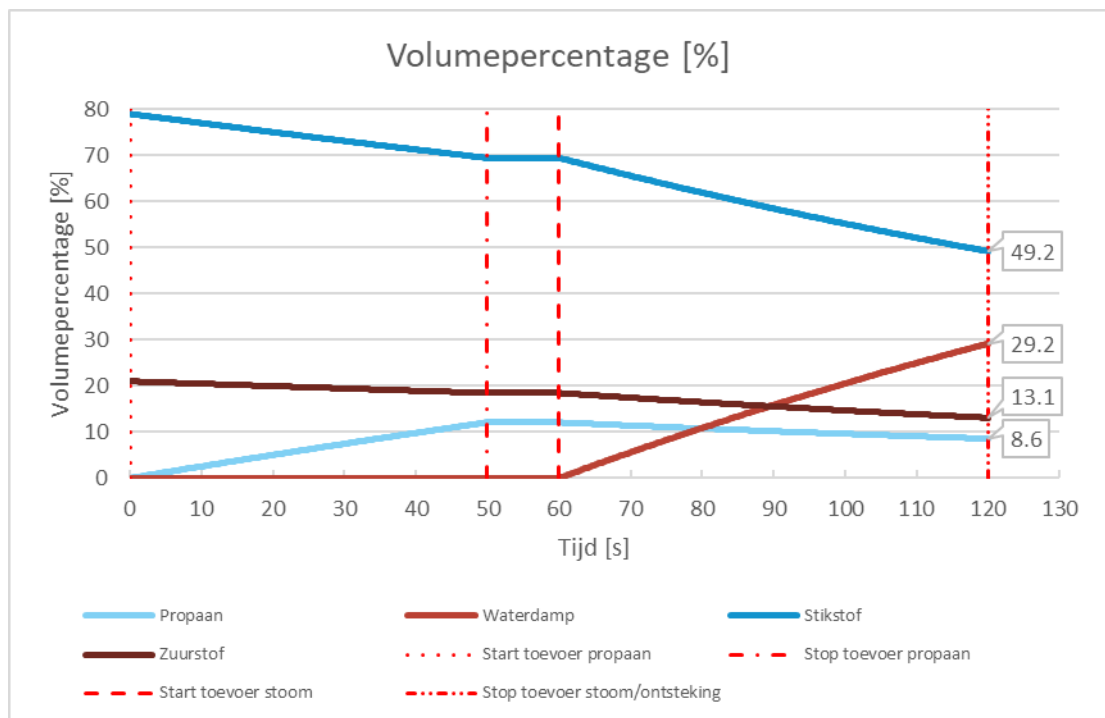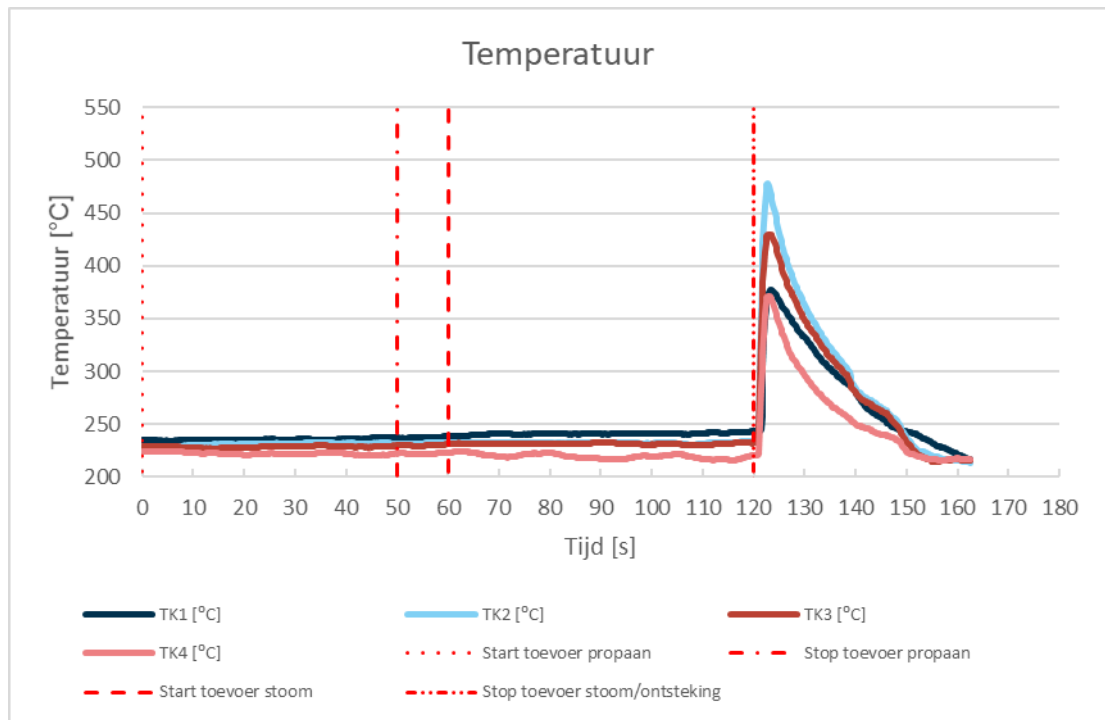
Figure 23: Test 10, 90-second supply
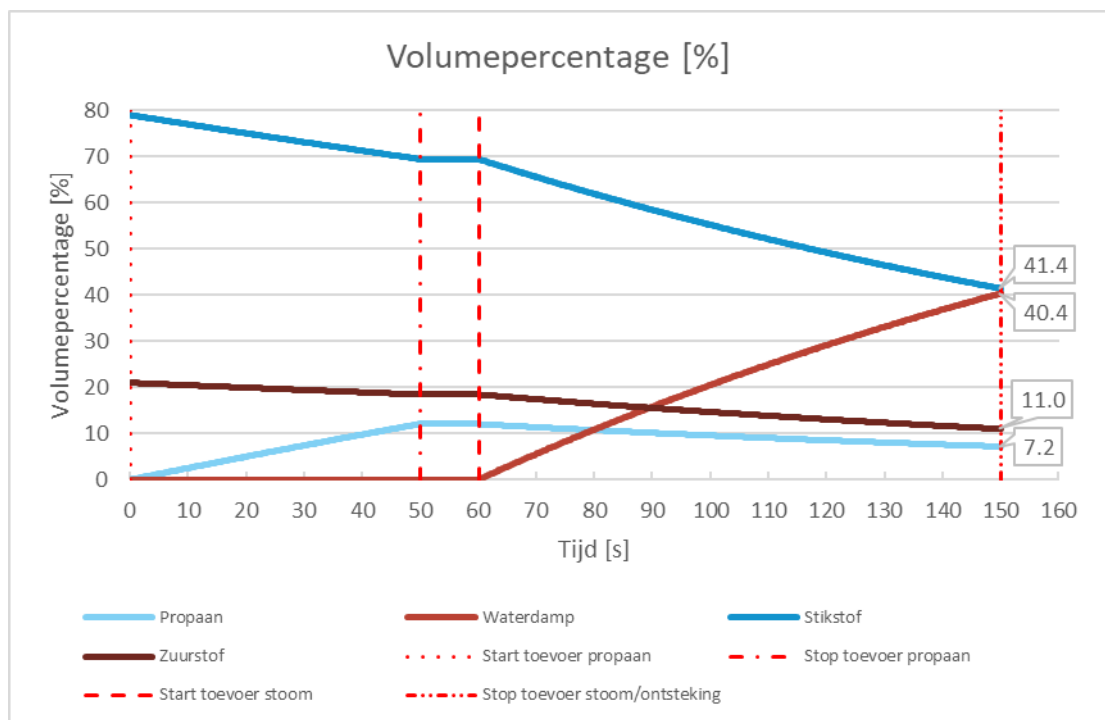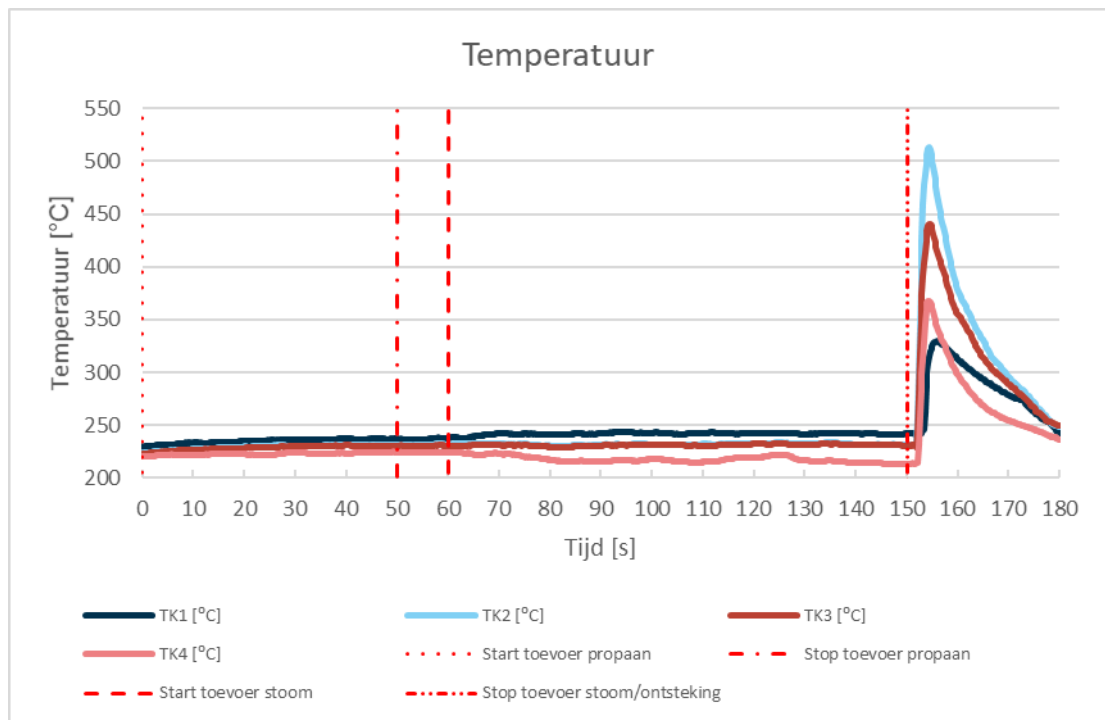
Figure 24: Test 13, 100-second supply
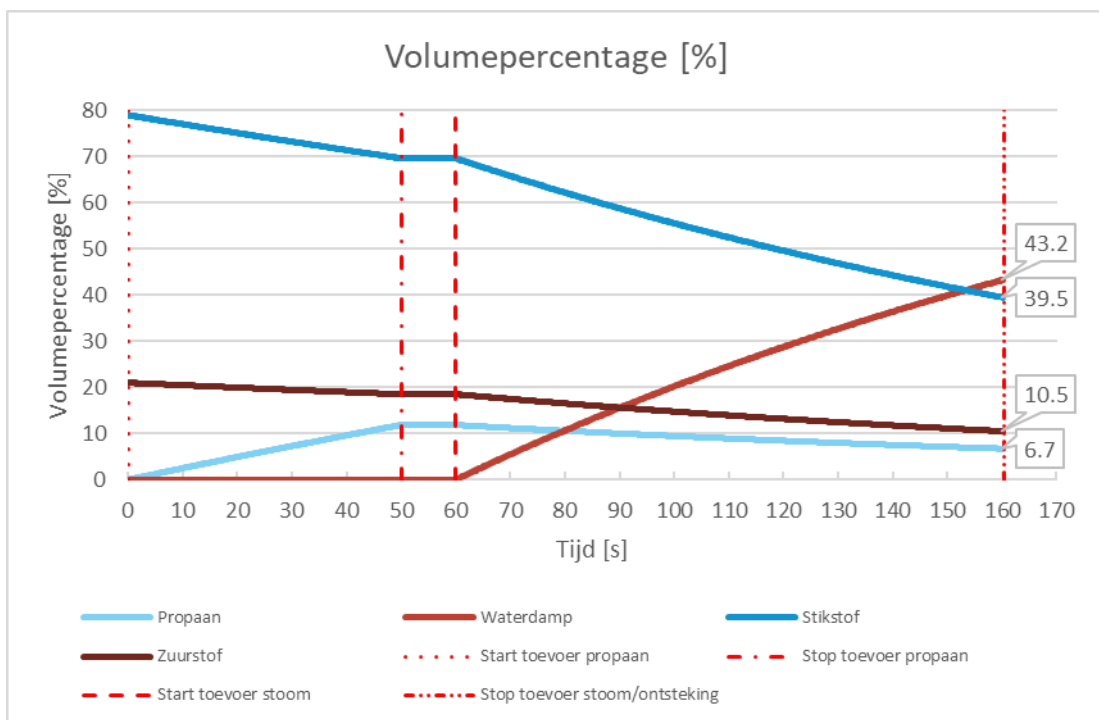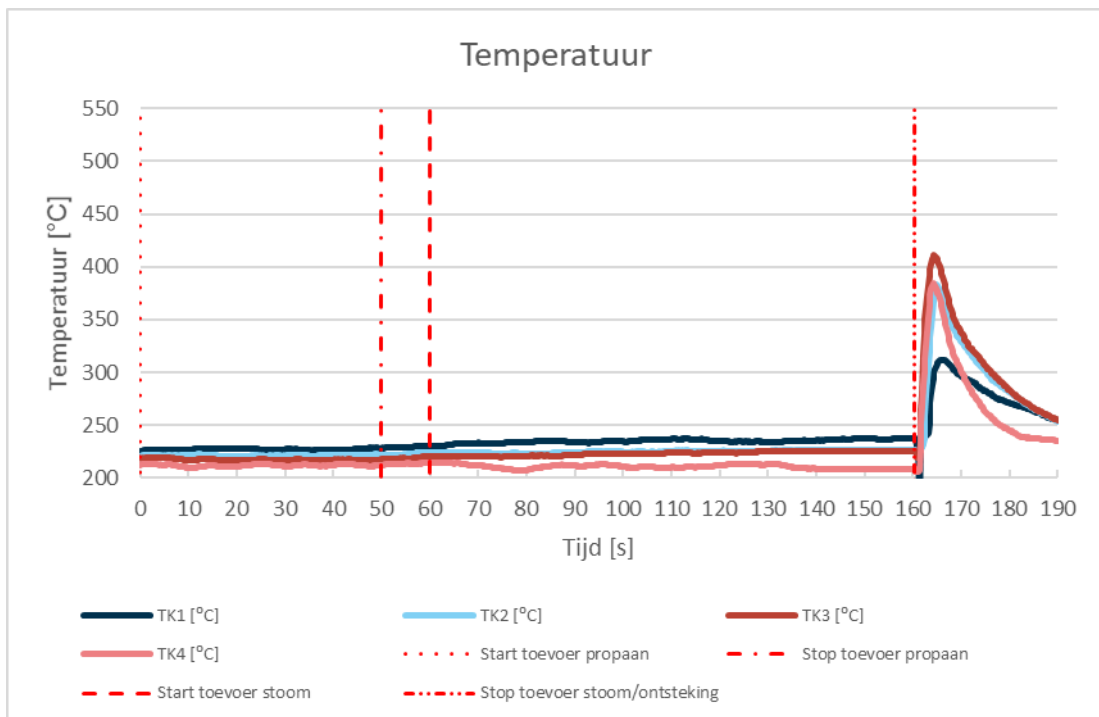
Figure 25: Test 14, 100-second supply
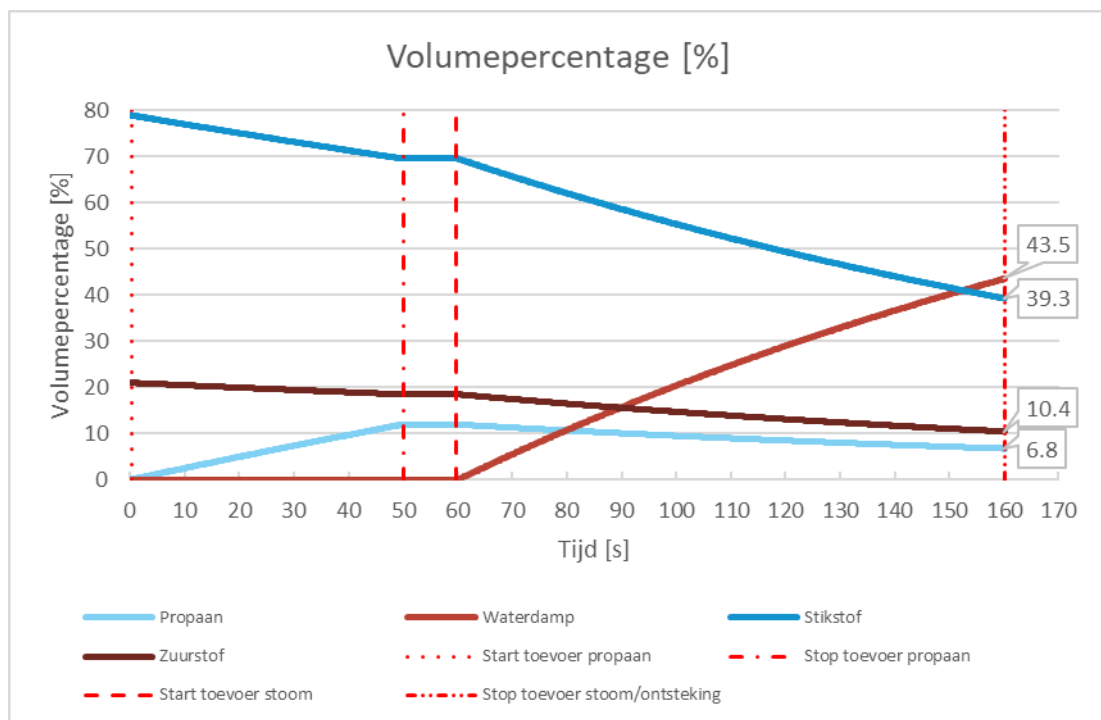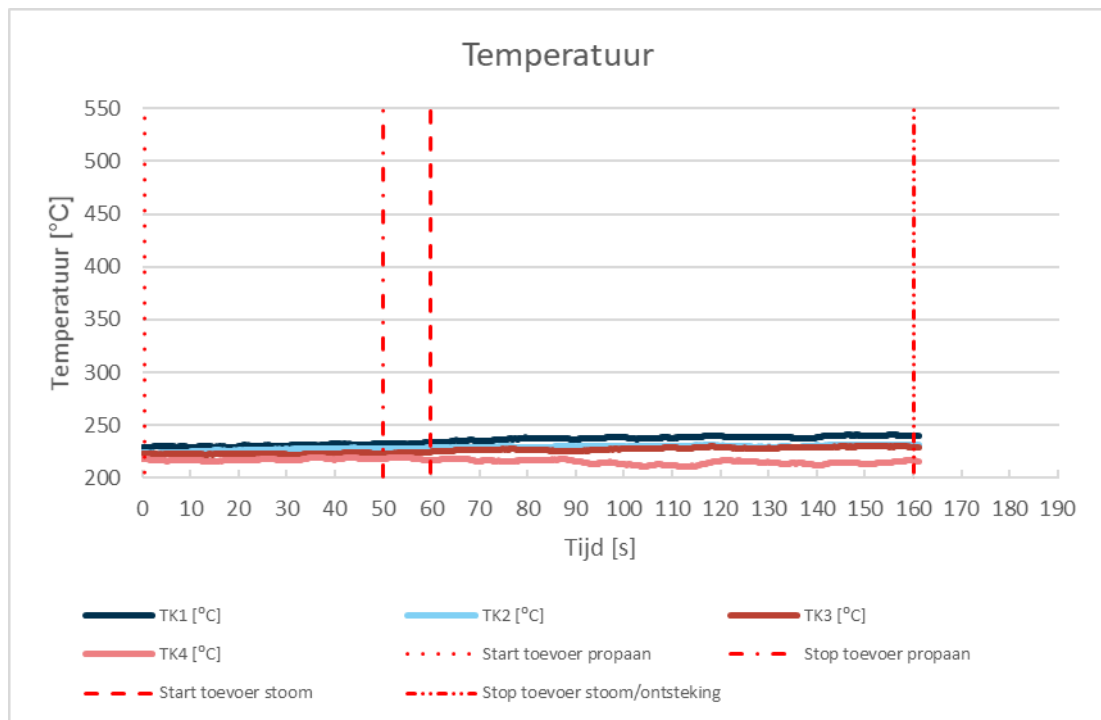
Overview

Table 17: Summary of the parameters of the steam experiments

Supply time [s]	Volume percentage [%]			Ignition [-]	Temperature [°C] [2]	
	Oxygen	Water vapour	Propane		Max. after explosion	Difference
10	17.3	5.8	11.8	Yes	519	265
20	16.5	10.7	10.7	Yes	466	243
30	15.5	18.9	10.2	Yes	475	243
60	13.1	29.3	8.6	Yes	493	259
90	11	40.4	7.2	Yes	509	277
100	10.5	43.4	6.7	Yes/no	383	156
120	9.4	49.5	6	No	-	-

[1] The maximum temperature and the temperature difference were determined on the basis of thermocouple 2.

Figure 26: Average volume percentages (%)

Gemiddelde temperatuur
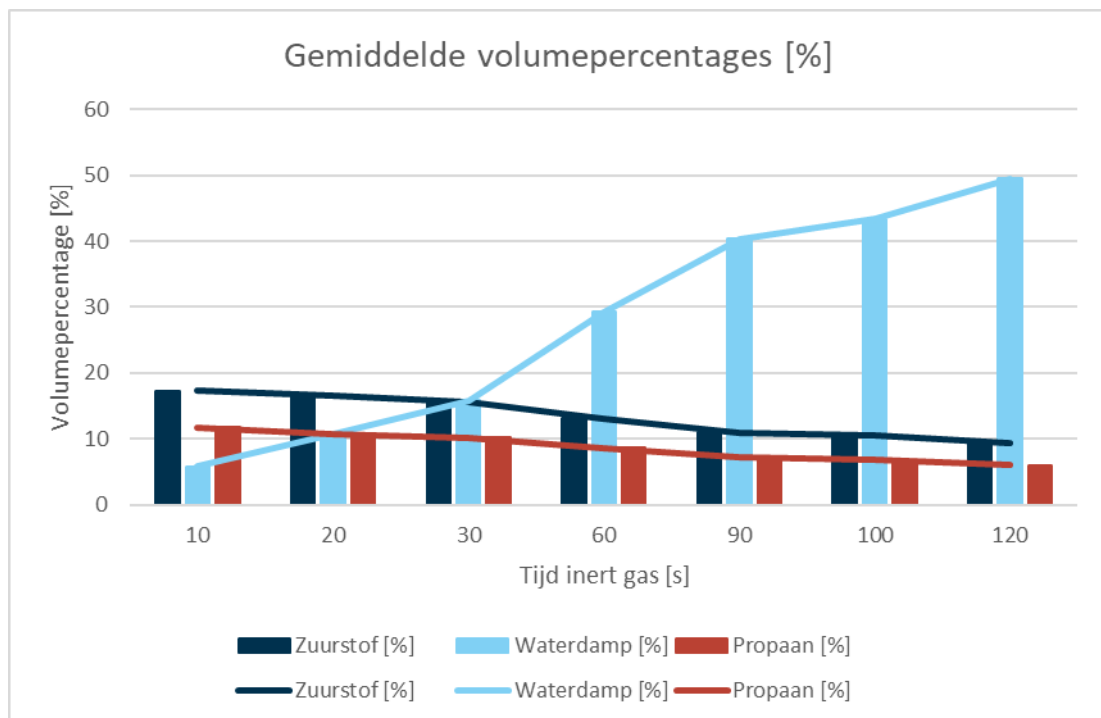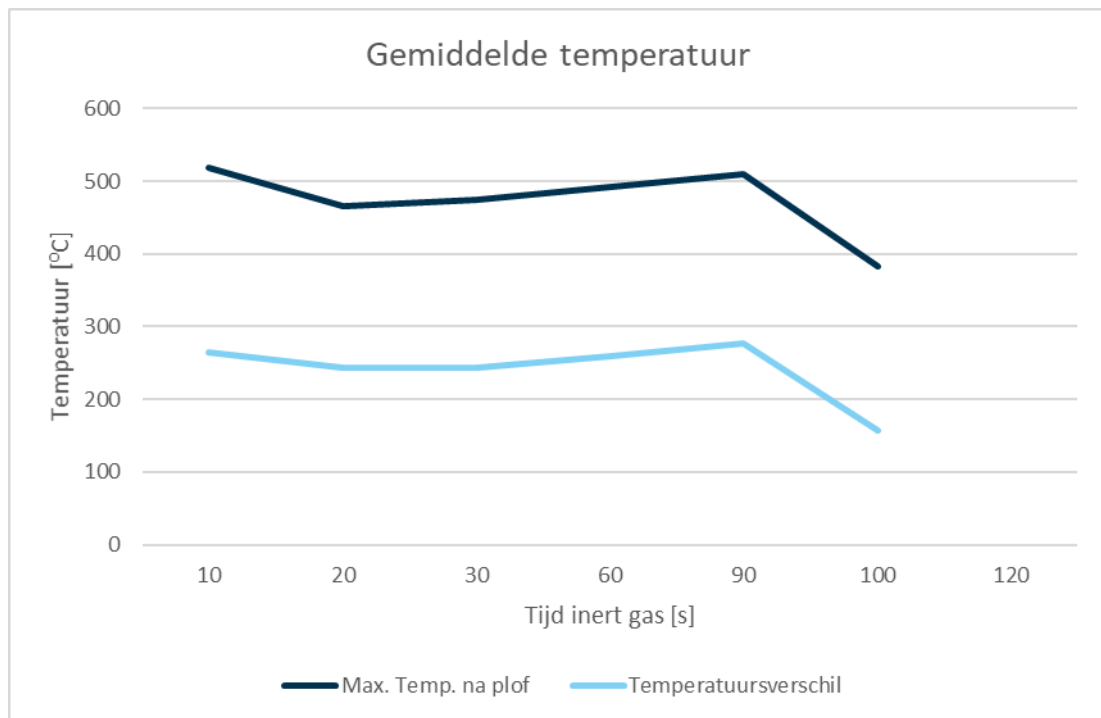
The results show the following:

> Ignition took place in all experiments where steam had been added for up to 100 seconds.

> Ignition occurred once, and no ignition occurred twice, in the experiments where steam was added for 100 seconds. No ignition took place if steam was added for 120 seconds.

> The volume percentage of propane gas was 12.1 % before adding steam and was at least approximately 6.0 % (after adding steam for 120 seconds).

> The volume percentage of oxygen was 18.5 % before adding steam and was at least approximately 9.4 % (after adding steam for 120 seconds).

> The maximum volume percentage of water vapour was 49.5% (adding steam for 120 seconds).

> The tipping point for ignition or no ignition was approximately between 43% and 44% of water vapour (10-11% of oxygen and 6-7% of propane).

> It should be noted that the above volume percentages apply to the temperatures then present (200-250 ºC) in the desktop flashover vessel.

> The maximum temperature after ignition was virtually equal for the first experiments (steam added for 10 to 90 seconds), i.e. between 470 ºC to 520 ºC. When steam was added for 100 seconds, the maximum temperature after ignition was lower (283 ºC).

> The same thing applies to the temperature difference as to the maximum temperature: between 240 ºC and 280 ºC for the first experiments and 156 ºC when steam was added for 100 seconds.

3.2.4 Summary of the results for mist

Figure 27: Test 4, 20-second supply
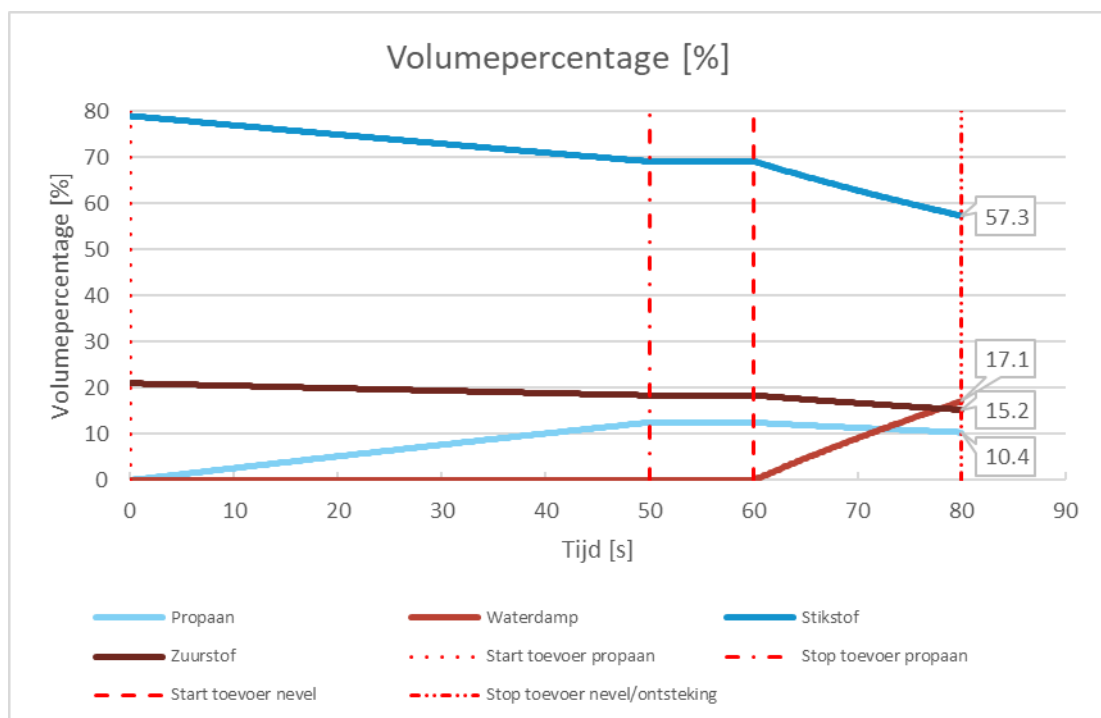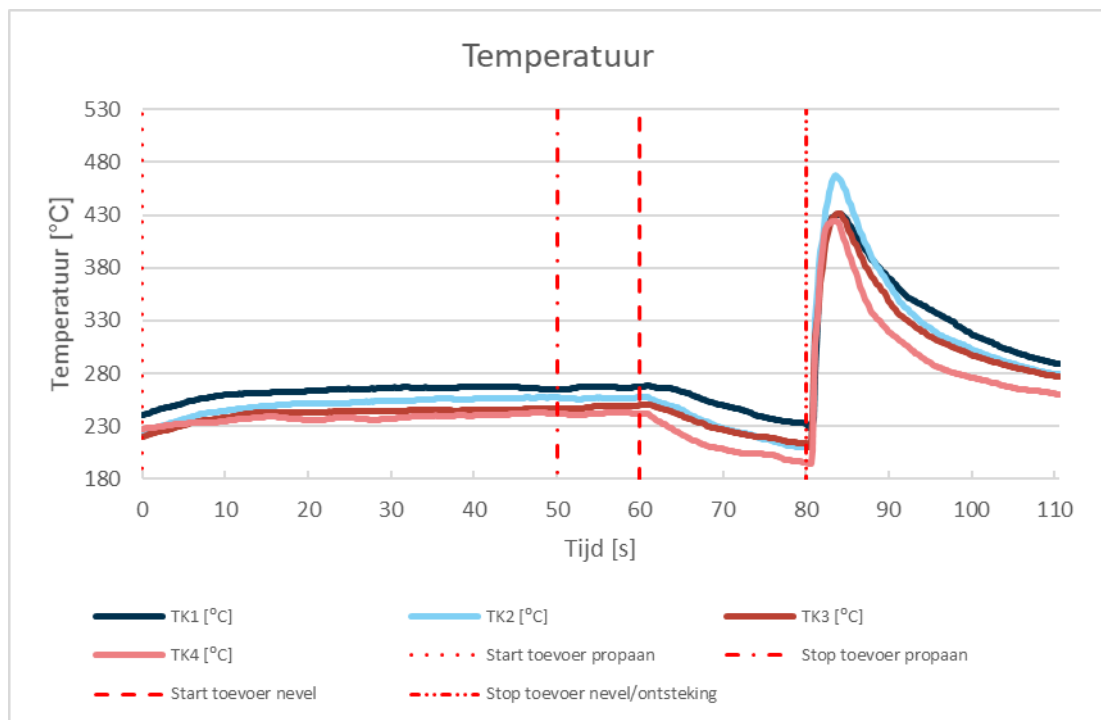
Figure 28: Test 8, 40-second supply
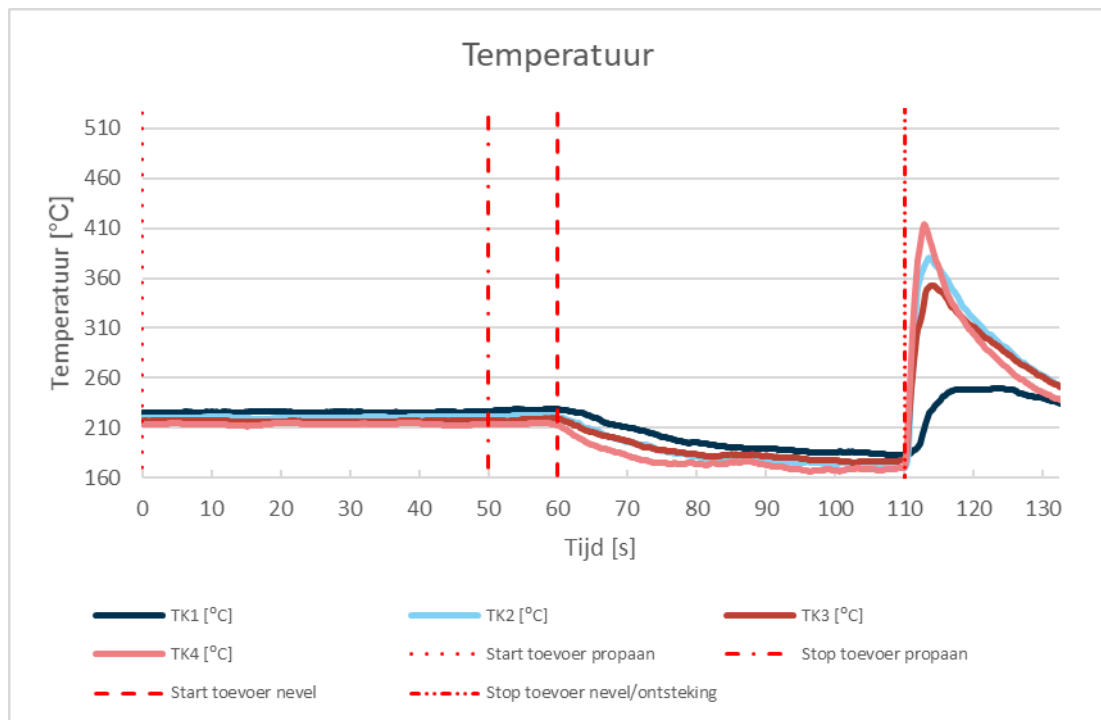
**Figure 29: Test 9, 50-second supply**
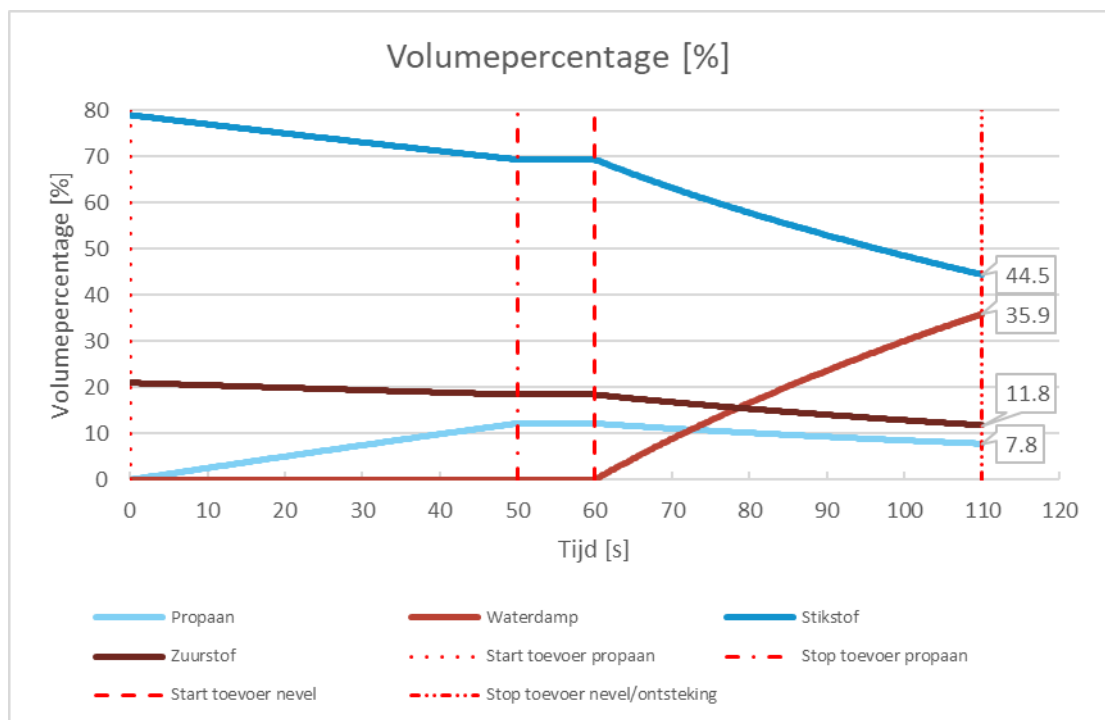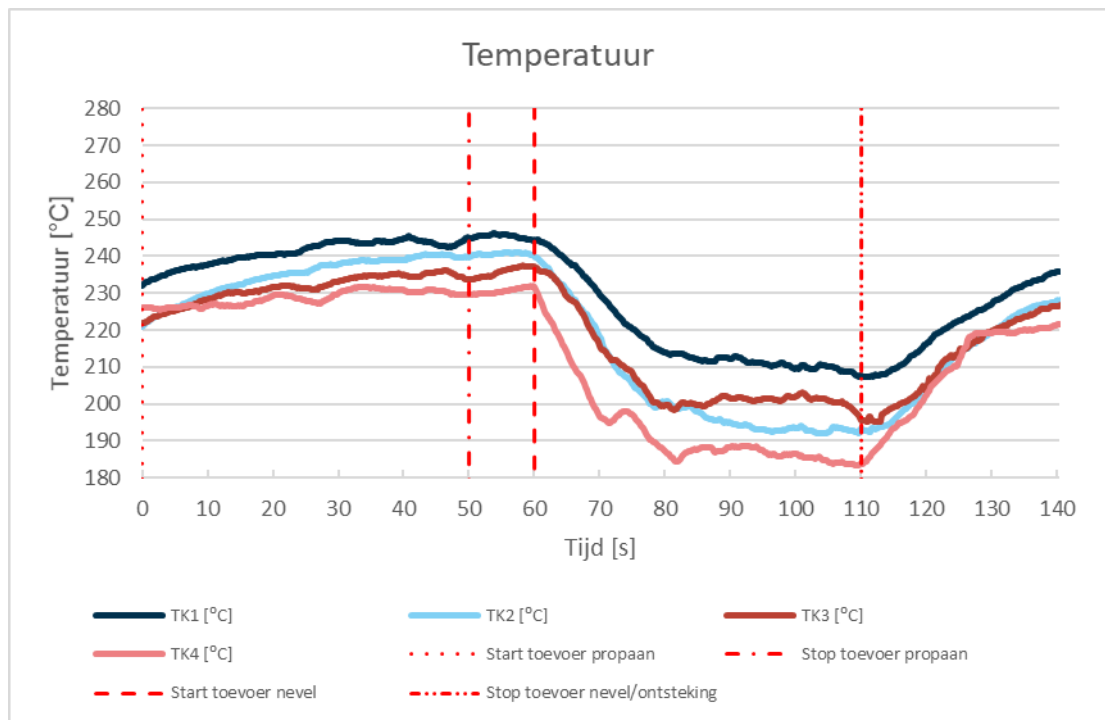
Figure 30: Test 10, 50-second supply
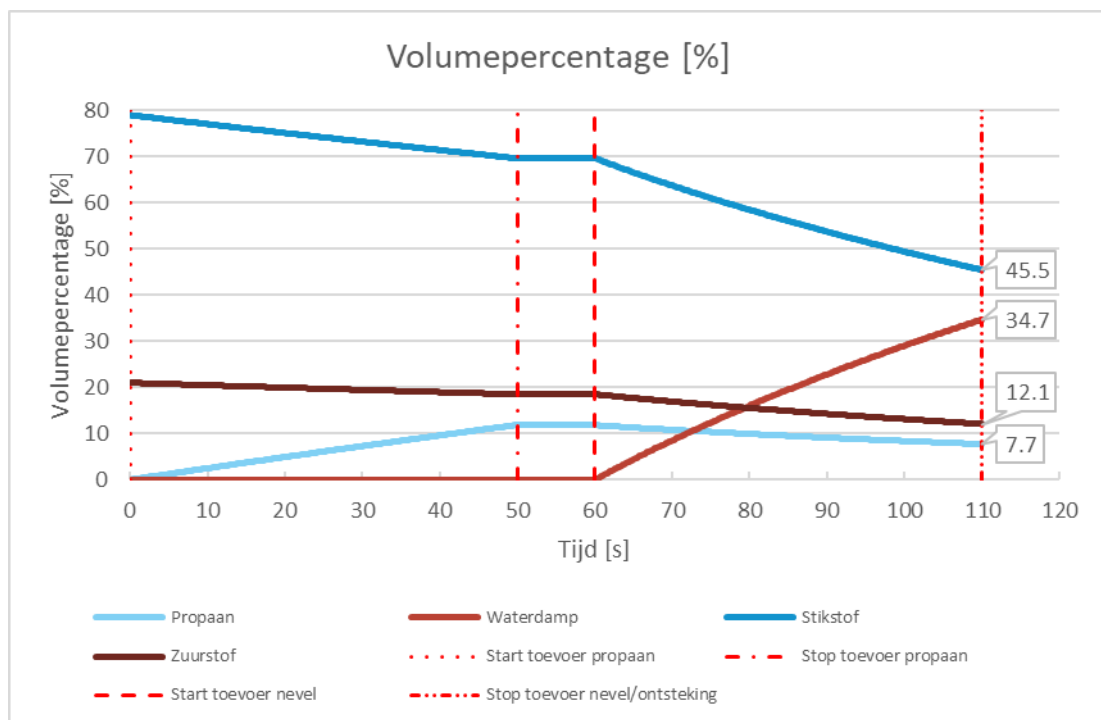
Overview

Table 18: Summary of results

Supply time [s]	Volume percentage [%]			Ignition [-]	Temperature [ºC] [1]	
	Oxygen	Water vapour	Propane		Max. after explosion	Difference
10	16.9	8.7	10.9	Yes	480	273
20	15.2	17.2	10.3	Yes	516	296
30	14.3	23.1	9.2	Yes	454	276
40	12.7	31.1	8.6	Yes	510	300
50	12	35.1	7.7	Yes/No	380	210

[1] The maximum temperature and the temperature difference were determined on the basis of thermocouple 2.

Figure 31: Average volume percentages (%)
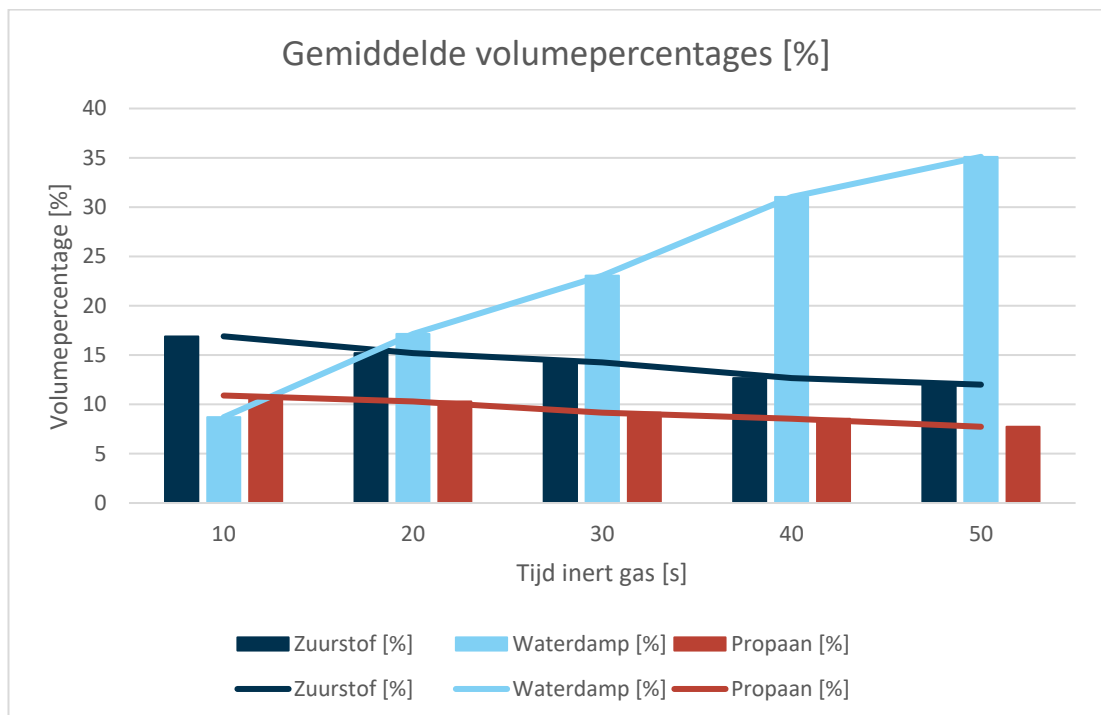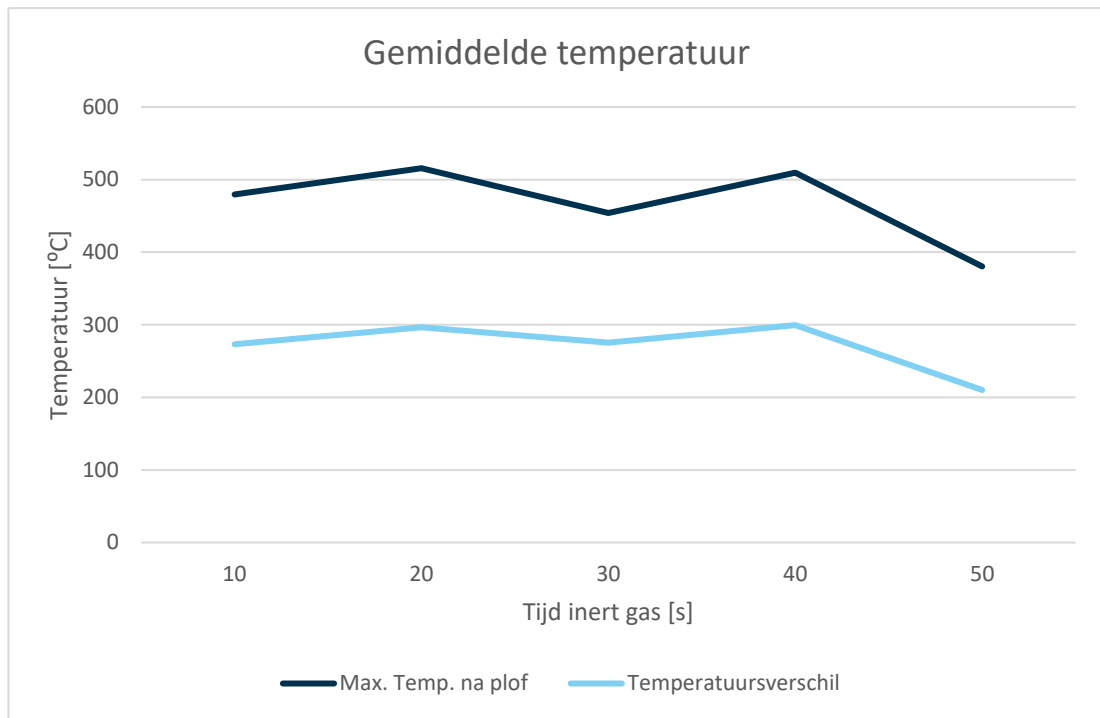
The results show the following:

> An ignition took place in all experiments where mist was added for up to 50 seconds.
> Ignition occurred once, and no ignition occurred twice, in the experiments where mist was added for 50 seconds.
> The volume percentage of propane gas was 12.6 % before adding mist and was at least approximately 7.7 % (after adding mist for 50 seconds).
> The volume percentage of oxygen was 18.3 % before adding mist and was at least approximately 12 % (after adding mist for 50 seconds).
> The maximum volume percentage of water vapour was 35.9 % (adding mist for 50 seconds).
> The tipping point///break-even point for ignition or no ignition is approximately between 31 % and 36 % of water vapour (12-13 % of oxygen and 7-9 % of propane).
> It should be noted that the above volume percentages apply to the temperatures then present (180-210 ºC) in the desktop flashover vessel.
> The maximum temperature after ignition was virtually equal for the first experiments (mist added for 10 to 40 seconds), i.e. between 450 ºC to 520 ºC. When mist was added for 50 seconds, the maximum temperature after ignition was lower (380 ºC).
> The same thing applies to the temperature difference as to the maximum temperature: between 270 ºC and 300 ºC for the first experiments and 210 ºC when adding mist for 50 seconds.

3.2.5 Summary of the results for experiments with the hot situation

Table 19: Summary of results for experiments with the hot situation

Time [s]	Volume percentage [%]			
	Steam	Explosion	Mist	Explosion
10	5.8	Yes	8.7	Yes
20	10.7	Yes	17.2	Yes
30	15.9	Yes	23.1	Yes
40	-	-	31.1	Yes
50	-	-	35.1	No/Yes
60	29.3	Yes	-	-
90	40.4	Yes	-	-
100	43.4	No/Yes	-	-
120	49.5	No	-	-

The results showed the following:
> In the experiments with steam, ignition was prevented when steam was added for 100 seconds (volume percentage of approx. 43 %).
> In the experiments with mist, ignition was prevented when mist was added for 50 seconds (volume percentage of approx. 35 %).

4 Analysis

4.1 General

Based on section 1.6, this chapter analyses the results of the experiments based on three criteria, i.e.: the flammability limits (LFL and UFL), the inert point (IP), and the LOC value. For a further explanation, see chapter 1.

Table 20: Flammability limits, IP and LOC value criteria

Criterion	Propane LFL – UFL [%]	IP [%]	LOC value [%]
Steam (cold)	2.2 – 9.5	28 – 42	11.5 – 14.5
Mist (cold)	2.2 – 9.5	28 – 42	11.5 – 14.5
Nitrogen (cold)	2.2 – 9.5	41.6	11.6
Steam (hot)	1.9 – 11.3	42.3	11.5
Mist (hot)	1.9 – 11.3	42.3	11.5

4.2 Cold situation

4.2.1 Steam

Figure 32 was used to assess the flammability limits and inert point criteria. This figure shows the results of the experiments for steam in the flammability diagram.

Figure 32: Flammability diagram for propane 298 K
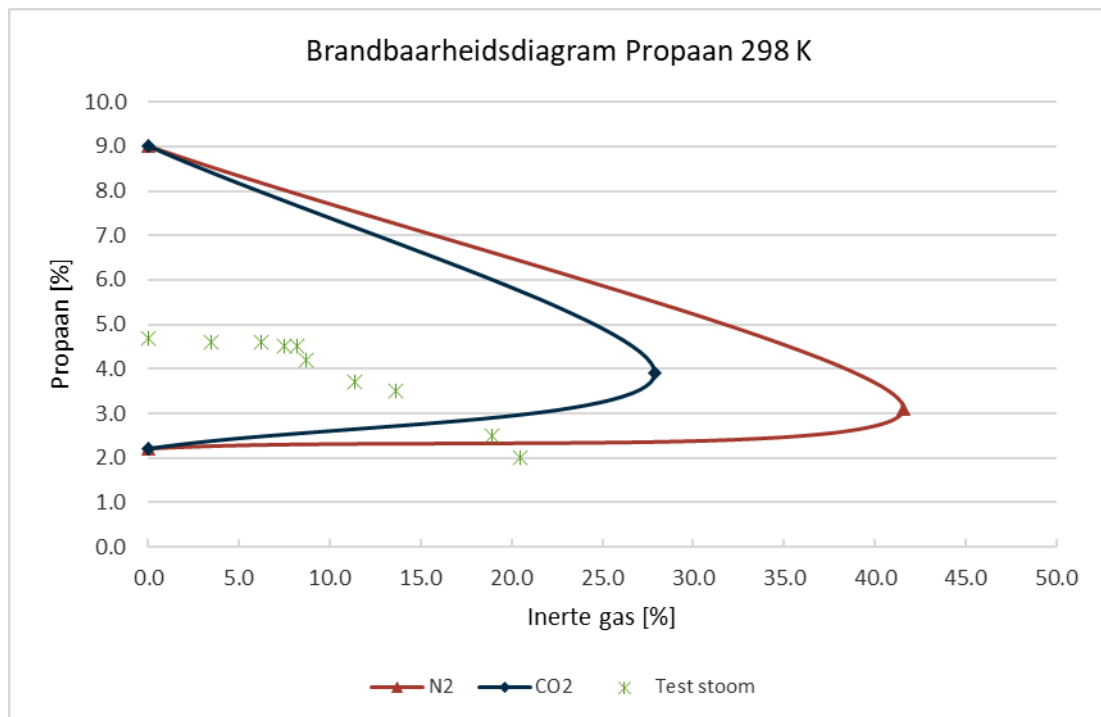
Figure 32 shows that the results for steam were largely within the flammability diagram. Although the flammability diagram does not include water vapour, this will have been somewhere between the lines of carbon dioxide (CO_2) and nitrogen (N_2).

Only the test results from adding steam for 300 seconds led to results that were possibly outside the flammability limits. There was still ignition in both tests. This may possibly be explained by:

> The average temperature during these experiments, before ignition, was around 58 ºC. The flammability diagram (LFL) and the calculated volume percentages have not been corrected for this.

> Although ignition occurred, it was less severe than with the other experiments where less steam was added. The difference between the temperatures before and during the ignition was also lower than in the other experiments. This indicates that the mixture was close to the lower flammability limit.

> The flammability diagram combines the results of various different studies. There is a certain margin of error, specifically as regards the limits. Due to this margin of error, the mixture tested may still have been just within the flammability limits.

> Furthermore, due to the assumptions and preconditions, the calculated volume percentages also have an margin of error. Due to this margin of error, the mixture tested may still have been just within the flammability limits.

This means that ignition did not occur in the experiments where steam was added as the inert substance. Where water vapour (steam) was added as the inert gas, the mixtures were diluted insufficiently to bring the gas mixture outside the flammability limits.

Figure 32 also shows that the inert point was not reached. The test results are still relatively far from the possible inert point (28 and 42%). The maximum volume percentage of water vapour was approximately 20%.

This may be explained by the fact that the saturation point was reached (see section 1.3 and figure 33). Air at a lower temperature than the boiling point of water can only contain a limited amount of water vapour. Adding steam (100 °C) increased the temperature in the desktop flashover cabinet, thus allowing more and more water vapour to be present in the air. However, the temperature was not high enough yet (58 °C) to reach the inertisation limit (of 35% at 73 °C).

Figure 33: Maximum volume percentage of water vapour
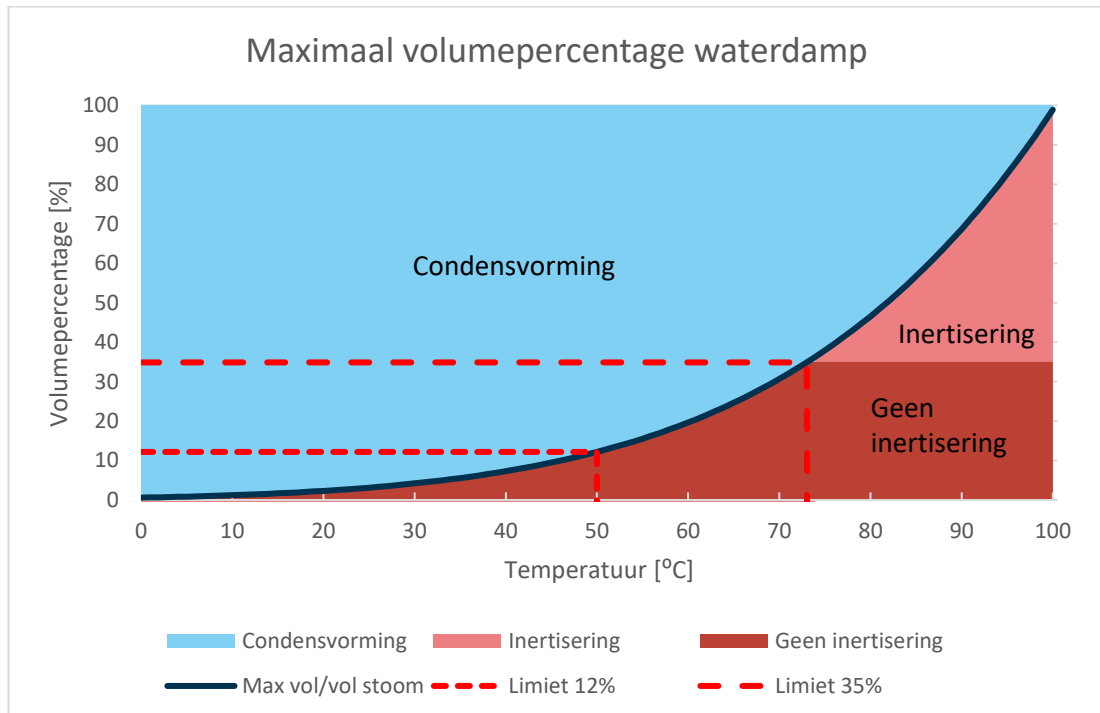
In principle, enough water vapour was added. The maximum amount of water vapour added was approximately 438 l (300 seconds at 100 °C). This is more than 2.6 times the total cubic capacity of the desktop flashover cabinet (166 l). However, a major share of the water vapour added will have condensed immediately due to the lower temperature in the desktop flashover cabinet. This was also observed visually on the inside of the housing during the experiments.

Since the percentage of water vapour was approximately 20%, the LOC value (11.5 – 14.5%) was not reached either. The minimum oxygen percentage was approximately 16.4 %.

Table 21: Summary of analysis of the results of steam based on three criteria

| Criterion	Limit value	Testing	Inertisation possible?
LFL	2.2%	Min. 2.0%	Yes [1]
IP	28 – 42%	Max. 20%	No
LOC	11.5 – 14.5%	16.4%	No

[1] Based on the theory, the lower value of the criterion was not reached. However, there was an ignition in the test.

The analysis shows that, based on two of the three criteria, inertisation with water vapour by adding steam was not possible with these experiments. Inertisation with water vapour (steam) as the inert gas is only possible below the saturation point for inertisation (73 ºC) by diluting the flammable gas mixture to below the lower flammability limit. In theory, inertisation is also possible at temperatures of above 73 ºC, based on the inert point and the LOC value.

4.2.2 Mist

To assess the criteria of flammability limits and inert point, figure Figure 34: Flammability diagram for propane 298 K was used. This figure shows the results of the experiments for mist in a flammability diagram.

Figure 34: Flammability diagram for propane 298 K
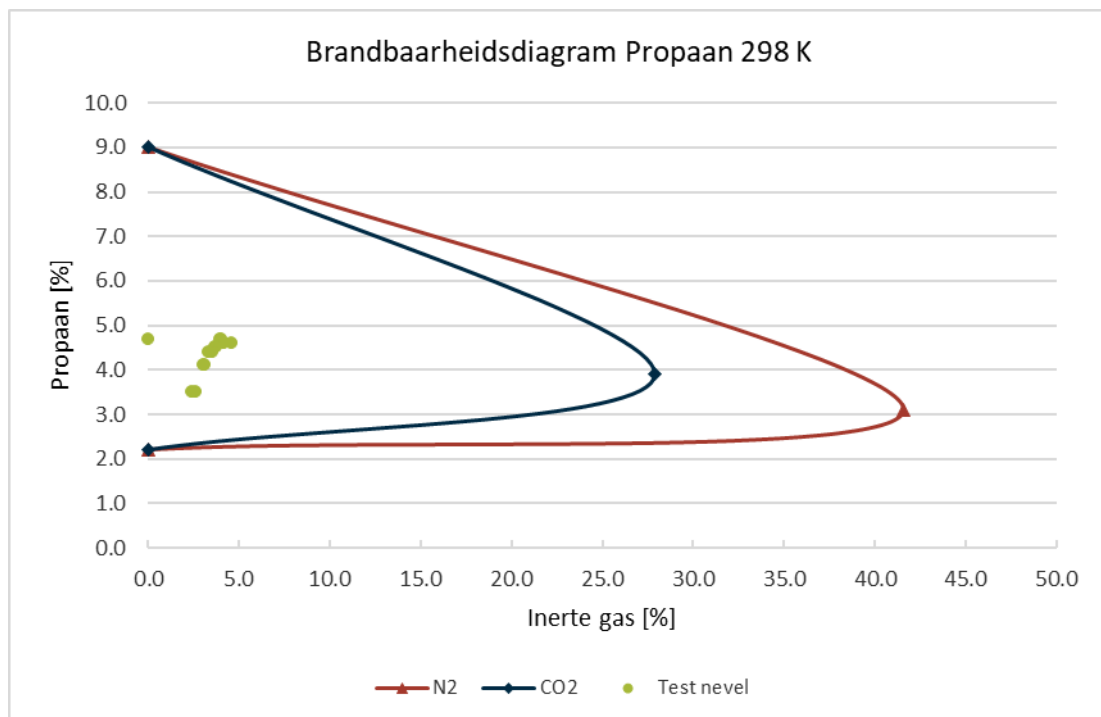
The figure shows that the results for mist were within the flammability diagram. Although the flammability diagram does not include water vapour, this will have been somewhere between the lines of carbon dioxide (CO_2) and nitrogen (N_2). This means that ignition did not occur where mist was added as the inert substance. This matches the test results. Using mist as

the inert substance does not enable the mixture to be diluted sufficiently to bring it outside the flammability limits.

The figure also shows that the inert point was not reached. In spite of the difference in the amount of mist supplied, the test results are relatively close to each other. The test results for mist show that the maximum volume percentage of water vapour in the air was approximately 4.6%, whereas the inert point at ambient temperature was between 28 and 42%.

This may be explained by the saturation point (see section 1.3 and figure 33). The addition of mist kept the temperature in the desktop flashover cabinet relatively low (ambient temperature), as a result of which the maximum amount of water vapour that could be present in the air remained below 5%. This was also confirmed visually during the experiments since condensation and/or water were observed on the inside of the housing.

Since the percentage of water vapour was approximately 5 %, the LOC value (11.5 – 14.5%) was not reached either. The minimum oxygen percentage was approximately 19.1%.

Table 22 Summary of the analysis of the results for mist based on the three criteria

Criterion	Limit value	Testing	Inertisation possible?
LFL	2.2%	Min. 3.5%	No
IP	28 – 42%	Max. 5%	No
LOC	11.5 – 14.5%	19.14%	No

[1] Based on the theory, the lower value of the criterion was not reached. However, ignition did occur in the test.

The analysis shows that, based on all three criteria, inertisation with water vapour by adding mist was not possible with these experiments. Inertisation with water vapour (mist) as the inert gas is only possible below the saturation point for inertisation (73 ºC) by diluting the flammable gas mixture to below the lower flammability limit. However, this requires a long dilution time, but in that case, air instead of mist is used for diluting. Since the temperature does not increase when mist is added, the saturation point for inertisation cannot be reached. Since there is insufficient dilution of the air, the LOC value will not be reached.

4.2.3 Nitrogen

To assess the criteria of flammability limits and inert point, figure 35 was used. This figure shows the results of the experiments for nitrogen in a flammability diagram.

Figure 35: Flammability diagram for propane 298 K
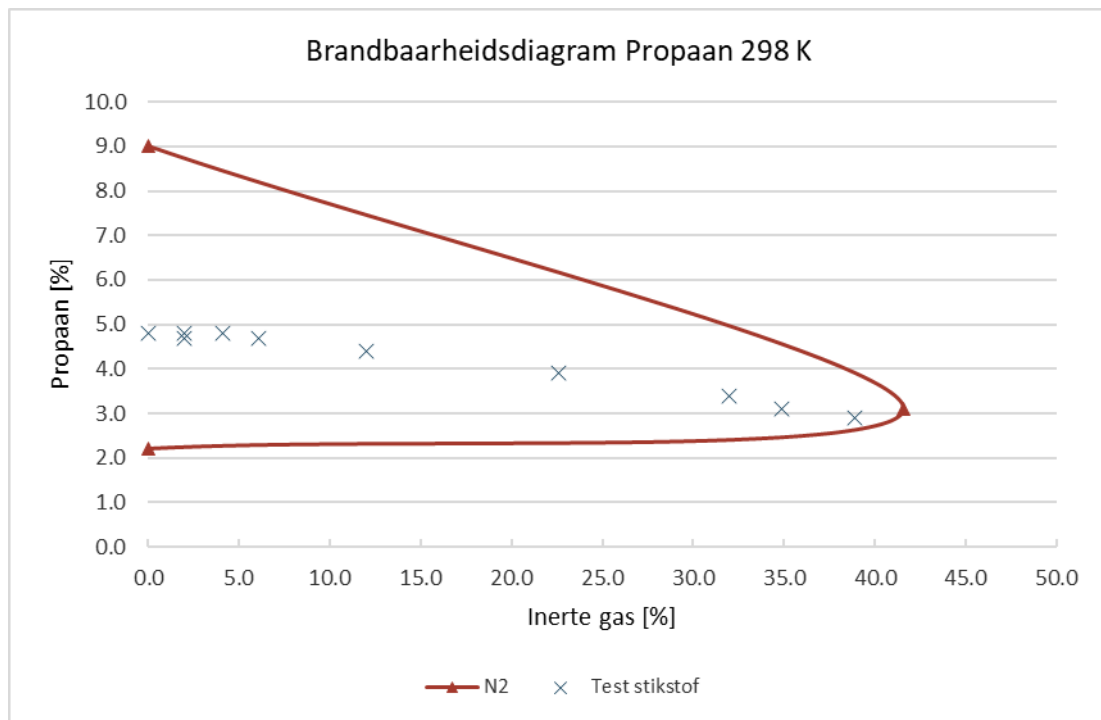
The figure shows that the results for nitrogen were within the flammability diagram. The flammability limits were not exceeded, nor did the values fall below these limits, although there was a very thin margin.

The figure also shows that the inert point was almost reached. When supplying nitrogen for 240 seconds, the volume percentage of nitrogen was approximately 39%; this was still below the inert point of 41.6%.

The LOC value for nitrogen as the inertisation gas, 11.6%, was almost reached. This value is at least approx. 12.2 % (if nitrogen is supplied for 240 seconds).

Table 23: Summary of the analysis of the results of nitrogen based on the three criteria

Criterion	Limit value	Testing	Inertisation possible?
LFL	2.2%	Min. 2.9%	No
IP	41.6%	Max. 38.9%	No
LOC	11.6%	Min. 12.2%	No

Based on the above table, it can be concluded that inertisation cannot be reached with the amount of nitrogen added. However, the test results show that no ignition took place when adding nitrogen for 240 seconds. So this means that inertisation did occur in these tests which may possibly be explained by a two-fold margin of error:

> Since the flammability diagram has resulted from several studies, there is a certain margin of error, specifically with regard to the limits. As a result of this, the mixture tested may have been just beyond the flammability limits.
> Due to the assumptions and preconditions, the calculated volume percentages also have a margin of error. This may also have led to the mixture tested being just beyond the flammability limits.

The analysis shows that inertisation by adding nitrogen is possible at ambient temperatures; this is also supported by various other studies (Zabetakis, 1965; CHEMSAFE, 2009). The test results also match values listed in chapter 1. However, it cannot be established with certainty what the decisive mechanism (LFL/UFL, IP or LOC) was in the tests that were conducted. It is probably a combination of these mechanisms that causes inertisation to take place.

4.3 Hot situation

4.3.1 Steam

To assess the criteria of flammability limits and inert point, figure 36 was used. This figure shows the results of the experiments for mist in the flammability diagram.

Figure 36: Flammability diagram for 473 K
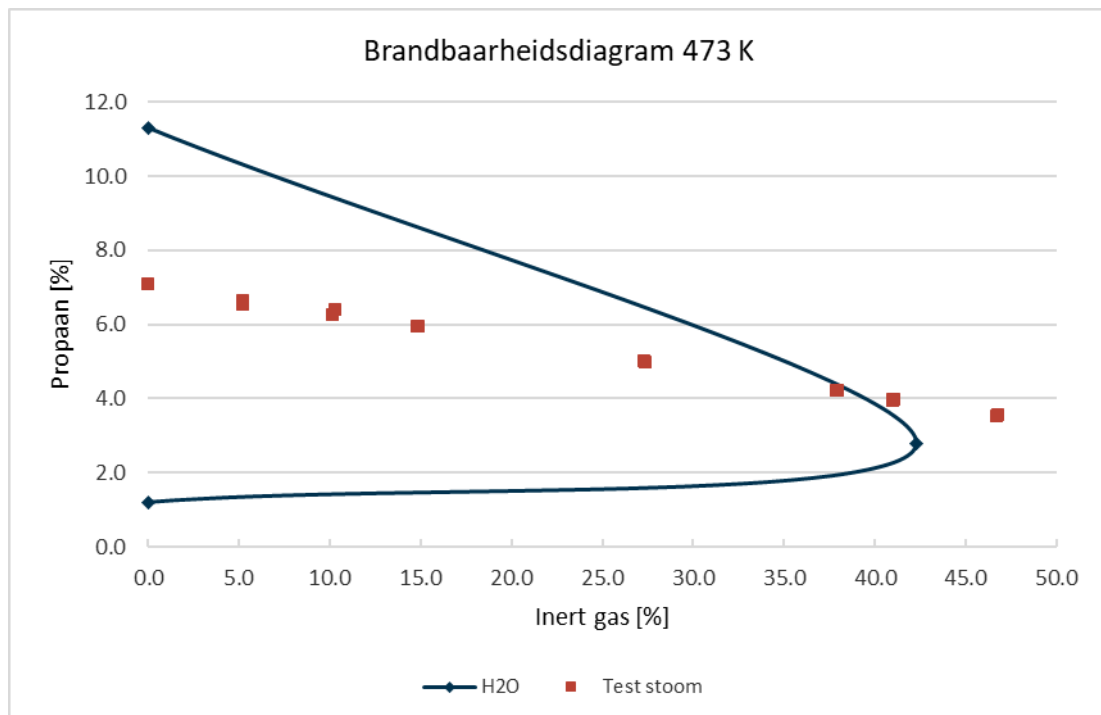
The figure shows that the results for steam, when supplied for up to 90 seconds, were within the flammability diagram. When steam was supplied for 100 s and for 120 s, the results were outside the diagram.

The figure also shows that the inert point was exceeded. When steam was supplied for 120 seconds, the volume percentage of water vapour was approximately 46.8%. This is above the inert point of 42.3%.

In addition, the LOC value for water vapour as the inertisation gas, of 11.5%, was not reached. This is at least approx. 9.4% (when supplying steam for 120 seconds).

Table 24: Summary of the analysis of the results of steam based on the three criteria

Criterion	Limit value	Testing	Inertisation possible?
LFL	1.9%	Min. 3.5% [1]	No
IP	42.3%	Max. 46.8%	Yes
LOC	11.5%	Min. 9.4%	Yes

[1] The volume percentages calculated were calculated back to ambient temperature (20 ºC).

[2] The volume percentages calculated were calculated back to the diagram temperature (200 ºC).

Based on the above table, it can be concluded that inertisation cannot be reached with the amount of steam added when supplying steam for 100 seconds or 120 seconds. However, the test results show that ignition still takes place with one of the three tests where steam was added for 100 seconds. The following can be noted about this:
> Although ignition occurred, it was less severe than with the other experiments where less steam was added. The difference in temperature before and during the ignition was also lower (approx. 100 °C) than in the other experiments. This indicates that the mixture is close to the flammability limit.
> Since the flammability diagram has resulted from several studies, there is a certain margin of error, specifically with regard to the limits. Due to this margin of error, the mixture tested might still have been just within the flammability limits.
> Furthermore, due to the assumptions and preconditions, the calculated volume percentages also have a margin of error. Also due to this margin of error, the mixture tested might still have been just within the flammability limits.

The analysis shows that inertisation by adding nitrogen is possible at a temperature of approx. 225 °C; this is also supported by various other studies (Zabetakis, 1965; CHEMSAFE, 2009). The test results therefore match the values found in the literature. However, it cannot be established with certainty what the decisive mechanism (IP or LOC) was in the tests that were conducted. It is probably a combination of these mechanisms that causes inertisation to take place.

4.3.2 Mist
To assess the criteria of flammability limit and inert point, figure 37 was used. This figure shows the results of the experiments for mist in the flammability diagram.

Figure 37: Flammability diagram for 473 K
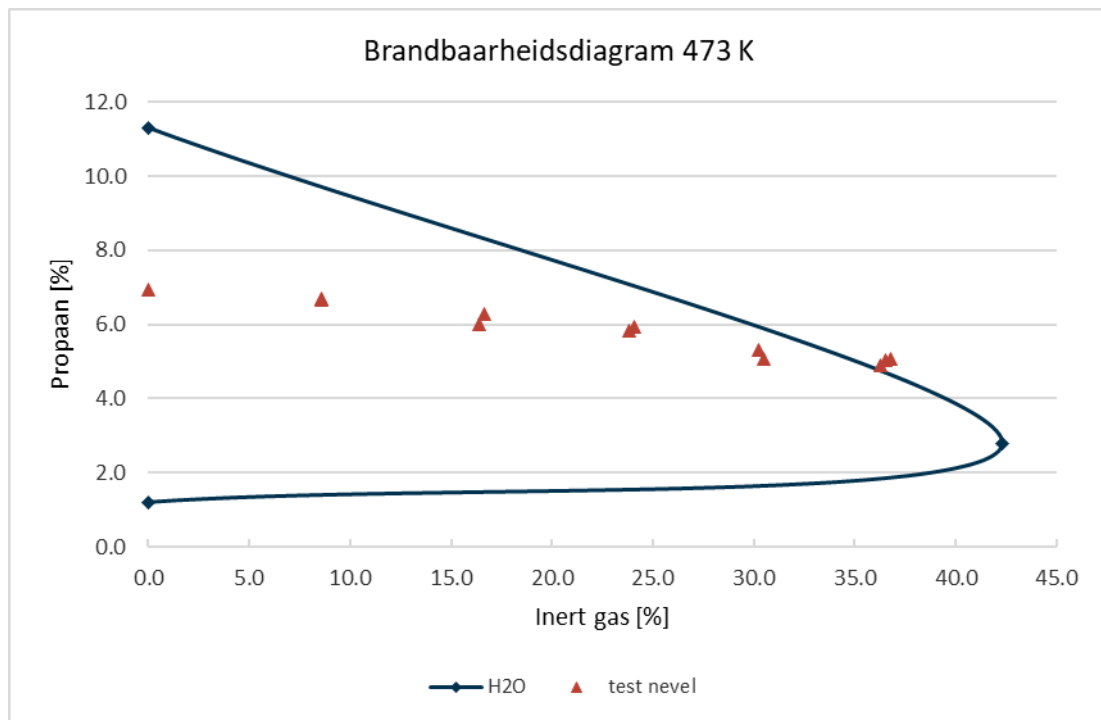
The figure shows that the results for supplying mist for up to 50 seconds are within the flammability diagram; if mist is supplied for 50 seconds, the results are outside the diagram.

The figure also shows that the inert point is not exceeded. When supplying mist for 50 seconds, the volume percentage of water vapour was approximately 36.8 %; this was below the inert point of 42.3 %.

In addition, the LOC value for water vapour as the inertisation gas, of 11.5 %, was reached. This was at least approx. 12% (if adding mist for 50 seconds).

Table 25: Summary of analysis of results of steam based on three criteria

Criterion	Limit value	Testing	Inertisation possible?
UFL	UFL	> UFL 5% [1]	Yes
IP	42.3%	Max. 36.8%	No
LOC	11.5%	Min. 12%	No

[1] The volume percentages calculated were calculated back to ambient temperature (20 ºC).

[2] The volume percentages calculated were calculated back to the diagram temperature (200 ºC).

Based on the above table it can be concluded that, with the amount of mist added during 50 seconds, inertisation can be reached for one criterion. However, the test results show that ignition still took place with one of the three tests where mist was added for 50 seconds. This may possibly be explained by the following:

> Although ignition occurred, it was less severe than with the other experiments where less mist was added. Both the maximum temperature during the ignition (approximately 380 ⁰C) and the difference between the temperature before and during the ignition were lower (approximately 210 ⁰C) than was the case with the other experiments (approximately 490 ⁰C and 390 ⁰C). This indicates that the mixture was close to the flammability limit.
> Since the flammability diagram has resulted from several studies, there is a certain margin of error, specifically with regard to the limits. Because of this margin of error, the mixture tested may still have been just within the flammability limits.
> Furthermore, due to the assumptions and preconditions, the calculated volume percentages also have a margin of error. Due to this margin of error, the mixture tested may still have been just within the flammability limits.

The analysis shows that inertisation by adding mist at a temperature of approximately 225 ⁰C is possible. This is also supported in several other studies (Zabetakis, 1965; CHEMSAFE, 2009). The test results therefore match the values found in the literature. The upper flammability limit was probably the decisive mechanism in the tests that were conducted.

4.4   Summary of the analysis

In summary, it can be concluded that a flammable gas mixture - here propane - can be inertised both when nitrogen is used as the dilution gas and when water vapour is used as the dilution gas. The analysis shows that inertisation can be brought about by several mechanisms. Dilution enables the gas mixture to be brought outside the flammability limits. Dilution enables the inert point (IP) to be reached, so that the flammability limits overlap. Dilution enables the oxygen percentage to be lowered to below the LOC value, so that ignition is no longer possible. The tests also show that it is not always apparent what the decisive mechanism was. In most situations, there is probably a combination of mechanisms. The results of the tests match the values found in international literature.

When water vapour is the dilution gas, the temperature of the mixture is also important, since adding water vapour draws energy from the gas mixture causing it to cool down. If the temperature of the gas mixture falls to below the boiling point of water, the volume of water vapour that can be in the air is limited, specifically in combination with ambient temperatures. This means that it is not realistic to expect that, when water vapour is used, the inert point (IP) and the LOC value can be reached at ambient temperature and ambient pressure. In that case, only dilution of the flammable mixture can then lead to inertisation.

5 Conclusion and discussion

5.1 Answer to the research question

The main research question is answered in this section: The main research question was:

Can the introduction of water (steam or mist), or nitrogen into a smoke gas layer prevent smoke gas ignition (inertisation)?

The experiments conducted justify the conclusion that, in keeping with the values found in international literature, both nitrogen and water vapour can be used as dilution gases enabling a flammable gas mixture (propane in these experiments) to be inertised, thus preventing a smoke gas ignition.

This inertisation can be achieved in different ways. Firstly, the gas mixture can be brought outside the flammability limits (LFL-UFL) by adding inert gas.
Secondly, the inert point (IP) can be reached because, if more inert gas is added, the flammability limits of the flammable gas mixture move towards each other. The flame will not be able to sustain itself after the IP and no ignition will take place.
Finally, further dilution enables the oxygen percentage to decrease to below the LOC value, so that ignition is no longer possible.
The tests did not always show clearly what the decisive mechanism was. In most situations, there is probably a combination of mechanisms.

As regards the use of water vapour as a dilution gas, it should be noted that the temperature of the mixture is important since adding water vapour draws energy from the gas mixture, as a result of which it will cool down. If the temperature of the gas mixture falls to below the boiling point of water, the volume of water vapour that can be in the air is limited, specifically in combination with ambient temperatures. This means that it is not realistic to expect that the inert point (IP) and the LOC value can be reached at ambient temperature and ambient pressure. In that case, only dilution of the flammable mixture can then lead to inertisation.

5.2 Discussion

Since the experiments were carried out using propane as the flammable gas, the calculations and conclusions are based on the properties of propane. This makes a direct translation of the results of these experiments to the real-life situation difficult. In practice, a large number of different gases can be present, each of which has its own specific properties as regards flammability limits, IP and LOC value. Carbon monoxide and methane are gases that are found quite frequently as constituents of smoke gas in a room where there is a fire. Carbon monoxide has a relatively high lower flammability limit (12.5%) and will therefore not easily be found to be present within the flammability limit. If the volume percentage of carbon monoxide in the smoke gases is within the flammability limits, it will be close to the lower flammability limit. This means that this mixture is relatively easy to influence by introducing

water vapour (dilution). This does not apply to methane. Although the lower explosion limit is higher than that of propane (5% compared to 2.1%), it is relatively low. This makes it less simple to inertise a mixture with methane within the flammability limits by the introduction of water vapour.

This may also apply to pyrolysis gases in the smoke gases. If there are synthetic fuels, pyrolysis gases will be comparable to propane. These gases have a relatively low lower flammability limit, which might be lower than that of propane. This means that these gases can ignite, even with low volume percentages. As a result, there will quickly be a need of more water vapour to be able to inertise such mixtures, specifically to get past the IP.

Furthermore, the experiments were carried out in a static situation. What is meant here is that an initial composition of the mixture is assumed, which will only change if an inert gas is introduced. In practice, there will often be a dynamic situation where the supply of smoke gases that contain flammable gases continues all the time. This also means that the gas mixture continually changes, making it even more complicated to inertise a gas mixture. Therefore, it is expected that such a situation will require much more water to make a mixture inert.

6 Interpretation

The current study shows that, in theory, it is possible to make a smoke gas layer inert by introducing water vapour. However, in practice it is often not clear which flammable gases are present in the smoke gas layer and what the properties (flammability limits, IP and LOC) of these gases are. The question is what the practical implications of this study are. In order to go into this in more detail, three particular elements have been identified:

1. The extent to which smoke gas cooling is also inertisation
2. Preventing smoke gas explosions
3. The use of smoke gas cooling

6.1 The extent to which smoke gas cooling is also inertisation

The current method of smoke gas cooling consists of introducing short pulses of water into the smoke layer. The Basic principles of fire suppression (Basisprincipes brandbestrijding) (Dutch Fire Service Academy, 2018) give the following key figures as constraints for smoke gas cooling: max. 70 m^2 and max. height 4 m. This means a maximum volume of 280 m^3. In the example below, it is assessed whether the pulses can inertise a smoke gas layer.

The volume percentage of water vapour can be determined for such a volume on the basis of this report and the following assumptions:

> The volume of the room, expressed in litres, is 280,000 l.
> The IP is used in order to make sure that inertisation will occur. The current study shows that the IP of water vapour is approximately 42%.
> 42% of 280,000 litres is 117,600 litres.
> This example assumes a temperature of the smoke gas layer of 400 ºC.
> Based on the ideal gas law, the volume of 1 litre of water after conversion to steam is approximately 3,065 l (ambient pressure, temperature 400 ºC, amount of gas in mol/l; water vapour 55.6 mol/l and a gas constant of 0.082057338 l.atm/K.mol)
> After conversion to steam, the volume of 1 litre of water becomes approximately 3,065 litres of water vapour at 400 ºC (ideal gas law).
> The basic assumption is that approx. 50% of the water introduced evaporates, i.e. an efficiency of 50%.

This means that inertising 280 m^3 of smoke gases requires approximately 77 litres of water (117,600/3,065 x 50%). In the current method of smoke gas cooling using short pulses (of a few seconds) and high pressure (125 l/min. = approximately 2.08 l/s) it takes 37 seconds (77/2.08) to achieve this and if low pressure of 450 l/min. = 7.5 l/s) is used it takes approximately 11 seconds (77/7.5) to achieve this.

Of course, such an example is based on all kinds of assumptions and uncertainties that affect the above outcome:

> The nature of the flammable gases and the temperature of the smoke gas layer are decisive for the inert point (IP). For example, longer or shorter carbon chains will have higher or lower inert points; the inert point will be lower at a lower temperature.
> The example assumes a static situation, whereas, as mentioned above, the real-life situation is usually a dynamic one in which the gas ratios change all the time. This also means that more water is needed.
> The static situation also applies to the temperature. The temperature can increase under the influence of the supply of smoke gases from the seat of the fire, but cooling by introducing water vapour will lower the temperature in the smoke gas layer.
> In practice it is often not clear which flammable gases are present in the smoke gas layer and what their properties (flammability limits, IP and LOC) are. That is why the example is based on the IP for inertisation. However, based on the other properties (flammability limit and/or LOC), inertisation can occur at an earlier stage.
> The amount of flammable gases is not known in real-life situations either, so it is not clear whether there is a rich or a poor mixture. If water is added to a smoke gas layer, it can be mixed with oxygen so that a smoke gas layer whose mixture is too rich can actually be brought to within the flammability limits.
> The efficiency for converting liquid water into steam is not known. This depends on the actual situation. Examples of factors that are important in this context are the technique used, its actual implementation (spray pattern, angle, water droplets), and the skills of the firefighters.

The example shows that large volumes require relatively much water to achieve inertisation. It is not unthinkable that inertisation may occur at some time with smaller volumes. However, this moment cannot be observed nor measured by the firefighters on the site. This means that this cannot be assumed in practice. Therefore, smoke gas cooling is not inertisation.

6.2 Preventing smoke gas explosions

In practice, there will be situations where smoke gas ignition and sometimes smoke gas explosions occur in rooms adjoining the room where there is a fire. In these situations, it is quite common that relatively cold pyrolysis gases will accumulate in a room that is not in direct contact with the fire in the room where the fire is. Since the pyrolysis gases are relatively cold, introducing water into this smoke gas layer seems to make little or no sense. Inertisation is not feasible, especially if the temperature of the smoke gas layer is low, since it will not be possible to create sufficient water vapour for inertisation at temperatures near the boiling point of water. And there is also the risk that, if the mixture is too rich, a mixing of the smoke gas layer will actually create a flammable mixture. Especially for gases with a low lower and a low upper flammability limit (for example bitumen and styrene), it does not take much for the risk of ignition to occur. Since any changes to the situation cannot, or can hardly, be observed or measured, there is a risk that an ignition will take place during such an attack.

6.3   The use of smoke gas cooling

The previous sections may have led you to believe that smoke gas cooling is of no use. However, the opposite is true. Cooling the smoke gases whilst progressing towards the seat of the fire is still very useful. However, as the description of the technique indicates, this concerns the cooling of the smoke gases. Cooling the smoke gases can temporarily prevent a flammable mixture from reaching its auto-ignition temperature. It is also a good method to make the direct vicinity of the branch man safer. The smoke gas layer is cooled temporarily, thus lowering the risk of a high heat load.

However, there is always a possibility of a gas mixture igniting. So it cannot be assumed that the current method of smoke gas cooling prevents ignition. The technique by which effective cooling and progressing towards the seat of the fire can be reached are part of supplementary studies.

6.4   In summary

Based on the experiments conducted, inertisation at some point in the real-life situation is not unthinkable. However, its occurrence cannot be observed nor measured by the firefighters on the site. This means that this **cannot** be assumed in practice. This means that, in real-life situations, the possibility of smoke gases igniting should always be taken into account regardless of whether smoke gas cooling has been applied.

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Bijlage 1 Kritische adiabatische vlamtemperatuur

Propaan

De kritische AFT kan worden bepaald op basis van de stoichiometrische oxidatiereactie van propaan:

$$C_3H_8 + 5O_2 + 18{,}8N_2 \rightarrow 3CO_2 + 4H_2O + 18{,}8N_2$$
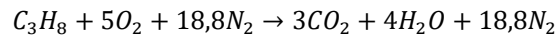
Deze reactie geeft voor elke verbrande mol propaan 2044 kJ aan energie vrij (SFPE, 2016). Van propaan is bekend dat de onderste explosiegrens bij omgevingstemperatuur ongeveer 2,2% bedraagt. De oxidatiereactie kan bij een dergelijk mengsel als volgt worden weergegeven:

$$0{,}022C_3H_8 + 0{,}978(0.21O_2 + 0{,}79N_2) \rightarrow producten$$
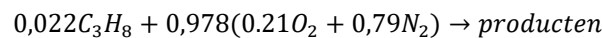
Door te delen door 0,022 kan de vergelijking als volgt worden weergegeven:

$$C_3H_8 + 9{,}34O_2 + 35{,}12N_2 \rightarrow 3CO_2 + 4H_2O + 4{,}34O_2 + 35{,}12N_2$$

De vrijkomende energie gaat naar het verwarmen van de reactieproducten. Voor bovenstaande reactievergelijking is dat 3 mol koolstofdioxide, 4 mol waterdamp, 4,34 mol zuurstof en 35,12 mol stikstof voor elke verbrande mol propaan. De thermische warmtecapaciteit van deze reactieproducten kan worden berekend uit de thermische warmtecapaciteit van de individuele gassen. In de tabel is deze berekening weergegeven.

Thermische warmtecapaciteit van de reactieproducten van een verbranding van een propaan/lucht mengsel bij de onderste explosiegrens

	Aantal mollen	Thermische warmtecapaciteit bij 1000 [a]K	
		(J/mol.K)	(J/K)
CO_2	3	54,3	162,9
H_2O	4	41,2	164,8
O_2	4,34	34,9	151,5
N_2	35,12	32,7	1.148,4
Totale thermische warmtecapaciteit = (per mol propaan)			1.627,6 J/K

[a] De thermische warmtecapaciteit is temperatuurafhankelijk. De gebruikte 1000 graden K wordt gebruikt als gemiddelde.

Op basis van de vrijkomende energie bij de verbranding van één mol propaan kan de maximale temperatuurstijging worden bepaald:

$$\Delta T = \frac{2044000}{1627,6} = 1256\ K$$

Uitgaande van een begin temperatuur van 298 K (25ºC) betekent dit een AFT van 1554 K.

De kritische AFT kan ook worden gebruikt om bijvoorbeeld te bepalen bij welke samenstelling van een gas/luchtmengsel en een toegevoegd inert gas er geen ontbranding meer kan plaats vinden.

Waterdamp als inert gas
Bijvoorbeeld, in een ruimte is een stoichiometrisch propaan/luchtmengsel aanwezig. Om te voorkomen dat het gasmengsel tot ontbranding komt, wordt waterdamp als inert gas toegevoegd. Op basis van de kritische AFT kan het minimale volume percentage waterdamp berekend worden waarbij ontbranding voorkomen kan worden. In de reactievergelijking kan dat als volgt worden weergegeven:

$$C_3H_8 + 5O_2 + 18,8N_2 + XH_2O \rightarrow 3CO_2 + 4H_2O + XH_2O + 18,8N_2$$
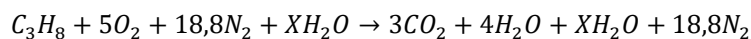
Hierin is X het aantal mollen waterdamp dat minimaal toegevoegd moet worden. Op basis van de tabel moet de totale warmtecapaciteit van het mengsel reactieproducten daarvoor hoger zijn dan 1627,6 J/K.

$$3CO_2 + (4 + X)H_2O + 18,8N_2 \rightarrow 3 \times 54,3 + 18,8 \times 32,7 + (4 + X) \times 41,2 = 1627,6 \rightarrow X = 16,6$$

Dit betekent dat 16,6 mol waterdamp nodig is bij 23,8 (5 + 18,8) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 41%.

Stikstof als inert gas
Zoals in voorgaande voorbeeld is weergegeven kan op basis van de kritische AFT het minimale volume percentage inert gas berekend worden waarbij ontbranding voorkomen kan worden ongeacht de ontstekingsbron. In dit geval dus stikstof:

$$C_3H_8 + 5O_2 + 18,8N_2 + XN_2 \rightarrow 3CO_2 + 4H_2O + XN_2 + 18,8N_2$$
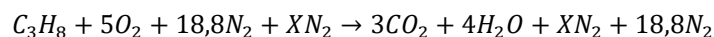
Hierin is X het aantal mollen stikstof dat minimaal toegevoegd moet worden. Op basis van tabel 4 moet de totale warmtecapaciteit van het mengsel reactieproducten daarvoor hoger zijn dan 1627,6 J/K.

$$3CO_2 + 4H_2O + (18,8 + X)N_2 \rightarrow 3 \times 54,3 + 4 \times 41.2 + (18,8 + X) \times 32,7 = 1627,6 \rightarrow X = 20,9$$

Dit betekent dat 20,9 mol stikstof nodig is bij 23,8 (5 + 18,8) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 47%.

Methaan
Bovenstaande uiteenzetting kan ook voor methaan worden uitgevoerd. De stoichiometrische oxidatiereactie van methaan kan als volgt worden weergegeven:

$$CH_4 + 2O_2 + 7,52N_2 \rightarrow CO_2 + 2H_2O + 7,52N_2$$
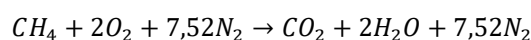
Deze reactie geeft voor elke verbrande mol methaan 800 kJ aan energie vrij. Van methaan is bekend dat de onderste explosiegrens bij omgevingstemperatuur ongeveer 5,2% bedraagt (SFPE, 2016). De oxidatiereactie kan bij een dergelijk mengsel als volgt worden weergegeven:

$$0,052CH_4 + 0,948(0,21O_2 + 0,79N_2) \rightarrow producten$$
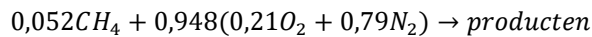
Door te delen door 0,052 kan de vergelijking als volgt worden weergegeven:
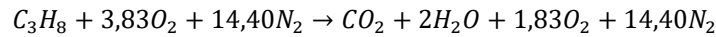
$$C_3H_8 + 3,83O_2 + 14,40N_2 \rightarrow CO_2 + 2H_2O + 1,83O_2 + 14,40N_2$$

De vrijkomende energie gaat naar het verwarmen van de reactieproducten. Voor bovenstaande reactievergelijking is dat 1 mol koolstofdioxide, 2 mol waterdamp, 1,83 mol zuurstof en 14,40 mol stikstof voor elke verbrande mol methaan. De thermische warmtecapaciteit van deze reactieproducten kan worden berekend uit de thermische warmtecapaciteit van de individuele gassen. In tabel is deze berekening weergegeven.

Thermische warmtecapaciteit van de reactieproducten van een verbranding van een methaan/lucht mengsel bij de onderste explosiegrens

	Aantal mollen	Thermische warmtecapaciteit bij 1000 K	
		(J/mol.K)	(J/K)
CO_2	1	54,3	54,3
H_2O	2	41,2	82,4
O_2	1,83	34,9	63,87
N_2	14,40	32,7	470,96
	Totale thermische warmtecapaciteit = (per mol methaan)		671,52 J/K

Op basis van de vrijkomende energie bij de verbranding van één mol methaan kan de maximale temperatuurstijging worden bepaald:

$$\Delta T = \frac{800000}{671,52} = 1191\ K$$

Uitgaande van een begin temperatuur van 298 K (25ºC) betekent dit een AFT van 1489 K.

Waterdamp als inert gas
De reactievergelijking kan als volgt worden weergegeven:

$$CH_4 + 2O_2 + 7,52N_2 + XH_2O \rightarrow CO_2 + 2H_2O + XH_2O + 7,52N_2$$
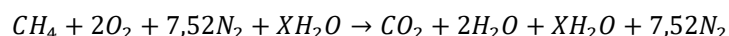
$$CO_2 + (2 + X)H_2O + 7,52N_2 \rightarrow 54,3 + 7,52 \times 32,7 + (2 + X) \times 41,2 = 671,5 \rightarrow X = 7,01$$

Dit betekent dat 7,01 mol waterdamp nodig is bij 9,52 (2 + 7,52) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 42%.

Stikstof als inert gas

De reactievergelijking kan als volgt worden weergegeven:

$$CH_4 + 2O_2 + 7.52N_2 + XN_2 \rightarrow CO_2 + 2H_2O + XN_2 + 7.52N_2$$
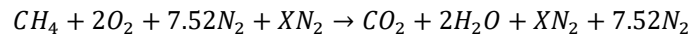
$$CO_2 + 2H_2O + (7.52 + X)N_2 \rightarrow 54.3 + 2 \times 41.2 + (7.52 + X) \times 32.7 = 671.5 \rightarrow X = 8.8$$

Dit betekent dat 8,8 mol stikstof nodig is bij 9,52 (2 + 7,52) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 48%.

Koolstofmonoxide

Bovenstaande uiteenzetting kan ook voor koolstofmonoxide worden uitgevoerd. De stoichiometrische oxidatiereactie van koolstofmonoxide kan als volgt worden weergegeven:

$$CO + 0{,}5O_2 + 1{,}88N_2 \rightarrow CO_2 + 1{,}88N_2$$
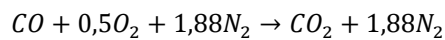
Deze reactie geeft voor elke verbrande mol koolstofmonoxide 283 kJ aan energie vrij. Van koolstofmonoxide is bekend dat de onderste explosiegrens bij omgevingstemperatuur ongeveer 13.1% bedraagt (SFPE, 2016). De oxidatiereactie kan bij een dergelijk mengsel als volgt worden weergegeven:

$$0{,}131CO + 0{,}869(0{,}21O_2 + 0{,}79N_2) \rightarrow producten$$
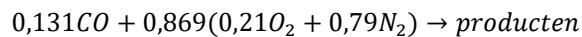
Door te delen door 0,131 kan de vergelijking als volgt worden weergegeven:
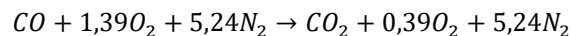
$$CO + 1{,}39O_2 + 5{,}24N_2 \rightarrow CO_2 + 0{,}39O_2 + 5{,}24N_2$$

De vrijkomende energie gaat naar het verwarmen van de reactieproducten. Voor bovenstaande reactievergelijking is dat 1 mol koolstofdioxide, 0,39 mol zuurstof en 5,24 mol stikstof voor elke verbrande mol koolstof monoxide. De thermische warmtecapaciteit van deze reactieproducten kan worden berekend uit de thermische warmtecapaciteit van de individuele gassen. In tabel is deze berekening weergegeven.

Thermische warmtecapaciteit van de reactieproducten van een verbranding van een koolstofmonoxide/lucht mengsel bij de onderste explosiegrens

	Aantal mollen	Thermische warmtecapaciteit bij 1000 K	
		(J/mol.K)	(J/K)
CO_2	1	54,3	54,3
H_2O	0	41,2	0
O_2	0,39	34,9	13,72
N_2	5,24	32,7	171,37
	Totale thermische warmtecapaciteit = (per mol koolstofmonoxide)		239,38 J/K

Op basis van de vrijkomende energie bij de verbranding van één mol propaan kan de maximale temperatuurstijging worden bepaald:

$$\Delta T = \frac{283000}{239,38} = 1182\ K$$

Uitgaande van een begin temperatuur van 298 K (25ºC) betekent dit een AFT van 1480 K.

Waterdamp als inert gas
De reactievergelijking kan als volgt worden weergegeven:

$$CO + 0,5O_2 + 1,88N_2 + XH_2O \rightarrow CO_2 + XH_2O + 1,88N_2$$
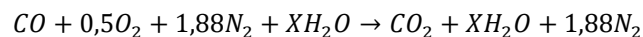
$$CO_2 + XH_2O + 1,88N_2 \rightarrow 54,3 + 1,88 \times 32,7 + X \times 41,2 = 239,38 \rightarrow X = 3,0$$

Dit betekent dat 3,0 mol waterdamp nodig is bij 2,38 (0,5 + 1,88) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 56%.

Stikstof als inert gas
De reactievergelijking kan als volgt worden weergegeven:

$$CO + 0,5O_2 + 1,88N_2 + XN_2 \rightarrow CO_2 + XN_2 + 1,88N_2$$
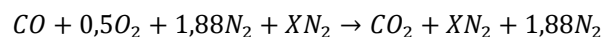
$$CO_2 + (1,88 + X)N_2 \rightarrow 54,3 + (1,88 + X) \times 32,7 = 239,38 \rightarrow X = 3,78$$

Dit betekent dat 3,78 mol stikstof nodig is bij 2,38 (0,5 + 1,88) mol lucht om het gasmengsel inert te maken. Dit komt overeen met volumepercentage van ongeveer 61%.

Samenvattend
In onderstaande tabel is een samenvatting op genomen van bovenstaande berekeningen.

Samenvattend kritische AFT en volumepercentages inert gas op basis van AFT en reactievergelijking

Gas	Kritische AFT [K]	Waterdamp [%]	Stikstof [%]
Propaan	1554	41	47
Methaan	1489	42	48
Koolstofmonoxide	1480	56	61

Zowel bij waterdamp als stikstof als inert gas worden bij koolstofmonoxide de hoogste waarden gevonden. In eerste instantie zou men dat misschien niet verwachten, omdat de verbrandingswarmte van koolstofmonoxide een factor 7 lager ligt dan die van propaan. Echter doordat de brandbaarheidsgrenzen van koolstofmonoxide ver uit elkaar liggen (LFL 12,5% en UFL 74%) is er veel inert gas nodig om het inertiseringspunt (IP) te bereiken. De stoichiometrische beginwaarde ligt voor koolstofmonoxide dan ook bij 34,8%, dit is in vergelijking tot propaan (3.8%) en methaan (9.6%).

Bijlage 2 Experimenten met koude gassen

Algemeen

In deze bijlage zijn de uitgebreide resultaten van de experimenten met koude gassen weergegeven. Niet van alle experimenten kon een volumebalans worden opgesteld door het ontbreken van relevante gegevens.

Stoom

Test 1 en 2: 10 seconden

Temperatuur

Volumepercentage [%]
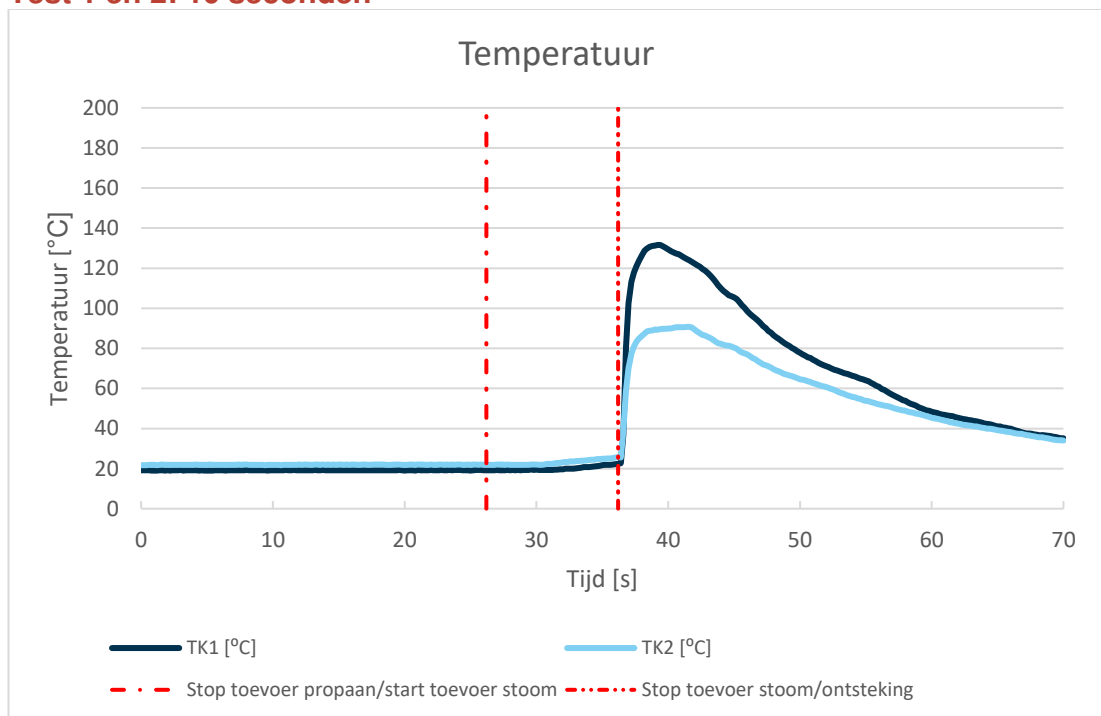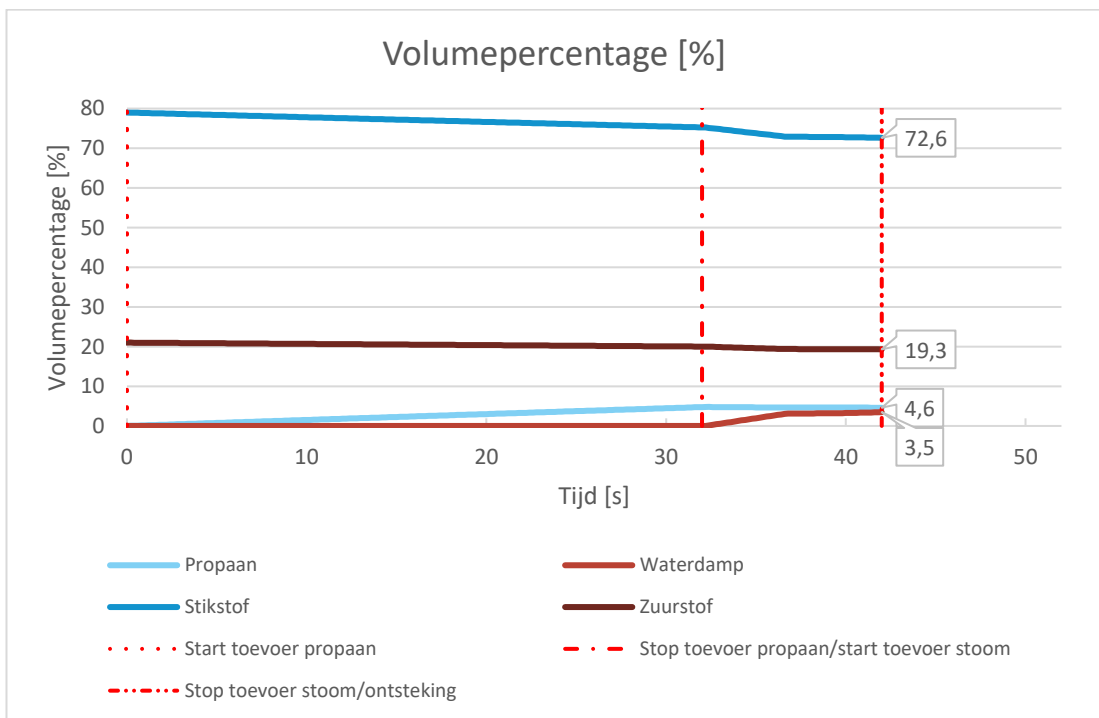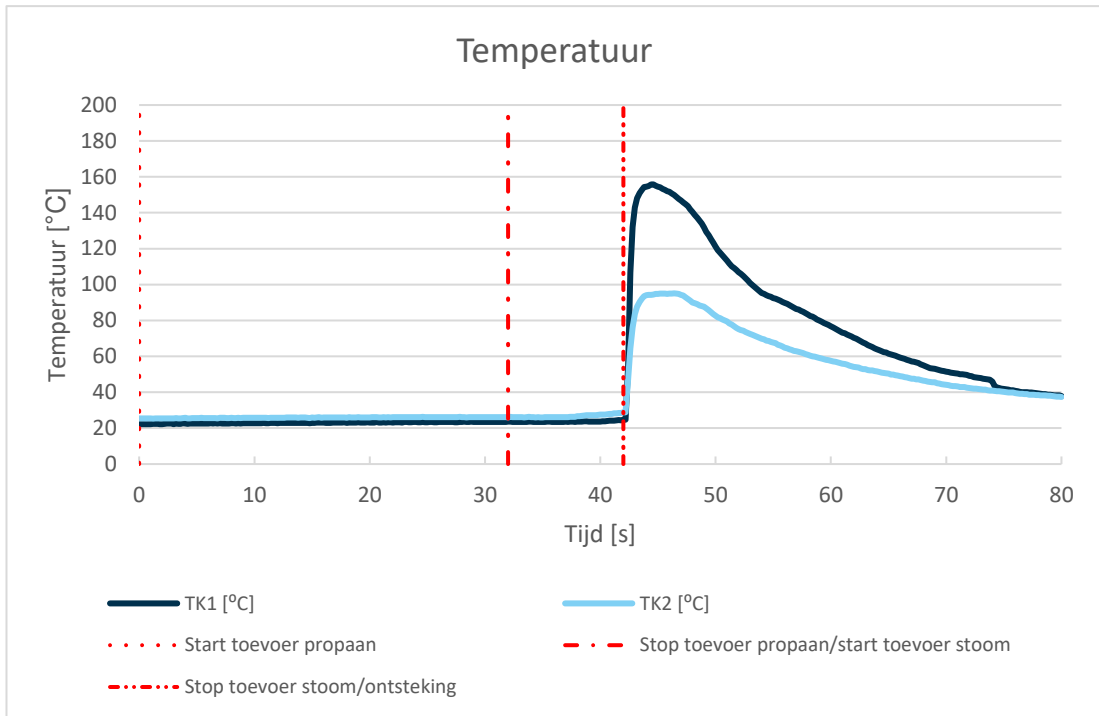
Test 1: Ontbranding bij 10 sec stoom

Test 2: Ontbranding bij 10 sec stoom

Test 3 en 4: 20 seconden

Temperatuur

Legenda:
— TK1 [°C] — TK2 [°C]
–·–· Stop toevoer propaan/start toevoer stoom ····· Stop toevoer stoom/ontsteking

Temperatuur

Legenda:
— TK1 [°C] — TK2 [°C]
····· Start toevoer propaan
–·–· Stop toevoer propaan/start toevoer stoom
–··–·· Stop toevoer stoom/ontsteking
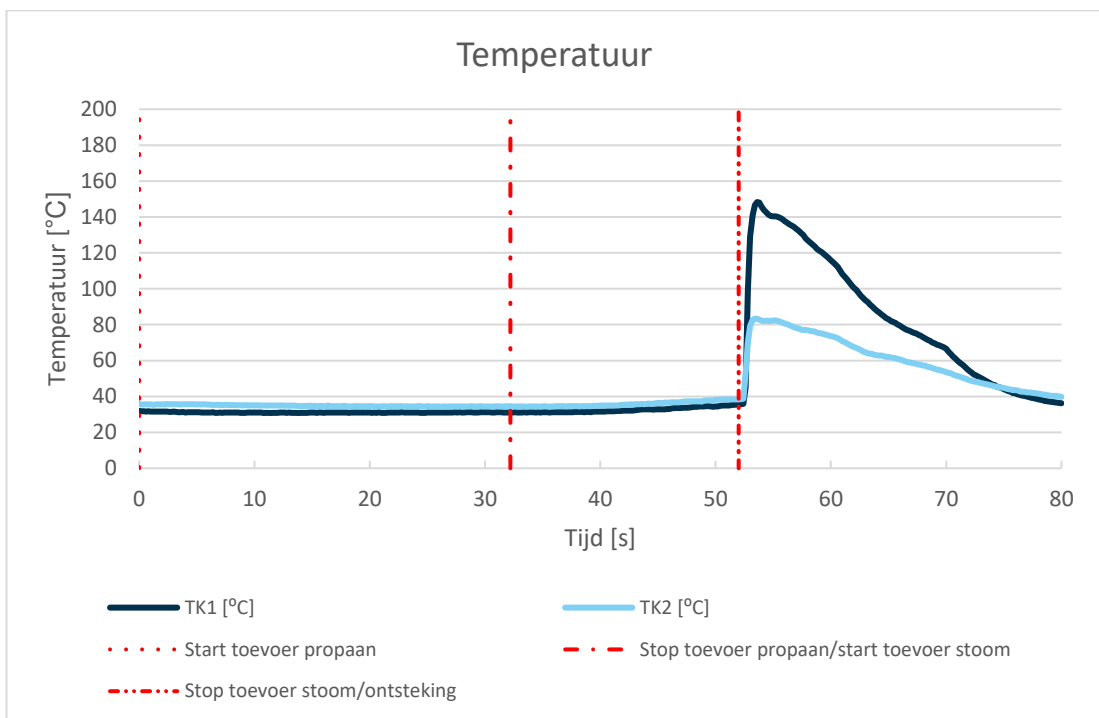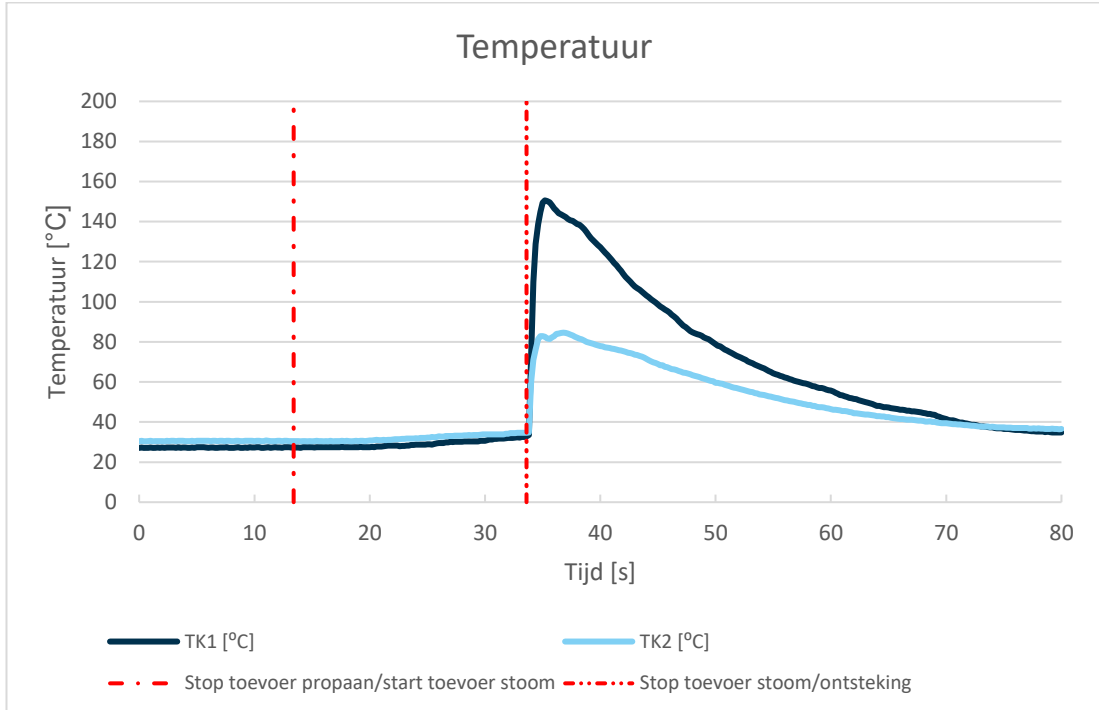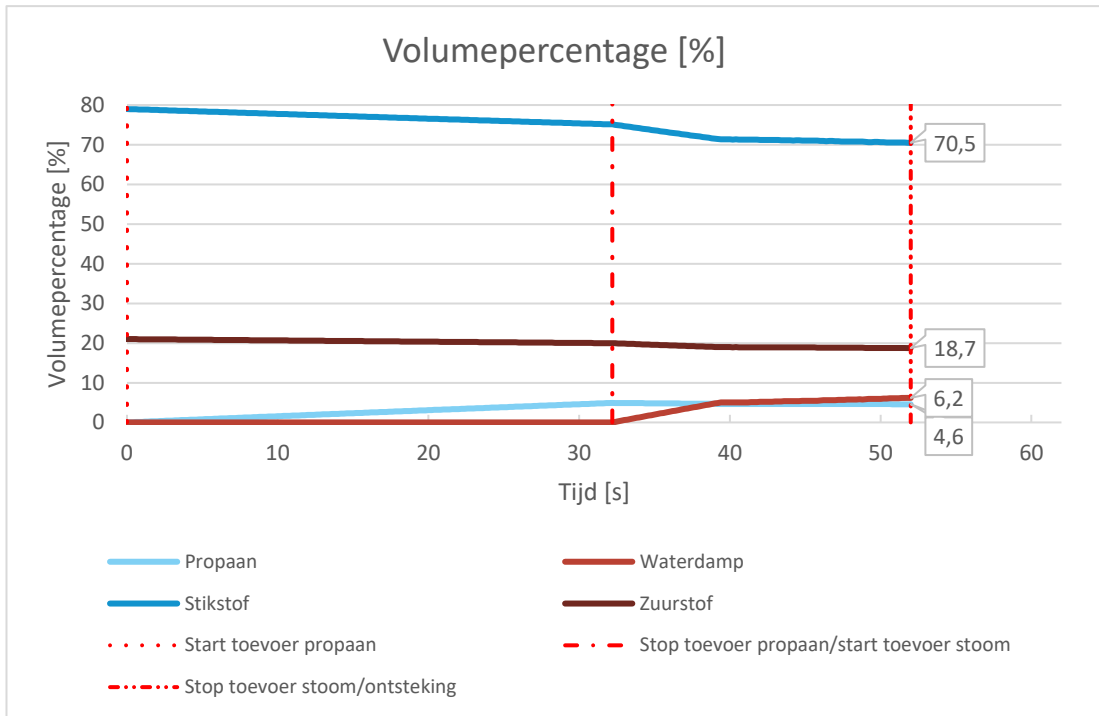
Test 3: Ontbranding bij 20 sec stoom

Test 4: Ontbranding bij 20 sec stoom

Test 5 en 6: 30 seconden

Temperatuur

Volumepercentage [%]

Temperatuur

Legend:
- TK1 [°C]
- TK2 [°C]
- ⋯⋯ Start toevoer propaan
- —·— Stop toevoer propaan/start toevoer stoom
- —··— Stop toevoer stoom/ontsteking

Volumepercentage [%]

69,0
18,3
8,2
4,5

Legend:
- Propaan
- Waterdamp
- Stikstof
- Zuurstof
- ⋯⋯ Start toevoer propaan
- —·— Stop toevoer propaan/start toevoer stoom
- —··— Stop toevoer stoom/ontsteking
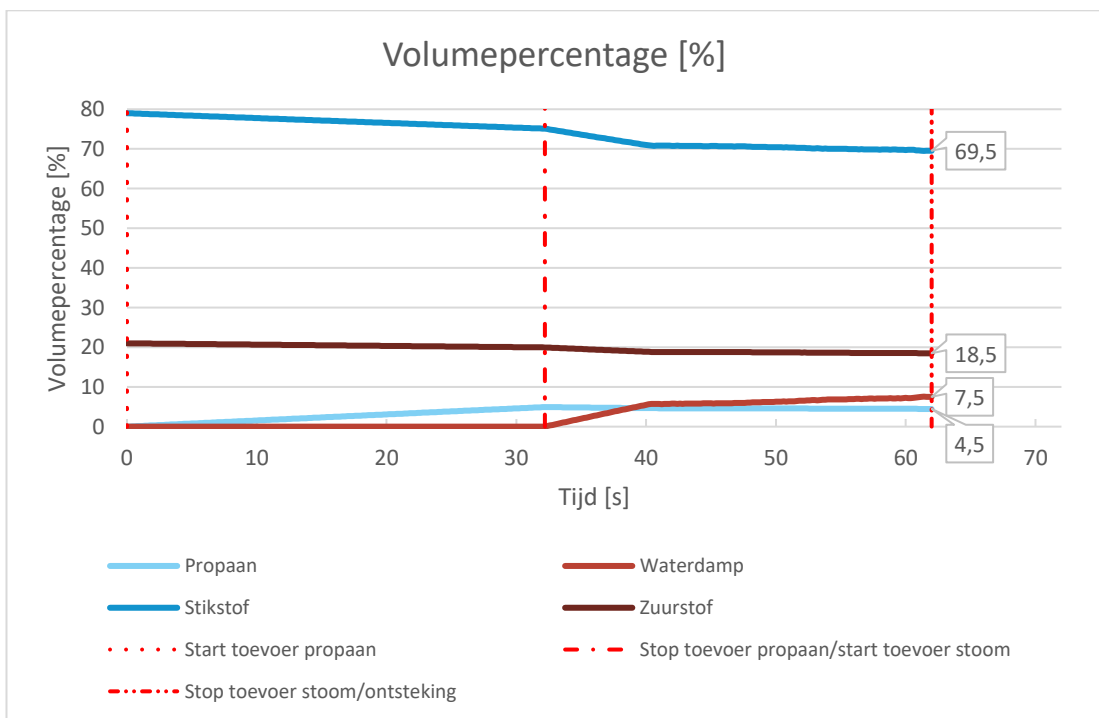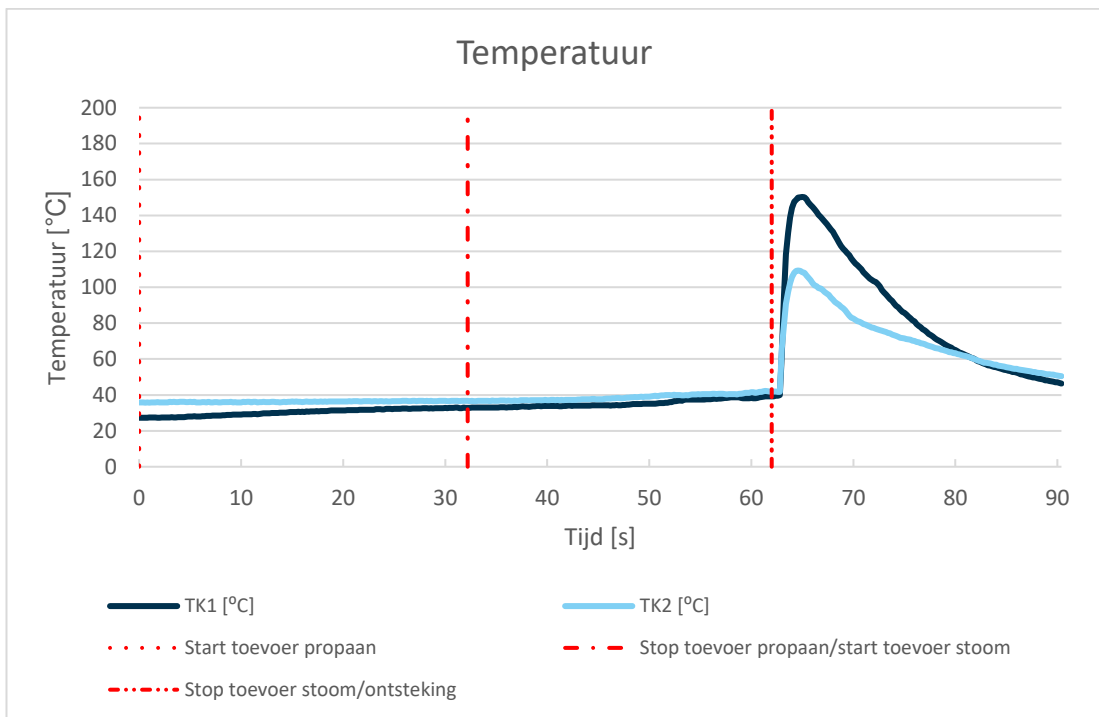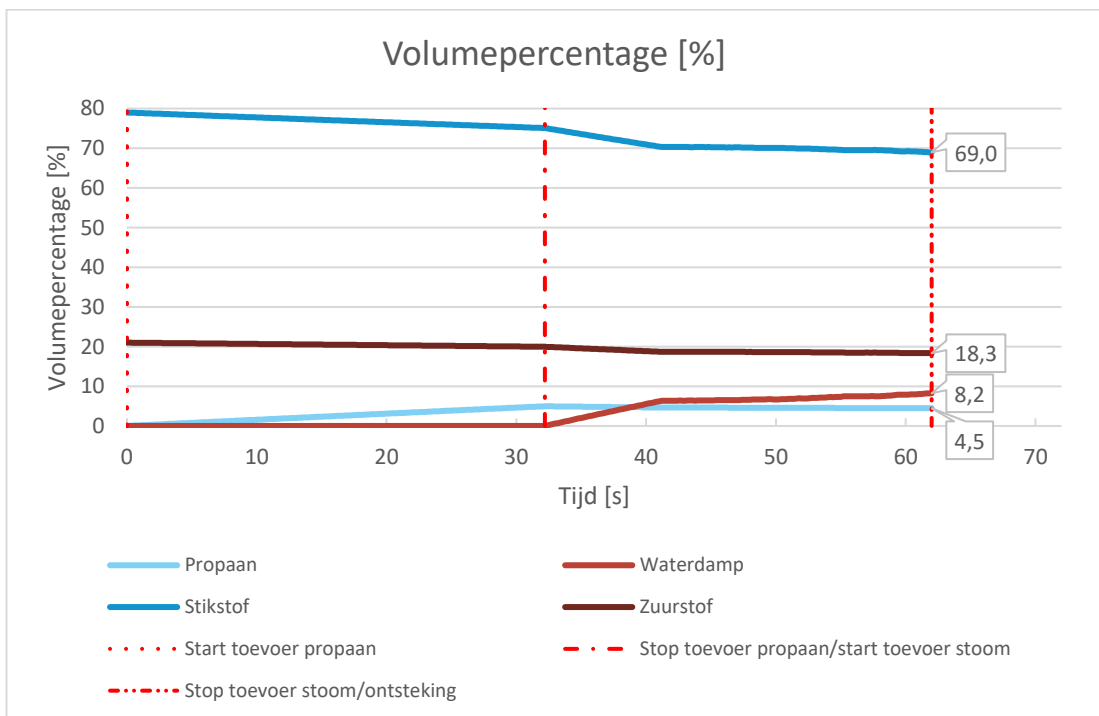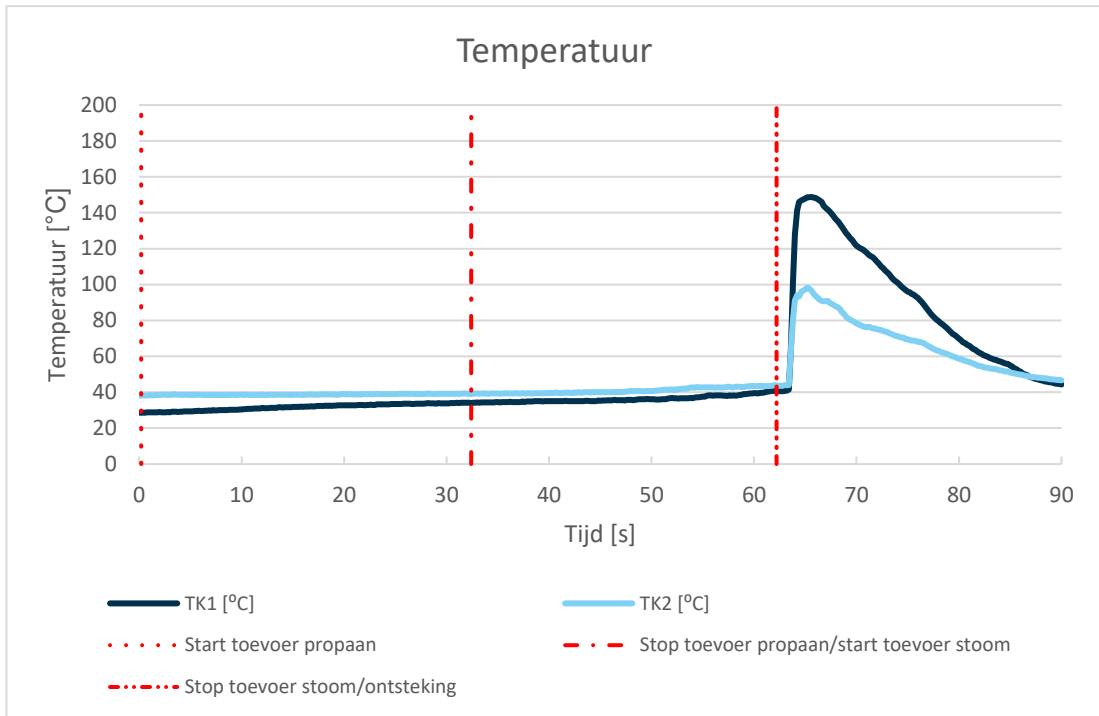
Test 5: Ontbranding bij 30 sec stoom

Test 6: Ontbranding bij 30 sec stoom

Test 7 en 8: 60 seconden
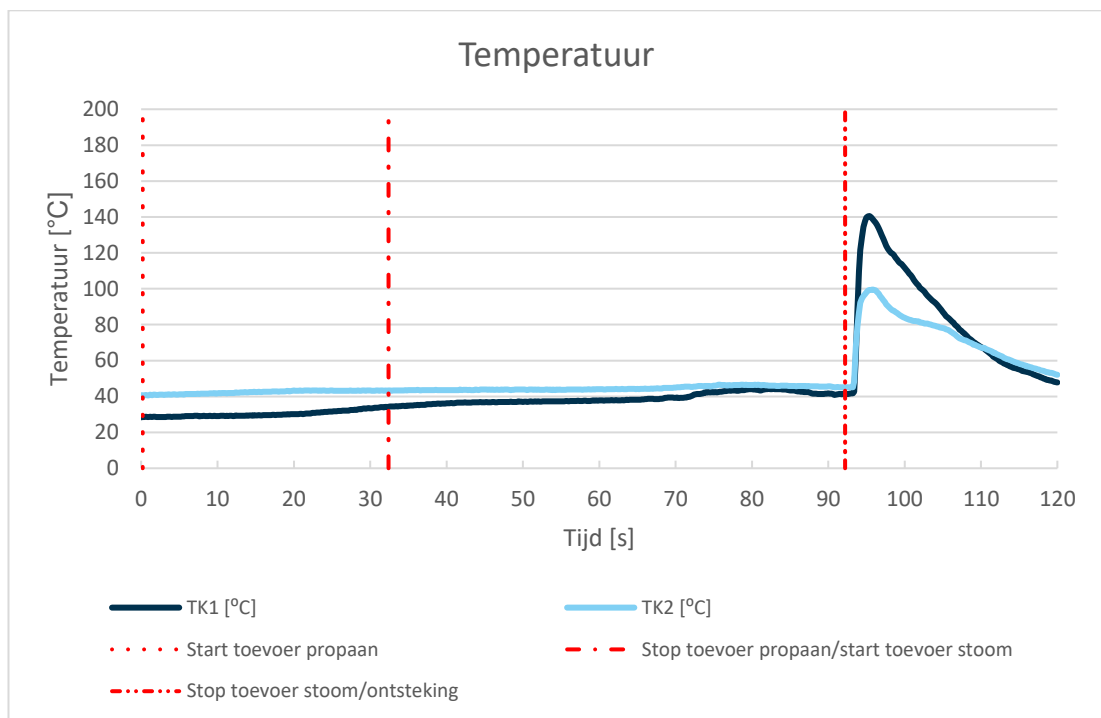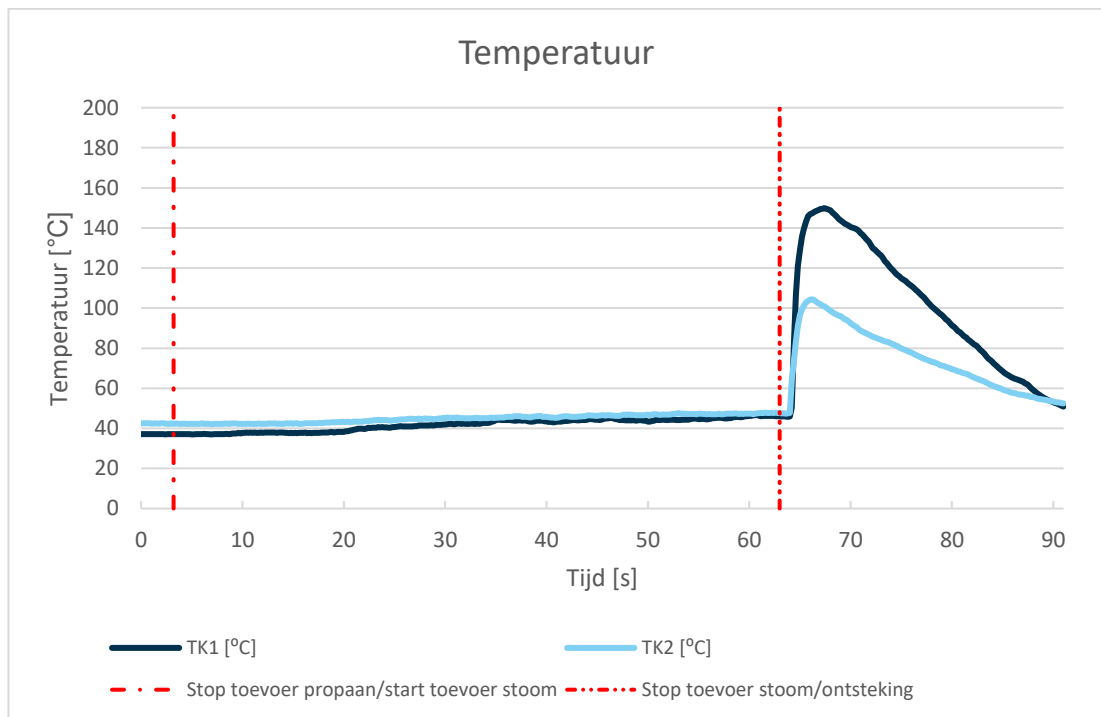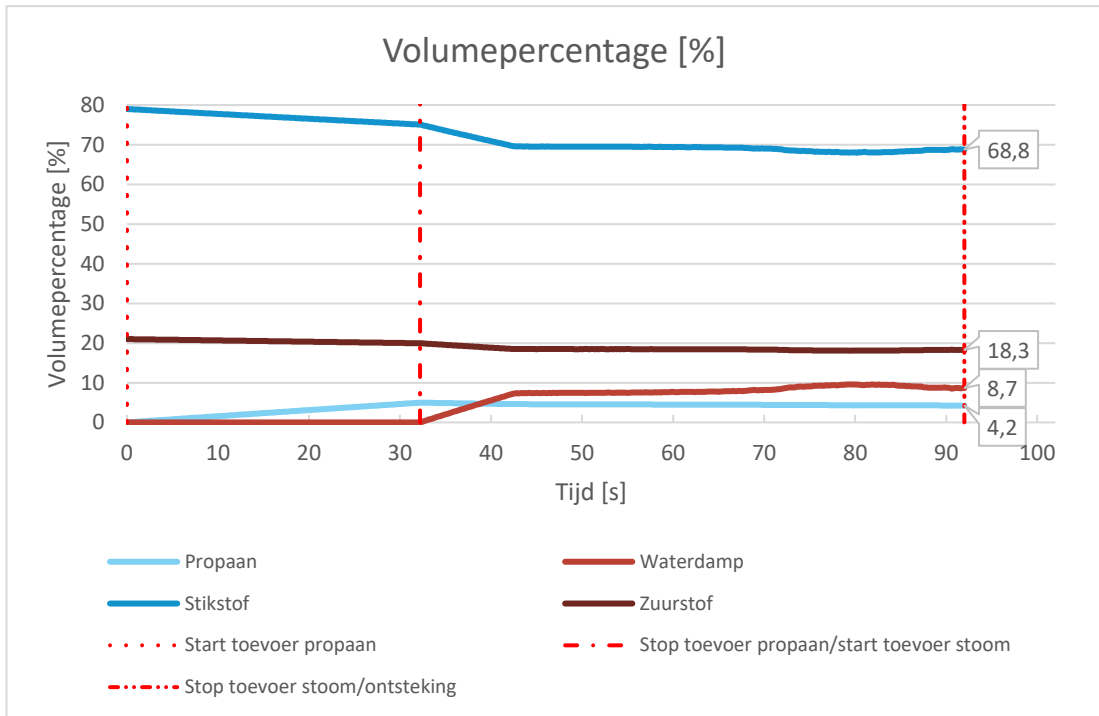
Test 7: Ontbranding bij 60 sec stoom

Test 8: Ontbranding bij 60 seconden stoom

Test 9 en 10: 120 seconden

Temperatuur

Volumepercentage [%]

Temperatuur
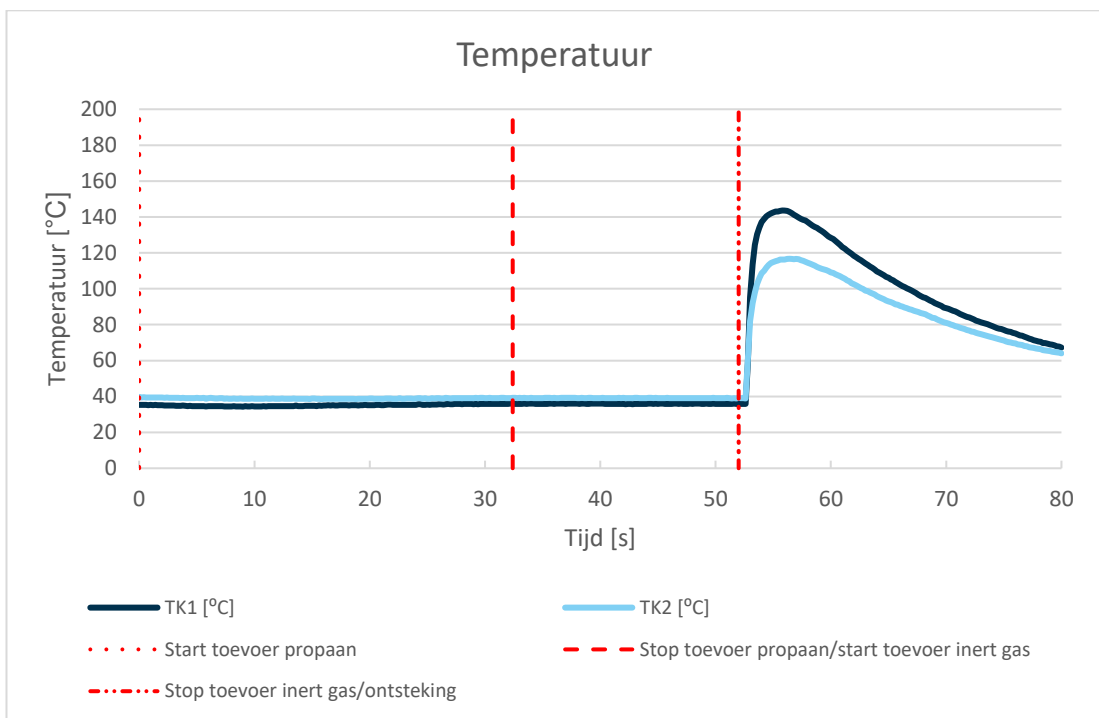

Volumepercentage [%]
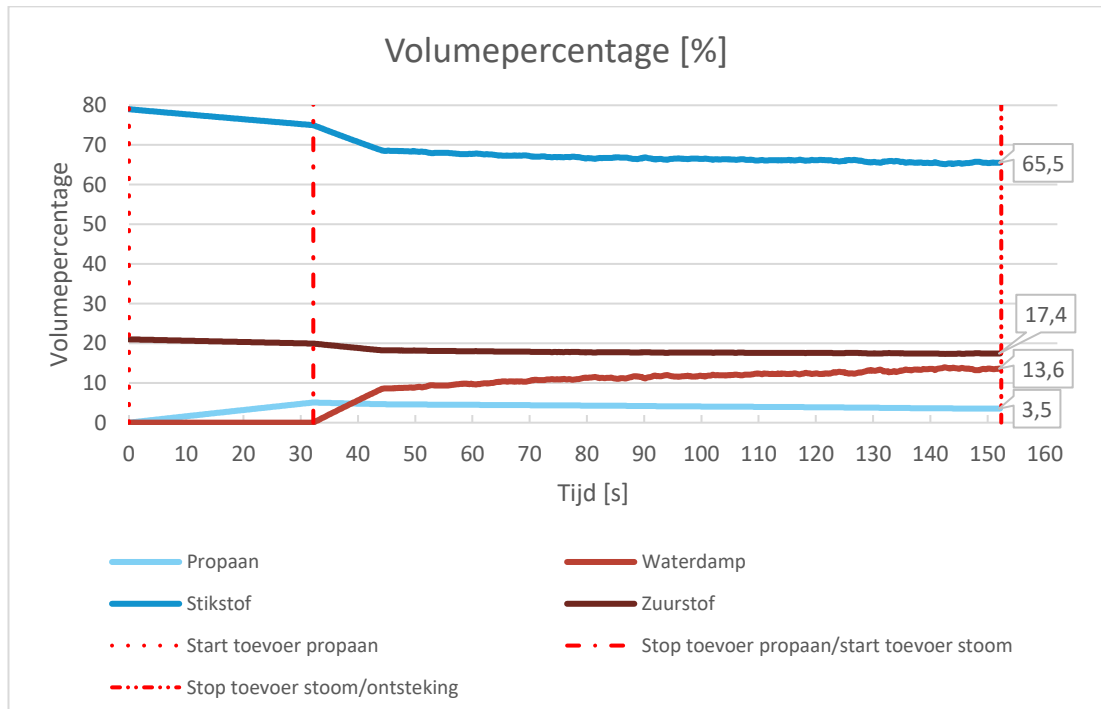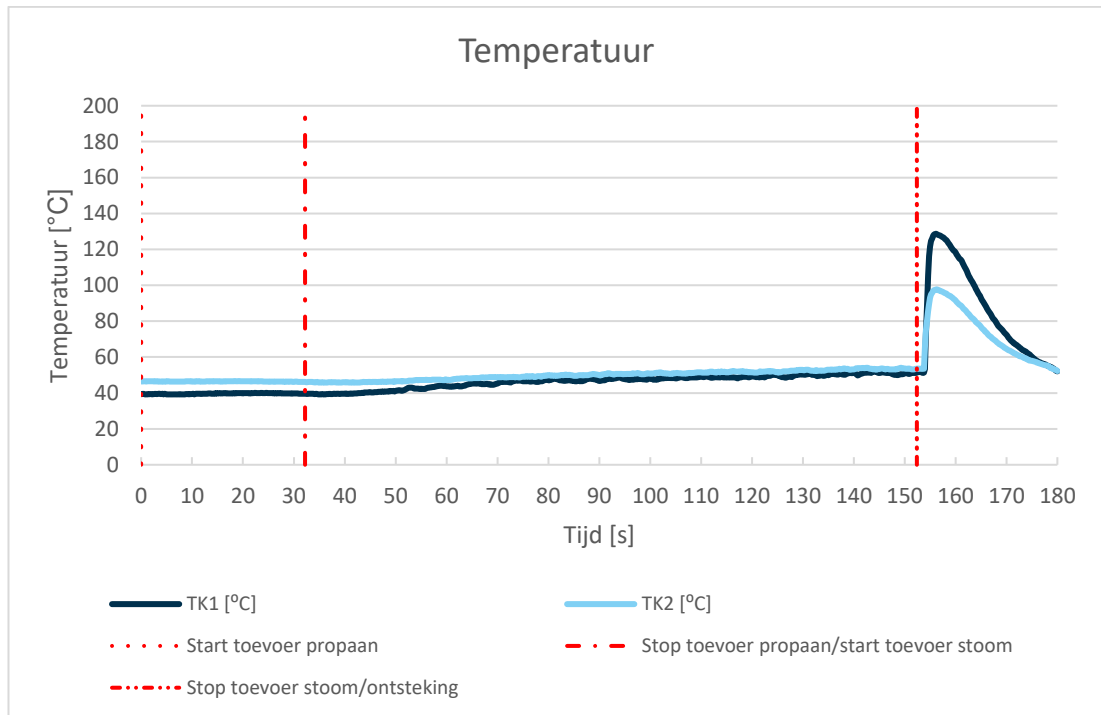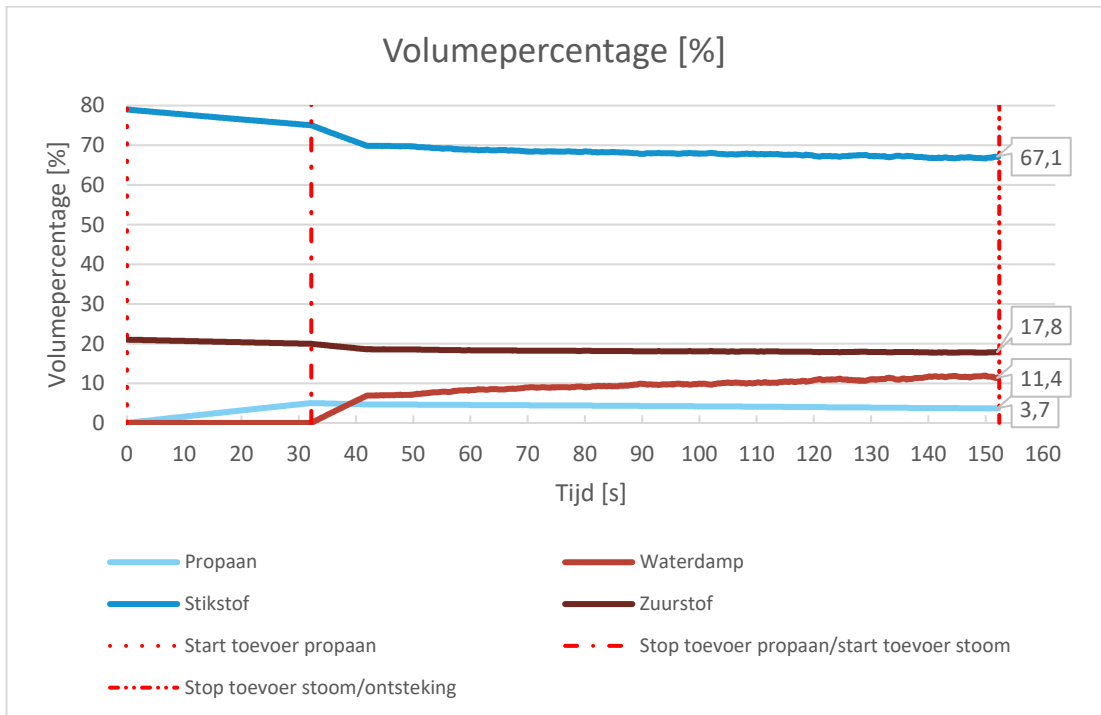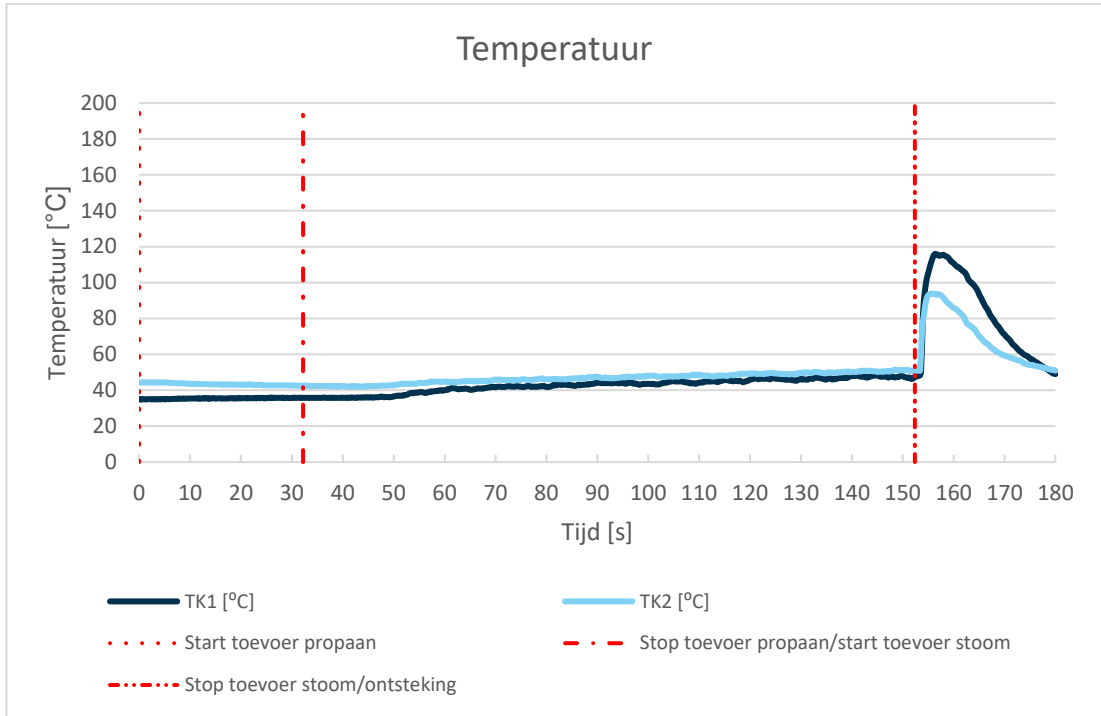
Test 9: Ontbranding bij 120 sec stoom

Test 10: Ontbranding bij 120 sec stoom

Test 11 en 12: 300 seconden

Temperatuur

Legend:
— TK1 [°C]
— TK2 [°C]
····· Start toevoer propaan
–·–· Stop toevoer propaan/start toevoer stoom
–··–· Stop toevoer stoom/ontsteking

Volumepercentage [%]

Labels: 61,2 — 20,5 — 16,3 — 2,0

Legend:
— Propaan
— Waterdamp
— Stikstof
— Zuurstof
····· Start toevoer propaan
–·–· Stop toevoer propaan/start toevoer stoom
–··–· Stop toevoer stoom/ontsteking

Temperatuur

Legenda:
- —— TK1 [°C]
- —— TK2 [°C]
- ····· Start toevoer propaan
- —·— Stop toevoer propaan/start toevoer stoom
- —··— Stop toevoer stoom/ontsteking

Volumepercentage [%]

Waarden bij einde: 62,1 — 18,9 — 16,5 — 2,5

Legenda:
- —— Propaan
- —— Waterdamp
- —— Stikstof
- —— Zuurstof
- ····· Start toevoer propaan
- —·— Stop toevoer propaan/start toevoer stoom
- —··— Stop toevoer stoom/ontsteking
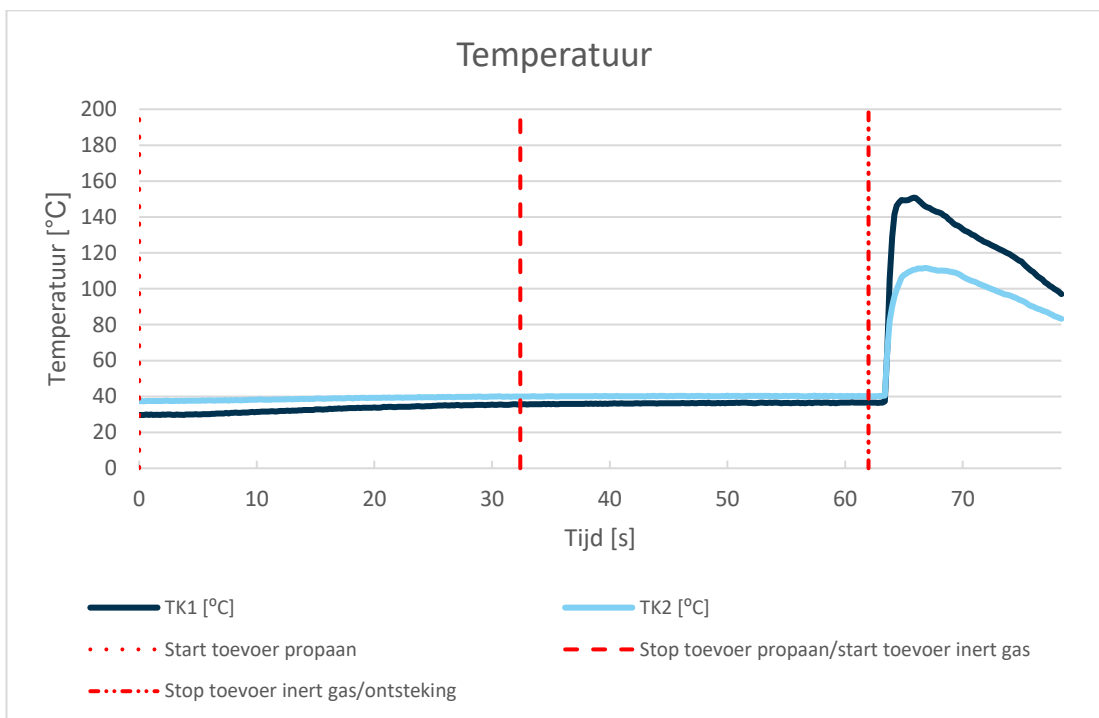
Test 11: Ontbranding bij 300 sec stoom

Test 12: Ontbranding bij 300 sec stoom

Samenvatting resultaten stoom koude gassen

Toevoertijd [s]	Volumepercentage [%]			Ontbranding [-]	Temperatuur [ºC]	
	Zuurstof	Waterdamp	Propaan		Max. na plof	Verschil
10 *	19,3	3,5	4,6	Ja	144	120
20 *	18,7	6,2	4,6	Ja	149	116
30	18,4	7,9	4,5	Ja	150	110
60 *	18,3	8,7	4,2	Ja	145	100
120	17,6	12,5	3,6	Ja	122	72
300	16,4	19,7	2,3	Ja	78	20

* Van deze experimenten kon de volumebalans maar voor één van de twee experimenten bepaald worden.

Gemiddelde temperatuur
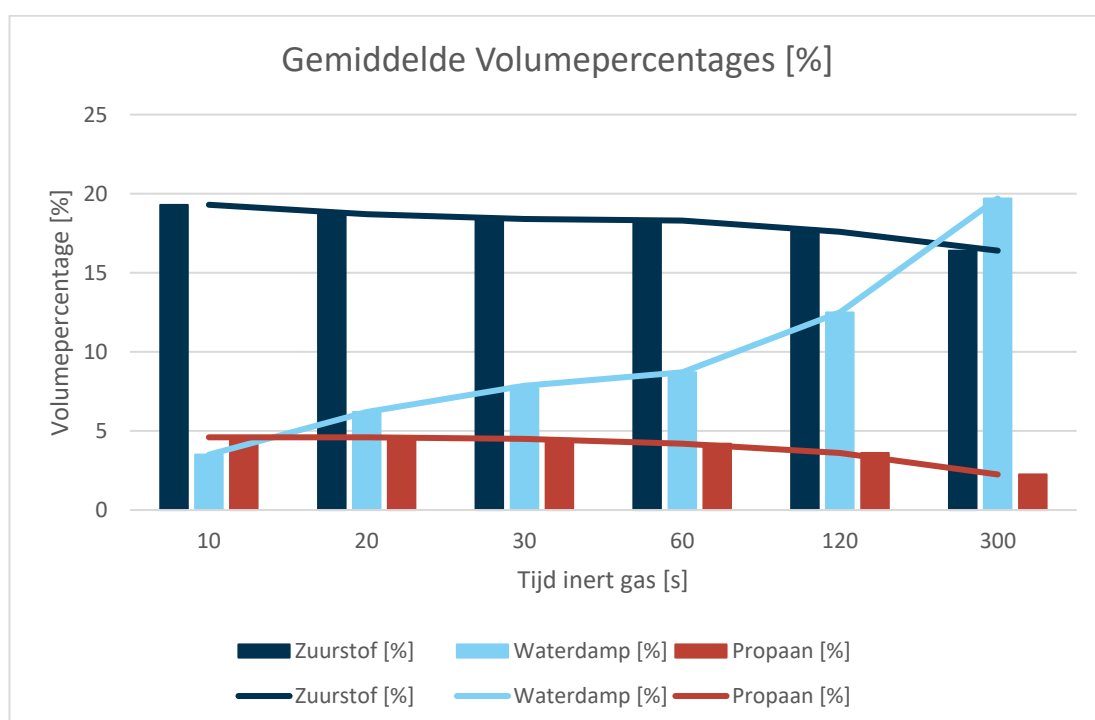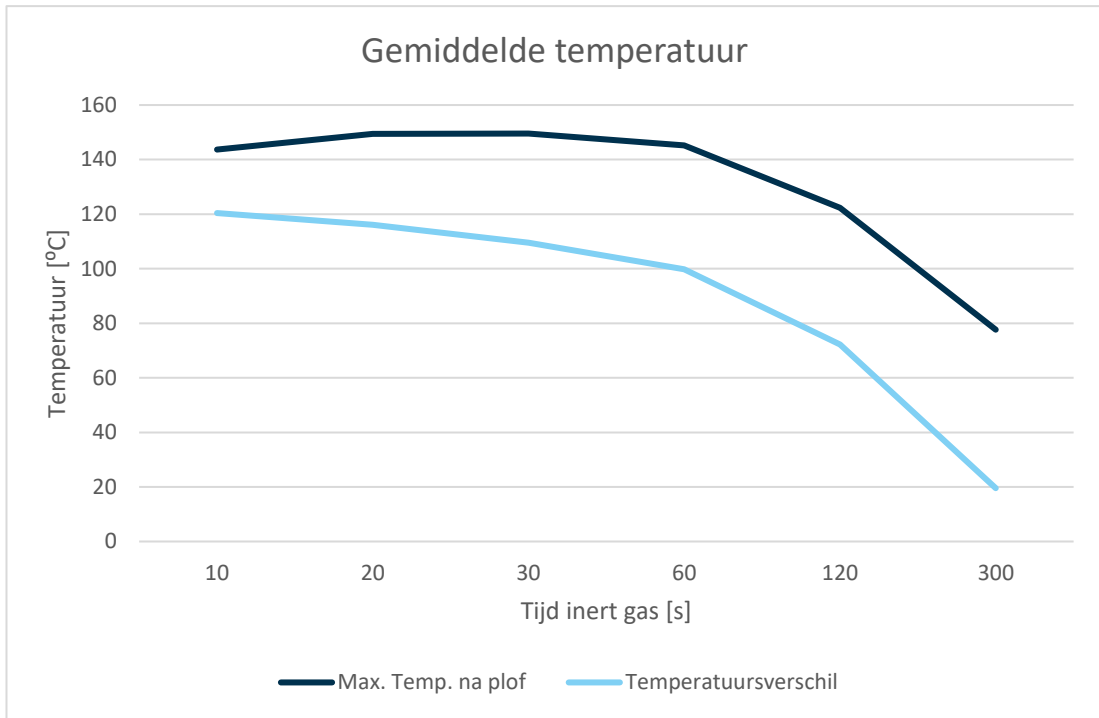
Nevel

Test 1 en 2: 10 seconden
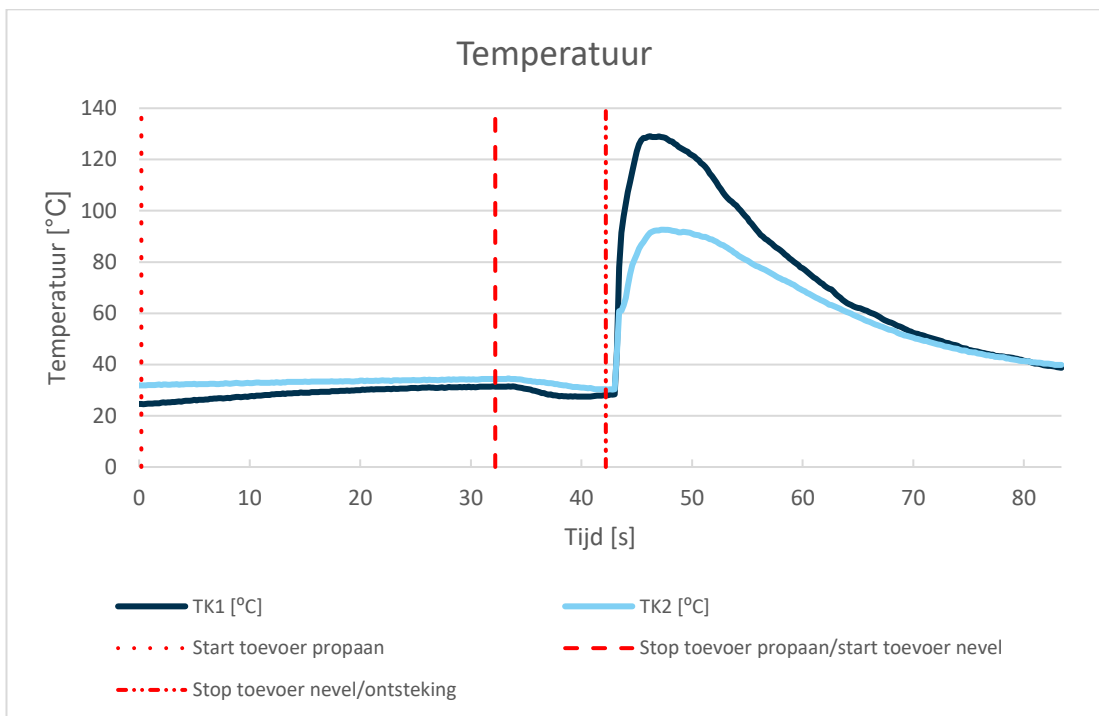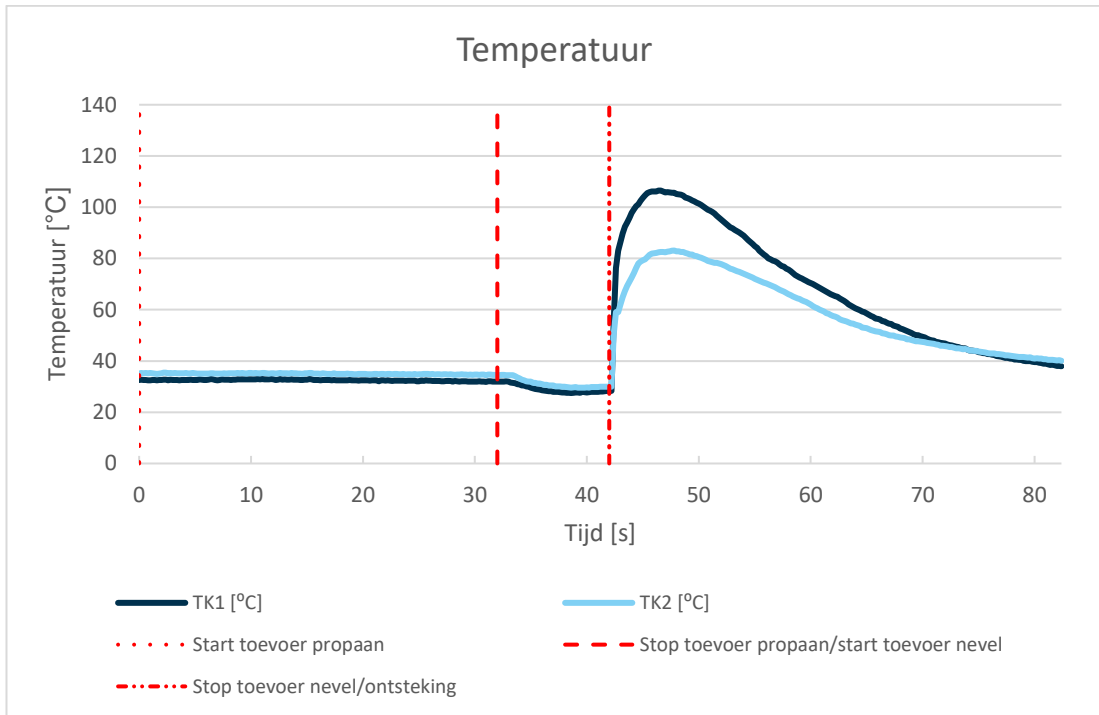
Test 1: Ontbranding bij 10 sec nevel

Test 2: Ontbranding bij 10 sec nevel

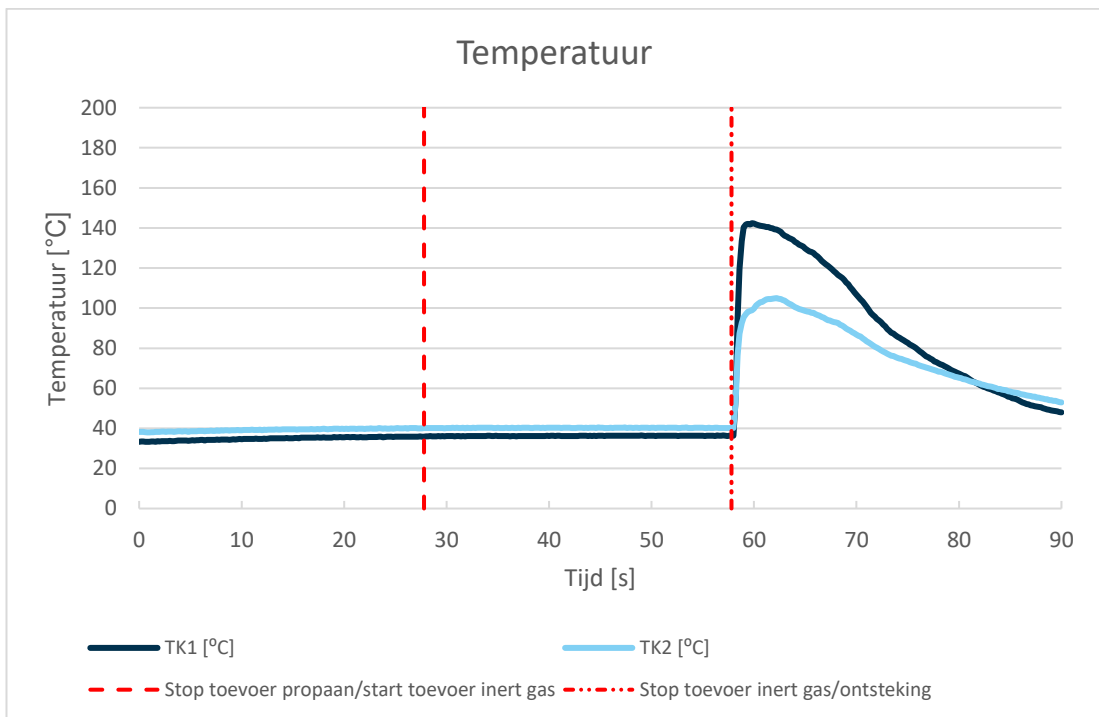**Test 3 en 4: 20 seconden**

Temperatuur

Temperatuur
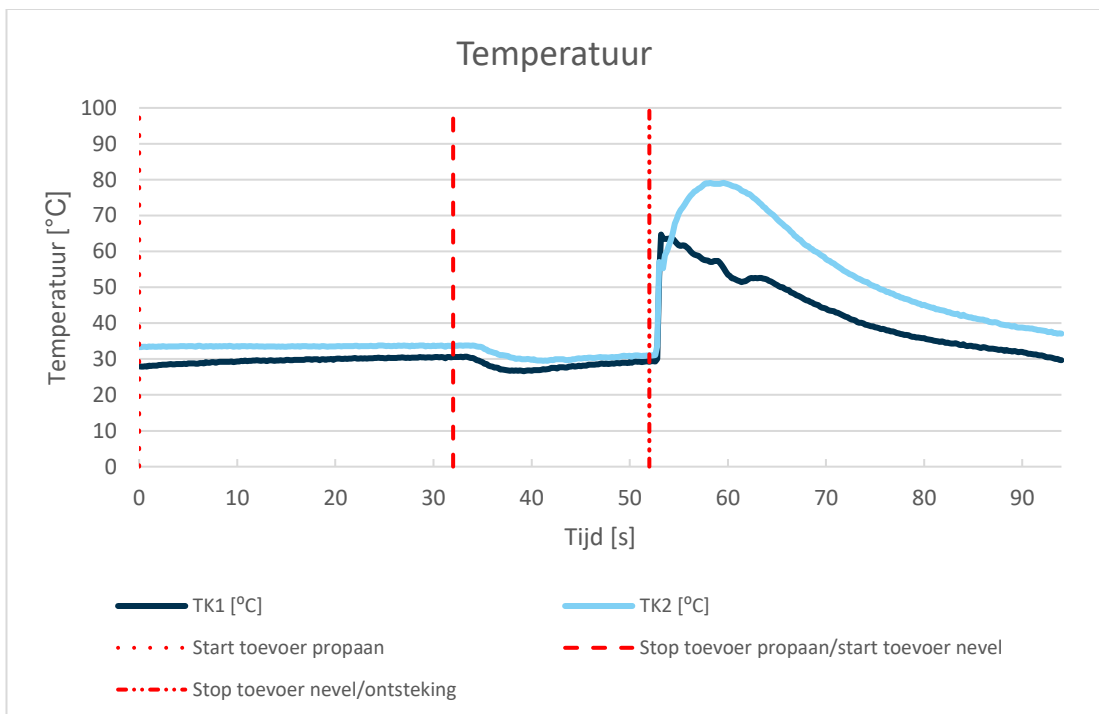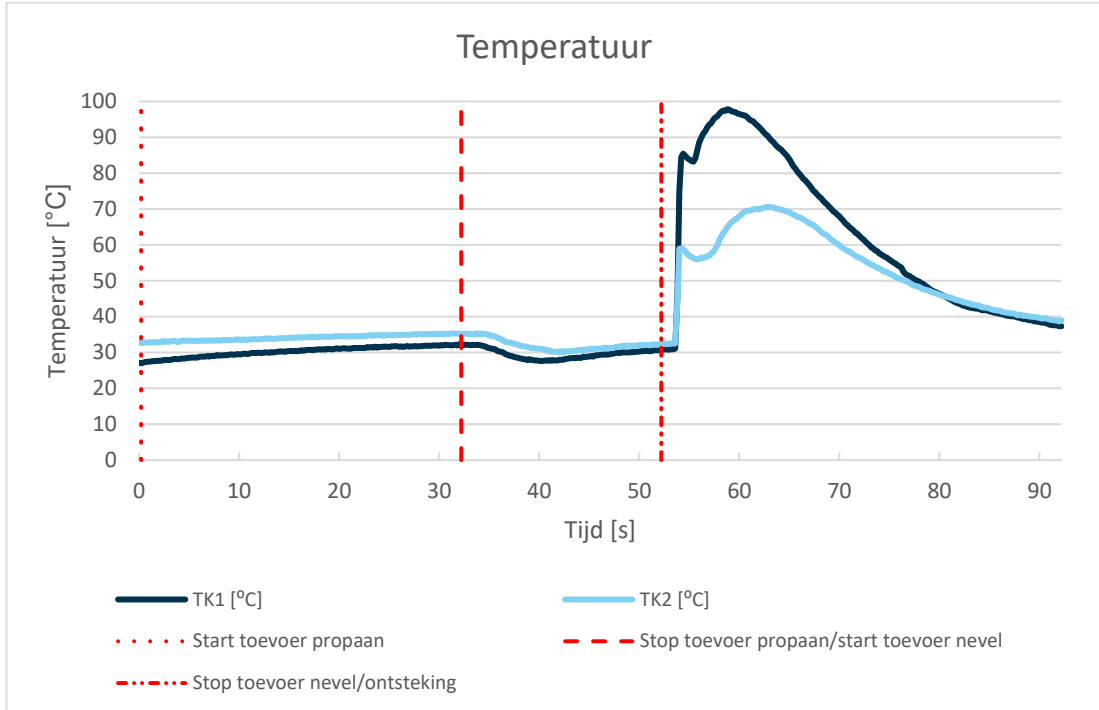
Test 3: Ontbranding bij 20 sec nevel

Test 4: Ontbranding bij 20 sec nevel

Test 5 en 6: 30 seconden

Temperatuur

TK1 [°C] TK2 [°C]
Start toevoer propaan Stop toevoer propaan/start toevoer nevel
Stop toevoer nevel/ontsteking

Temperatuur

TK1 [°C] TK2 [°C]
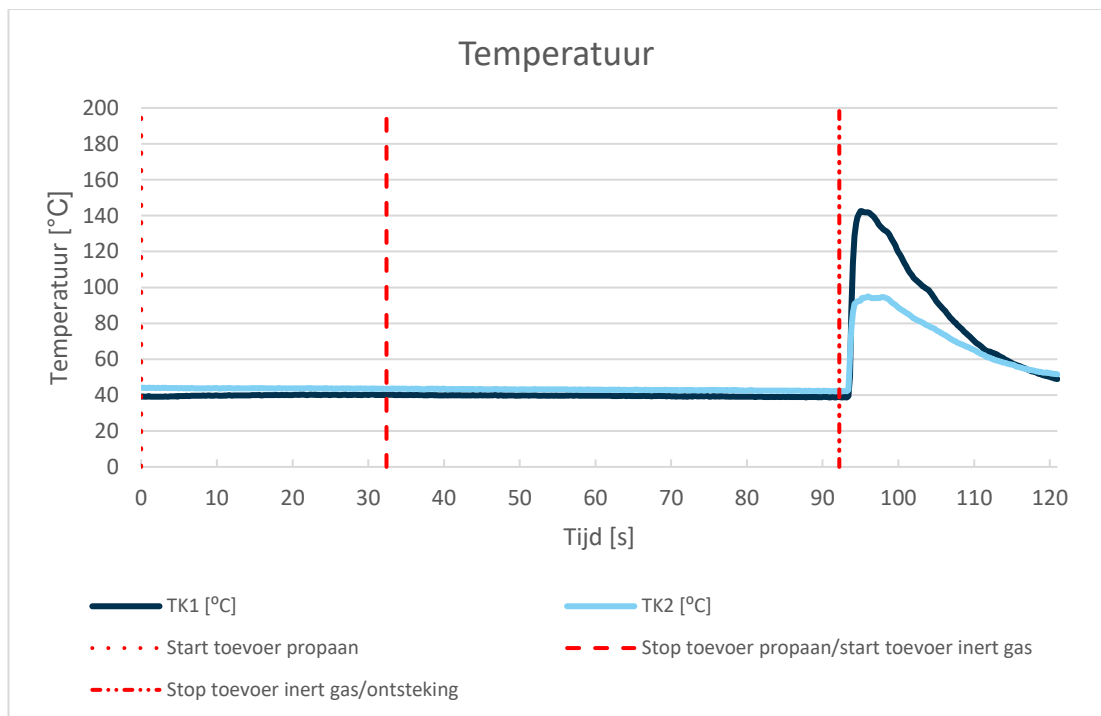Start toevoer propaan Stop toevoer propaan/start toevoer nevel
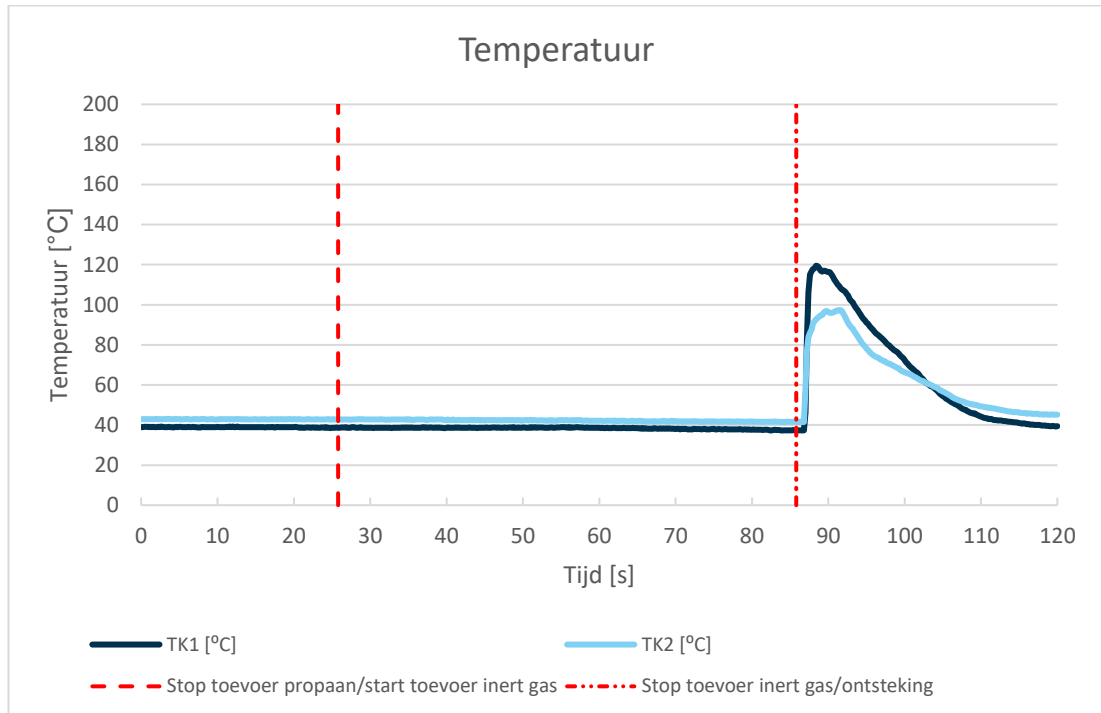Stop toevoer nevel/ontsteking
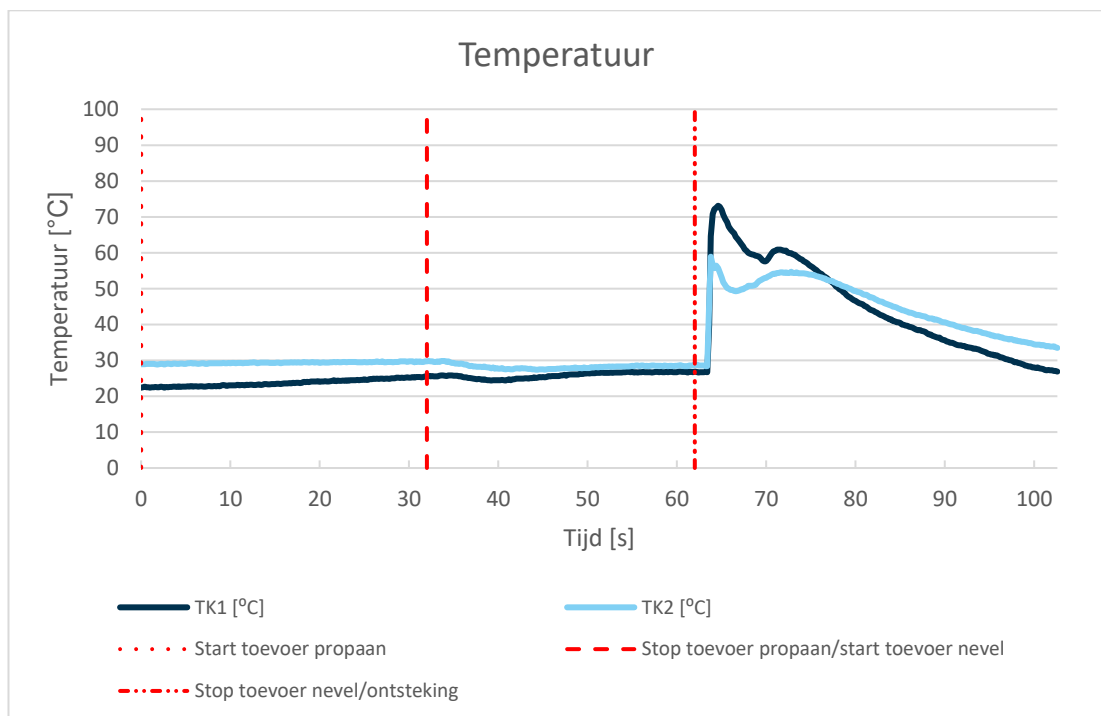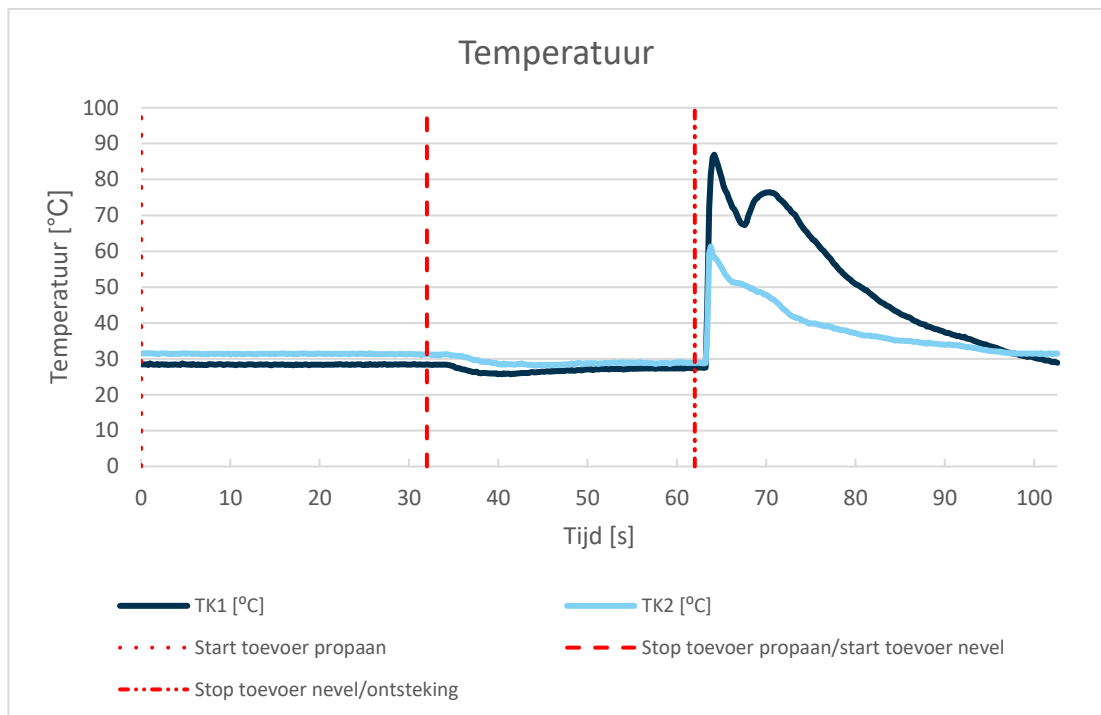
Test 5: Ontbranding bij 30 sec nevel

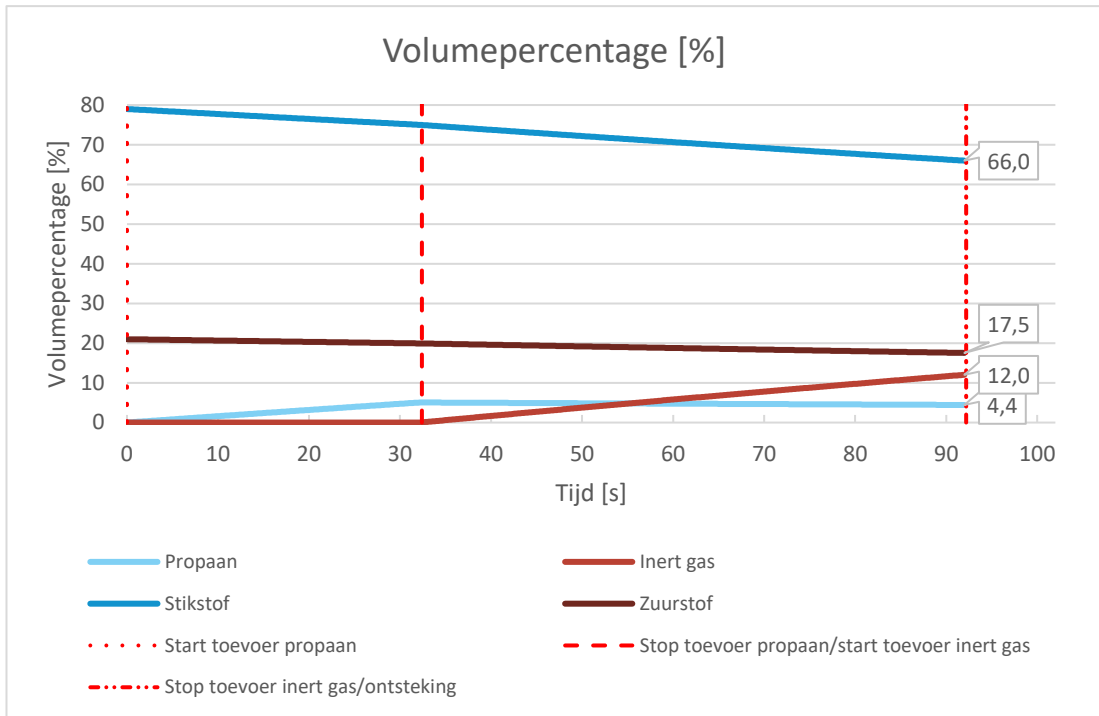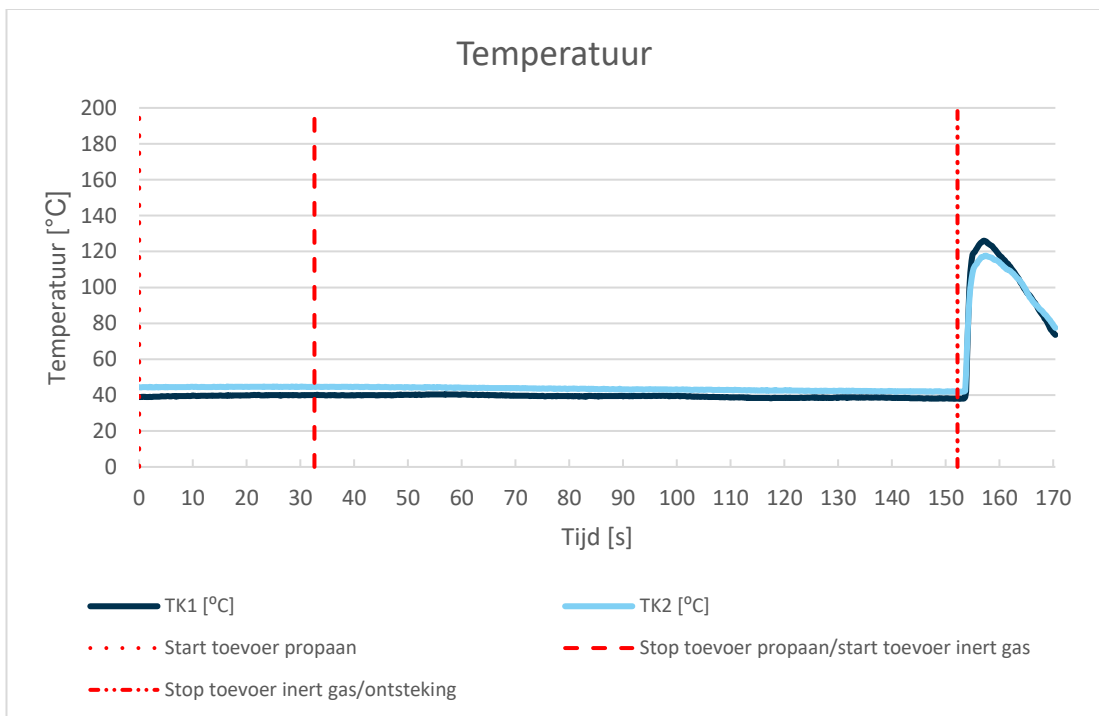

Test 6: Ontbranding bij 30 sec nevel

Test 7 en 8: 60 seconden
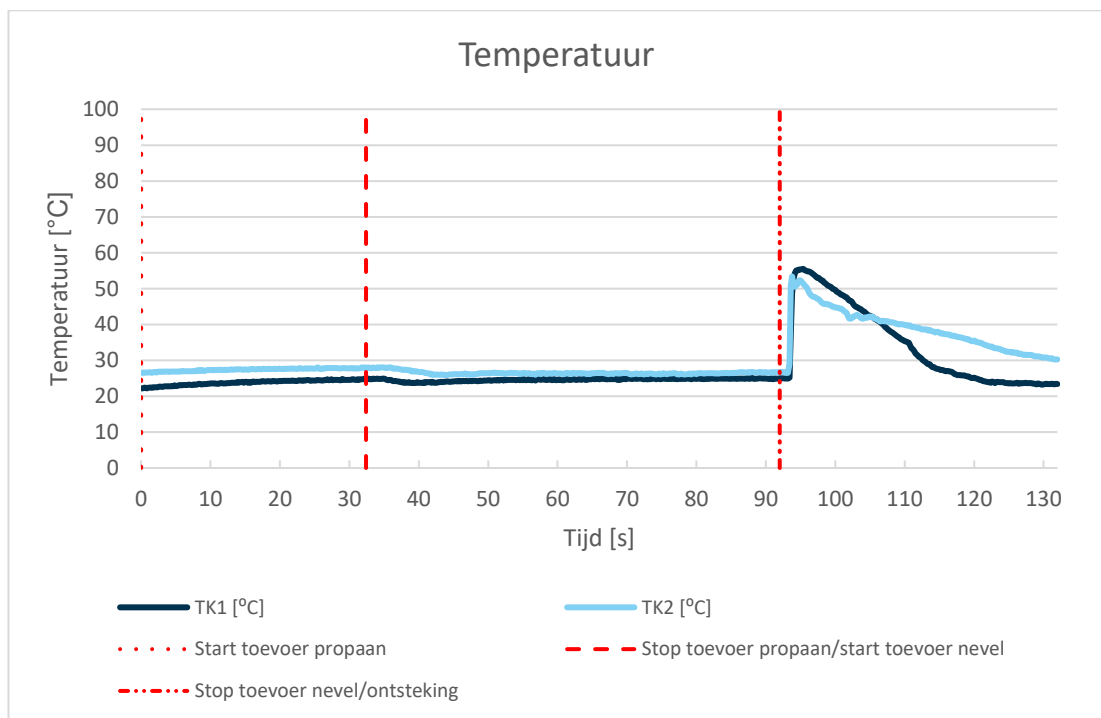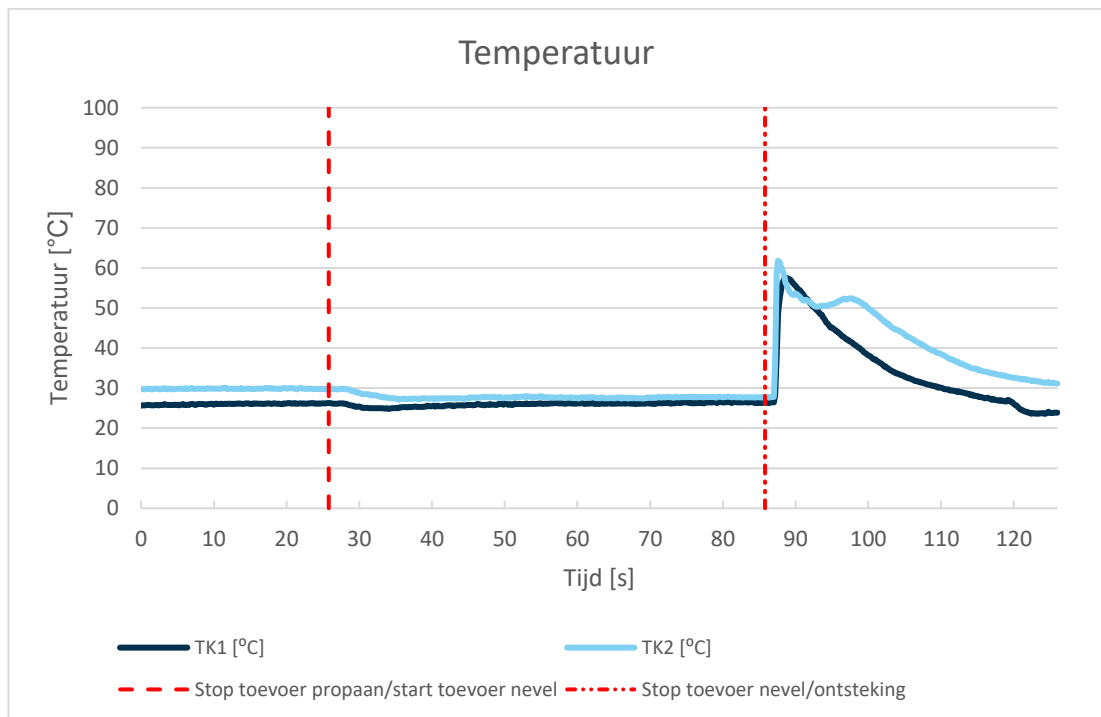
Test 7: Ontbranding bij 60 sec nevel

Test 8: Ontbranding bij 60 sec nevel

Test 9 en 10: 120 seconden

Temperatuur

TK1 [°C] TK2 [°C]
Stop toevoer propaan/start toevoer nevel Stop toevoer nevel/ontsteking

Temperatuur

TK1 [°C] TK2 [°C]
Start toevoer propaan Stop toevoer propaan/start toevoer nevel
Stop toevoer nevel/ontsteking
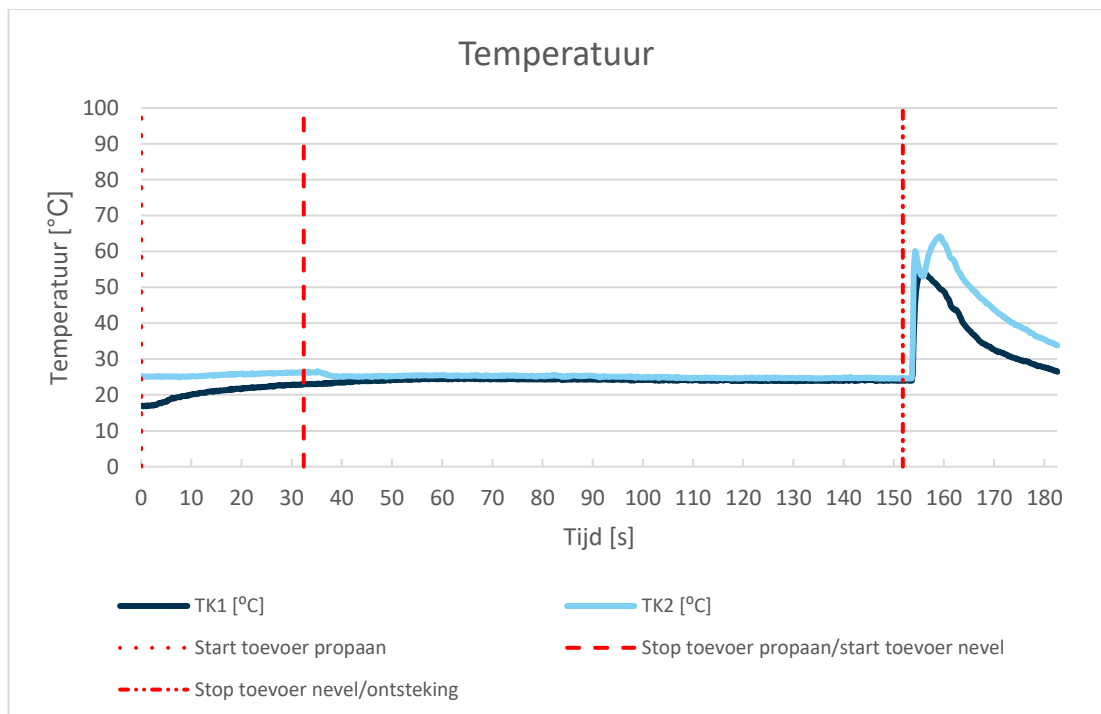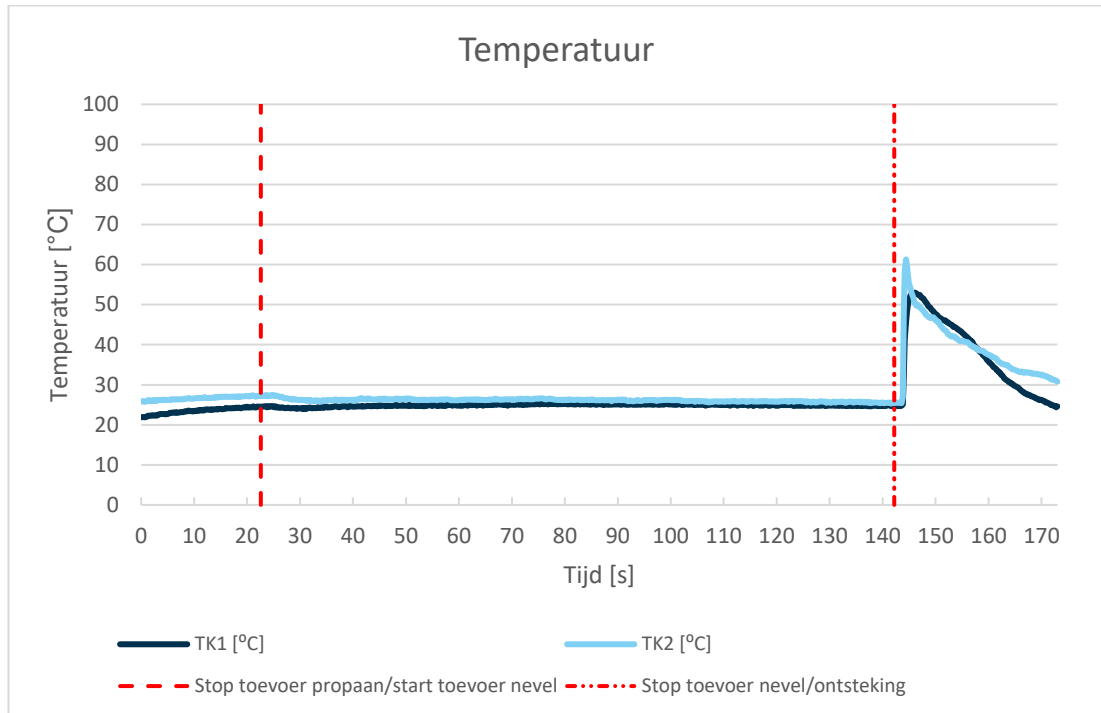
Test 9: Ontbranding bij 120 sec nevel

Test 10: Ontbranding bij 120 sec nevel

Test 11 en 12: 300 seconden

Temperatuur

Temperatuur [°C] / Tijd [s]

TK1 [°C]   TK2 [°C]
– – – Stop toevoer propaan/start toevoer nevel   – · · – Stop toevoer nevel/ontsteking

Temperatuur

Temperatuur [°C] / Tijd [s]

TK1 [°C]   TK2 [°C]
· · · · Start toevoer propaan   – – – Stop toevoer propaan/start toevoer nevel
– · · – Stop toevoer nevel/ontsteking
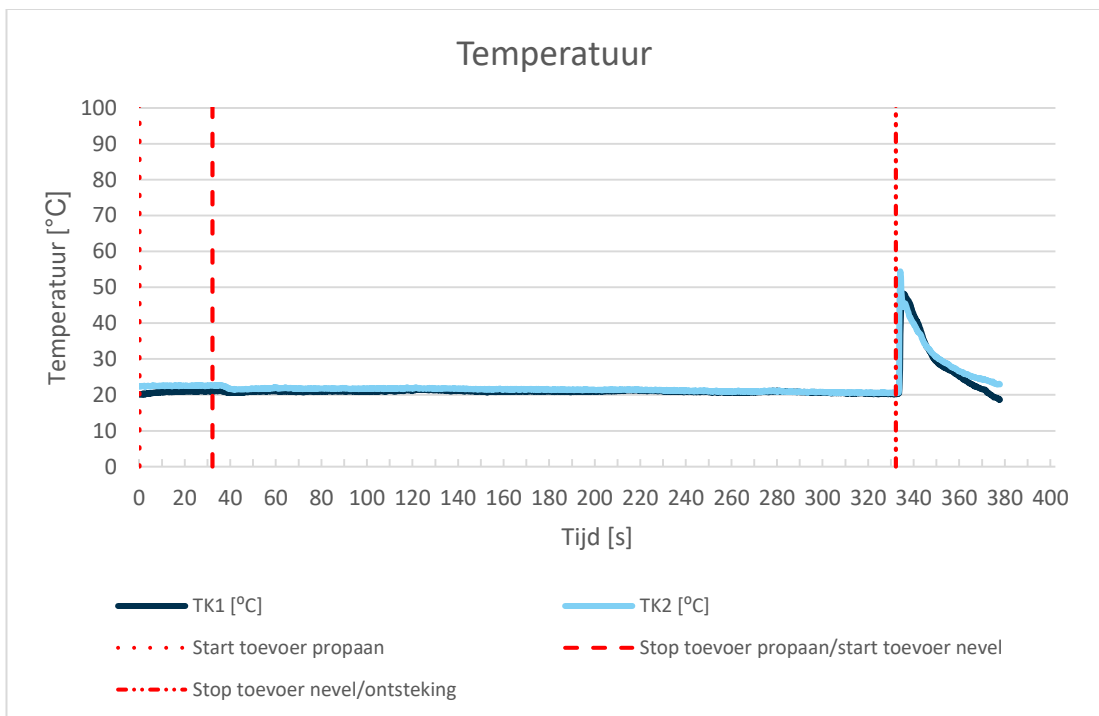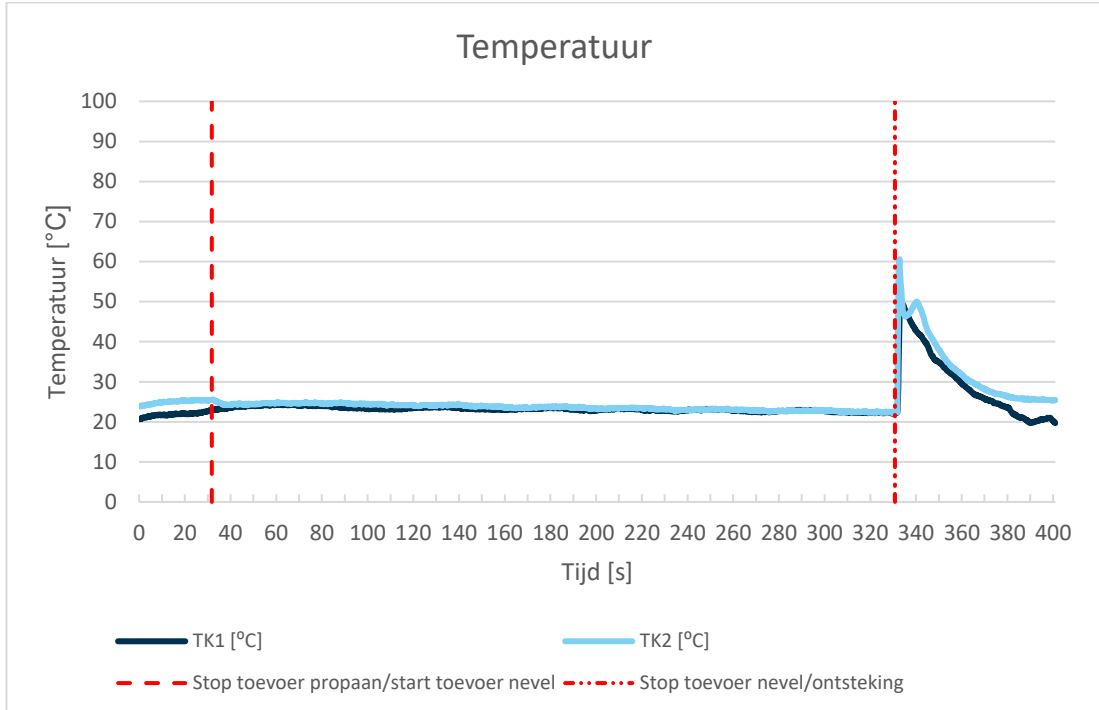
Test 11: Ontbranding bij 300 sec nevel

Test 12: Ontbranding bij 300 sec nevel

Samenvatting resultaten nevel koude gassen

Toevoertijd [s]	Volumepercentage [%]			Ontbranding [-]	Temperatuur [ºC]	
	Zuurstof	Waterdamp	Propaan		Max. na plof	Verschil
10	-	4,0	-	Ja	118	90
20	-	4,4	-	Ja	81	51
30	-	3,7	-	Ja	80	53
60	-	3,4	-	Ja	57	31
120	-	3,1	-	Ja	54	29
300	-	2,5	-	Ja	49	28

Gemiddelde temperatuur

Temperatuur [ºC] / Tijd inert gas [s]

— Max. Temp. na plof   — Temperatuursverschil

Stikstof

Test 1 en 2: 10 seconden

Temperatuur

TK1 [°C]   TK2 [°C]

· · · · Start toevoer propaan   —·—· Stop toevoer propaan/start toevoer inert gas

—··—· Stop toevoer inert gas/ontsteking

Volumepercentage [%]

73,7
19,6
4,7
2,0

Propaan   Inert gas

Stikstof   Zuurstof

· · · · Start toevoer propaan   —·—· Stop toevoer propaan/start toevoer inert gas

—··—· Stop toevoer inert gas/ontsteking

O2

O2 [ppm] vs Tijd [s]

- ——— ppm O2 (3)
- – – – Start toevoer propaan
- – – – Stop toevoer propaan/start toevoer inert gas
- – – – Stop toevoer inert gas/ontsteking

Temperatuur

Temperatuur [°C] vs Tijd [s]

- ——— TK1 [°C]
- ——— TK2 [°C]
- · · · · Start toevoer propaan
- – – – Stop toevoer inert gas/ontsteking
- –··–··– Stop toevoer inert gas/ontsteking

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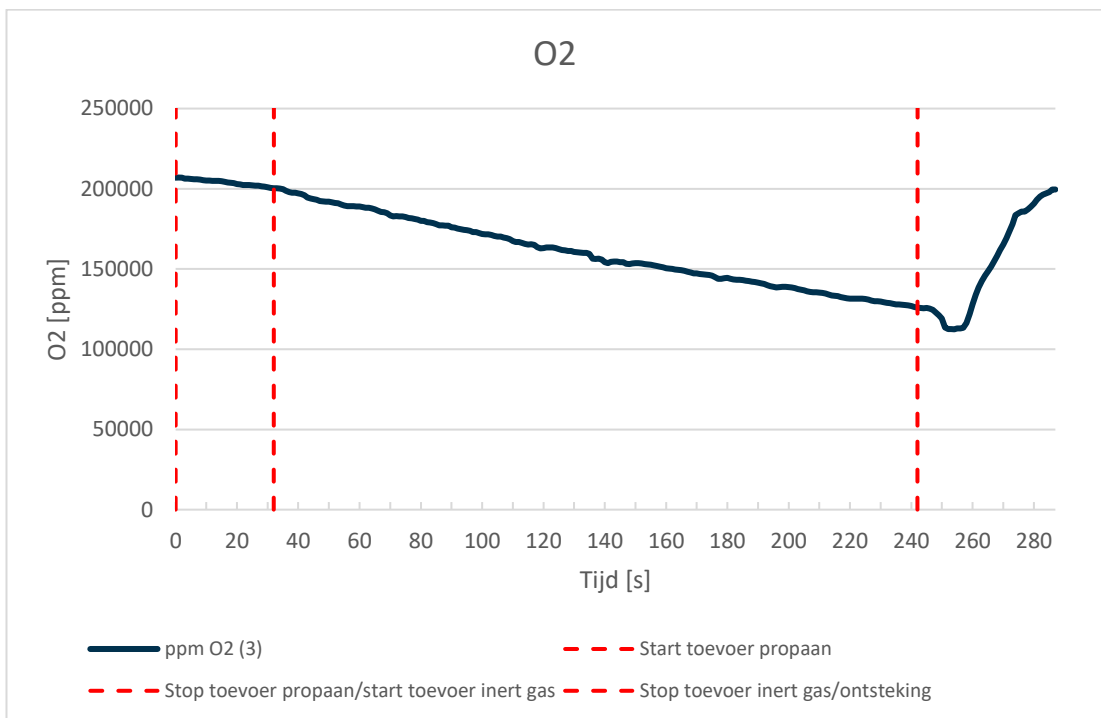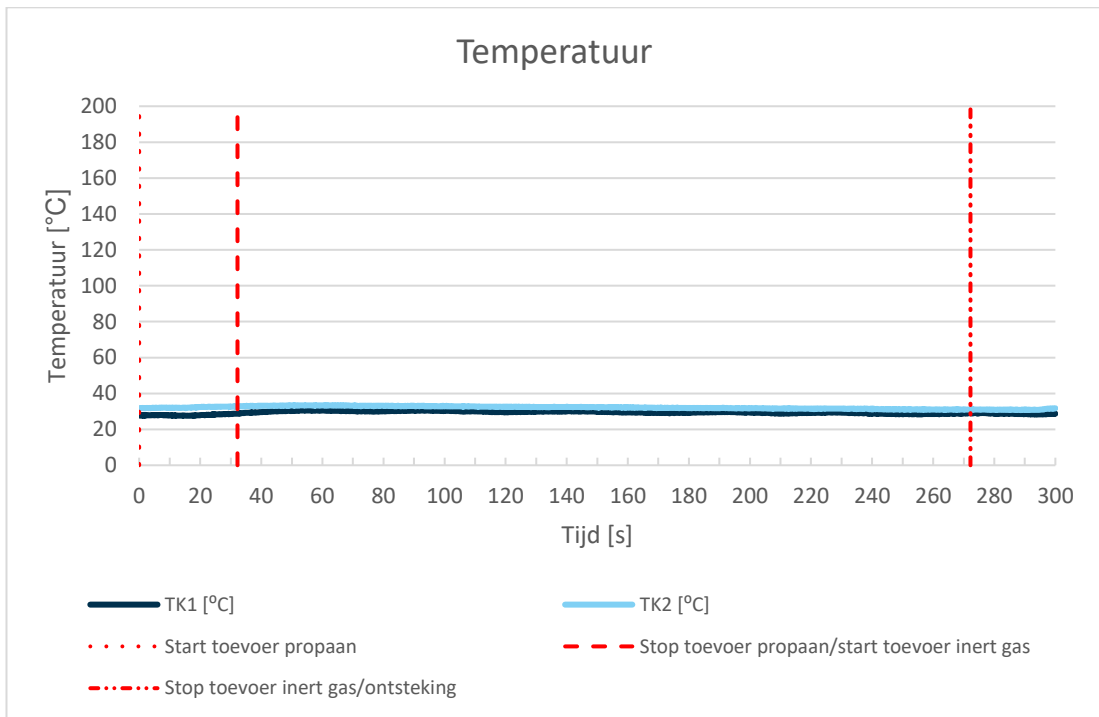Volumepercentage [%]

O2

Test 1: Ontbranding bij 10 sec stikstof

Test 2: Ontbranding bij 10 sec stikstof

Test 3 en 4: 20 seconden

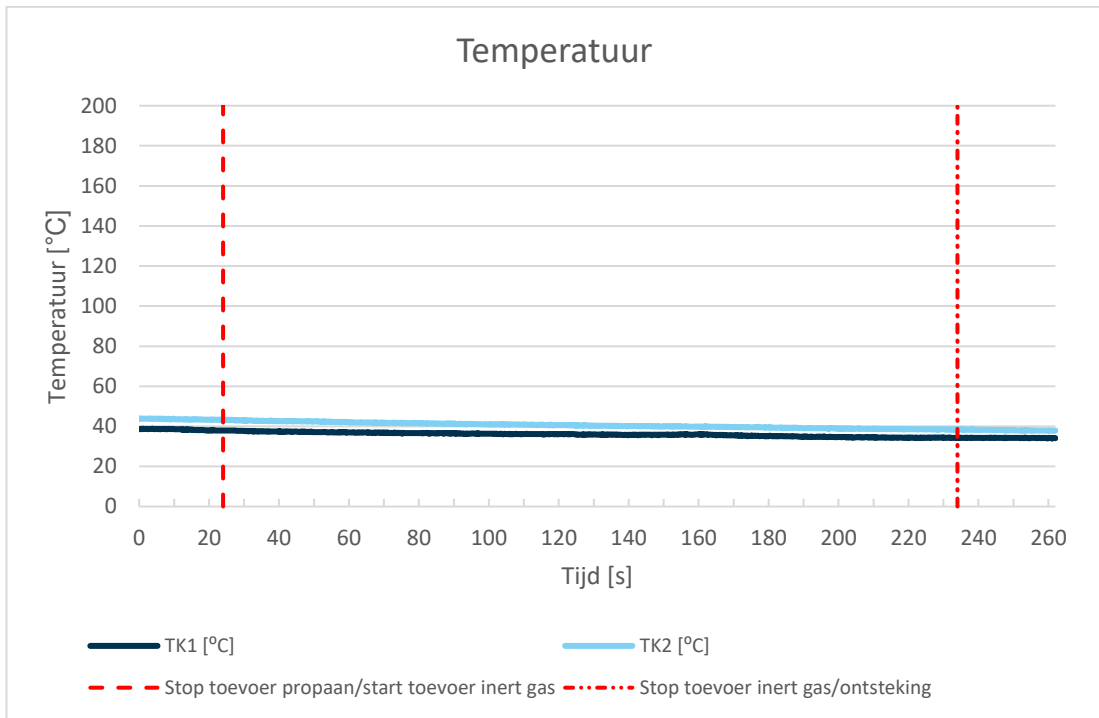
Temperatuur

Temperatuur

Volumepercentage [%]

Legend:
- Propaan
- Stikstof
- Start toevoer propaan
- Stop toevoer inert gas/ontsteking
- Inert gas
- Zuurstof
- Stop toevoer propaan/start toevoer inert gas

Labels on chart: 72,0 · 19,1 · 4,8 · 4,1

O2

Legend:
- ppm O2 (3)
- Stop toevoer propaan/start toevoer inert gas
- Start toevoer propaan
- Stop toevoer inert gas/ontsteking
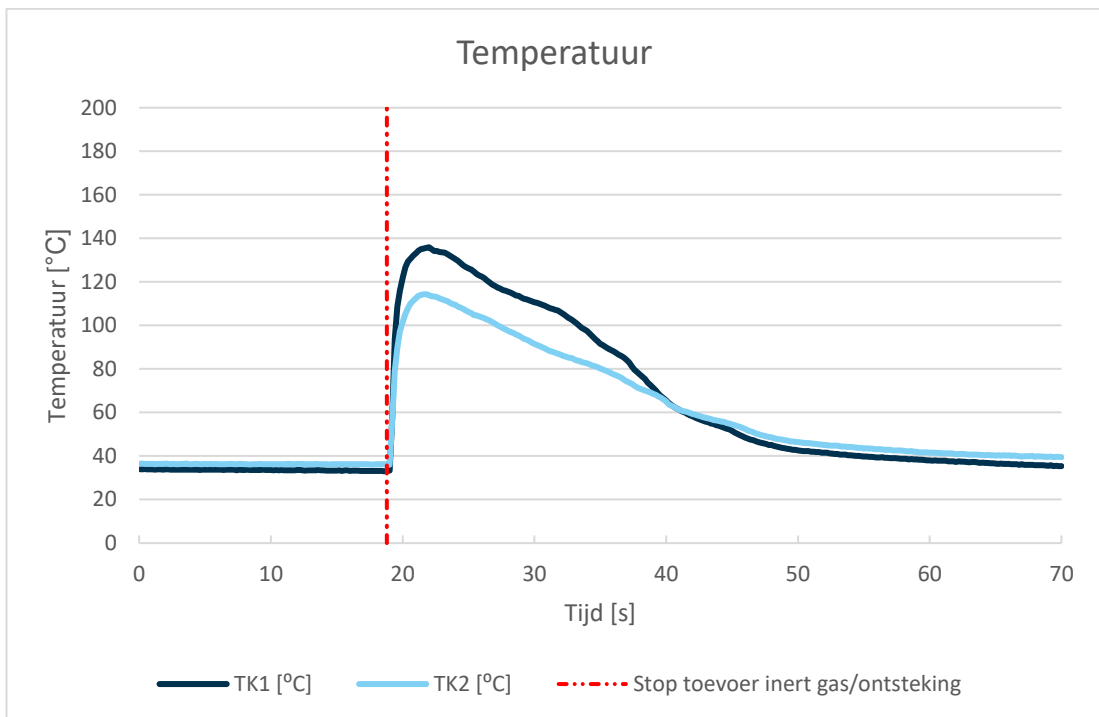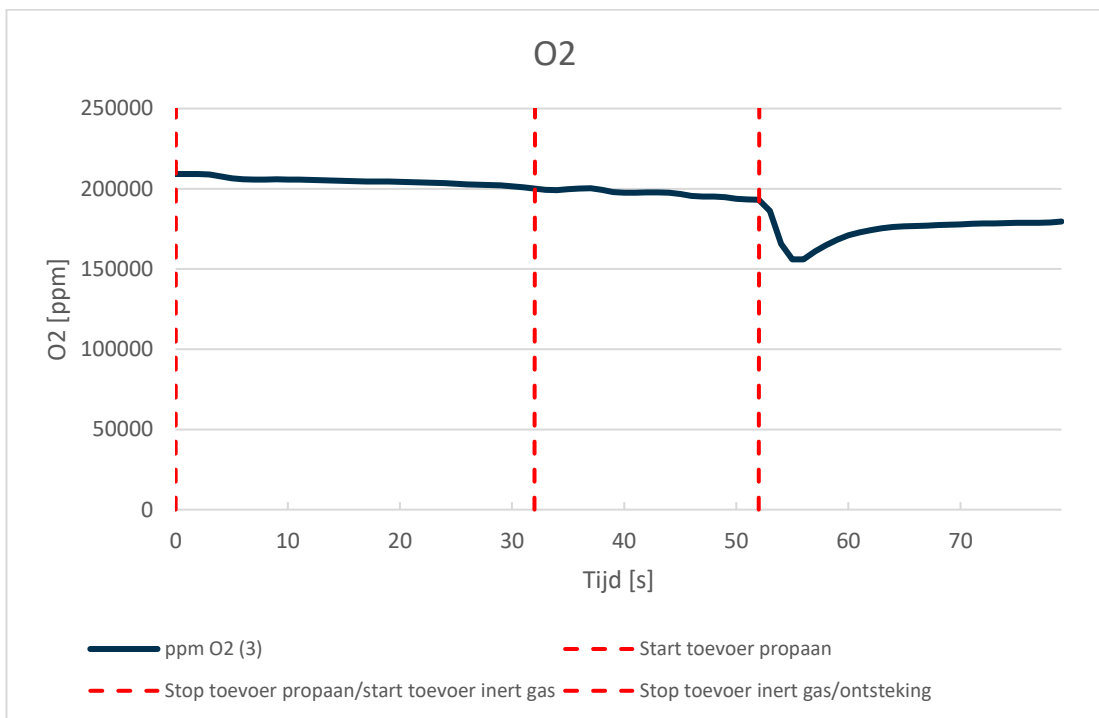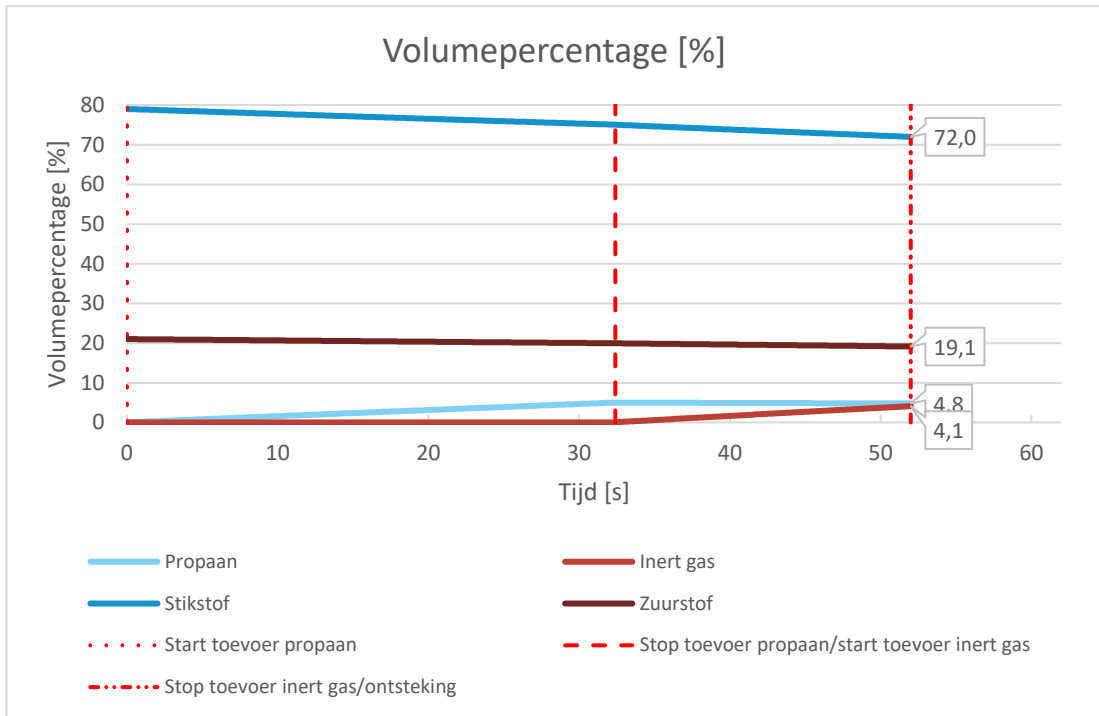
Test 3: Ontbranding bij 20 sec stikstof

Test 4: Ontbranding bij 20 sec stikstof

Test 5 en 6: 30 seconden

Temperatuur

TK1 [°C]   TK2 [°C]
- - - Stop toevoer propaan/start toevoer inert gas   -·-·- Stop toevoer inert gas/ontsteking

Temperatuur

TK1 [°C]   TK2 [°C]
····· Start toevoer propaan   - - - Stop toevoer propaan/start toevoer inert gas
-·-·- Stop toevoer inert gas/ontsteking

Volumepercentage [%]

O2
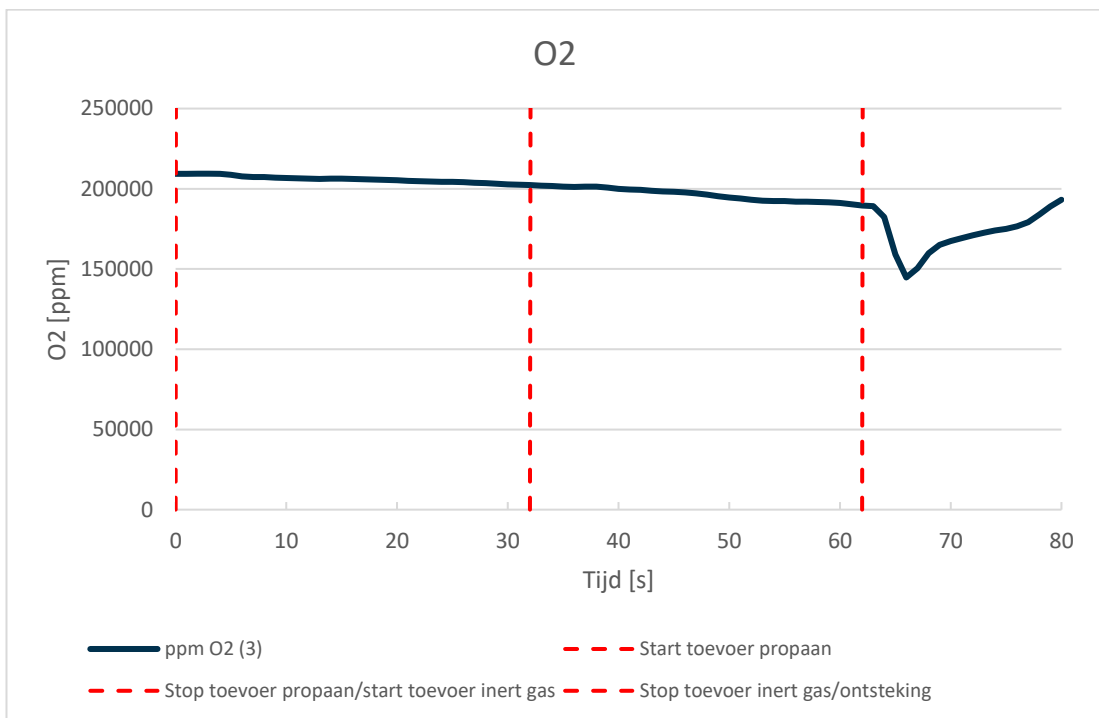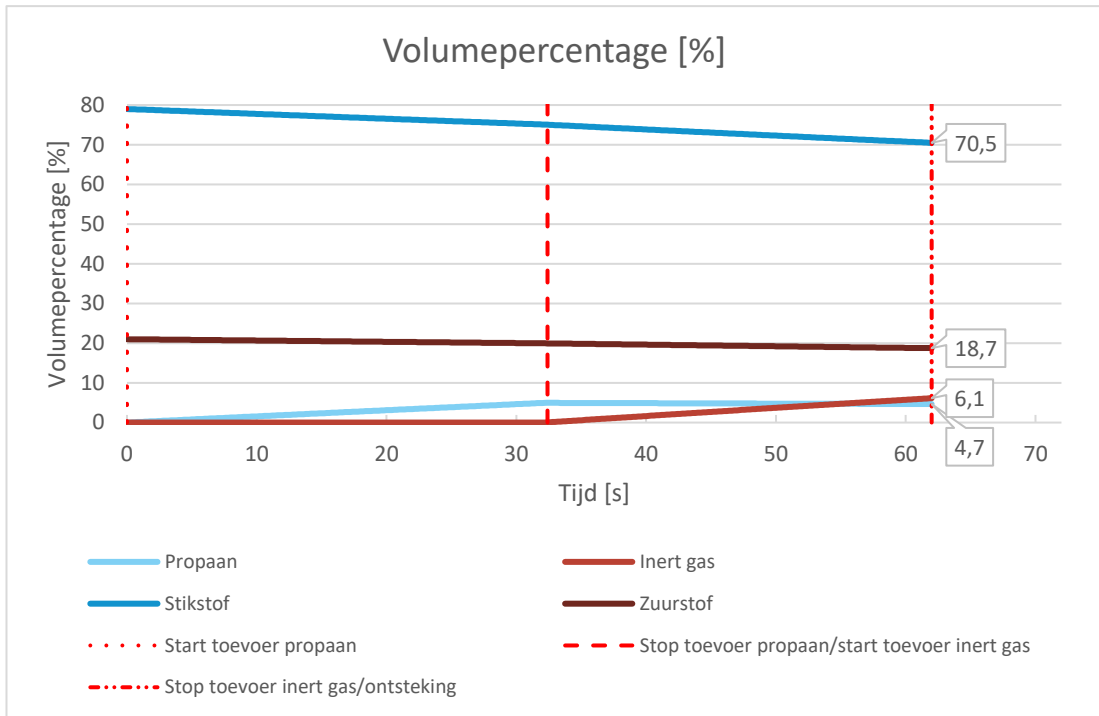
Test 5: Ontbranding bij 30 sec stikstof

Test 6: Ontbranding bij 30 sec stikstof

Test 7 en 8: 60 seconden

Temperatuur

TK1 [°C]	TK2 [°C]

--- Stop toevoer propaan/start toevoer inert gas   ---·--- Stop toevoer inert gas/ontsteking

Temperatuur

TK1 [°C]	TK2 [°C]

····· Start toevoer propaan   --- Stop toevoer propaan/start toevoer inert gas

---·--- Stop toevoer inert gas/ontsteking

Volumepercentage [%]

Chart showing Volumepercentage [%] on the y-axis (0 to 80) versus Tijd [s] on the x-axis (0 to 100). Lines labeled with end values: 66,0; 17,5; 12,0; 4,4.

Legend:
- Propaan
- Inert gas
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

O2

Chart showing O2 [ppm] on the y-axis (0 to 250000) versus Tijd [s] on the x-axis (0 to 110).

Legend:
- ppm O2 (3)
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

Test 7: Ontbranding bij 60 sec stikstof

Test 8: Ontbranding bij 60 sec stikstof

Test 9 en 10: 120 seconden

Temperatuur

TK1 [°C] — TK2 [°C] — Stop toevoer inert gas/ontsteking

Temperatuur

TK1 [°C] — TK2 [°C]
Start toevoer propaan — Stop toevoer propaan/start toevoer inert gas
Stop toevoer inert gas/ontsteking

Volumepercentage [%]

Legend:
- Propaan
- Inert gas
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

Values: 58,1 · 22,6 · 15,4 · 3,9

O2

Legend:
- ppm O2 (3)
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
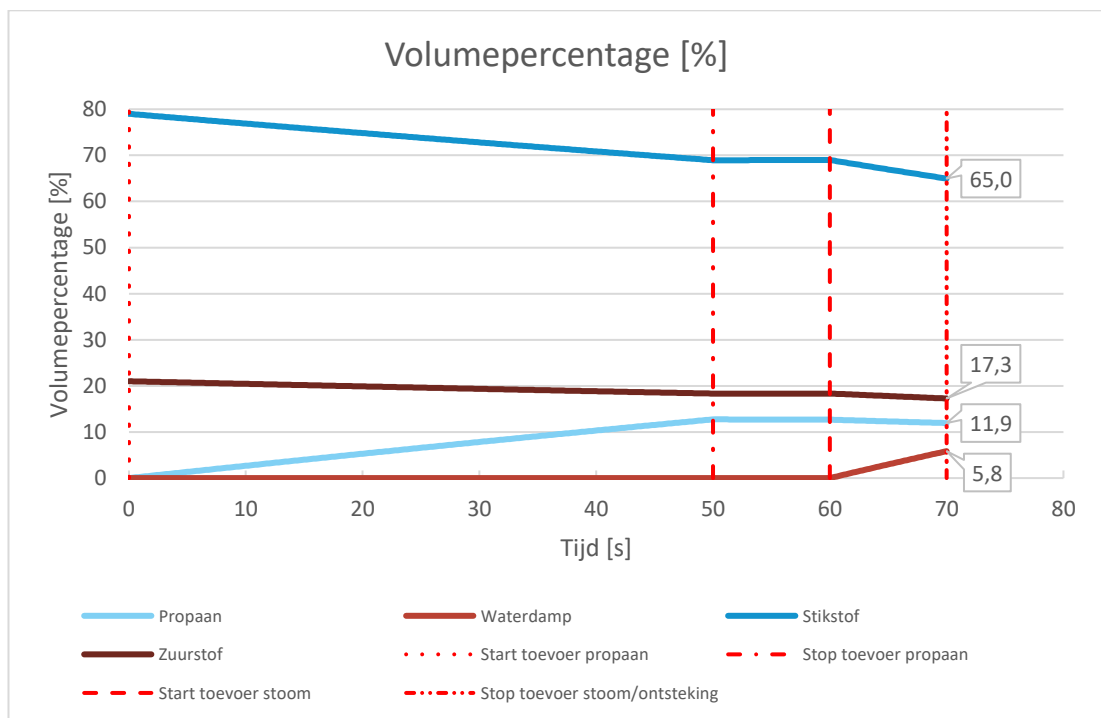- Stop toevoer inert gas/ontsteking

Test 9: Ontbranding bij 120 sec stikstof

Test 10: Ontbranding bij 120 sec stikstof

Test 11 en 12: 180 seconden

Temperatuur

Legend:
- —— TK1 [°C]
- —— TK2 [°C]
- – – – Stop toevoer propaan/start toevoer inert gas
- –·–·– Stop toevoer inert gas/ontsteking

Temperatuur

Legend:
- —— TK1 [°C]
- —— TK2 [°C]
- ····· Start toevoer propaan
- – – – Stop toevoer propaan/start toevoer inert gas
- –·–·– Stop toevoer inert gas/ontsteking

Volumepercentage [%]

O2
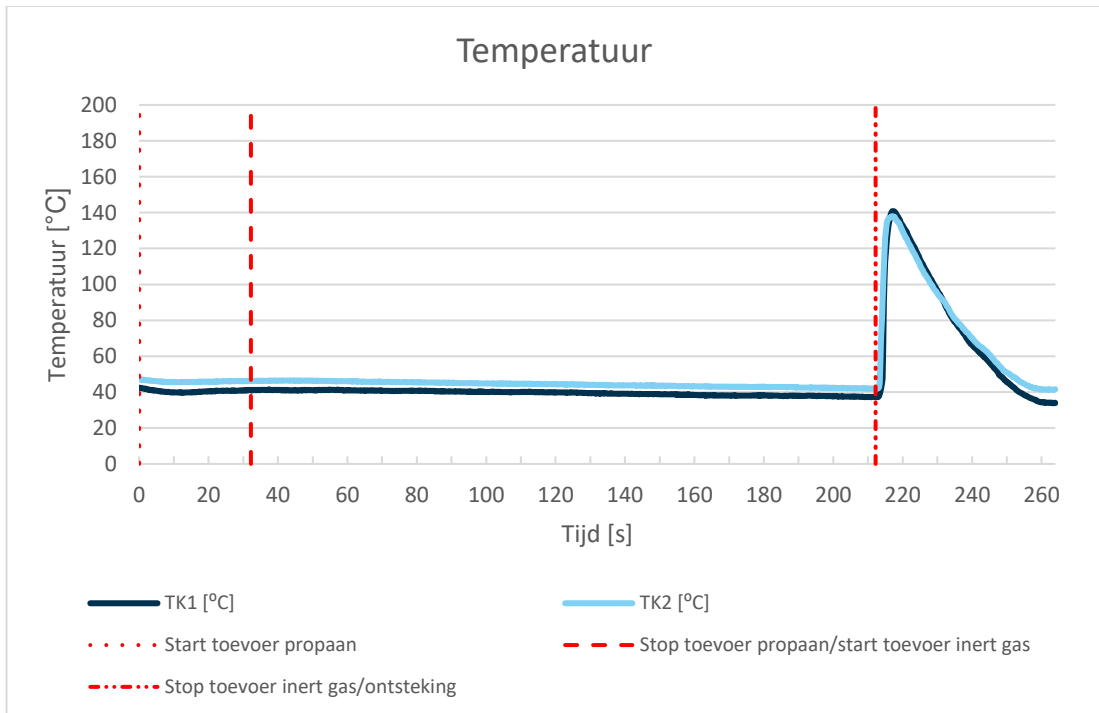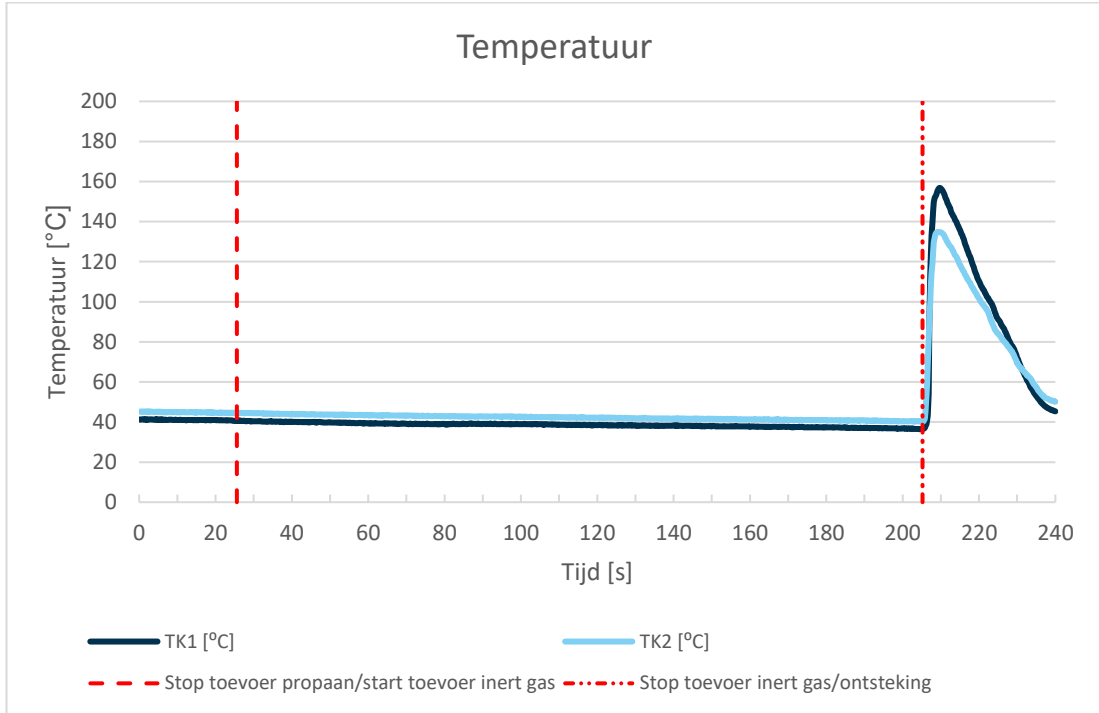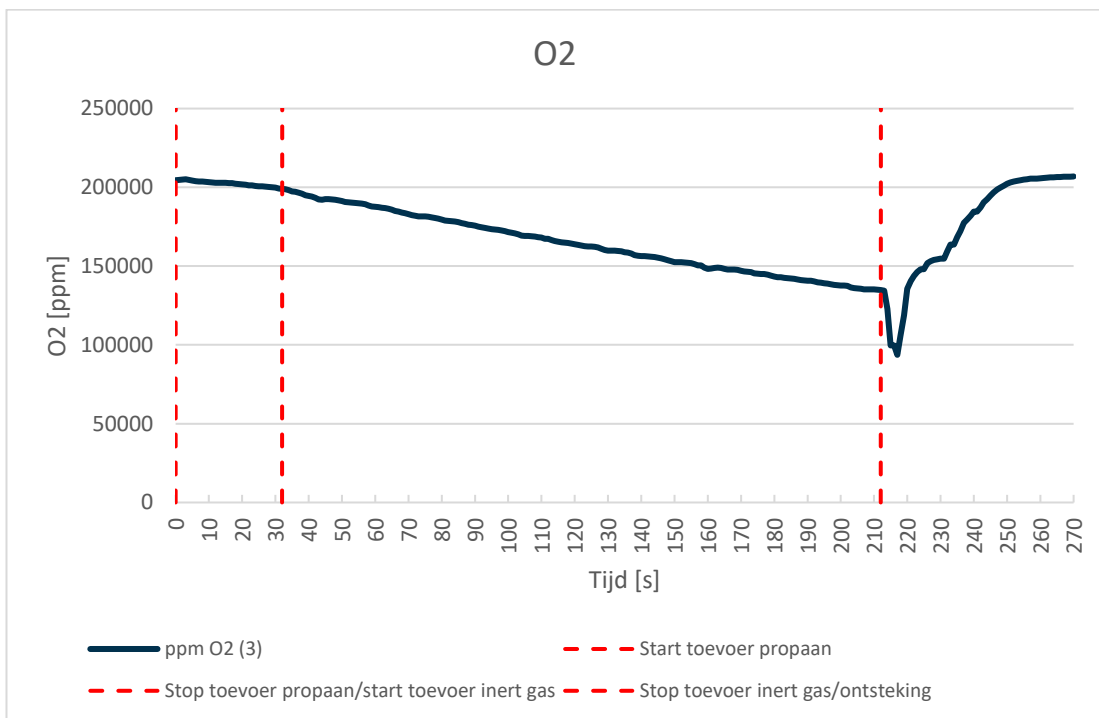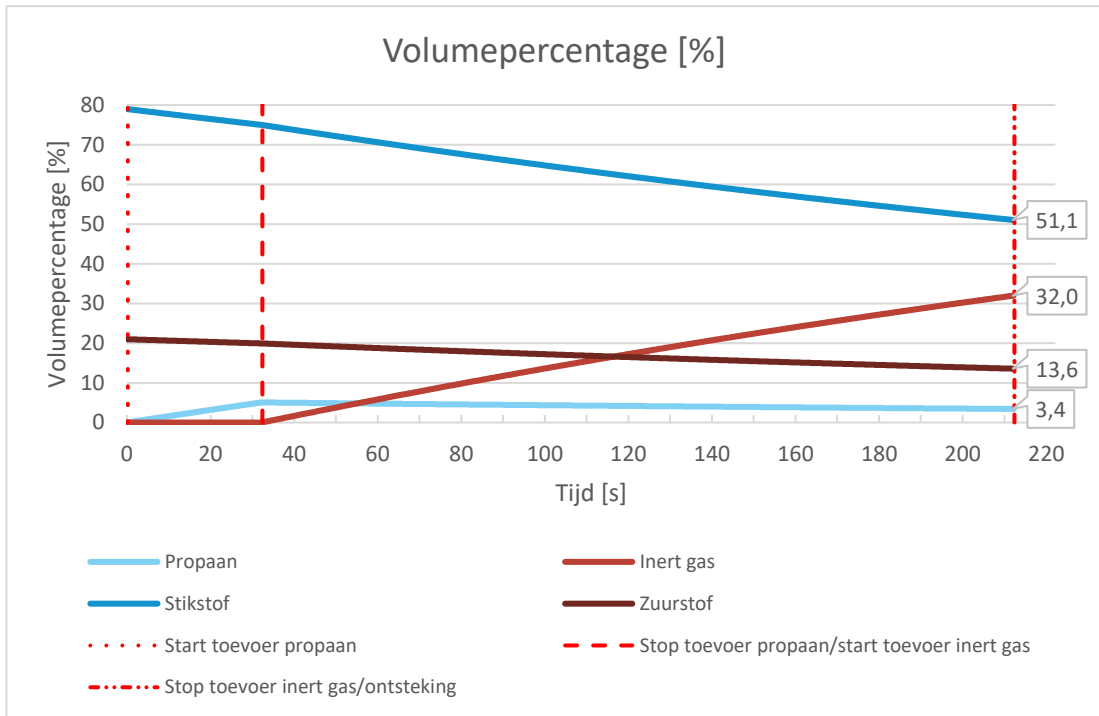
Test 11: Ontbranding bij 180 sec stikstof

Test 12: Ontbranding bij 180 sec stikstof

Test 13 en 14: 210 seconden

Temperatuur

Legenda grafiek 1:
— TK1 [°C] — TK2 [°C]
– – – Stop toevoer propaan/start toevoer inert gas   – · – · Stop toevoer inert gas/ontsteking

Temperatuur

Legenda grafiek 2:
— TK1 [°C] — TK2 [°C]
· · · · Start toevoer propaan   – – – Stop toevoer propaan/start toevoer inert gas
– · – · Stop toevoer inert gas/ontsteking

Volumepercentage [%]

Volumepercentage [%] vs Tijd [s]

- Propaan
- Stikstof
- Inert gas
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

49,0
34,9
13,0
3,1

O2

O2 [ppm] vs Tijd [s]

- ppm O2 (3)
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

Test 13: Ontbranding bij 210 sec stikstof

Test 14: Ontbranding bij 210 sec stikstof

Test 15 en 16: 240 seconden

Temperatuur

Temperatuur

Volumepercentage [%]

Legend:
- Propaan (light blue)
- Inert gas (red)
- Stikstof (blue)
- Zuurstof (dark red)
- Start toevoer propaan (dotted red)
- Stop toevoer propaan/start toevoer inert gas (dashed red)
- Stop toevoer inert gas/ontsteking (dash-dot red)

Data labels: 45,9 / 38,9 / 12,2 / 2,9

O2

Legend:
- ppm O2 (3)
- Start toevoer propaan
- Stop toevoer propaan/start toevoer inert gas
- Stop toevoer inert gas/ontsteking

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Test 15: Ontbranding bij 240 sec stikstof

Test 16: Ontbranding bij 240 sec stikstof

Samenvatting resultaten stikstof koude gassen

Toevoertijd [s]	Volumepercentage [%]			Ontbranding [-]	Temperatuur [ºC]	
	Zuurstof	Inert gas	Propaan		Max. na plof	Verschil
10	19,6	2	4,75	Ja	145	115
20	19,1	4,1	4,8	Ja	140	105
30	18,7	6,1	4,7	Ja	147	110
60	17,5	12	4,4	Ja	131	91
120	15,4	22,6	3,9	Ja	134	94
180	13,6	32	3,4	Ja	149	107
210	13	34,9	3,1	Ja	36	8
240	12,2	38,9	2,9	Nee	-	-

Gemiddelde volumepercentages [%]
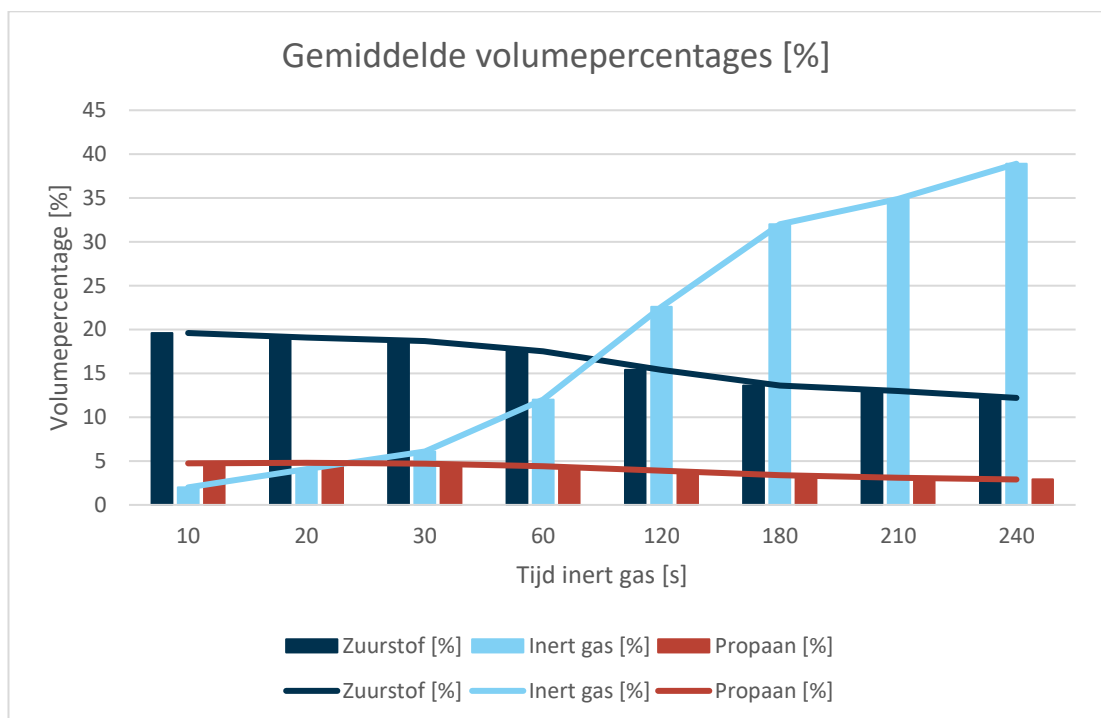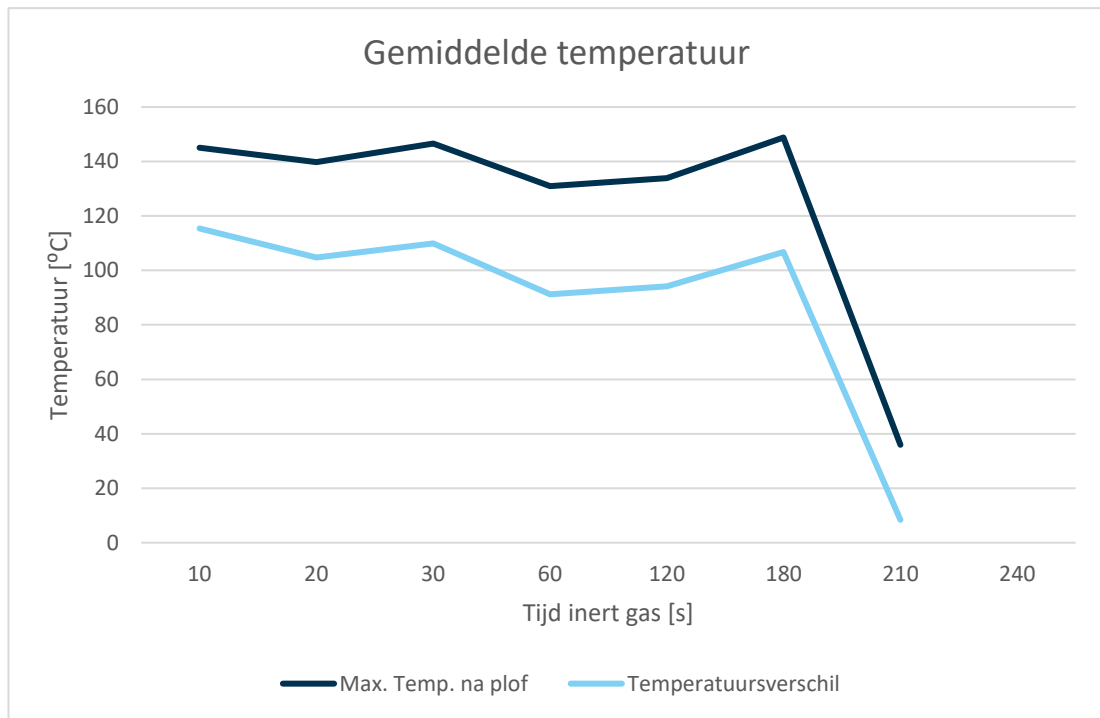
De totale toegevoerde hoeveelheid stikstof is maximaal 80 l. Dit komt overeen met een maximaal toegevoerd volumepercentage van maximaal 48,1 % (het resulterend volumepercentage in de plofkast bedraagt 39 %). Het resulterend volumepercentage komt overeen met waarden uit de literatuur van circa 40 %.

1.1   Samenvatting resultaten experimenten koude gassen

Tijd [s]	Volumepercentage [%]					
	Stoom	Plof	Nevel	Plof	Stikstof	Plof
10	3,5	Ja	4	Ja	2	Ja
20	6,2	Ja	4,4	Ja	4,1	Ja
30	7,9	Ja	3,7	Ja	6,1	Ja
60	8,7	Ja	3,4	Ja	12	Ja
120	12,5	Ja	3,1	Ja	22,6	Ja
180	-	-	-	-	32	Ja
210	-	-	-	-	34,9	Ja
240	-	-	-	-	38,9	Nee
300	19,7	Ja	2,5	Ja	-	-

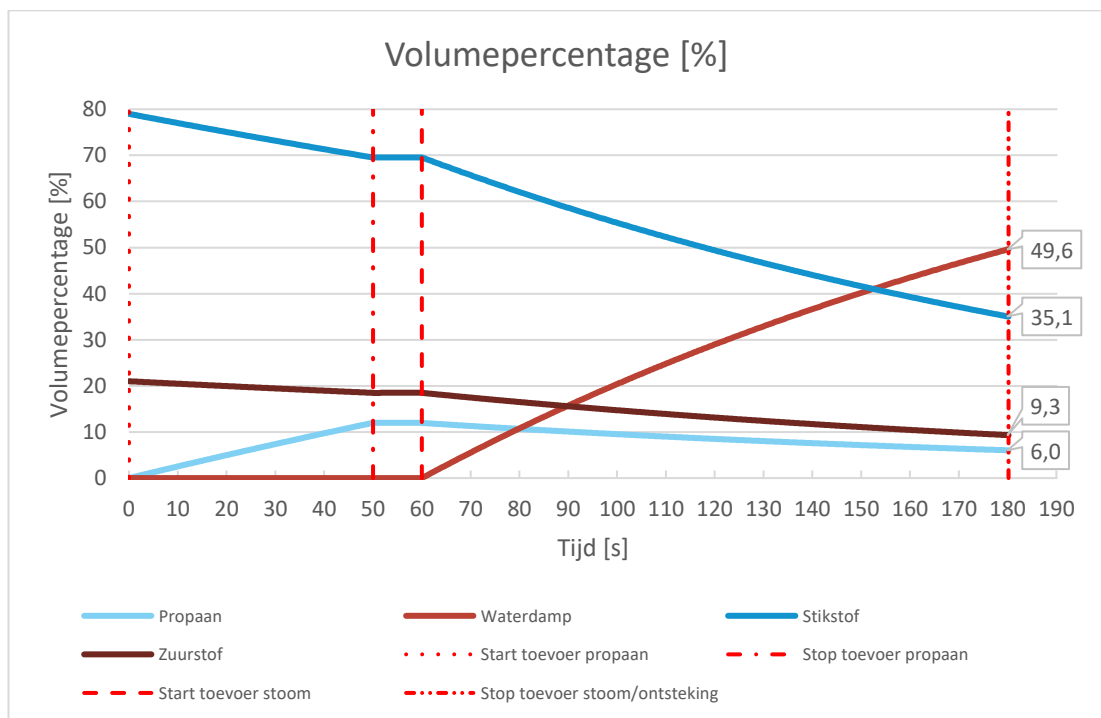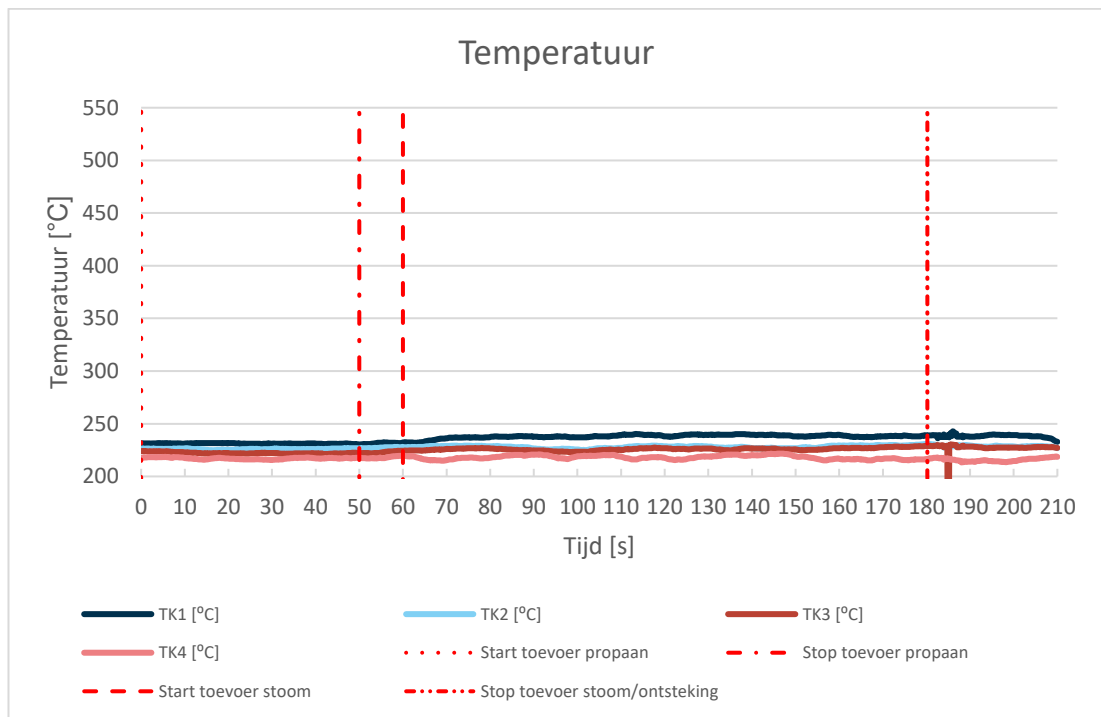# Bijlage 3 Resultaten met warme gassen

Stoom

Test 1: 10 seconden
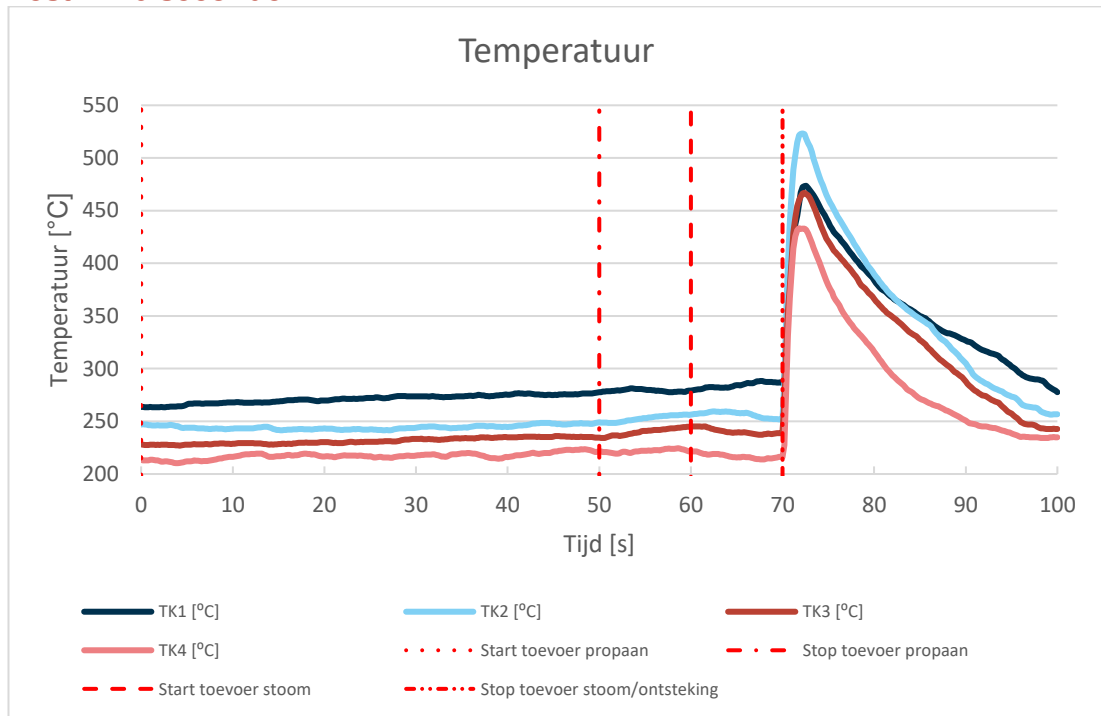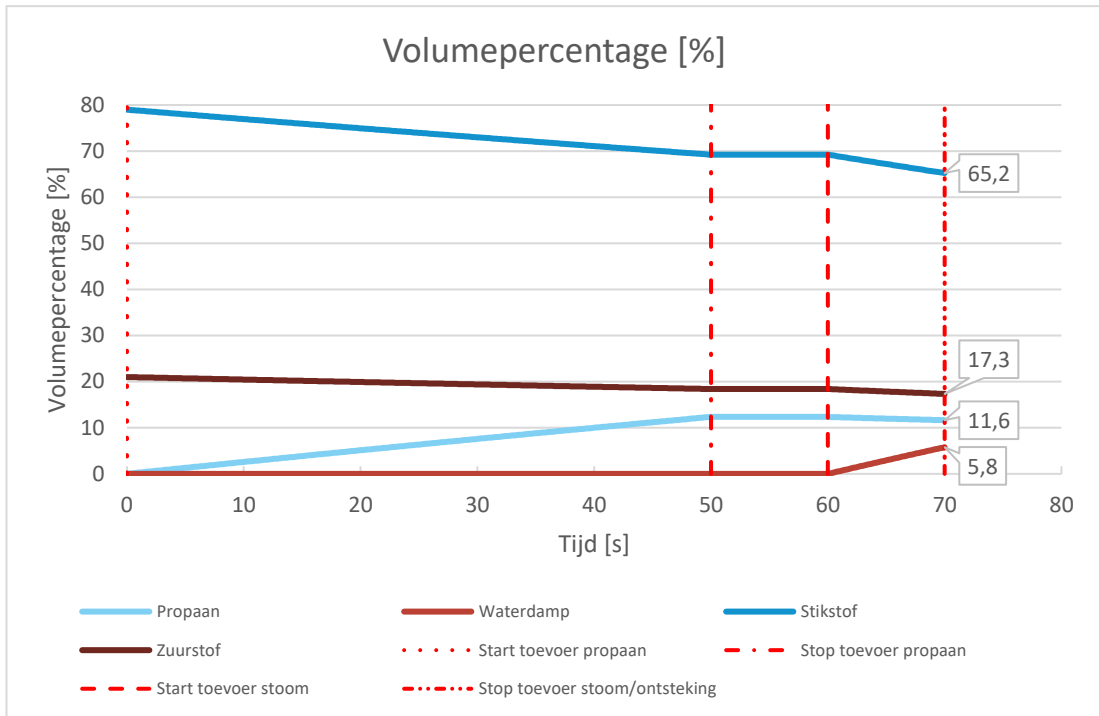
Test 1: Ontbranding bij 10 sec stoom

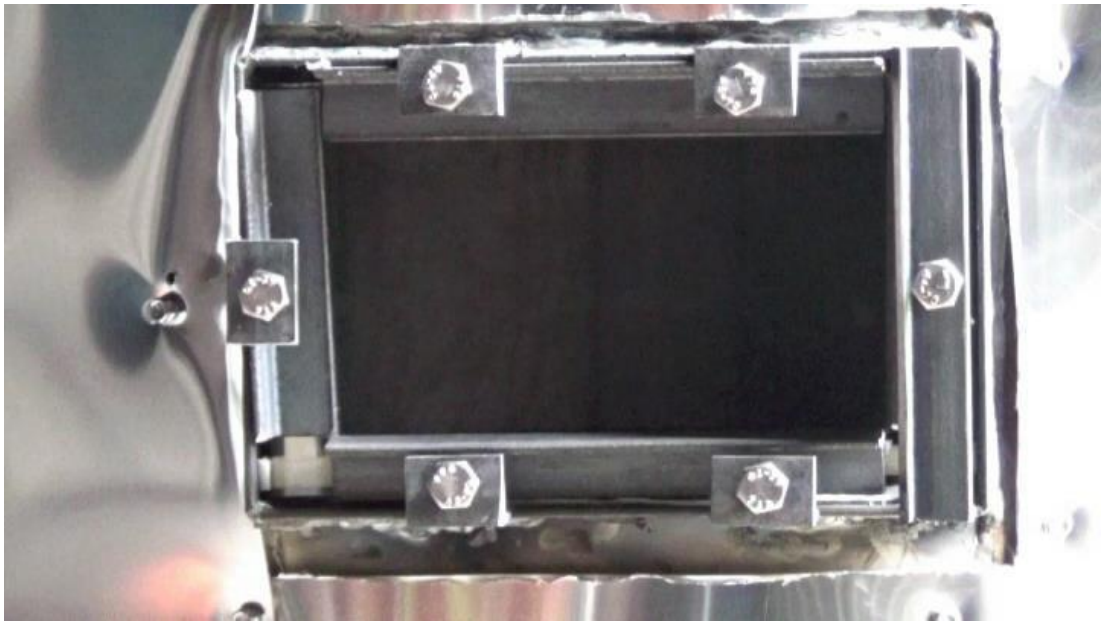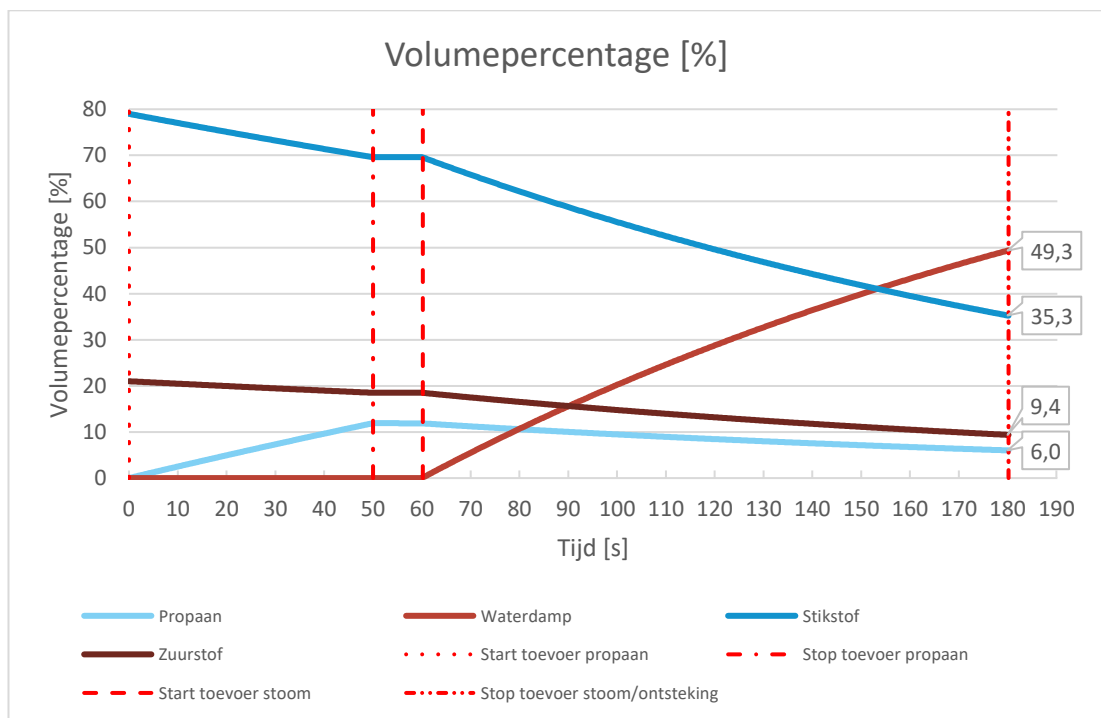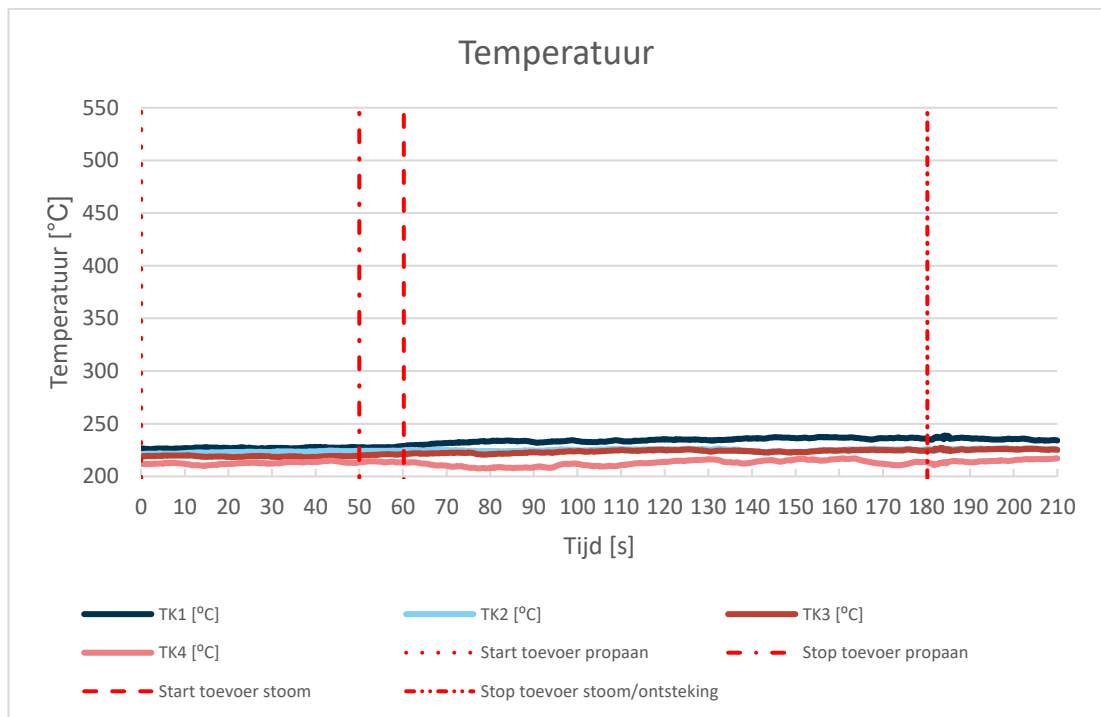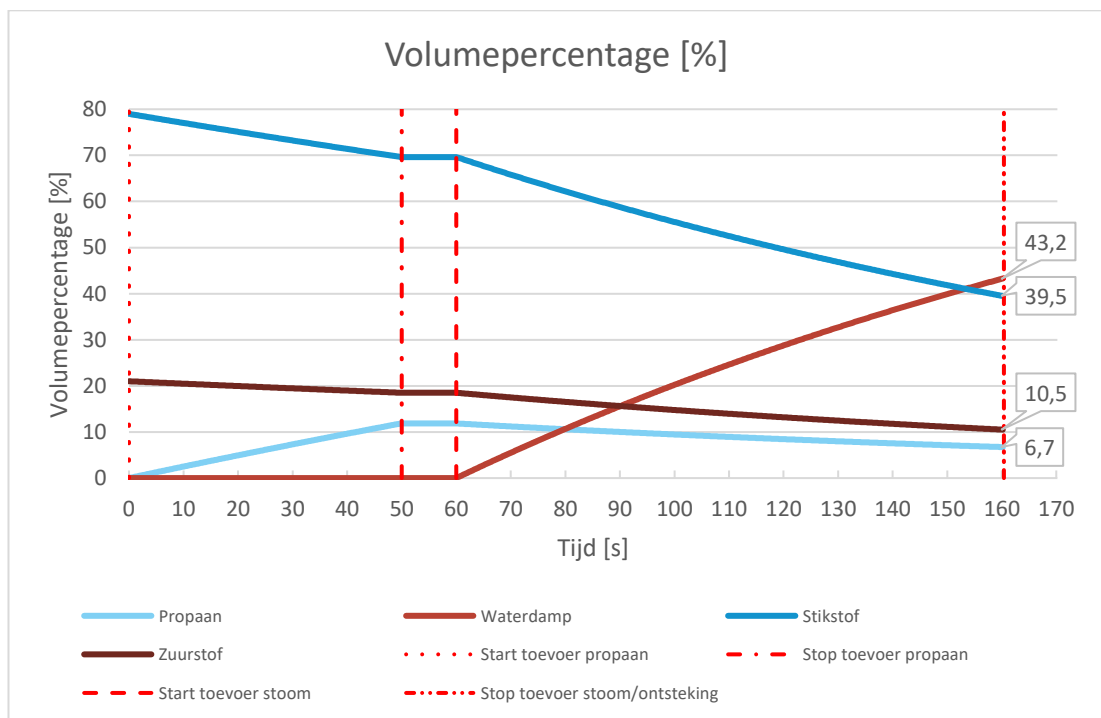## Test 2: 10 seconden

Temperatuur

Volumepercentage [%]

Test 3: 20 seconden

Temperatuur

Volumepercentage [%]

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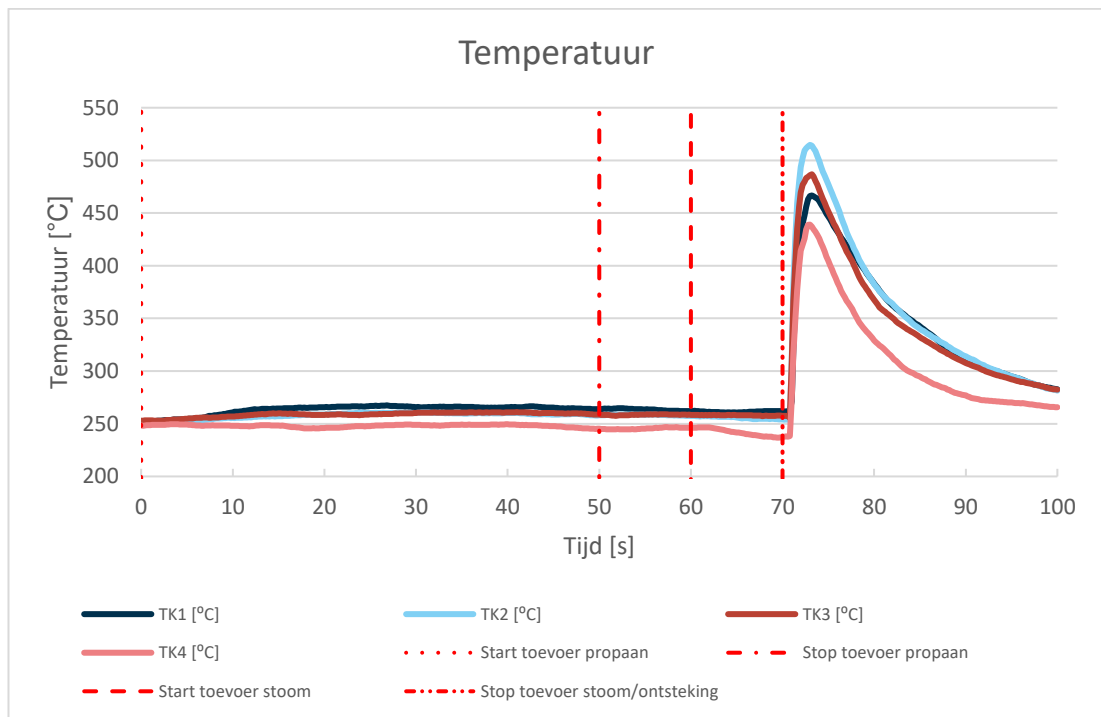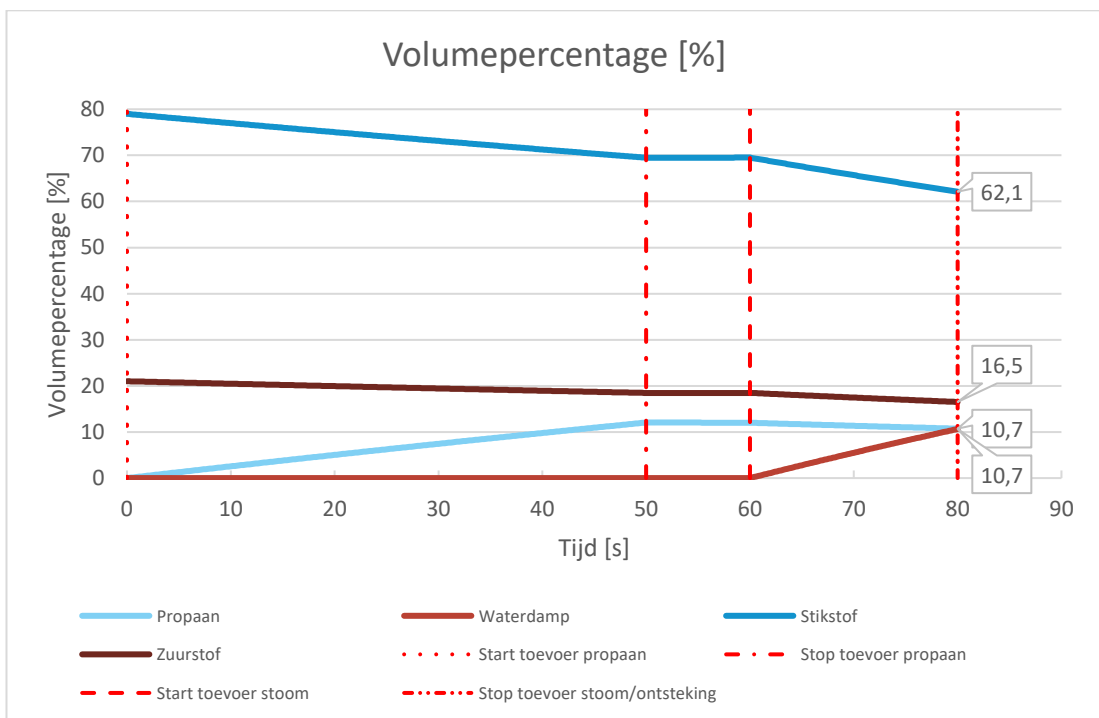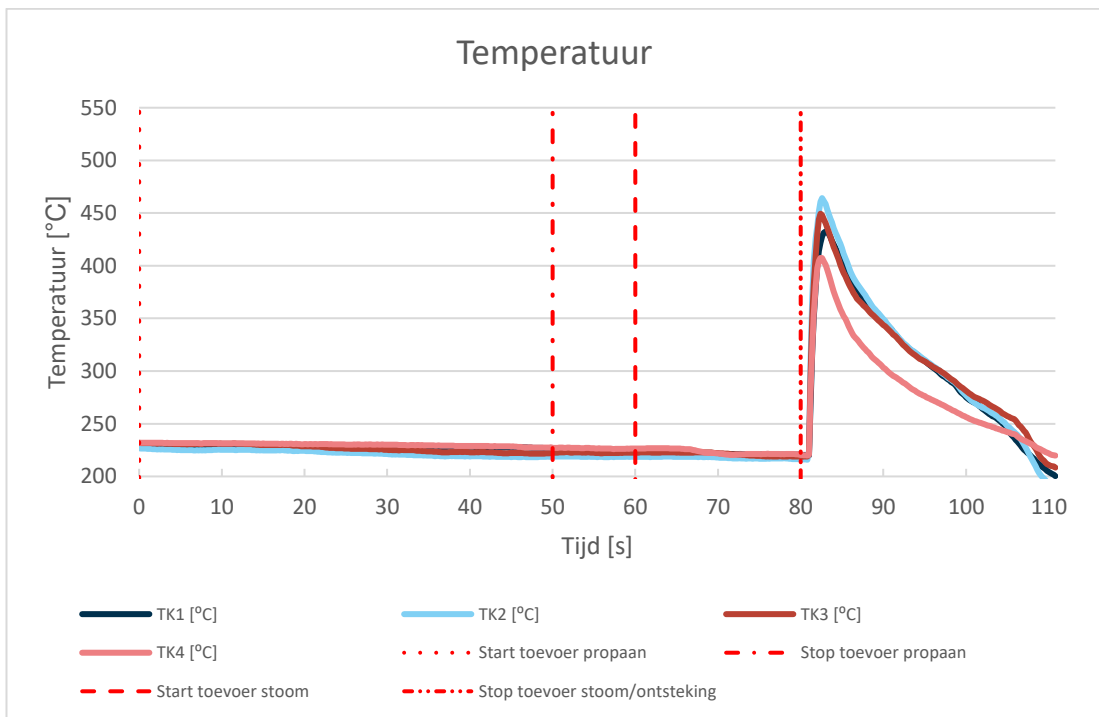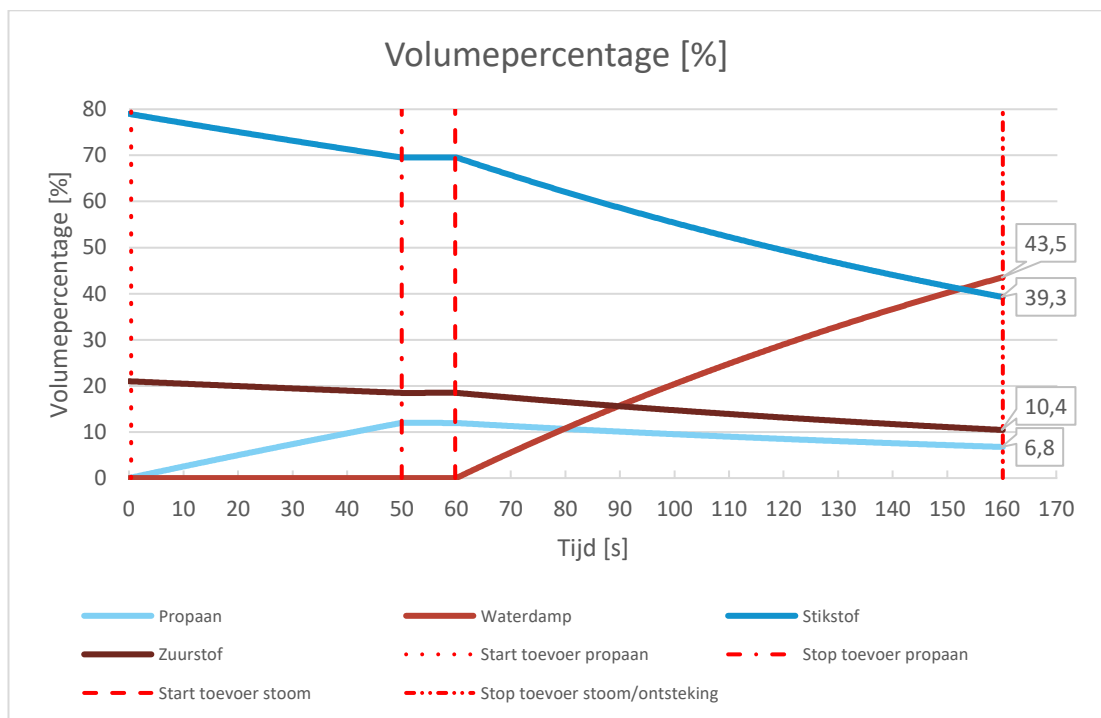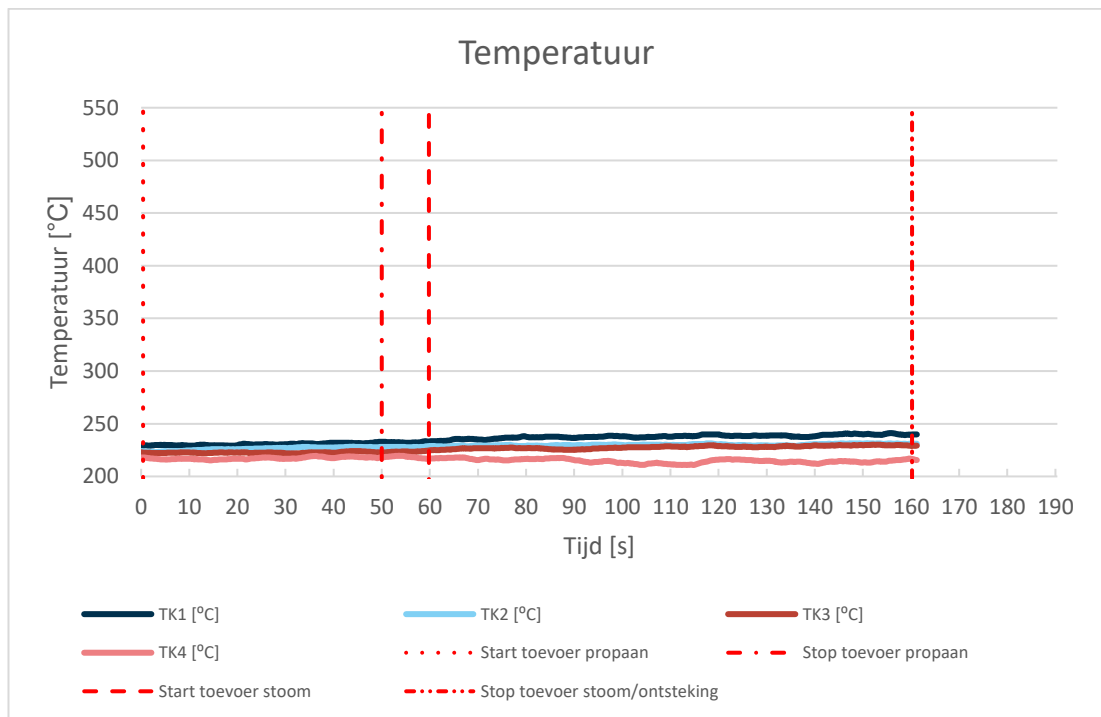
Test 3: Ontbranding bij 20 sec stoom

Test 4: 20 seconden

Temperatuur

Legenda: TK1 [°C], TK2 [°C], TK3 [°C], TK4 [°C], Start toevoer propaan, Stop toevoer propaan, Start toevoer stoom, Stop toevoer stoom/ontsteking

Volumepercentage [%]

62,2
16,5
10,6
10,7

Legenda: Propaan, Waterdamp, Stikstof, Zuurstof, Start toevoer propaan, Stop toevoer propaan, Start toevoer stoom, Stop toevoer stoom/ontsteking
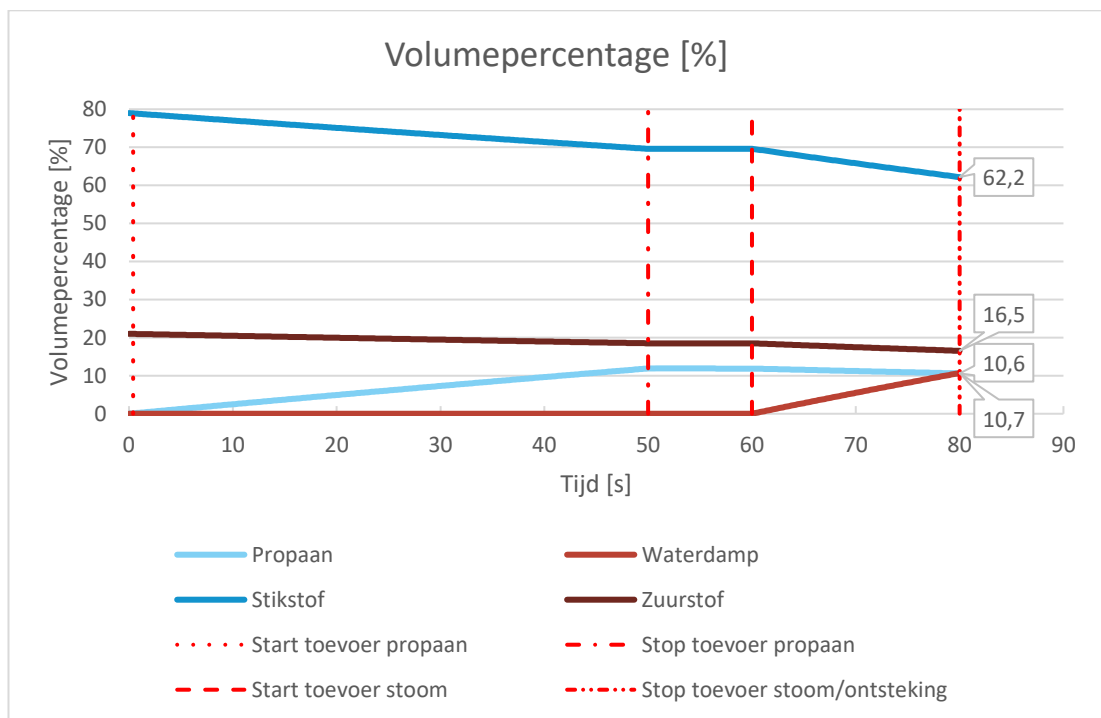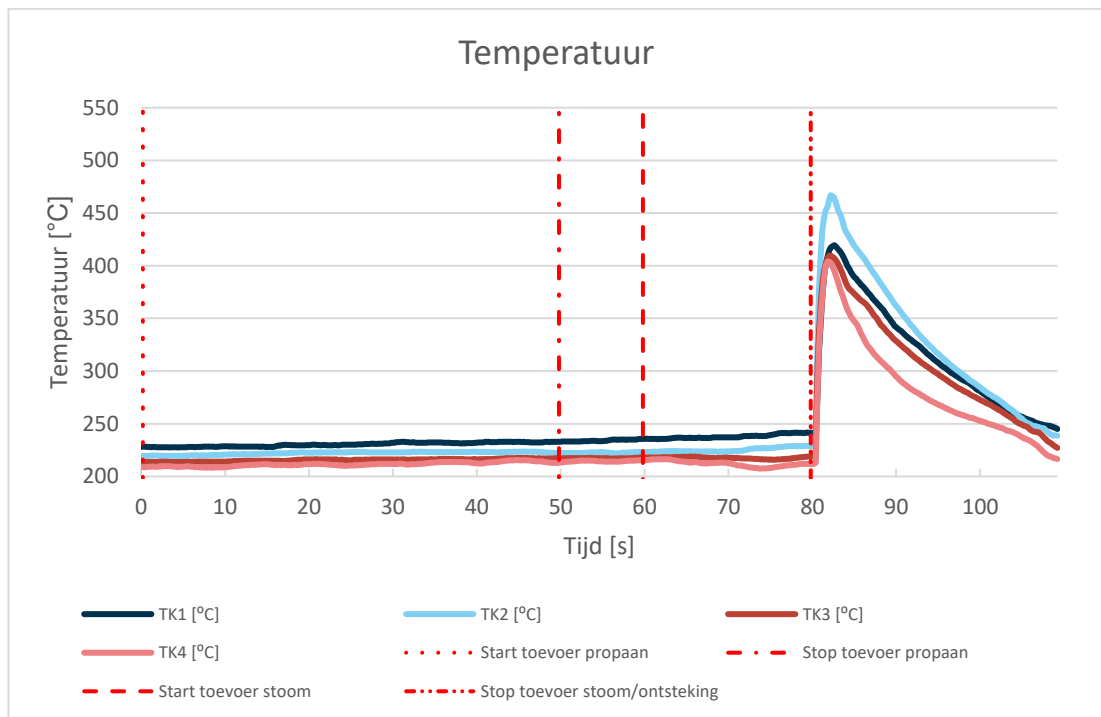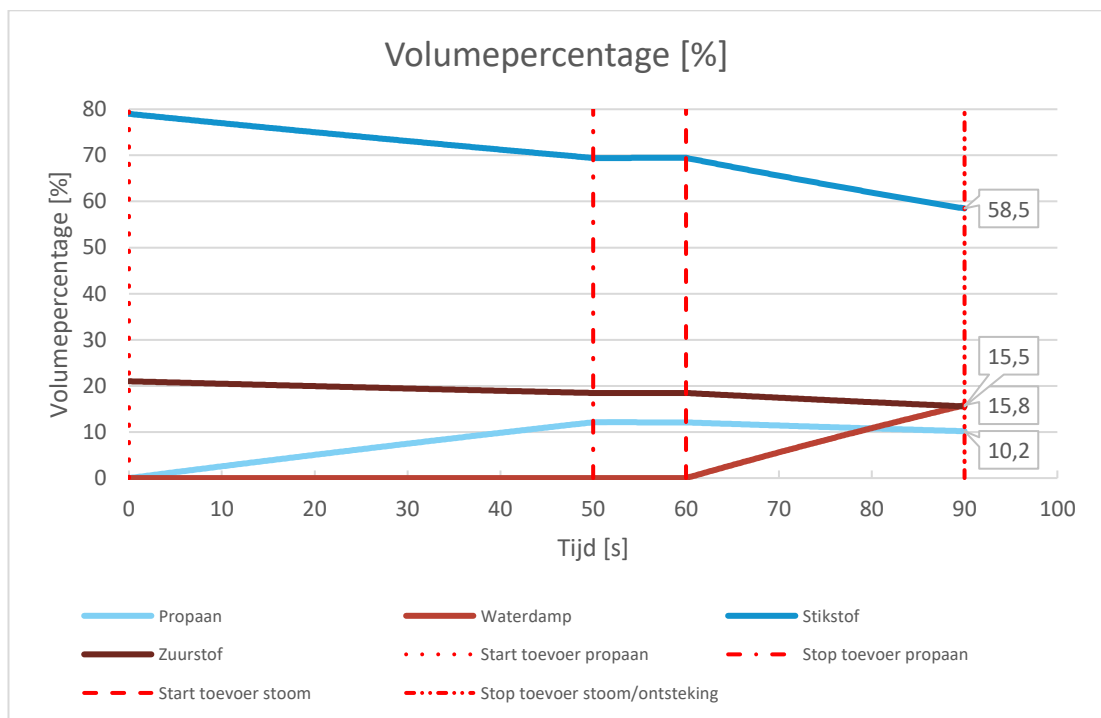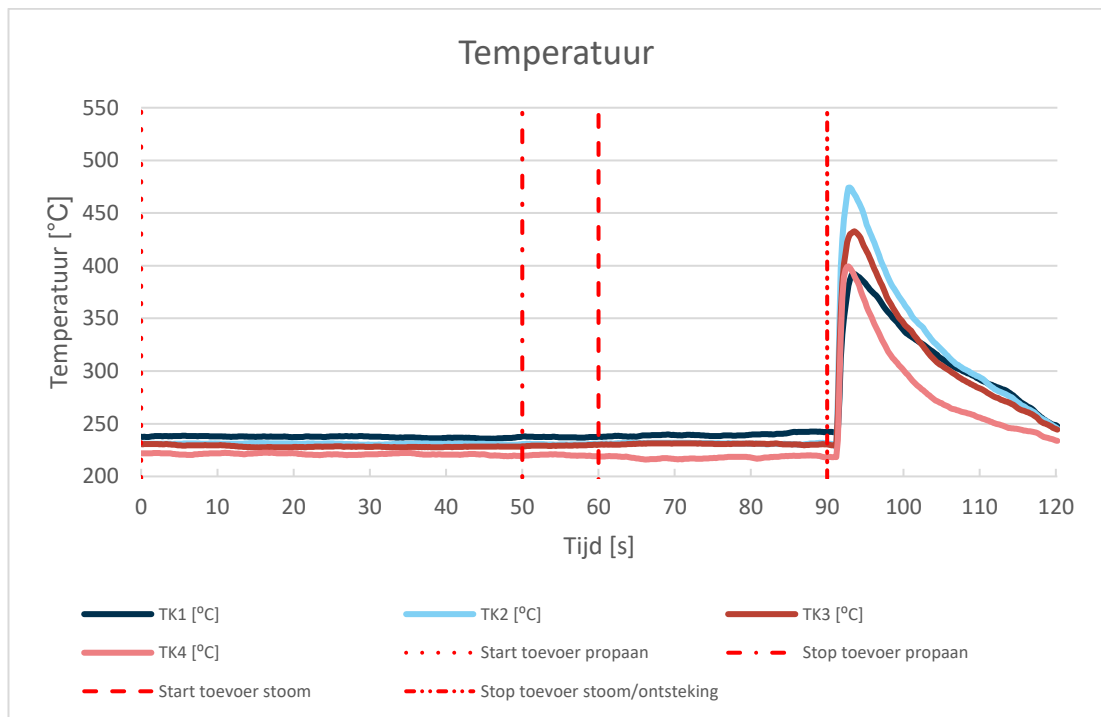
Test 5: 30 seconden

Test 5: Ontbranding bij 30 sec stoom

Test 6: 30 seconden

Temperatuur

Volumepercentage [%]

Test 7: 60 seconden

Temperatuur

Volumepercentage [%]
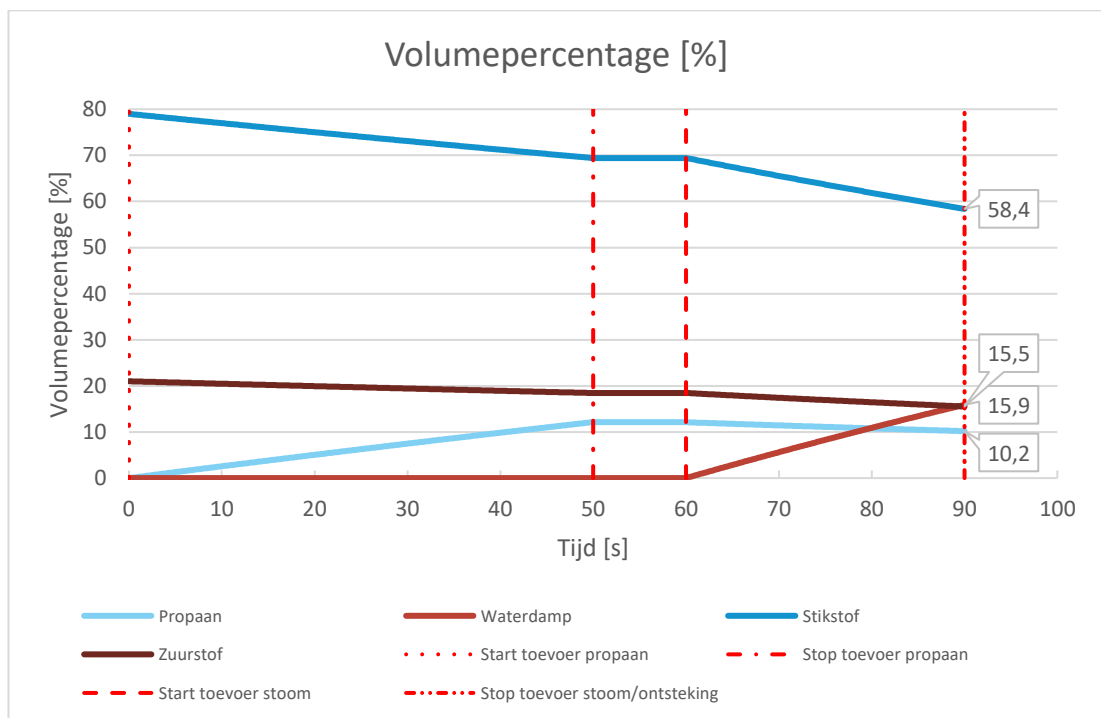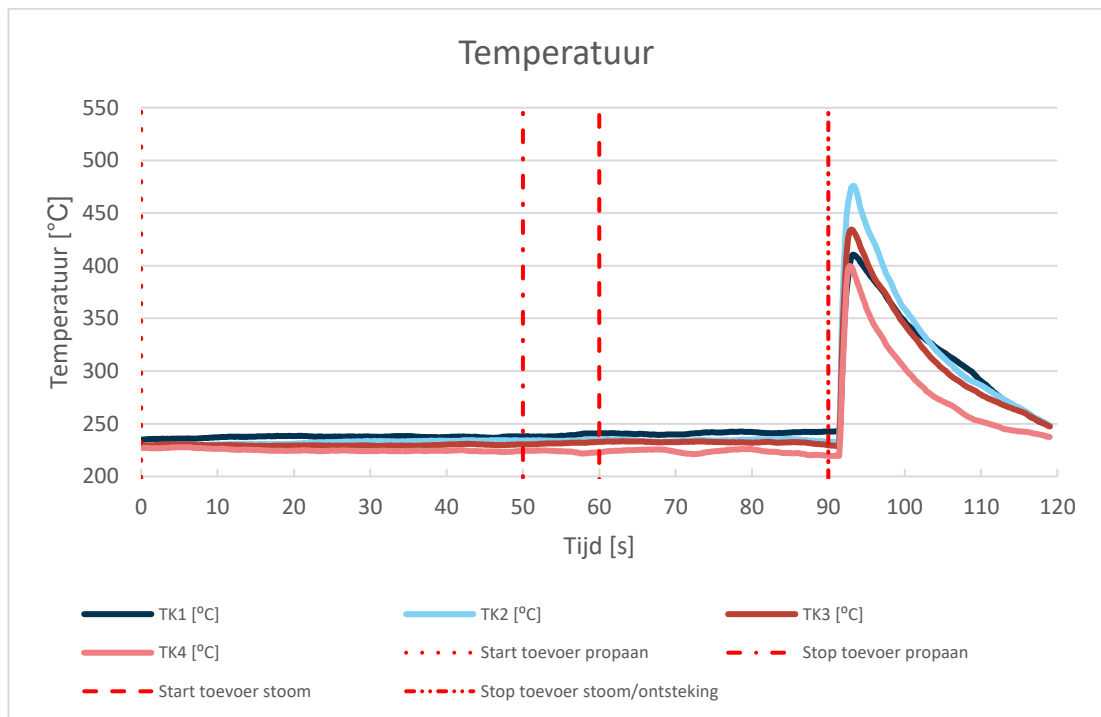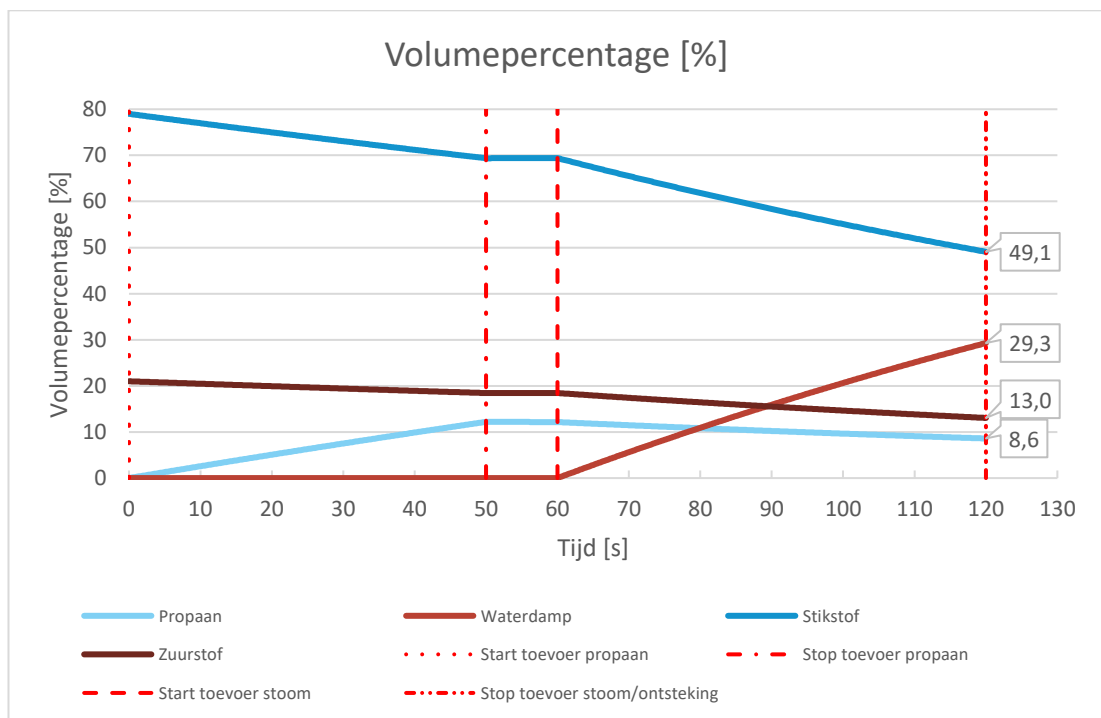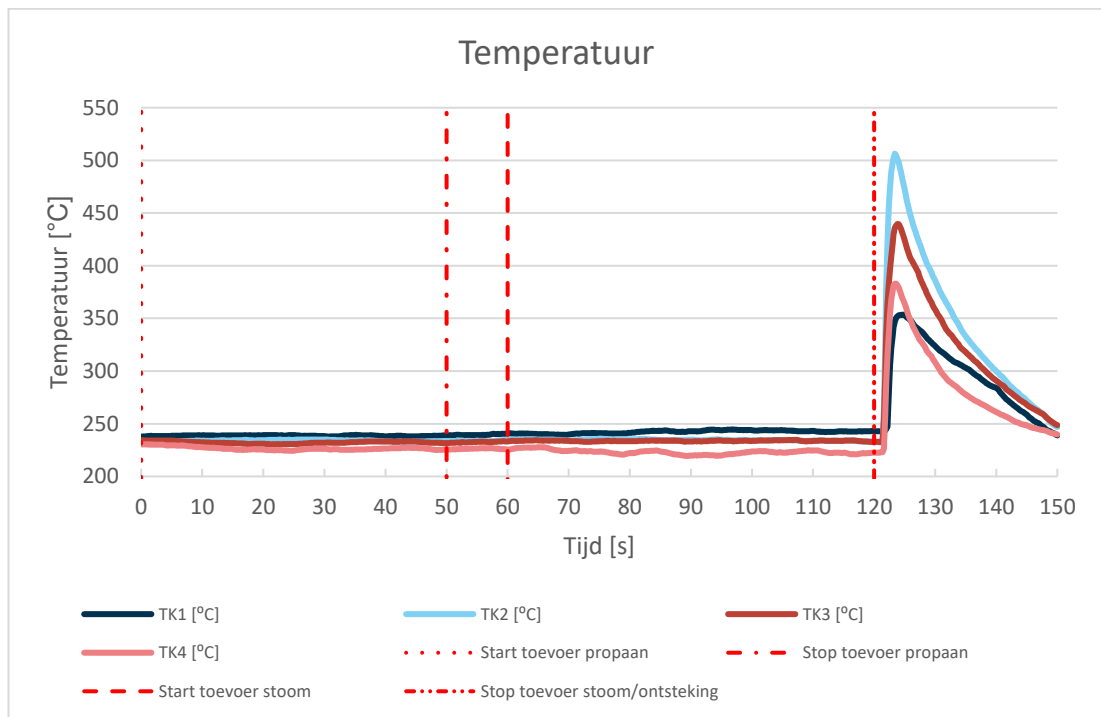
Test 7: Ontbranding bij 60 sec stoom

Test 8: 60 seconden

Temperatuur

Volumepercentage [%]

Test 9: 90 seconden

Temperatuur

Volumepercentage [%]
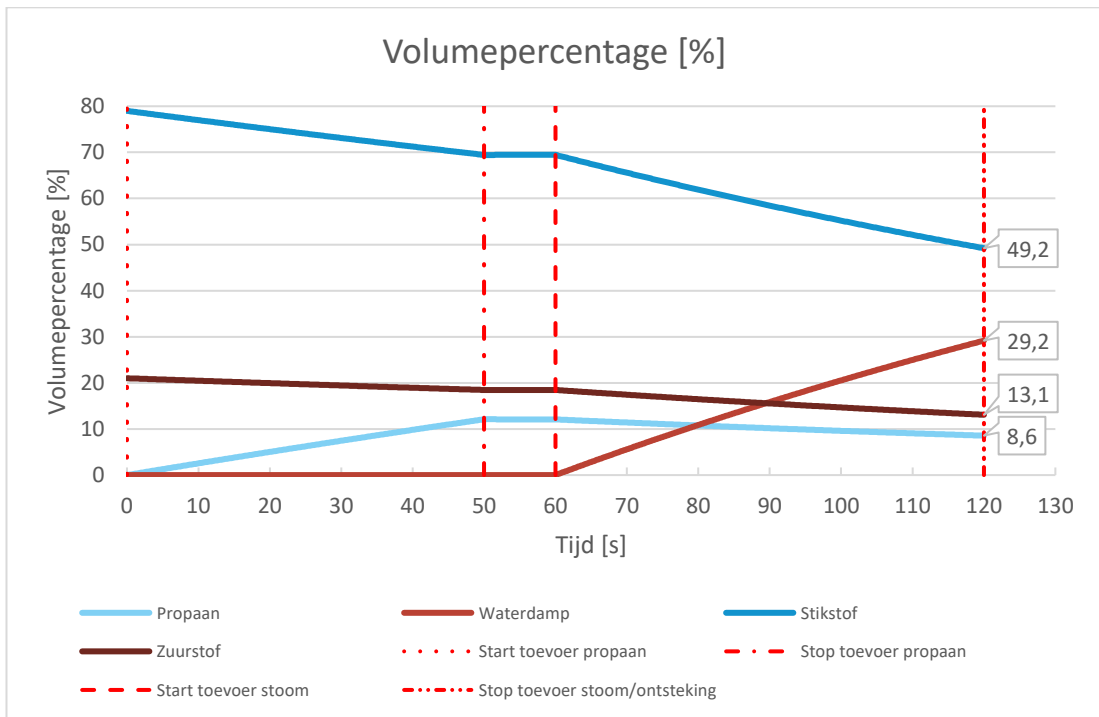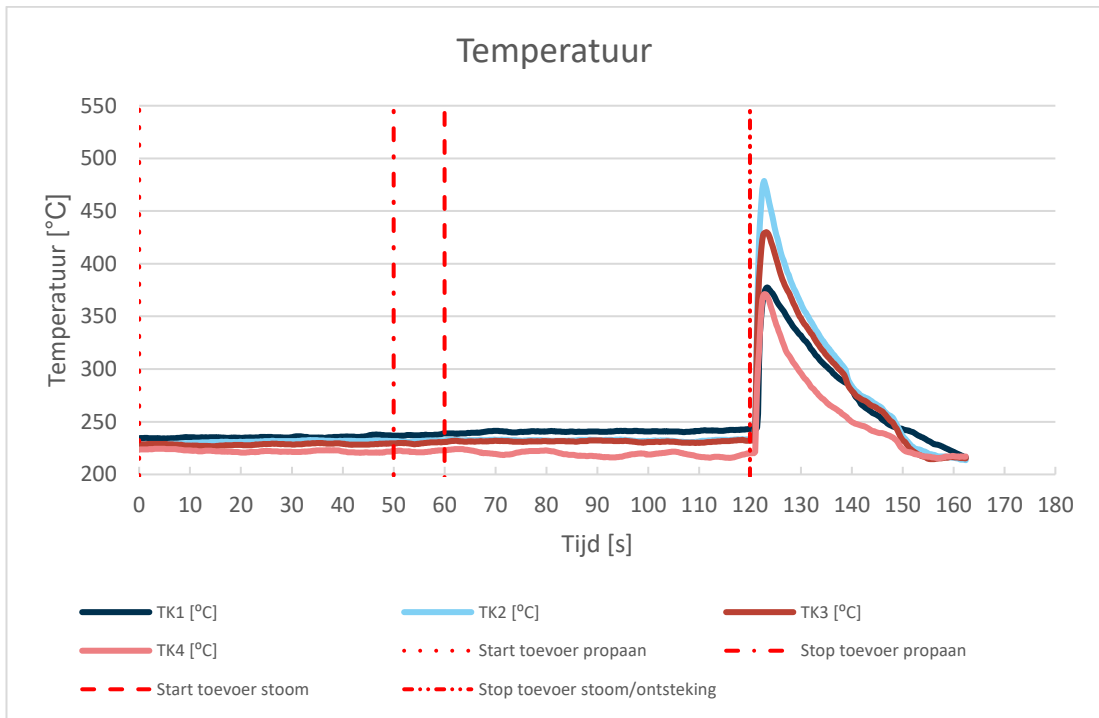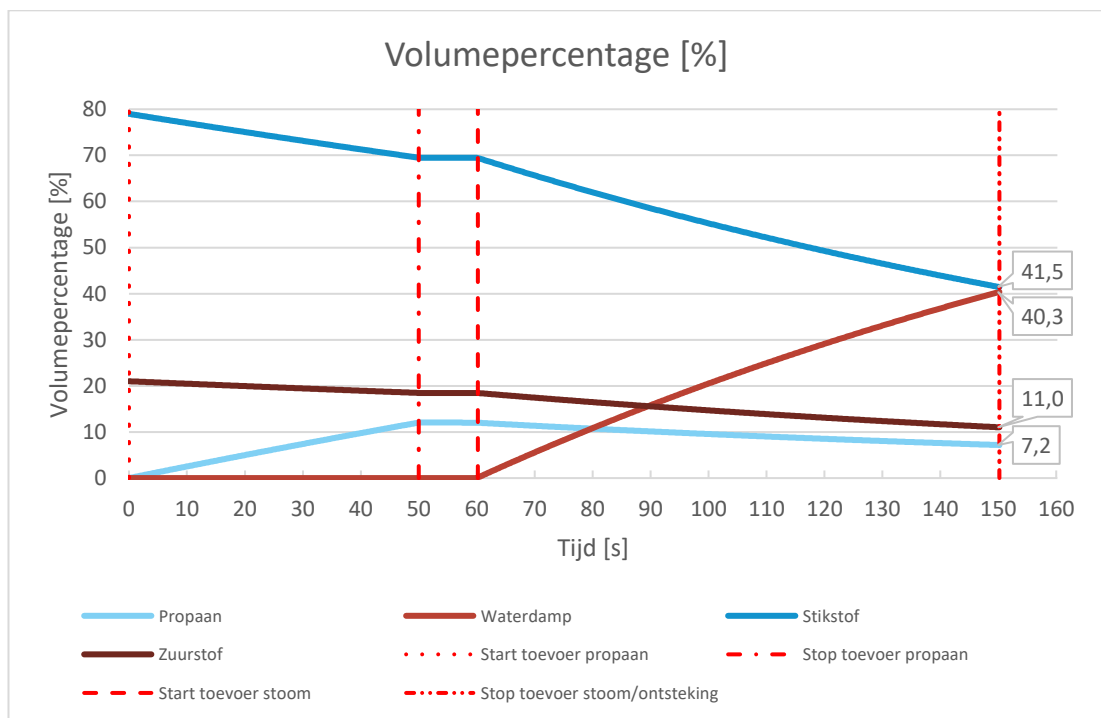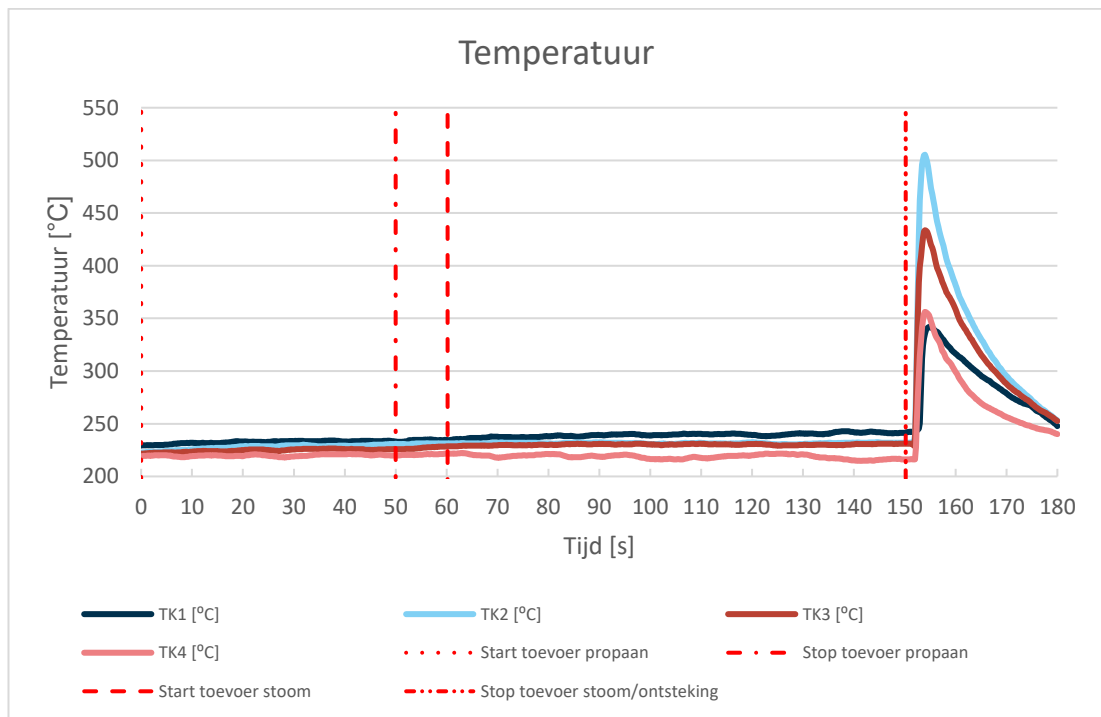
Test 9: Ontbranding bij 90 sec stoom

Test 10: 90 seconden

Temperatuur

Legend:
- TK1 [°C]
- TK2 [°C]
- TK3 [°C]
- TK4 [°C]
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer stoom
- Stop toevoer stoom/ontsteking

Volumepercentage [%]

41,4
40,4
11,0
7,2

Legend:
- Propaan
- Waterdamp
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer stoom
- Stop toevoer stoom/ontsteking

Test 11: 120 seconden

Temperatuur

TK1 [°C] · TK2 [°C] · TK3 [°C] · TK4 [°C] · Start toevoer propaan · Stop toevoer propaan · Start toevoer stoom · Stop toevoer stoom/ontsteking

Volumepercentage [%]

Propaan · Waterdamp · Stikstof · Zuurstof · Start toevoer propaan · Stop toevoer propaan · Start toevoer stoom · Stop toevoer stoom/ontsteking

49,6
35,1
9,3
6,0

Test 11: Ontbranding bij 120 sec stoom

Test 12: 120 seconden

Temperatuur

Legend:
- TK1 [°C]
- TK2 [°C]
- TK3 [°C]
- TK4 [°C]
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer stoom
- Stop toevoer stoom/ontsteking

Volumepercentage [%]

Waarden: 49,3 · 35,3 · 9,4 · 6,0

Legend:
- Propaan
- Waterdamp
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer stoom
- Stop toevoer stoom/ontsteking

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Test 13: 100 seconden

Temperatuur

Volumepercentage [%]

Test 13: Ontbranding bij 100 sec stoom

Test 14: 100 seconden

Temperatuur

Volumepercentage [%]

Test 14: Ontbranding bij 100 sec stoom

Test 15: 100 seconden
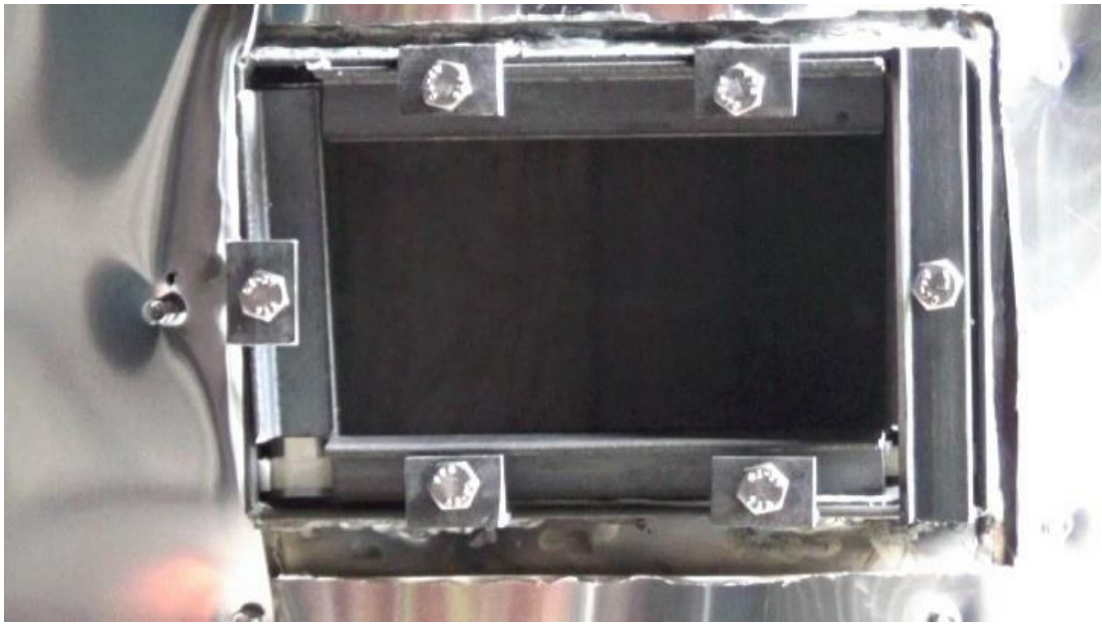
Temperatuur
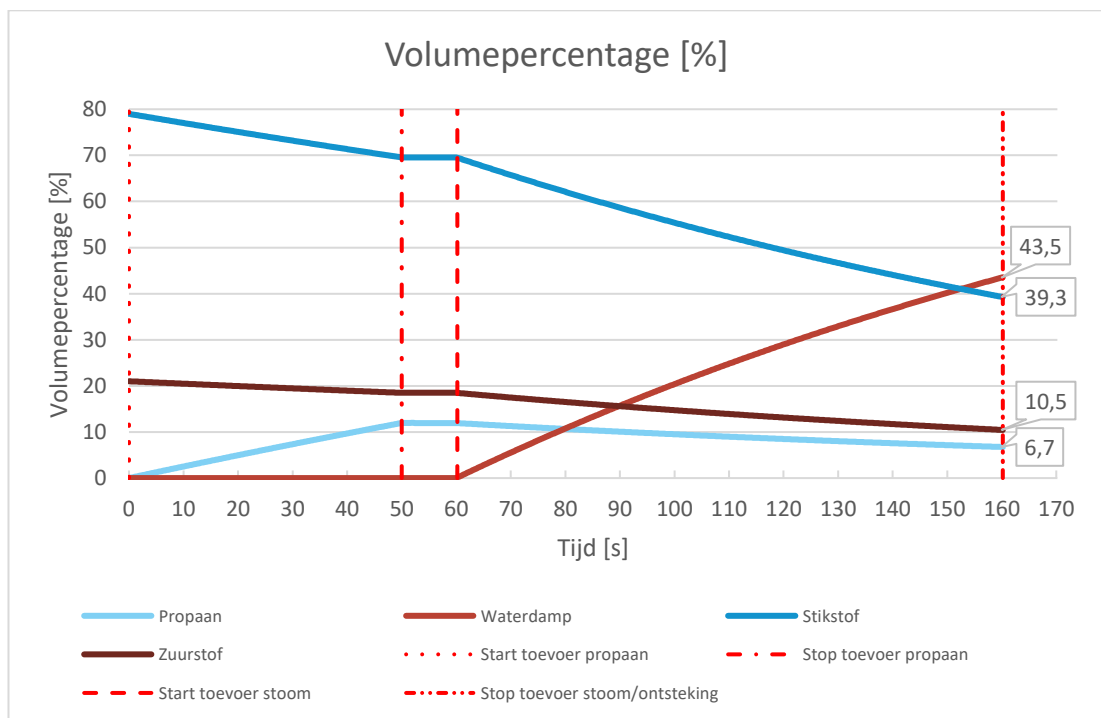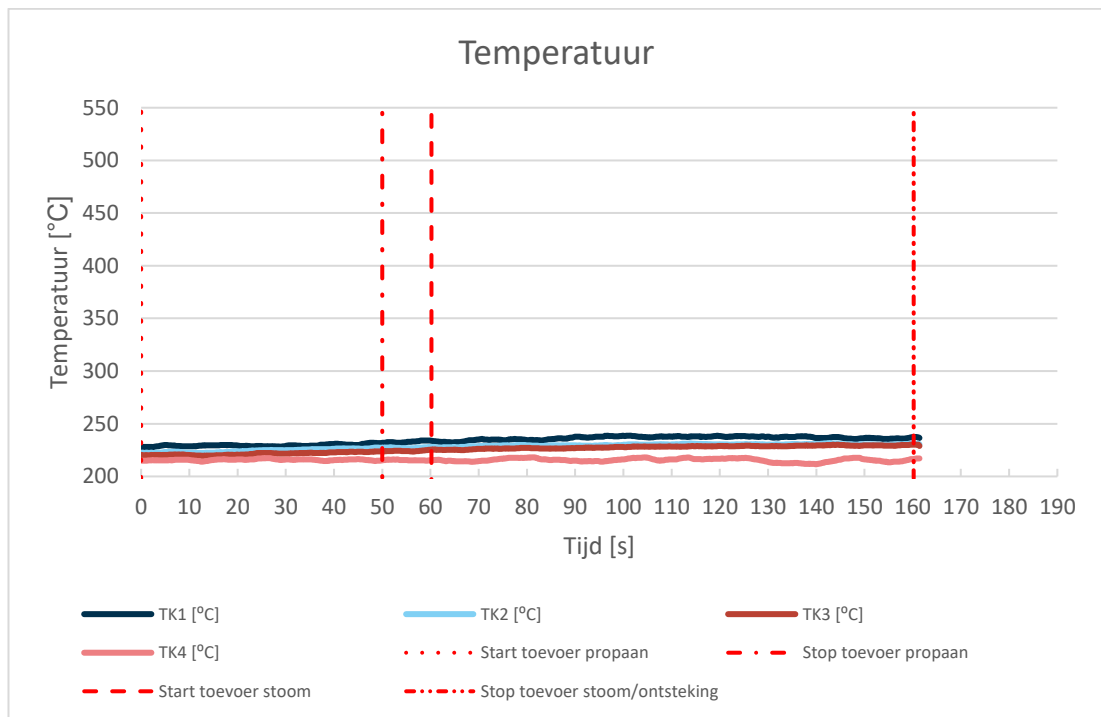
Volumepercentage [%]

Test 15: Ontbranding bij 100 sec stoom

Samenvatting experimenten stoom warme gassen

Toevoertijd [s]	Volumepercentage [%]			Ontbranding [-]	Temperatuur [ºC]	
	Zuurstof	Waterdamp	Propaan		Max. na plof	Verschil
10	17.3	5.8	11.8	Ja	519	265
20	16.5	10.7	10.7	Ja	466	243
30	15.5	18.9	10.2	Ja	475	243
60	13.1	29.3	8.6	Ja	493	259
90	11	40.4	7.2	Ja	509	277
100	10.5	43.4	6.7	Ja/nee	383	156
120	9.4	49.5	6	Nee	-	-
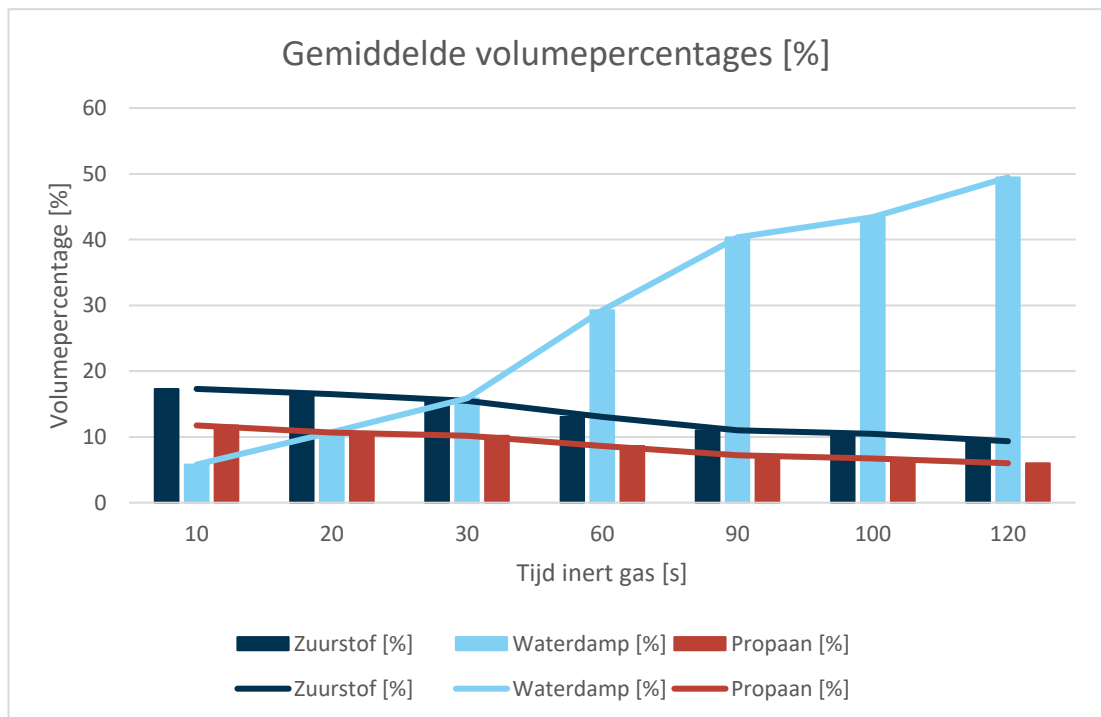
De maximaal toegevoerde hoeveelheid waterdamp (100 x 0.86 g/s = 86 g) komt overeen met 146 l bij 100 ºC. De plofkast heeft een volume van 343 l., dus de toevoer is ongeveer 43 % bij 100 ºC. Dit komt overeen met een volumepercentage van 57 % bij 227 ºC (500 K). Het resulterende percentage in de plofkast bedraagt ongeveer 43 % bij 227 ºC.

Gemiddelde temperatuur

Nevel

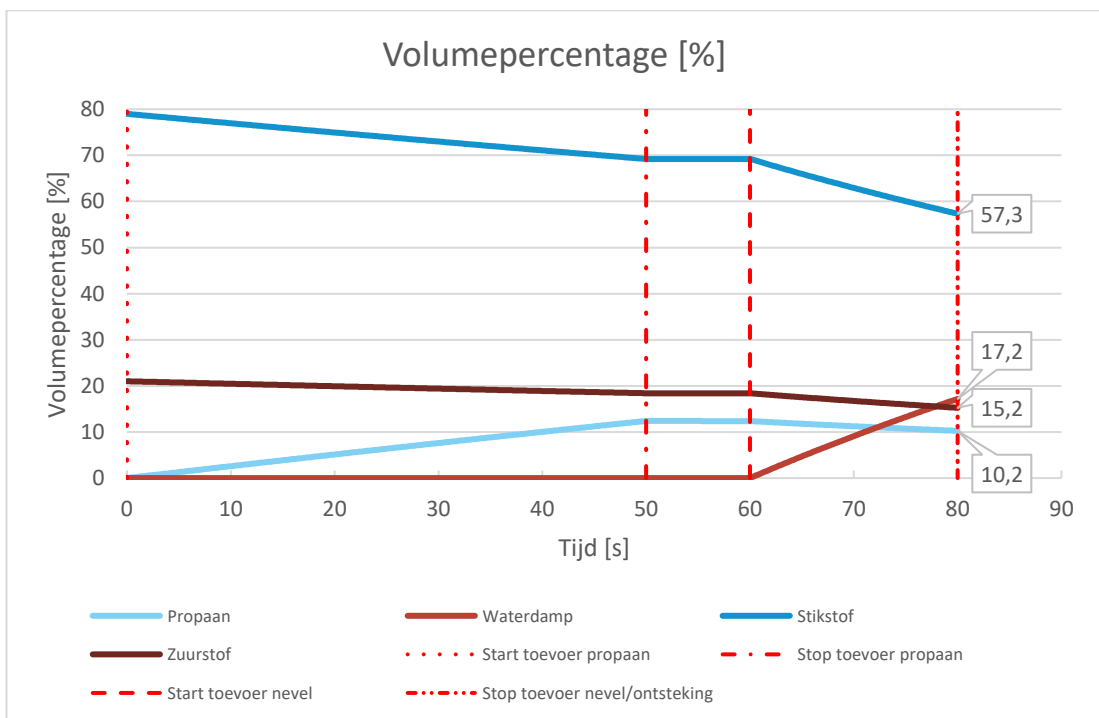## Test 1: 10 seconden

Temperatuur

Volumepercentage [%]
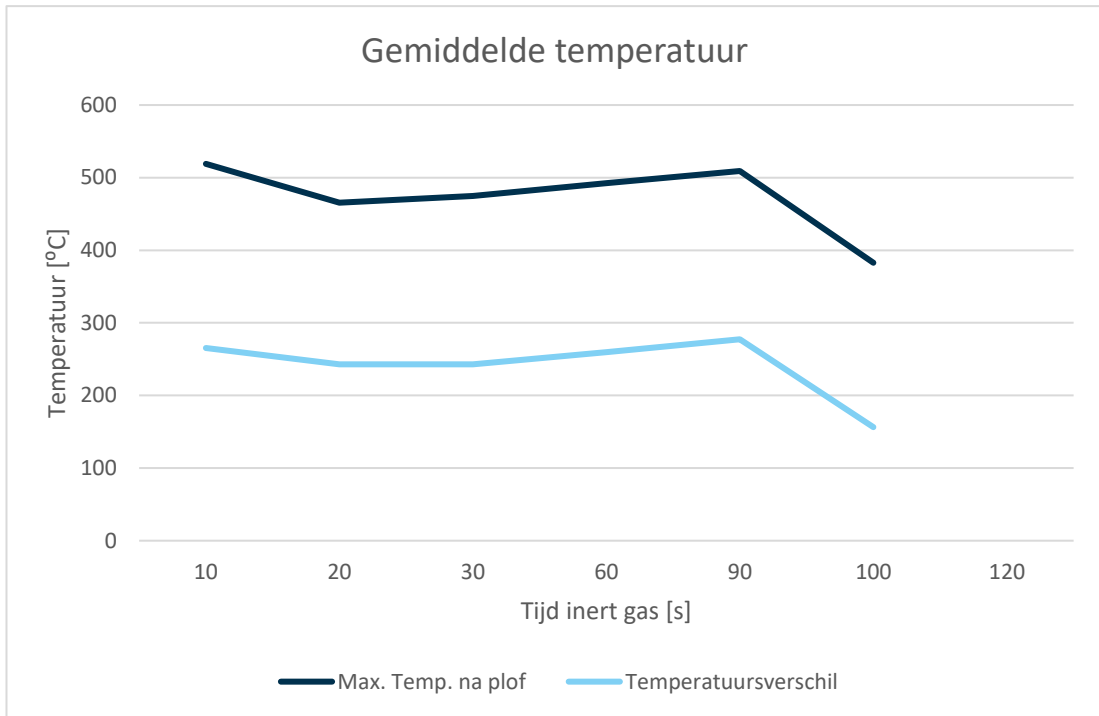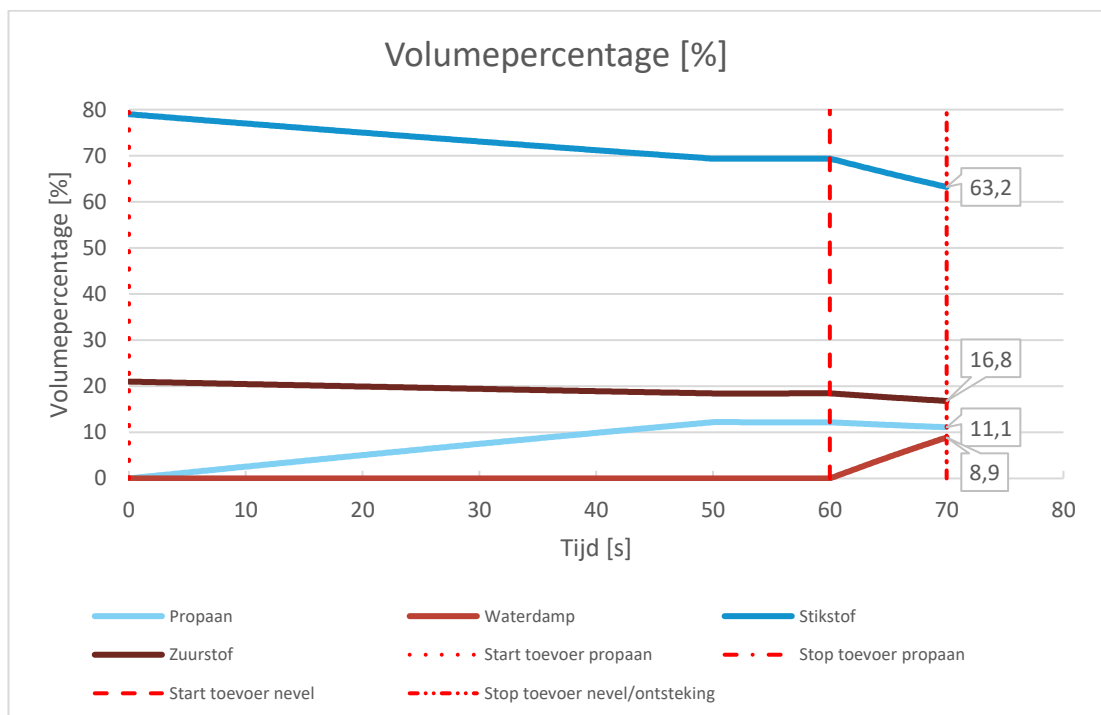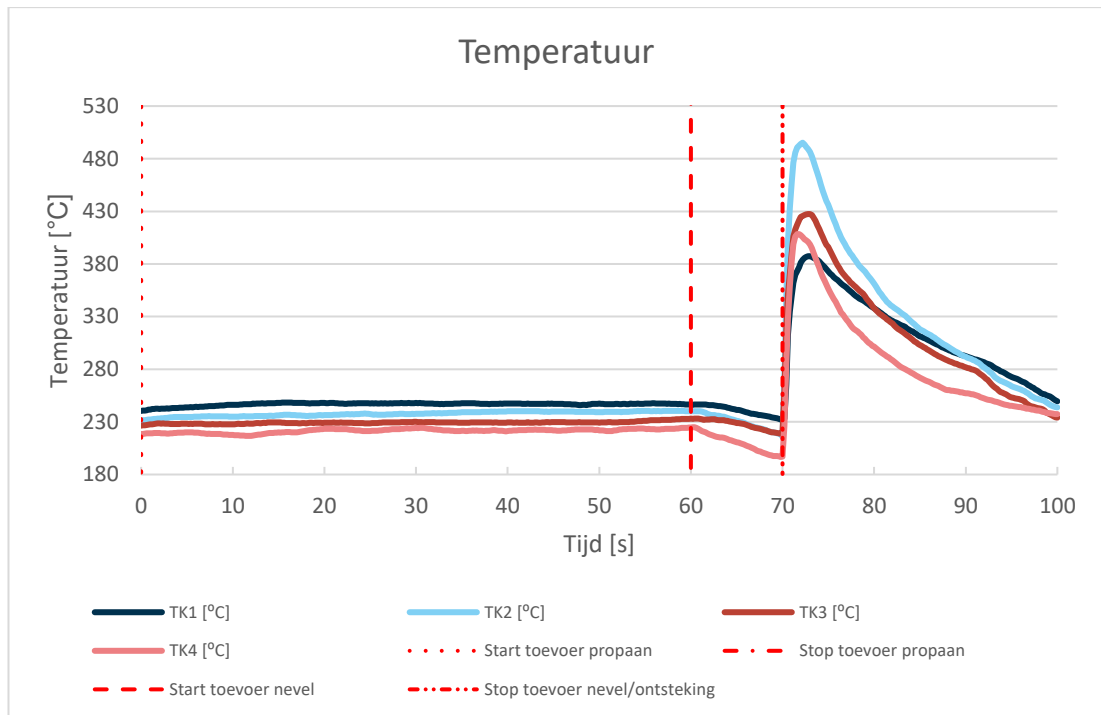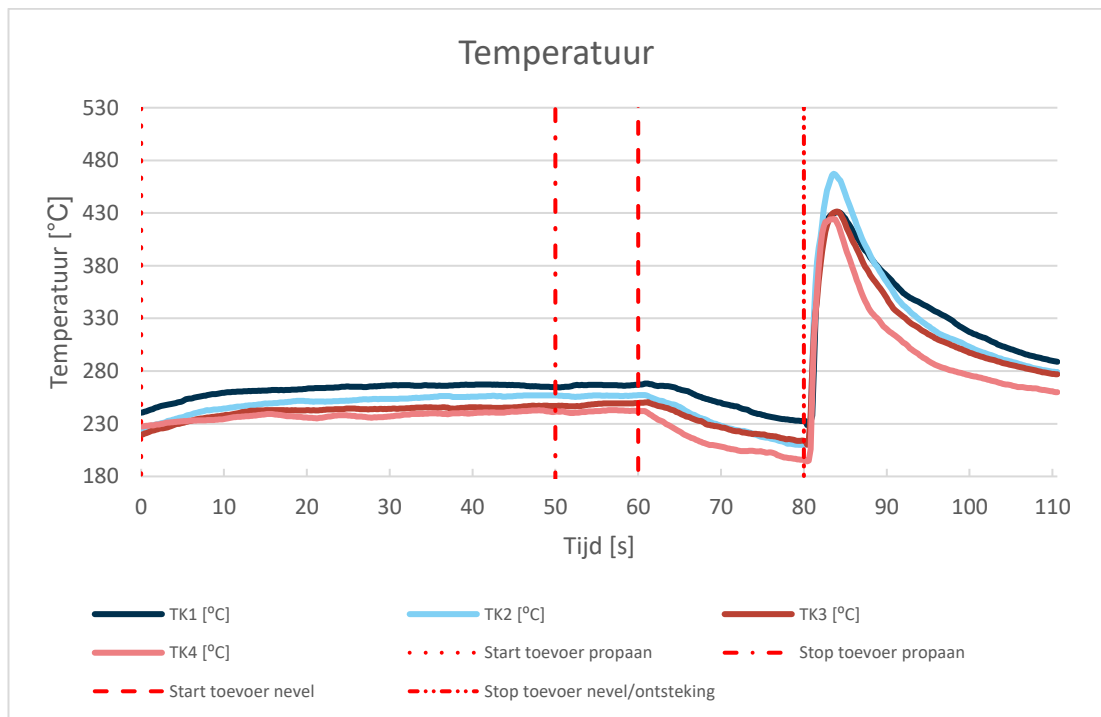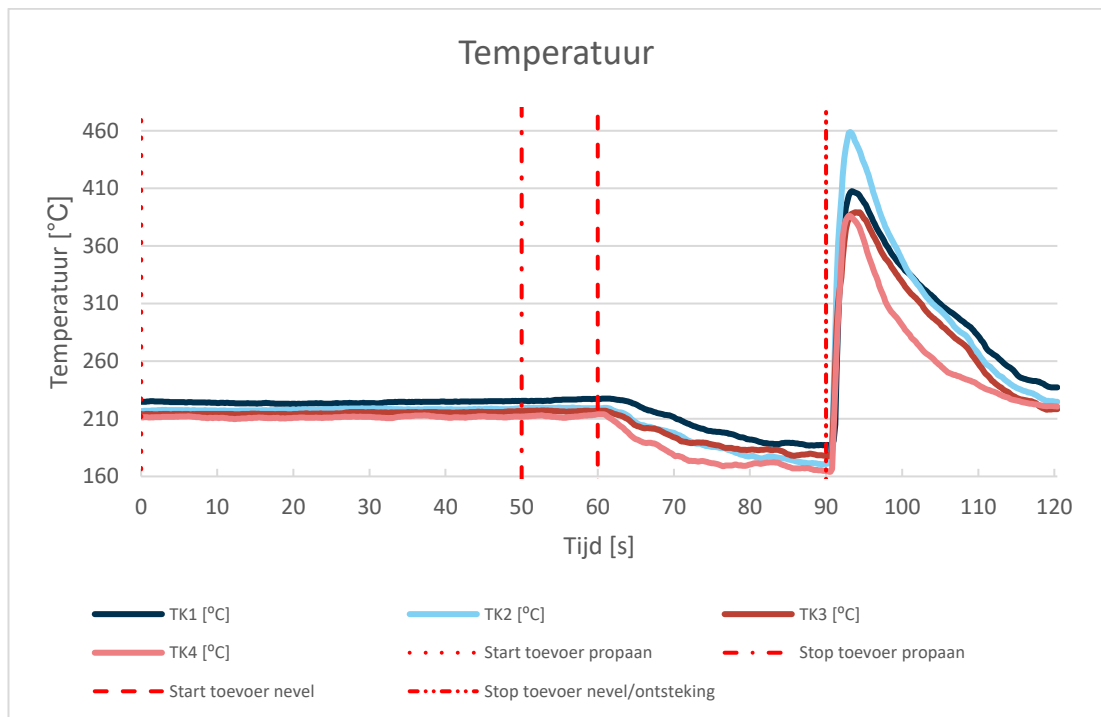
Test 1: Ontbranding bij 10 sec nevel

Test 2: 10 seconden

Temperatuur

Legenda: TK1 [°C], TK2 [°C], TK3 [°C], TK4 [°C], Start toevoer propaan, Stop toevoer propaan, Start toevoer nevel, Stop toevoer nevel/ontsteking

Volumepercentage [%]

63,8
17,0
10,7
8,5

Legenda: Propaan, Waterdamp, Stikstof, Zuurstof, Start toevoer propaan, Stop toevoer propaan, Start toevoer nevel, Stop toevoer nevel/ontsteking

Test 3: 20 seconden

Temperatuur

TK1 [°C] — TK2 [°C] — TK3 [°C] — TK4 [°C] — Start toevoer propaan — Stop toevoer propaan — Start toevoer nevel — Stop toevoer nevel/ontsteking

Volumepercentage [%]

Propaan — Waterdamp — Stikstof — Zuurstof — Start toevoer propaan — Stop toevoer propaan — Start toevoer nevel — Stop toevoer nevel/ontsteking

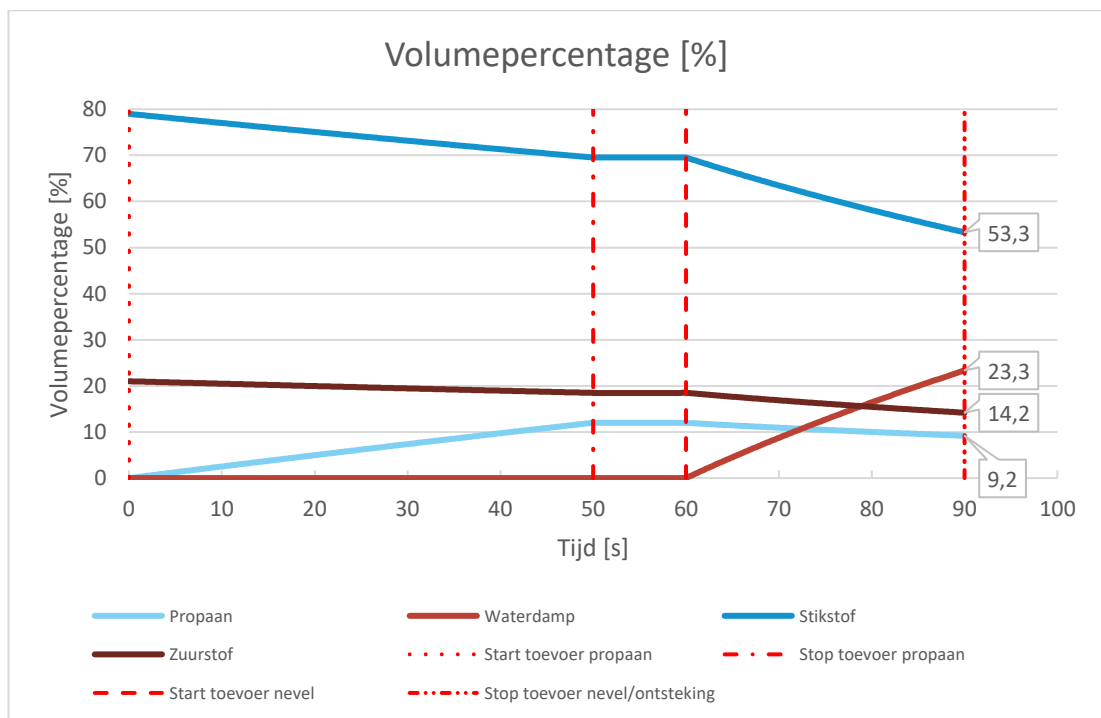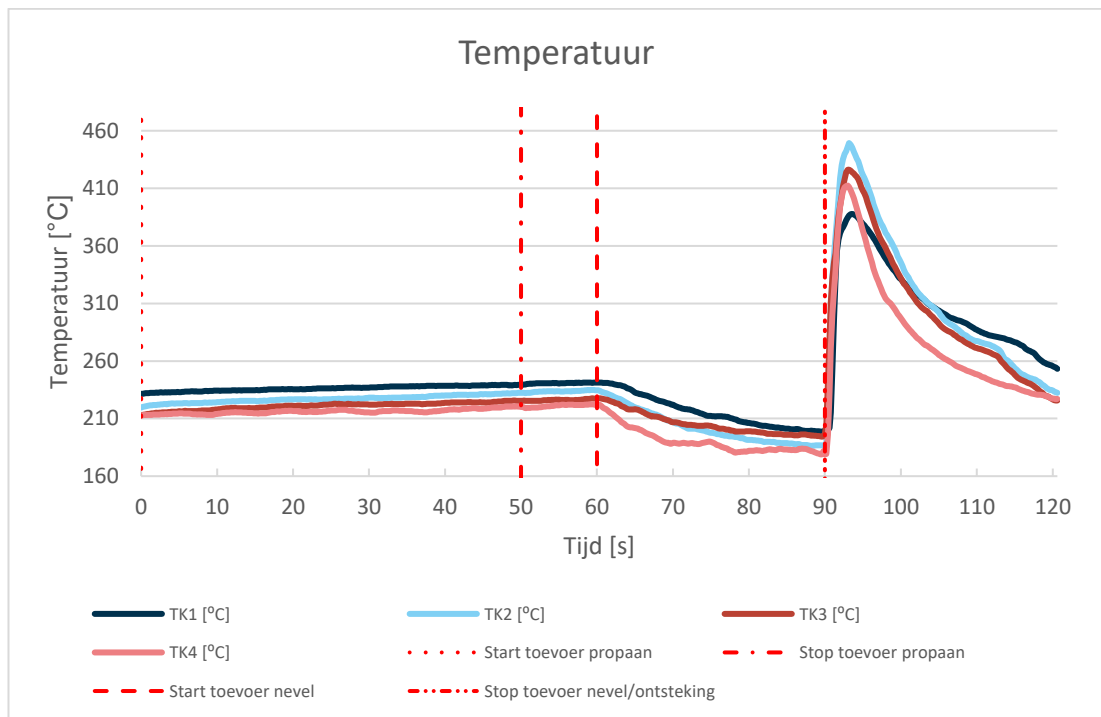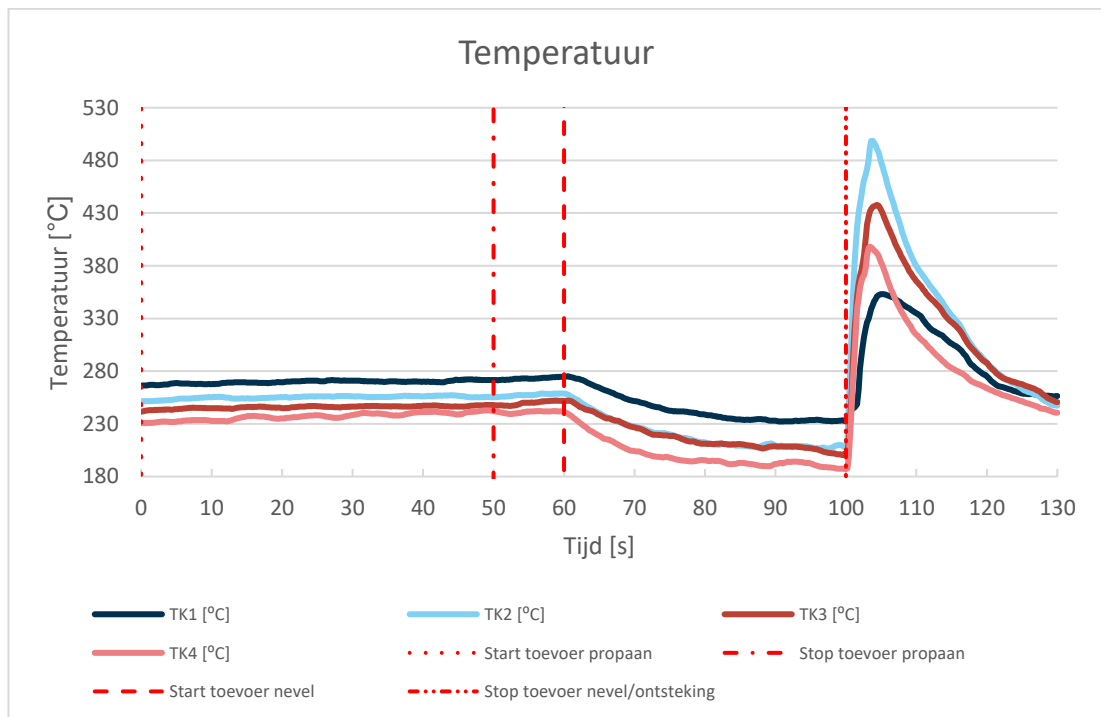Test 3: Ontbranding bij 20 sec nevel

Test 4: 20 seconden

Temperatuur

Legenda:
- TK1 [°C]
- TK2 [°C]
- TK3 [°C]
- TK4 [°C]
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer nevel
- Stop toevoer nevel/ontsteking

Volumepercentage [%]

Waarden: 57,3 — 17,1 — 15,2 — 10,4

Legenda:
- Propaan
- Waterdamp
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer nevel
- Stop toevoer nevel/ontsteking

Test 5: 30 seconden

Temperatuur

Volumepercentage [%]

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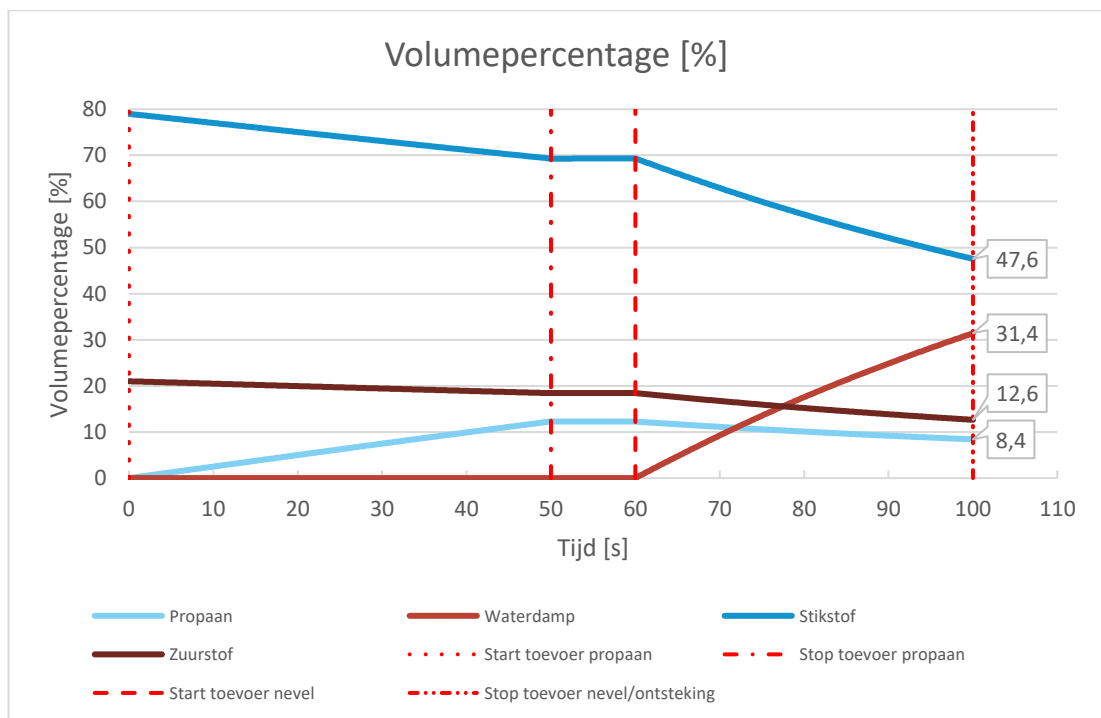
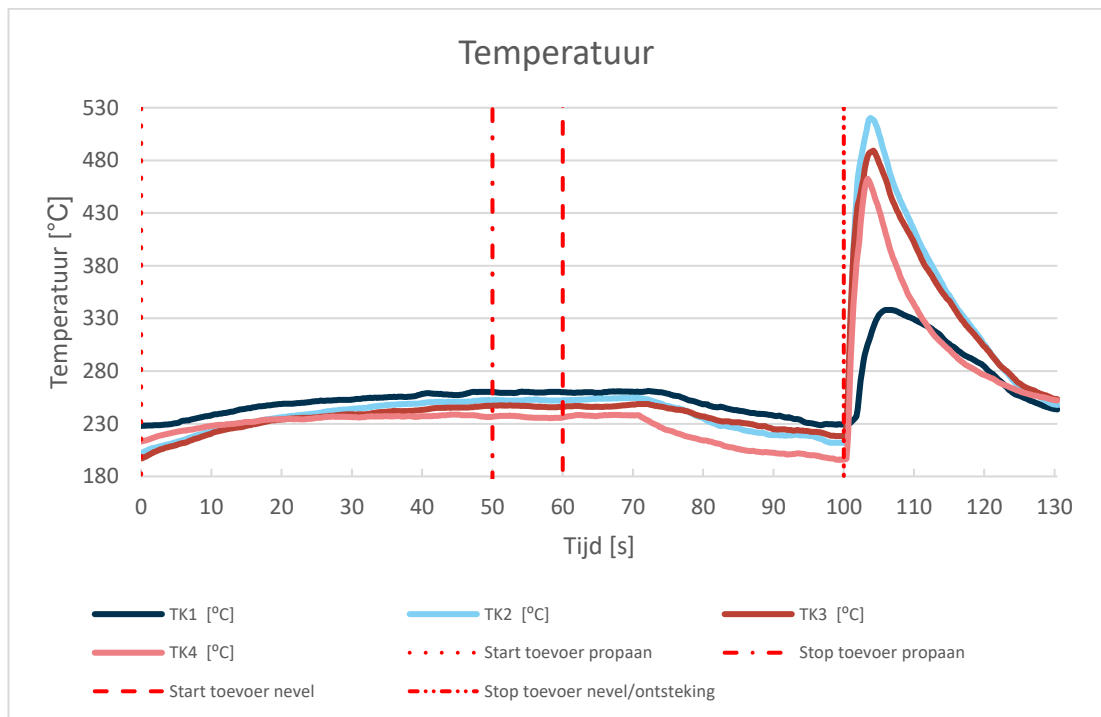Test 5: Ontbranding bij 30 sec nevel

Test 6: 30 seconden

Temperatuur

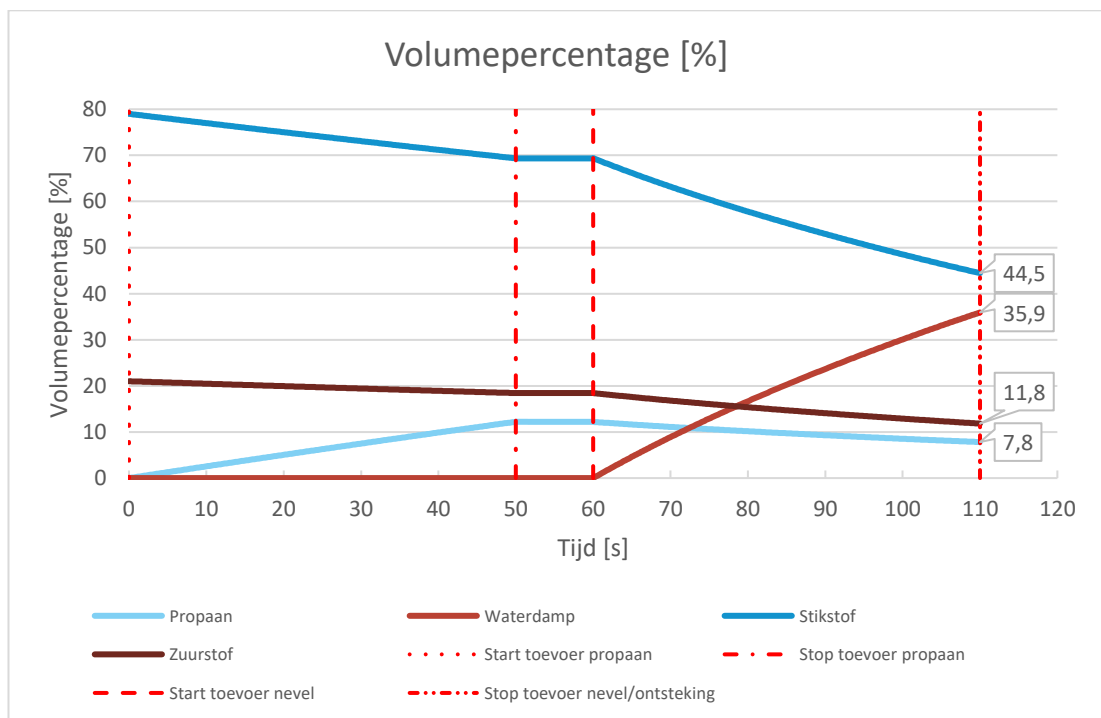Volumepercentage [%]

Test 7: 40 seconden

Temperatuur

Volumepercentage [%]
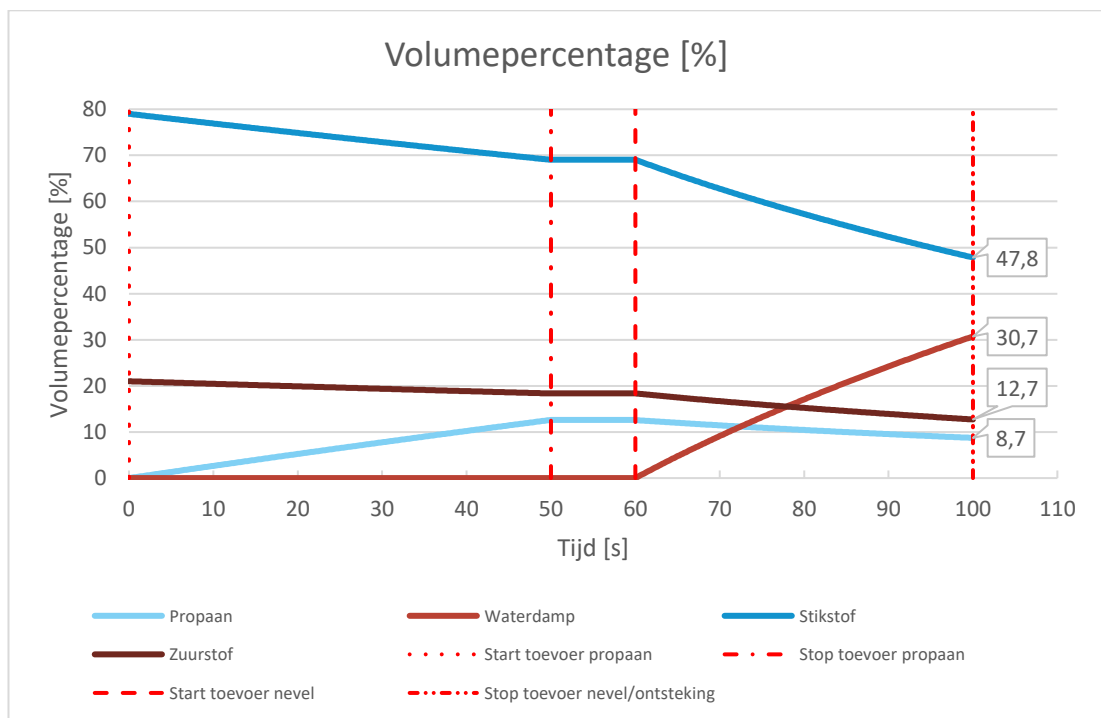
Test 7: Ontbranding bij 40 sec nevel

Test 8: 40 seconden
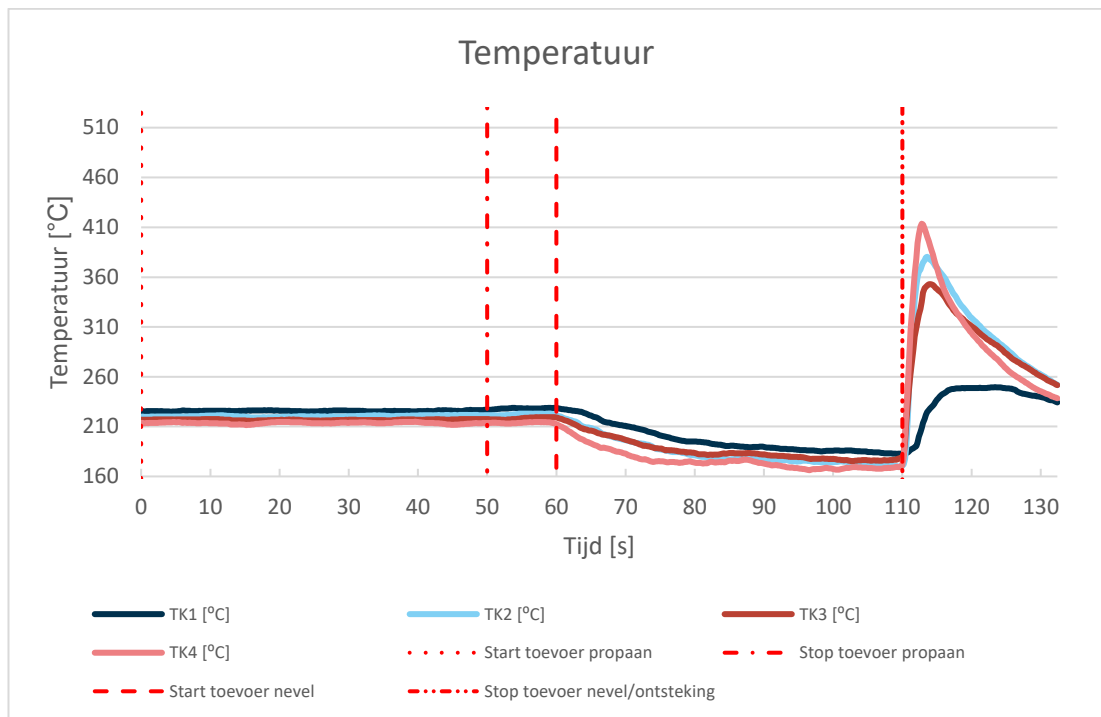

Temperatuur

Legenda:
- TK1 [°C]
- TK2 [°C]
- TK3 [°C]
- TK4 [°C]
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer nevel
- Stop toevoer nevel/ontsteking

Volumepercentage [%]

47,6
31,4
12,6
8,4

Legenda:
- Propaan
- Waterdamp
- Stikstof
- Zuurstof
- Start toevoer propaan
- Stop toevoer propaan
- Start toevoer nevel
- Stop toevoer nevel/ontsteking

Test 9: 50 seconden

Temperatuur
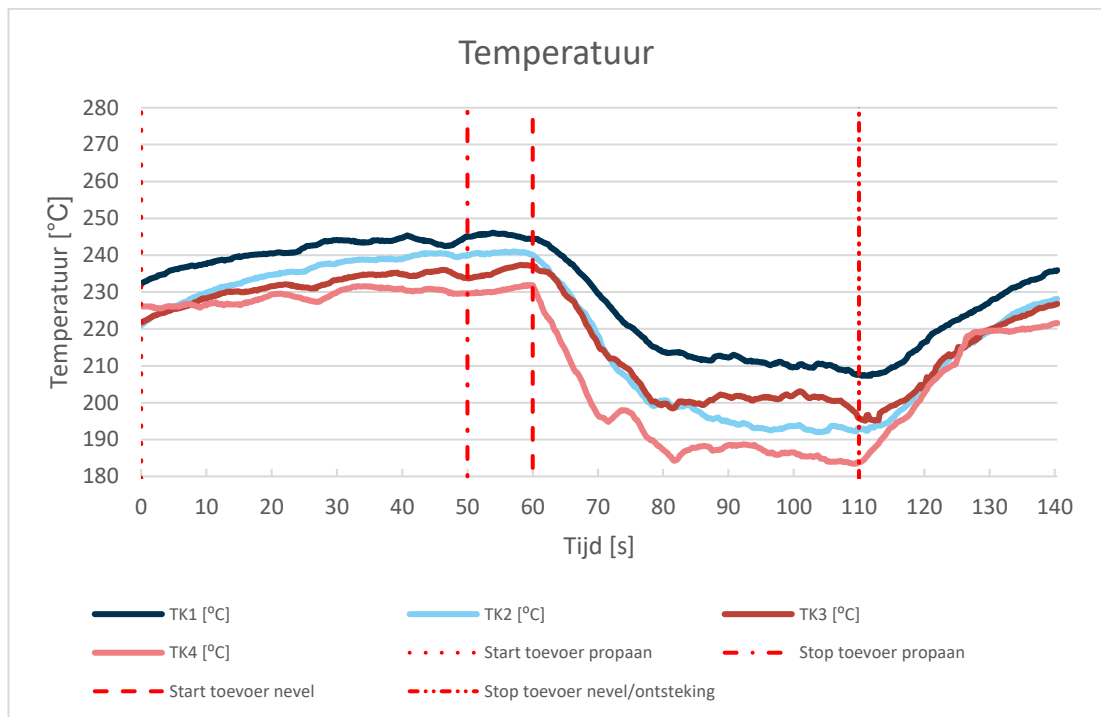
Volumepercentage [%]

Test 9: Ontbranding bij 50 sec nevel

Test 10: 50 seconden

Temperatuur
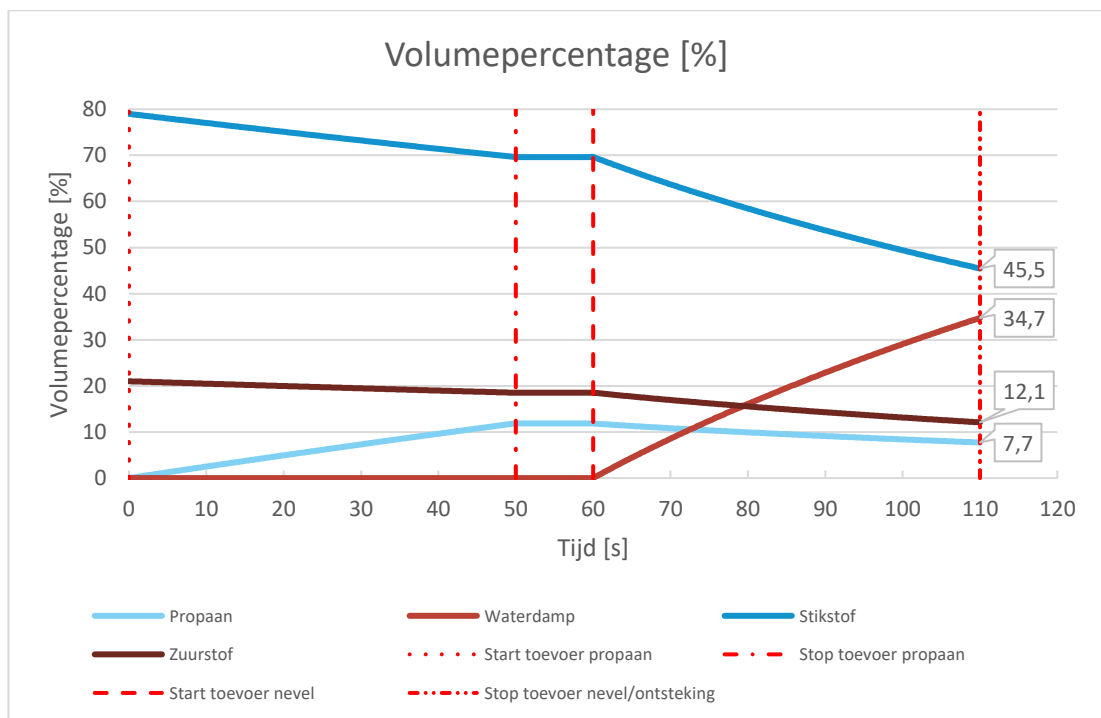
Volumepercentage [%]

Test 10: Ontbranding bij 50 sec nevel

Test 11: 50 seconden
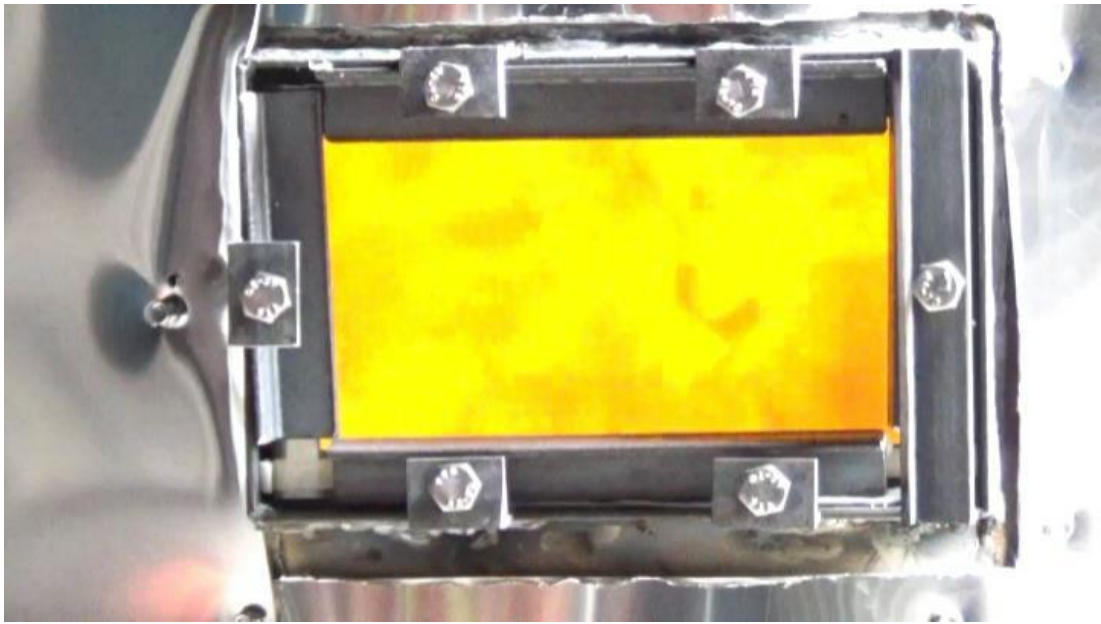
Temperatuur
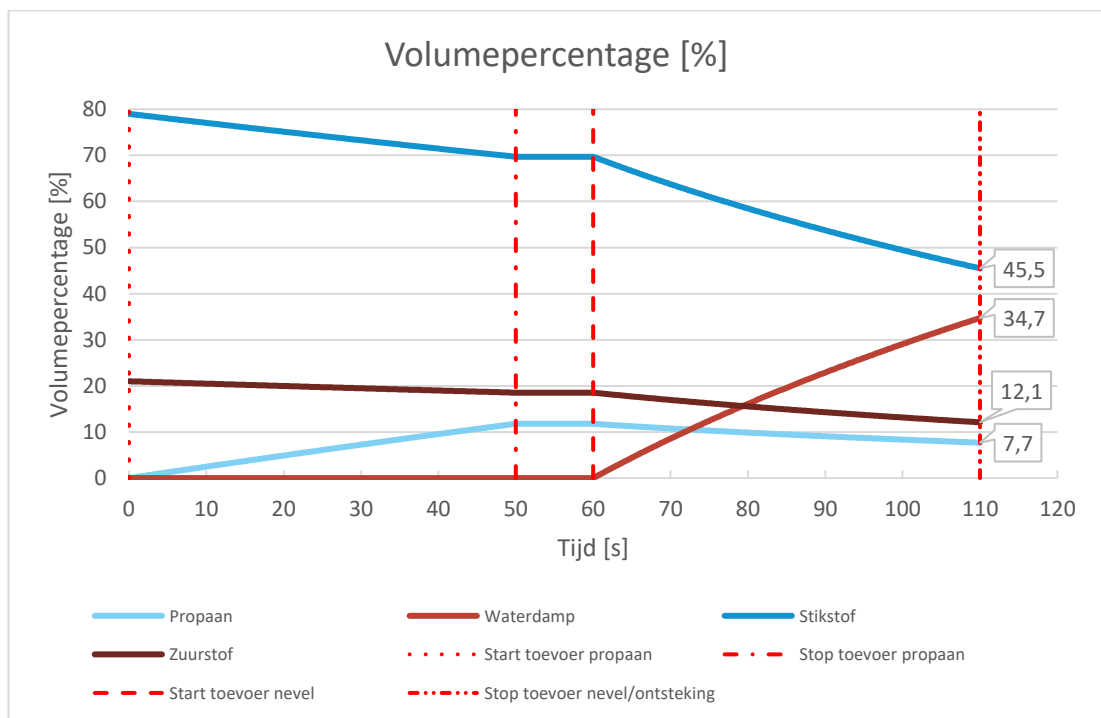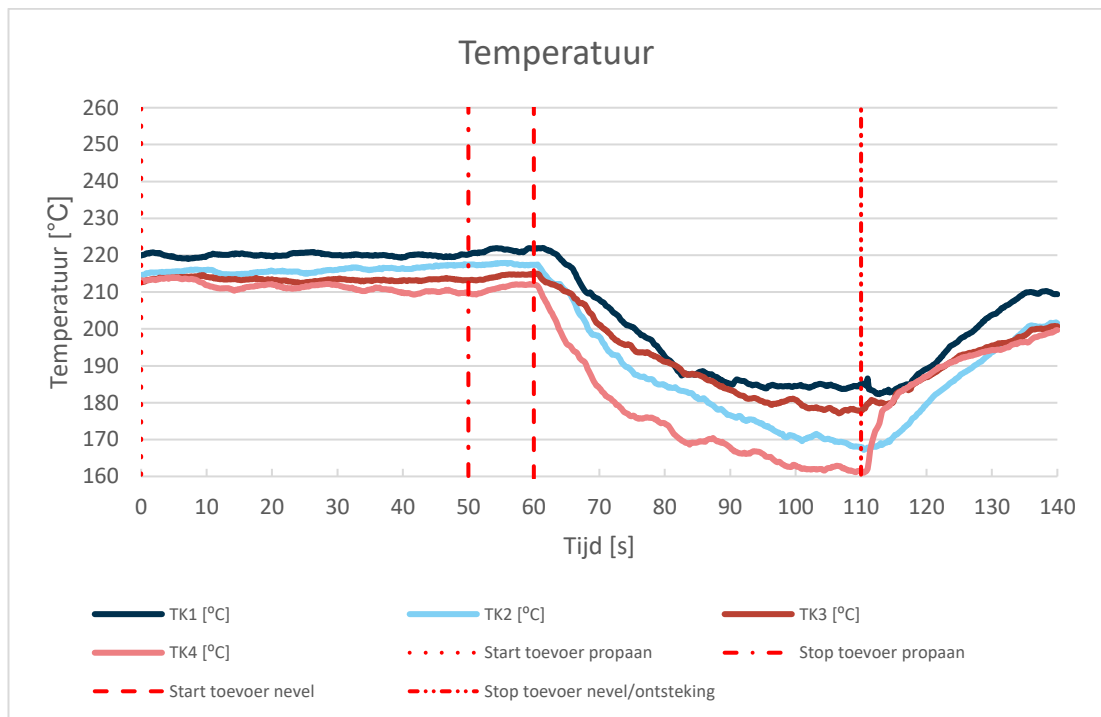
Volumepercentage [%]

Test 11: Ontbranding bij 50 sec nevel

Samenvatting experimenten nevel warme gassen

Toevoertijd [s]	Volumepercentage [%]			Ontbranding [-]	Temperatuur [ºC]	
	Zuurstof	Waterdamp	Propaan		Max. na plof	Verschil
10	16.9	8.7	10.9	Ja	480	273
20	15.2	17.2	10.3	Ja	516	296
30	14.3	23.1	9.2	Ja	454	276
40	12.7	31.1	8.6	Ja	510	300
50	12	35.1	7.7	Ja/Nee	380	210

De maximaal toegevoerde hoeveelheid nevel is 70 g (50 x 1,4 g/s = 70). Deze 70 gram wordt omgezet naar stoom met een volume van ongeveer 143 l bij 176 ºC (449 K). Dit komt overeen met een volumepercentage van 42 % bij 176 ºC. Het resulterende volumepercentage bedraagt ongeveer 35 % bij 176 ºC.

Gemiddelde temperatuur
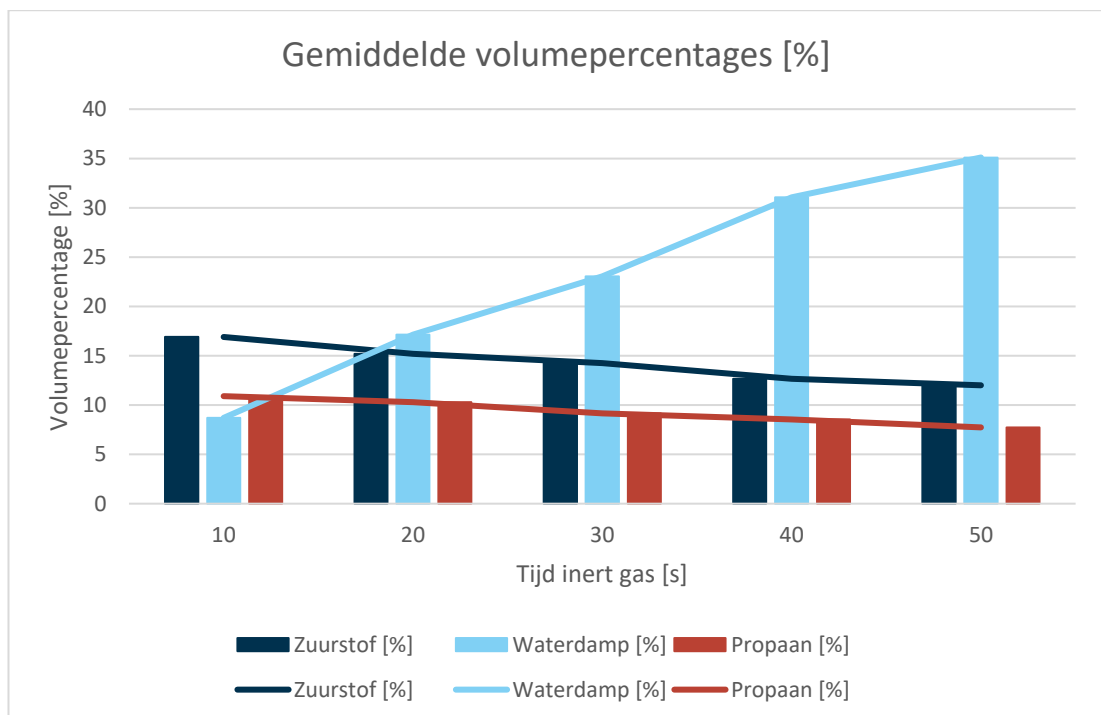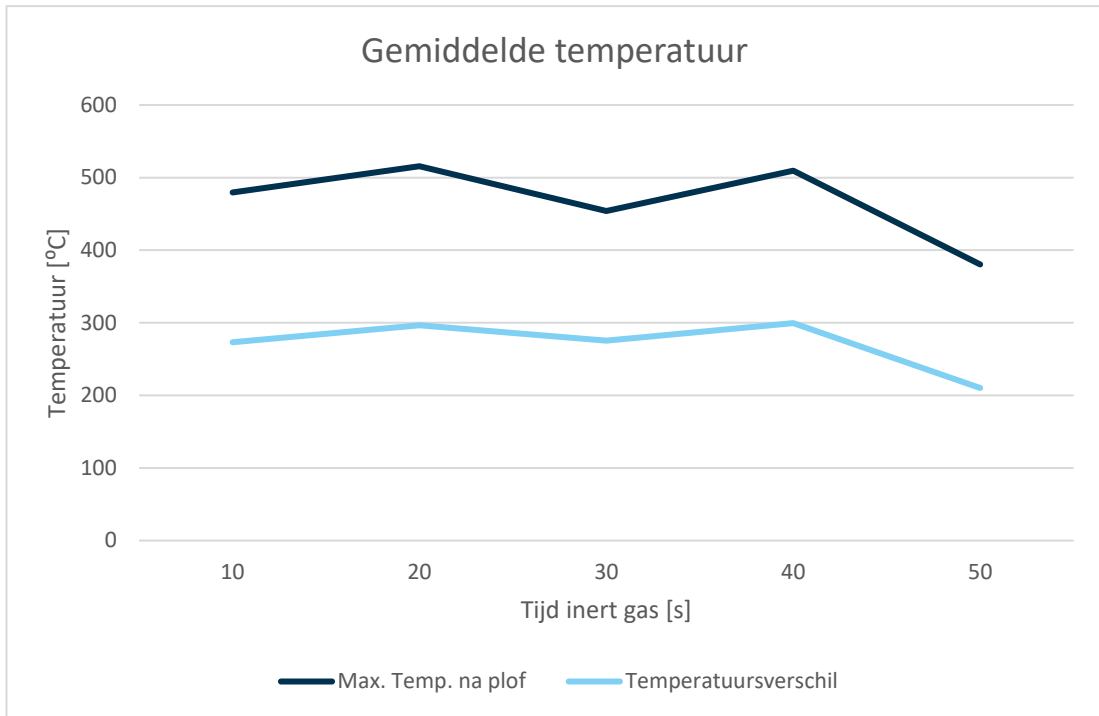
Bijlage 4 Volumebalans

Bij de analyse van de resultaten van zowel de koude als warme experimenten is uitgegaan van de volgende volumebalans:

$$V_x[t] = \frac{T[t]}{T[t-1]} \cdot (V_x[t-1] - Vuit_x[t-1]) + Vin_x[t]$$

Hierin is:

V_x het partiële volume van stof x

$Vuit_x$ de uitvoer van stof x

Vin_x de invoer van stof x

T de temperatuur

Hierbij is uitgegaan van de volgende uitgangspunten en randvoorwaarden:

> Input voor de analyse zijn: temperatuurverloop gedurende de propaantoevoer, eventuele wachttijd en stoomtoevoer [K], propaanduur [s], stoomduur [s], wachttijd [s], propaantoevoer [m3/s], stoomtoevoer [m3/s], volume kast/vat [m3] en ploftijdstip [s].
> Algemeen geldt dat de temperatuur van de propaantoevoer 20 °C is, en de temperatuur van de stoomtoevoer 100 °C. Verder geldt:

	Niet-verwarmd	Verwarmd
Propaantoevoer [m³/s]	5.167e^{-4}	2.5e^{-4}
Propaanduur [s]	32	50
Wachttijd [s]	0	10
Watertoevoer [m³/s]	1.46e^{-3}	1.46e^{-3}
Volume [m³]	1.6644 e^{-1}	3.43e^{-1}
Middeling over aantal thermokoppels	2	4

> De uitgevoerde berekeningen zijn integratieberekeningen met stap dt = 0.2 s. Dit is de meetfrequentie van de thermokoppels. De berekeningen lopen tot het moment van de ontsteking.
> Voor zuurstof en stikstof is Vinx [t-1] i.p.v. [t], omdat deze later in de loop van het experiment uitgerekend wordt.
> Het totale volume Vtot is de som van de partiële volumes van propaan, zuurstof, stikstof en water.
> Het totale volume kan, als gevolg van de invoer van stoffen en de temperatuursverandering, groter zijn dat het volume van het vat. De uitvoer van stoffen is dan gelijk aan het totale volume minus het volume van het vat (constante):

$$Vuit[t] = Vtot[t] - V$$

> Het kan zijn dat de uitvoer van stoffen negatief is. Dit betekent dat, in vergelijking met de vorige tijdstap, het vat afgekoeld is en lucht het vat zal instromen. Voor zuurstof en stikstof geldt dan:

$$Vin_x[t] = -1 * f_x * Vuit[t]$$

Met f_x de fractie zuurstof (0.21) en stikstof (0.79) in lucht. Hierna wordt de uitvoer op nul gesteld.

> De volumepercentages van stof x (Vol_x) worden gegeven door:
$$Vol_x[t] = \frac{V_x[t]}{V[t]} \cdot 100$$

 Waarbij V het totale volume is.

> De uitvoer van stof x wordt dan bepaald door:
$$Vuit_x[t] = \frac{Vol_x[t] \cdot Vuit[t]}{100}$$

> De beginwaarden zijn:

$V_{zuurstof} = V \cdot 0.21$

$V_{stikstof} = V \cdot 0.79$

$Vin_{propaan} = propaantoevoer \cdot \frac{T[t]}{T_p}$, met T_p = de temperatuur van het propaan (Charles'wet) op

moment van toevoeren

$Vol_{zuurstof} = 21$

$Vol_{stikstof} = 79$

Alle overige beginwaarden zijn 0.