Van Amstelpark 8
2629 JJ Delft
The Netherlands

www.tno.nl

T +31 88 866 30 00

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Effect of hydrogen gas mixes on gas hob emissions

Date	8 December 2022
Author(s)	Ir. P. Jacobs Ing. H.J.M. Cornelissen BSc.
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Summary

Background
The EU is currently updating the Ecodesign legislation with regard to cooking appliances. It concerns Ecodesign Regulation EC No 66/2014 on domestic ovens, hobs and range hoods and the Energy Label Regulation EC No 65/2014 on domestic ovens and range hoods. In parallel, the United Kingdom (UK) government is conducting a review of these same two regulations, as they are still applicable under UK law. These regulatory reviews present an opportunity to include requirements in both the EU and UK law that necessitate domestic appliances will not expose users to harmful levels of indoor air pollution.

Research questions
The main research questions to be answered in this study are:
- *What is the methane leakage during and in between use of gas hobs?*
- *What is the effect of adding hydrogen (H_2) gas to natural gas on gas hob emissions?*
- *What is the difference with regard to emissions between boiling water on a natural gas hob or with an electric hob?*

Approach
To answer these questions in the TNO Indoor Air Quality lab six different gas hobs, all with electronic ignition, an induction and a ceramic hob have been tested for the following emissions: nitrogen dioxide (NO_2), nitrogen oxide (NO), carbon monoxide (CO), carbon dioxide (CO_2), Ultra-fine particles (UFP) larger than 5.9 nm and methane (CH_4). Five gas fuel blends were tested: 100% natural gas and then four samples of 10% hydrogen increments with the highest being 40% hydrogen/60% natural gas blend. All measurement have been carried out with a constant gas flowrate of 4.5 l/min. The emission measurements with the gas hobs have been executed with naked gas flames. For the determination of the difference in emissions between natural gas hobs and electric hobs four pans filled with cold water were put on the hobs.

Results
Methane leakage
During use, the average methane emission of the 6 gas hobs was 35 ng/J, this correspondents with 331 mg/h. The average leakage of the six gas hobs between use, thus when the hobs were off and not in use, was 56 mg/h. These two values coincide well with the findings of a recent US study. A gas hob with natural gas containing a relative high benzene content may due to gas leakage when being off introduce a benzene concentration in the kitchen near the EU Ambient air quality Limit Value.

Effect of hydrogen on emissions
There is no clear trend with regard to the effect of H_2 addition and the gaseous emissions coefficients of the gas hobs. The only clear trend is that the CO_2 emission coefficient is reduced with increased H_2 content.
For each gas hob the addition of hydrogen significantly reduced the median particle size. There was one exception, for one gas hob the median UFP diameter

increased from going from 30% to 40% hydrogen. The flame colour and the stability might be an indicator for increased CO and particle number emissions.

Although this report focusses on emission rates, the emissions of gas burning with and without H_2 addition can lead to exceeding national or international indoor concentration limit values. An example is given in this study for benzene, but other compounds for instance NO_2 can exceed these limit values which is shown in a recent ventilation simulation study[1]. The results of this report can be input for requirements in both the EU and UK law that necessitate domestic appliances to prevent exposure of users to harmful levels of indoor air pollution.

Emission with boiling water on gas and electric hobs
While the gas hobs do emit considerable amounts of NO_2, NO, CO_2, CO and methane, these emissions were absent with the two electric hobs considered.
With regard to ultra-fine particle emissions both the induction and the ceramic hob did not emit measurable amounts of particles when heating pots with water. For comparison the gas hob heating pots with water with 100% natural gas had an emission coefficient of 785 x 10^4 particles/J. This is of the same order as for the gas hobs with naked flame, were the emission coefficient for ultra-fine particles ranged between 144 and 1136 x 10^4 particles/J.

Contents

1. Introduction

The EU is currently updating the Ecodesign legislation with regard to cooking appliances. It concerns Ecodesign Regulation EC No 66/2014 on domestic ovens, hobs and range hoods and the Energy Label Regulation EC No 65/2014 on domestic ovens and range hoods. In parallel, the United Kingdom (UK) government is conducting a review of these same two regulations, as they are still applicable under UK law. These regulatory reviews present an opportunity to include requirements in both the EU and UK law that require that domestic appliances do not expose users to harmful levels of indoor air pollution. To support these regulatory reviews, evidence concerning the health impacts of gas cooking appliances was compiled in this report.

The overall study of the health impacts of gas cooking appliances consists of two phases. Among other work, the first phase consists of a literature and a simulation study in which air pollution in the home and solutions will be studied. The first phase also contains an experimental study in which the effect of hydrogen (H_2) gas mixes on gas hob emissions will be explored.
In the second phase, a field-measurement study will be conducted in a number of relevant EU countries to validate the simulation study and to show the current situation with regard to indoor air quality and gas hob usage. This report concerns results and findings for the experimental study in phase 1.

The main research questions to be answered in this study are:

– *What is the methane leakage during and in between use of gas hobs?*

– *What is the effect of adding hydrogen (H_2) gas to natural gas on gas hob emissions?*

– *What is the difference with regard to emissions between boiling water on a natural gas hob or with an electric hob?*

2. Approach

2.1 Experimental conditions

The following burning fuel mixtures have been tested on gas appliances:
1) Natural gas – 100%
2) Natural gas – 90% Hydrogen 10%
3) Natural gas – 80% Hydrogen 20%
4) Natural gas – 70% Hydrogen 30%
5) Natural gas – 60% Hydrogen 40%

The following air pollutants in the exhaust are measured:
- Nitrogen dioxide (NO_2) and nitrogen oxide (NO)
- Carbon monoxide (CO)
- Carbon dioxide (CO_2)
- Ultra-fine particles (UFP)
- Methane (CH_4)

All gaseous emissions are reported in ng/J. Ultra-fine particles are reported in #particles/J. Corrections for background concentrations are made.

2.2 Experimental setup

All emission experiments were executed in the TNO Indoor Air Quality (IAQ) Lab, see Figure 1. The volume of this lab is 46 m^3, dimensions are 4.24 x 4.21 x 2.60 m.

Figure 1 Overview of the experimental setup in TNO IAQ laboratory. On the right the red H_2 bottle is visible. Natural gas was supplied from the gas net.

The gas hobs were placed below a hood. To ensure that all exhaust gases are directly captured an aluminium enclosure was setup (See Figure 1). The volume of this enclosure is about 0.5 m^3. Directly after this volume sampling was performed with two sampling lines, a silicon line for the gases and a metal duct for the particles. The velocity in the metal sampling line was 1,5 m/s and the velocity in the air exhaust duct was 1,3 m/s. This can be considered nearly isokinetic.
In all experiments the exhaust flow was maintained at 200 m^3/h with an fan placed outside the measurement room. The flowrate was measured with an orifice and temperature corrected. The air going into the IAQ room was filtered with F9 particle filters. No gas filters were applied.

Table 1 lists the measurement equipment. The combination of the TSI 3080 electrostatic classifier and the 3775 Condensation Particle Counter constitute a Scanning Mobility Particle Sizer.

Table 1 Overview of measurement equipment

NO and NO_2	Thermo 42i Chemiluminiscence analyzer
CH_4, CO_2, CO	Picarro G2401
Ultra-fine particles	TSI 3080 Electrostatic classifier TSI 3775 Condensation Particle Counter
Mass flow controllers	2 x Bronkhorst F-201EV-AAD-22-V, 10 l/min @ 1 bar 1 x Bronkhorst F-201C-FAC-33-V, 10 l/min @ 3 bar

Measurement interval for the Picarro was about 5 seconds and the measurement interval for the Thermo 42i was 10 seconds. The SMPS scanned particle numbers between 5.9 and 150 nm, each scan lasting 3 minutes. The sample flow rate was 1.5 liter/min.

2.3 Measurement procedure

After connecting the gas hob with the gas network supply possible leakage of connections was checked with soap bubbles. Inside the gas hobs no leakage tests have been carried out.

In the experiments the gas flow was set according to the values in Table 2. The total gas flow for all mixes has been kept constant at 4,5 liter/min. The gas flow was controlled with three parallel mass flow controllers. Two for the natural gas and one for the hydrogen supply. At the start of each experiment all burners were turned fully open and ignited with the electronic system. Note that due to the pressure drop over the mass flow controllers the gas flow was limited to 4,5 liter per minute, which was for all hobs too low to burn all burners at their maximum capacity.
Emission peaks due to ignition or gas flame blowout have been left out of the data analysis. The emission measurements with the gas hob have been executed with a naked gas flame, see also the photos in Appendix 2.

Table 2 Overview of gas flowrates and the combustion heat for each condition.

Condition	**CH_4 flow [l/min]**	**H_2 flow [l/min]**	**Heat of combustion [W]**
100% CH_4	4,5	0	2625
90% CH_4 / 10% H_2	4,05	0,45	2444
80% CH_4 / 20% H_2	3,6	0,9	2262
70% CH_4 / 30% H_2	3,15	1,35	2081
60% CH_4 / 40% H_2	2,7	1,8	1899

Before starting the measurements all gas hobs burners were operated with the 100% natural gas condition during 15 minutes. Directly after this the natural gas and the hydrogen mix conditions were measured. This 'hot' start was to obtain stable emissions and to enable a comparison between the different gas mixes. For this reason all conditions were measured directly after each other per individual gas stove. The first minute of data after changing the gas composition was excluded from the analysis.

The measurement time per condition was 30 minutes. This delivered about 360 measurement points for CH_4/CO_2/CO, about 180 measurement points for NO/NO_2 and 10 measurement points for ultra-fine particles.

All measured concentrations were corrected for background concentrations which were derived from the average concentrations before starting the experiments.

During the measurement the flame characteristics, like changing colour or unstable flame due to H_2 addition were noted.

After the emission measurements the gas hob burners were closed but the appliance was kept on pressure during one hour to determine possible methane leakage. The methane concentration during this hour was compared to the methane concentration after closure of the methane inlet valve.

To simulate the particle emissions of the electric hobs during cooking four pans filled with cold water were put on the hobs. The power settings of the induction hob cooking zones were set according to manufacturer information to achieve the same heating power as for the gas hob with the 100% CH_4 condition. The ceramic hob was connected to a power meter and with a transformer the same heating power as for the gas hob was set. All cooking zones were on position 4 except for one, which was on position 5 out of 6.

2.4 Description of hob characteristics

All hobs, except the induction hob, were purchased new and delivered by CLASP to the TNO lab. All gas hobs were provided with electronic ignition. The orifices in the gas hobs were suited for natural gas and have not been changed. The surface of the induction hob, which was used in earlier research projects, was thoroughly cleaned. Table 3 list the hob characteristics with indicative prices.

Table 3 Description of hob characteristics and indicative consumer price.

Nr.	**Type**	**Burner power [W]**					**Price**
		1	2	3	4	5	[euro]
1	gas hob	1750	1750	1000	3000	-	210
2	gas hob	1700	1700	1000	3000	-	180
3	gas hob	1650	1650	1000	3000	-	140
4	gas hob	1750	1750	1000	3500	-	600
5	gas hob	1700	1700	950	2900	-	120
6	gas hob	1750	1750[1]	1000[1]	3000	3500	400
7	Induction[2]	2000	1400	1400	2300	-	400
8	Ceramic[2]	1500	1000	1000	2000	-	200

[1] *not used during measurements as these burners went out.*

[2] *both 1 phase and 2 phase connection possible.*

3. Results

3.1 Emissions during use

Appendix A shows the raw measurement results with regard to the gaseous emissions. Appendix B shows photos of the hobs in the experimental setup.

The emissions of the 6 gas hobs are listed in table 4 to table 9. The NO emission coefficient is calculated with a molar weight of 30 g/mol. In table 10 the particle number emissions for the two electric hobs are listed. All hydrogen mix emission coefficients did significantly ($p < 0,05$) differ from 100% CH_4 coefficients, except the values printed in bold.

Table 4 Emission coefficients determined for gas hob 1.

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	14.8	27.5	24.9	19.1	15.5
NO [ng/J]	19.3	10.4	10.7	12.1	11.6
CO [ng/J]	27.4	25.8	27.6	29.3	35.1
CO_2 [ng/J]	60248	60271	59945	58305	52763
CH_4 [ng/J]	< 1	< 1	< 1	< 1	< 1
PN [10^4/J]	1136	1100	1092	1182	1433

Table 5 Emission coefficients determined for gas hob 2.

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	15.5	15.6	20.8	23.9	18.3
NO [ng/J]	20.9	18.7	13.8	10.1	11.0
CO [ng/J]	23.6	25.3	31.5	38.6	42.4
CO_2 [ng/J]	64253	62301	58786	55895	52978
CH_4 [ng/J]	7.2	21.1	13.2	9.9	6.8
PN [10^4/J]	395	319	228	195	290

Table 6 Emission coefficients determined for gas hob 3.

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	16.8	16.5	15.9	15.0	14.1
NO [ng/J]	20.1	18.3	16.5	14.1	11.7
CO [ng/J]	38.2	40.2	43.7	47.4	53.6
CO_2 [ng/J]	62589	61999	59131	55775	52096
CH_4 [ng/J]	3,6	4,0	8,9	10,0	10,6
PN [10^4/J]	144	**149**	127	127	105

Table 7 Emission coefficients determined for gas hob 4.

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	23.3	22.6	20.3	18.9	22.1
NO [ng/J]	14.1	12.3	10.4	8.3	11.6
CO [ng/J]	104	107	114	124	72
CO_2 [ng/J]	66853	64679	61242	57203	57137
CH_4 [ng/J]	64	64	70	65	48
PN [10^4/J]	386	324	229	187	15

Table 8 Emission coefficients determined for gas hob 5,

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	16.7	15.4	14.2	14.2	19.6
NO [ng/J]	19.8	17.6	15.9	13.6	9.6
CO [ng/J]	31	35	34	43	270
CO_2 [ng/J]	67905	65643	61928	58981	53841
CH_4 [ng/J]	43	24	12	12	37
PN [10^4/J]	785	509	468	406	1791

Table 9 Emission coefficients determined for gas hob 6.

	100% CH_4	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
NO_2 [ng/J]	20.9	20.2	18.9	17.8	16.2
NO [ng/J]	16.1	14.8	13.2	11.7	10.0
CO [ng/J]	80	85	98	109	121
CO_2 [ng/J]	64335	65274	62767	61300	57262
CH_4 [ng/J]	90	98	105	113	120
PN [10^4/J]	790	**860**	708	603	480

Table 10 Emission coefficients determined for hob 7 (induction unit) and hob 8 (ceramic) compared with gas hob 5 fed with 100% natural gas.

	concentration [#/cm^3]	**PN [10^4/J]**	**Median diameter [nm]**
Hob 5	0.4 x 10^6	785	9,6
Hob 5 – 4 pots with water	0.2 x 10^6	374	8.9
Hob 7 – 4 pots with water	-32	-0.07	-
Hob 8 – 4 pots with water	-225	-0.51	-
Hob 8 – no water	6.7 x 10^6	15252	33

During the heating of the water with the induction hob (hob 7) and the ceramic hob (hob 8) a decrease in particle number has been observed. The particle number emission due to hob 7 and 8 was slightly negative after the correction for the background concentration.

Figure 10 in Appendix A shows that the gaseous emissions of hob 5 during boiling 4 pots of water are identical compared to a naked flame.
Figure 2 and Figure 3 show the particle number distributions for simulated cooking on gas with gas hob 5 with naked flame and with 4 pots of water.

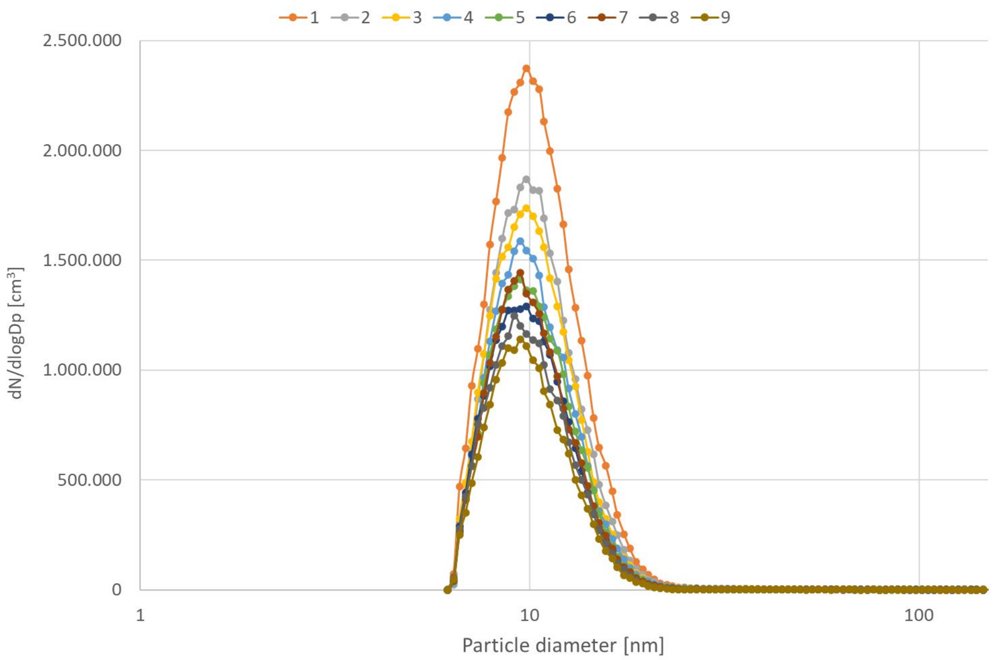

Figure 2 Particle size distribution during 9 scans, gas hob 5, 100% CH_4, naked flame.

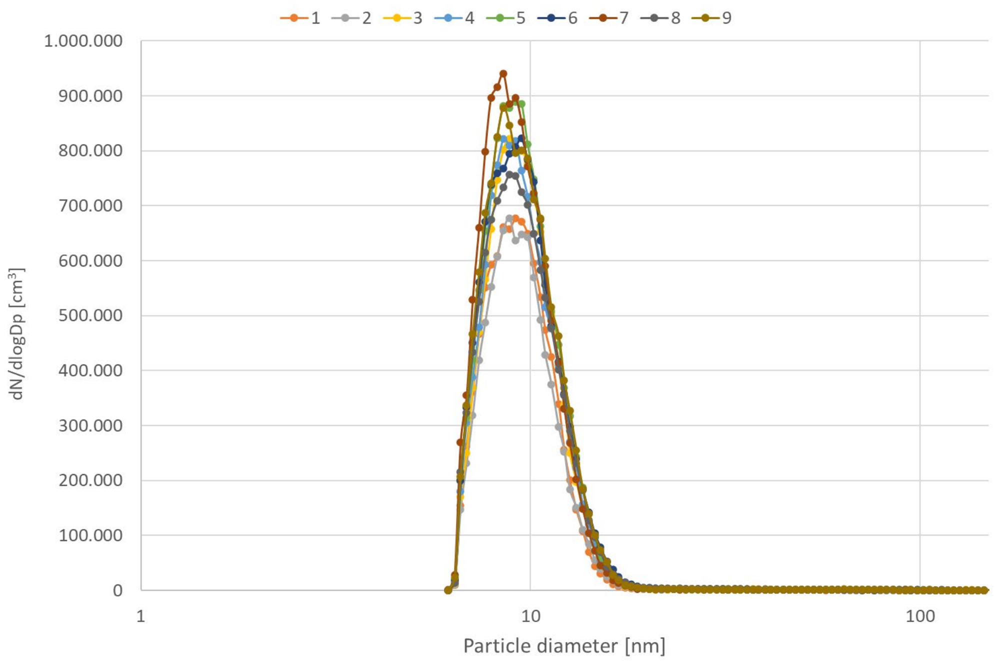

Figure 3 Particle size distribution during 9 scans, gas hob 5, 100% CH_4, 4 pots of water.

Figure 4 shows the particle size distribution during two SMPS scans for the electric resistance hob 8 without any pots of water on it. The difference between the scan might be explained by further heating up of the hob surface.

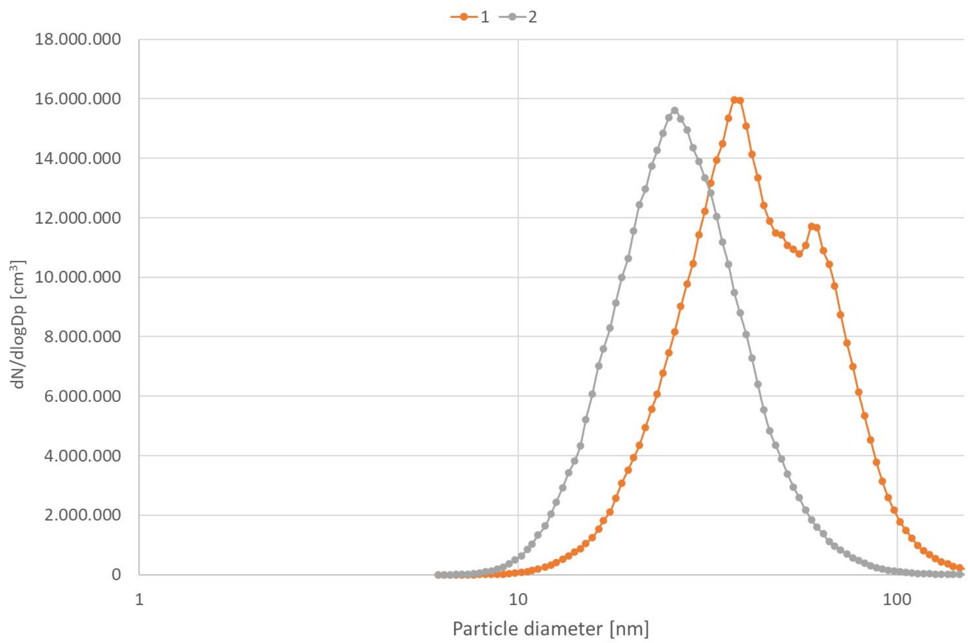

Figure 4 Particle size distribution during 2 scans, electric hob 8, 2400W, without pots of water.

Typically for each fuel mix 10 SMPS scans were made. Table 11 lists the average median measured particle diameters for each fuel mix for the 6 gas hobs. For each gas hob, all mentioned average particle diameters for the fuel mixes did significantly differ ($p<0.05$) from 100% CH_4 condition.

Table 11 Average median particle diameter in nm determined by SMPS.

Gas hob Nr.	**100% CH_4**	**90% CH_4 10% H_2**	**80% CH_4 20% H_2**	**70% CH_4 30% H_2**	**60% CH_4 40% H_2**
1	9.8	8.8	8.5	8.5	8.5
2	8,8	8.4	8.1	7.9	7.9
3	8.1	8.0	7.8	7.6	7.6
4	9.0	8.6	8.3	8.0	7.1
5	9.6	9.0	8.6	8.2	10.2
6	9.1	8.9	8.5	8.2	7.8

3.2 Flame colour and other observations

Table 12 lists the flame colour and flame stability of the 6 gas hobs. Pictures of the hobs during the 100% natural gas and the 60% natural gas and 40% hydrogen burning conditions are listed in Appendix B. Note that the maximum gas flow for all gas hobs was limited to 4,5 liter/min due to the pressure drop over the mass flow controllers.

Table 12 Flame colour and flame stability.

Hob nr.	Flame colour	Flame stability
1	≥ 20% H_2 light orange flames	
2	≥ 40% H_2 light orange flames	
3	≥ 40% H_2 light orange flames	
4	Normal blue colour	@ 40% H_2 front burners went out[1]
5	≥ 20% H_2 light orange flames	Weak flames
6	Normal blue colour	2 front burners went out[2]

[1] measurement with 40% hydrogen was repeated with only the two left burners on.
[2] all five burning fuel mixes executed with the 3 burners on the back.

3.3 Methane leakage in between use

Table 13 lists the estimates for methane leakage when the stove is off. The average value is 56 mg/h. The uncertainty of these values is quite high as the ambient CH_4 can change during the measurements. In case of hob nr. 1 no difference could be observed between the situation with the methane valve open or closed. For the other hobs a more clear distinction could be made, see for example Annex 1 for hob nr. 3.

Table 13 Estimates for methane leakage of gas hobs in between use.

Hob nr.	Leakage [mg/h]
1	Not detectable
2	8
3	78
4	44
5	75
6	130

4. Discussion research questions

4.1 What is the methane leakage during and in between use of gas hobs?

During use, the average methane emission of the 6 gas hobs was 35 ng/J, this correspondents with 331 mg/h. This coincides reasonable with the average value of 259 mg/h measured by Lebel[2] for 53 gas hobs.

The average leakage of the six gas hobs when the hobs were off, was 56 mg/h. This value coincides well with the average value of 58 measured by Lebel[2].

In a follow up study in California, Lebel[3] analysed the composition of natural gas in California. Combining the composition with the natural gas leakage from stoves and ovens while not in use, can result in indoor benzene concentrations that can according to Lebel[3] exceed the California Office of Environmental Health Hazard Assessment 8-h Reference Exposure Level of 0.94 ppbv (3 μg/m^3).
In Europe, gas originating from the North sea may contain a relative high benzene concentration up to 0.35 %mass[4]. Assuming ventilation in the kitchen according to the Dutch Building Decree (75 m^3/h) leakage of this gas from a gas hob may lead to an equilibrium benzene concentration in the kitchen of 2.6 μg/m^3. This concentration is higher than the WHO guideline[5] of 1.7 μg/m^3 derived from a lifetime risk of leukaemia above 1/100 000. And it is near the EU directive 2008/50/EC[6] on Ambient air quality Limit Value of 5 μg/m^3.

4.2 What is the effect of adding hydrogen (H2) gas to natural gas on gas hob emissions?

There is no clear trend with regard to the effect of H_2 addition and the emissions of the gas hobs. The only clear trend is that the CO_2 emission coefficient is reduced with increased H_2 content.

For each hob the addition of hydrogen significantly reduced the median particle size. There was one exception. In case of Gas hob 5 the median diameter was reduced with increasing hydrogen content up to 30%, but at 40% the median particle diameter was increased to 10.2 nm. This particle diameter increase was also accompanied with a more than fourfold increase in particle number emission compared to the 30% hydrogen mix.

The flame colour and stability might be an indicator for increased emissions. In case the flame remains blue (hob 4 and 6) with increasing H_2 content the particle number emissions become lower.

For gas hob 1 and 5 orange flames do already occur from hydrogen concentrations of 20% and larger. In particular for hob 5 the ultra-fine particle emission and the CO emissions do strongly increase with high hydrogen content. The NO_2 emission is only slightly increased. The increased CO and ultra-fine particles emissions might also correlate with the observation that the flames were weak.

Comparison gas hob emissions 100% natural gas with literature data

The NO_2 emissions reported here for burning natural gas, between 14,8 and 23,9 ng/J, are higher than reported in literature by Singer[7] (5 – 18 ng/J) and Lebel[2] on average 7,8 ng/J. This may be explained by two factors:

1 In our experiments we used an ‘hot’ start for more accurately determining emission coefficients. Thus we analysed the measurement data after a 15 minutes heating period. During the pre-heating it was clearly visible that the NO_2 concentration was rising. Only after about 15 minutes a stationary level was reached, most probably because only then a stable temperature level is reached. Lebel used burning periods of about 6 minutes, therefore the stationary levels were not reached and lower emission factor may have be obtained. Singer[7] has used 15 minutes burns.

2 Singer has fired all burners at highest setting. With regard to Lebel it is not clear which settings have been used. In the experiments reported here the setting was 24% up to 36% of the maximum hob burning power. It might be possible that lower power settings generate more emissions per J. This has also been remarked by Poppendieck[8] with regard to simmering increased formaldehyde emissions.

The median particle diameter measured with the gas hobs fed with the 100% natural gas condition was between 8.1 and 9.8 nm. The smallest median diameter was measured with gas hob 3, which was also the hob with the lowest particle number emission. The median particle diameters are larger than the peak values at 5.3 nm reported by Wallace[9]. This difference may be caused by different pit settings. Wallace used a single pit at maximum setting burning 4.2 l/min. While here 4,5 l/min was burned with 4 or 5 burners, being 24% up to 36% of the maximum hub burning power. Another reason might be that due to the volume of the enclosure coagulation might occur leading to larger particle diameters as reported by Wallace[9]. However this effect will be limited as the residence time in the enclosure was only about 9 seconds. A third reason may be that the CPC used in this study had a minimum particle size detection limit of 5.9 nm while Wallace used a CPC with 2 nm minimum particle size.

Figure 5 compares the emissions from the different gas hobs with each other. The following remarks can be made:

- Four hobs have higher NO than NO_2 emissions, while two hobs have lower NO than NO_2 emissions.
- The CO emissions varies more than a factor four between the different hobs.
- The methane emission varies between not detectable and 90 ng/J.
- The particle number emission of hob 1 is about 8 times higher than of hob 3.
- There is no clear relation between the gaseous emissions and the particle emissions. This has also been observed by Singer[7], see Figure 6.

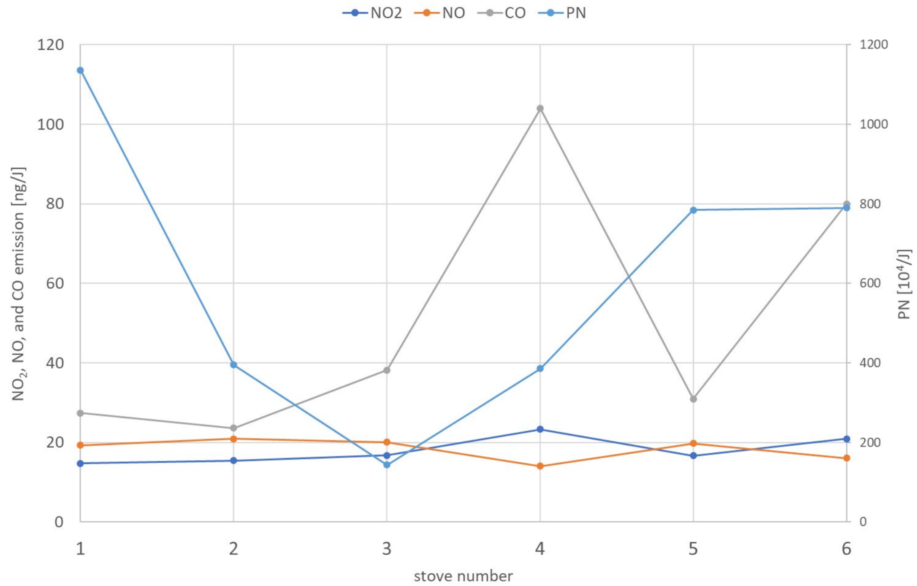

Figure 5 Comparison of NO_2, NO, CO emission and ultra-fine particle of the 6 gas hobs for the 100% natural gas condition.

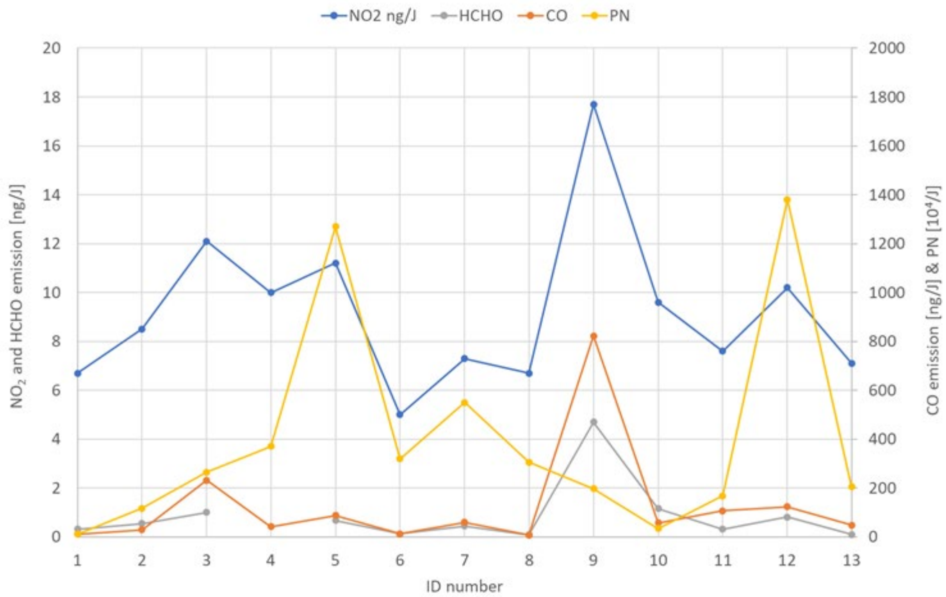

Figure 6 NO_2, NO, CO emission and ultra-fine particle of 13 gas hobs measured by Singer[7].

4.3 What is the difference with regard to emissions between boiling water on a natural gas hob or with an electric hob?

While the gas hobs do emit considerable amounts of NO_2, NO, CO_2, CO and methane these emissions were absent with the two electric hobs considered.

With regard to ultra-fine particle emissions both the induction and the ceramic hob, while heating up four pots filled with water, did not emit measurable amounts of particles. This is in line with Dennekamp[10] who also concluded that ultra-fine particle emissions did not occur when a pot of water was on the rings.

Without pots of water the ceramic hob became very hot and emitted high numbers of particles. The average particle size was 33 nm. This value coincides well with the values of 32 and 37 nm measured by Dennekamp[10].

5. Literature

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6. Signature

Delft, 8 December 2022

TNO

ValidSigned by Ir. ing. M. Steins
on 2022-12-08 16:51:03

ValidSigned by Ir. P. Jacobs
on 2022-12-08 16:57:43

Ir. ing. M. Steins
Research Manager

Ir. P. Jacobs
Author

A Measurement results gases

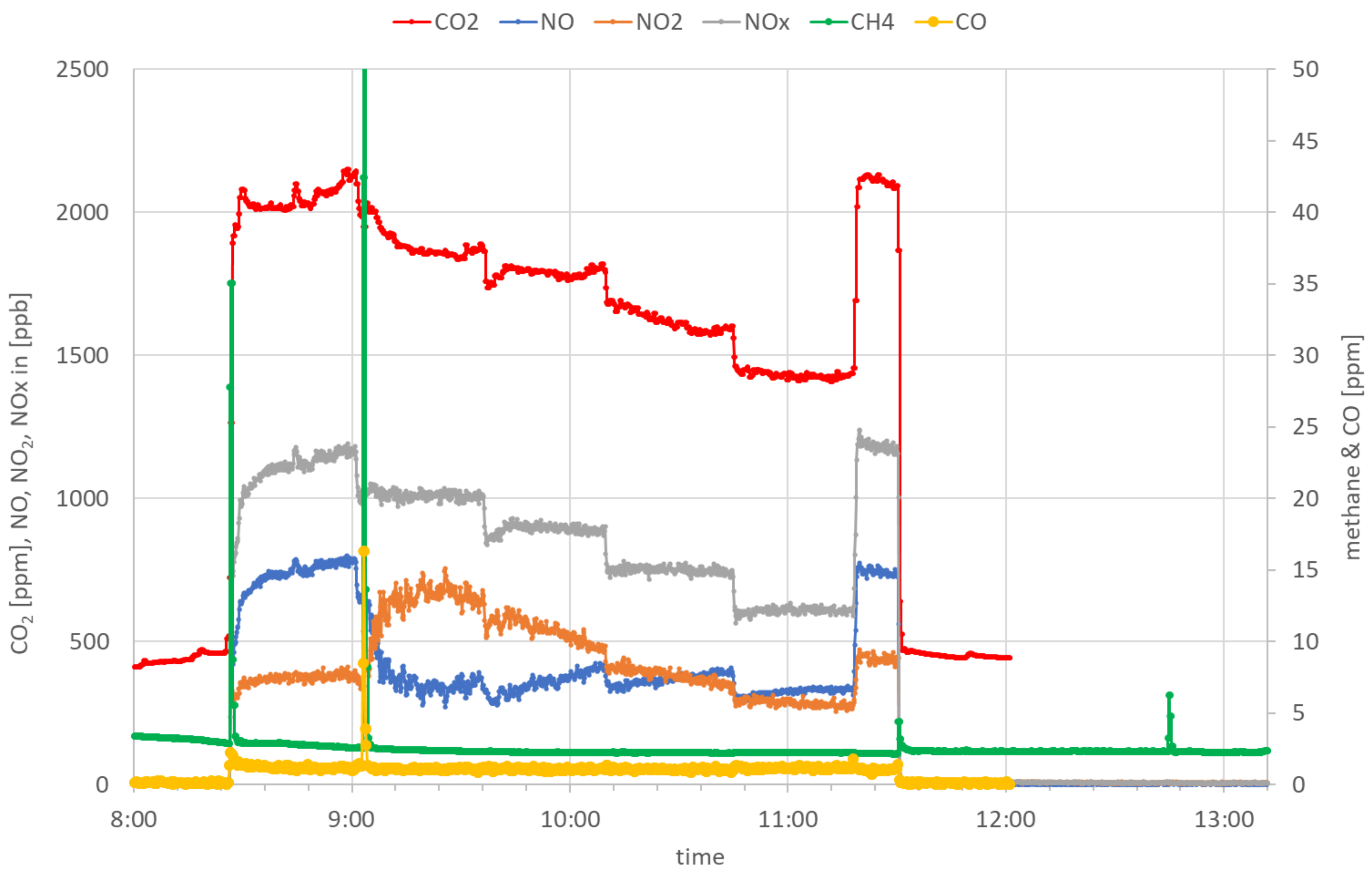

Figure 7 Pollutant concentrations for gas hob 1, at 8.30 hour the gas supply was opened.

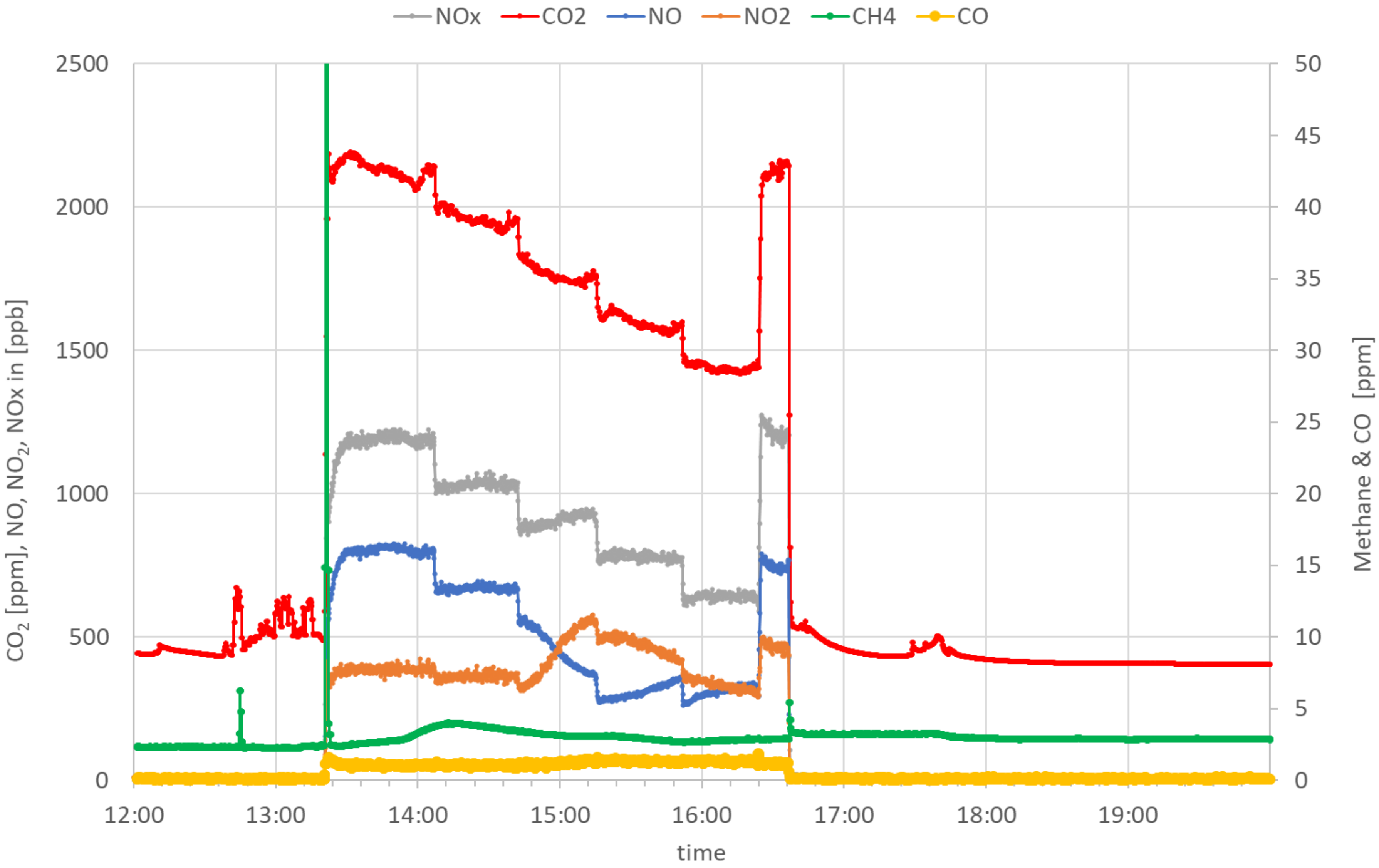

Figure 8 Pollutant concentrations for gas hob 2, at 17.38 h the gas supply was closed.

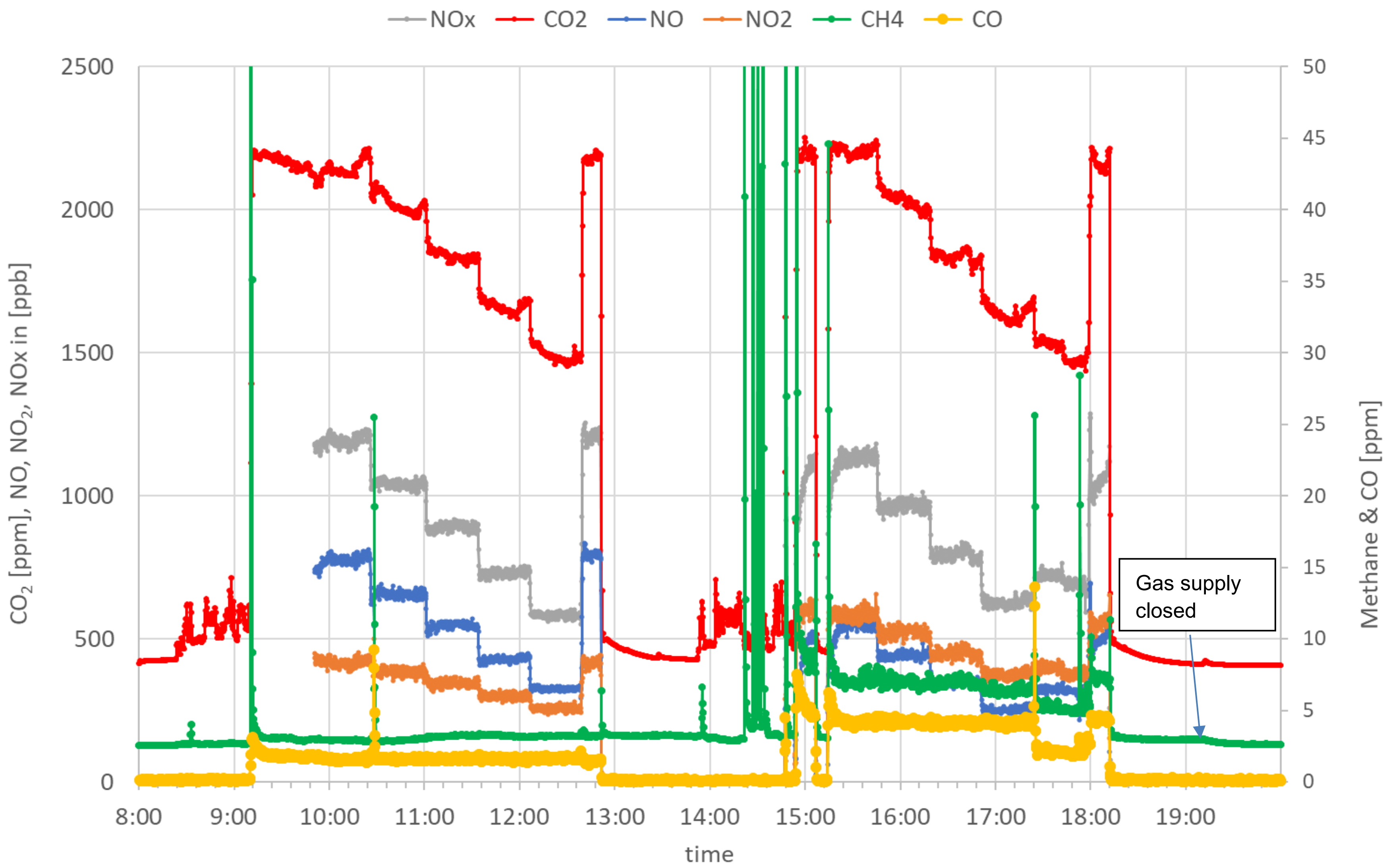

Figure 9 Pollutant concentrations for gas hob 3 (9.54 – 12.38 hour) and gas hob 4 (15.15 – 17.55 hour).

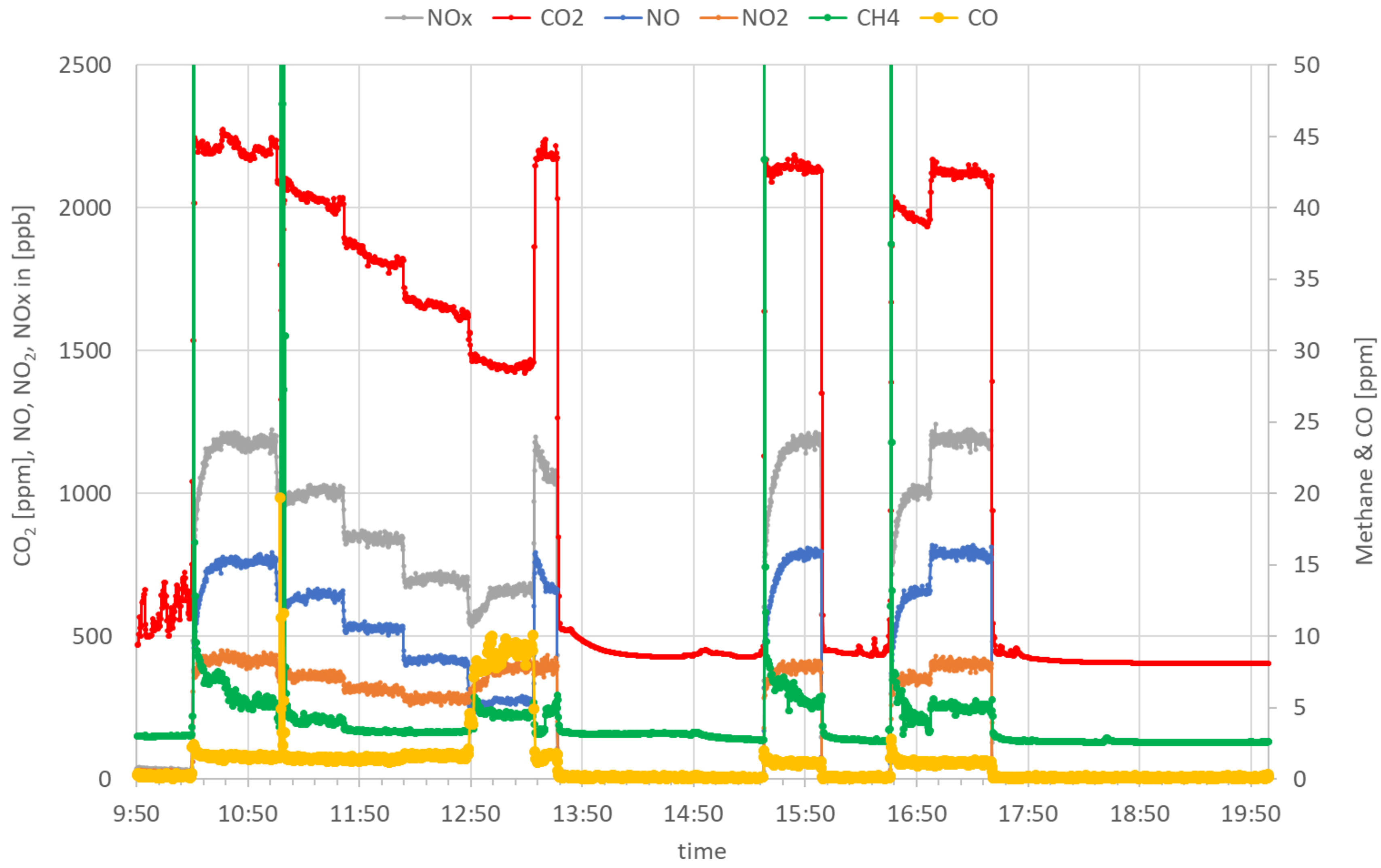

Figure 10 Pollutant concentrations for gas hob 5 naked flame (10.34 – 13.20 hour) and with 4 pots of water (15.29 – 17.30 hour). Gas supply closed at 17.30 hour.

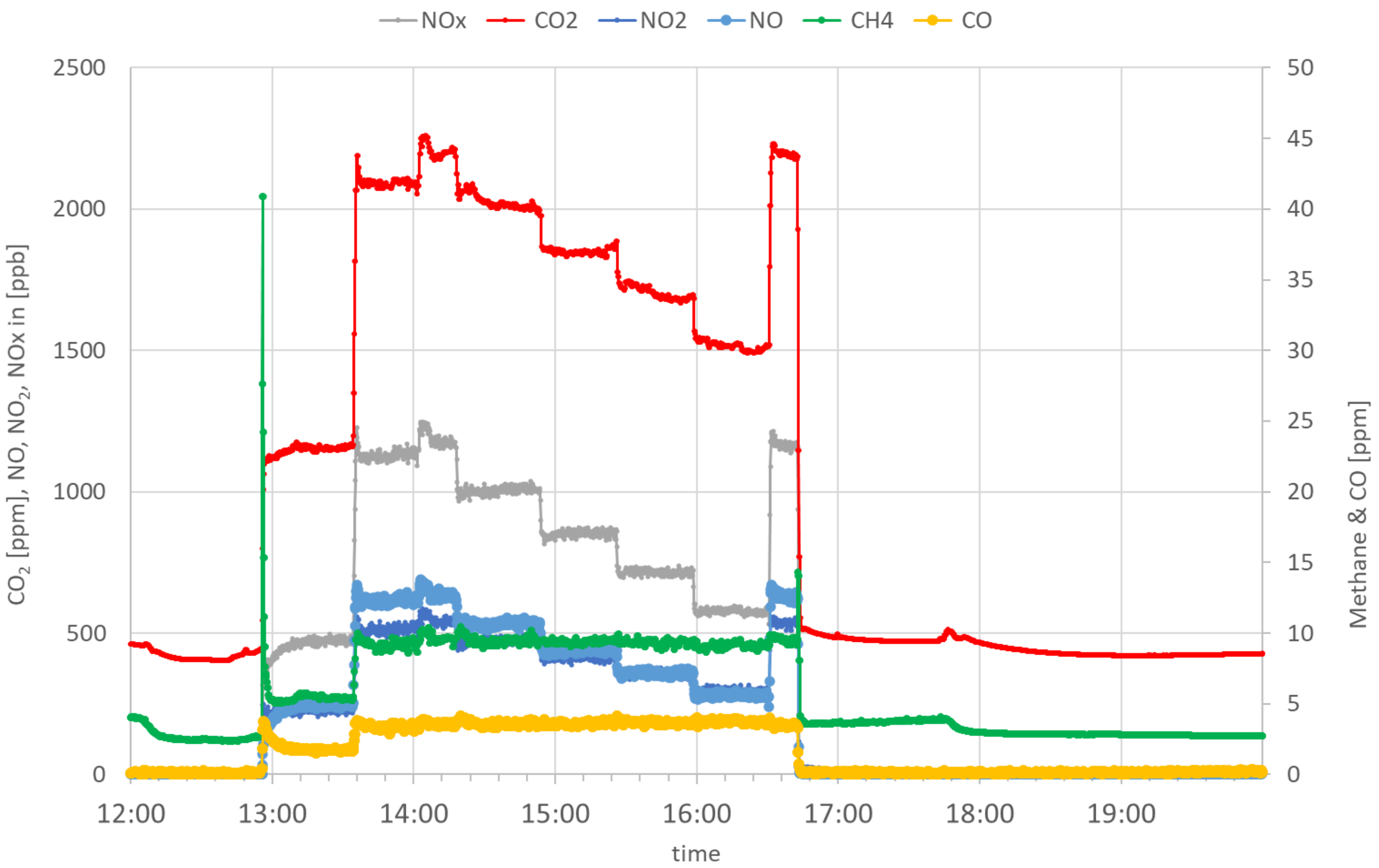

Figure 11 Pollutant concentrations for gas hob 6. Gas supply closed at 17.43 hour.

B Photos of hobs in experimental set up

Figure 12 Gas hob 1, 100% natural gas.

Figure 13 Gas hob 1, 60% natural gas - 40% hydrogen. Right pit on the back orange coloured.

Figure 14 Gas hob 2, 100% natural gas.

Figure 15 Gas hob 2, 60% natural gas - 40% hydrogen.

Figure 16 Gas hob 3, 100% natural gas.

Figure 17 Gas hob 3, 60% natural gas - 40% hydrogen.

Figure 18 Gas hob 4, 100% natural gas.

Figure 19 Gas hob 4, 60% natural gas - 40% hydrogen.

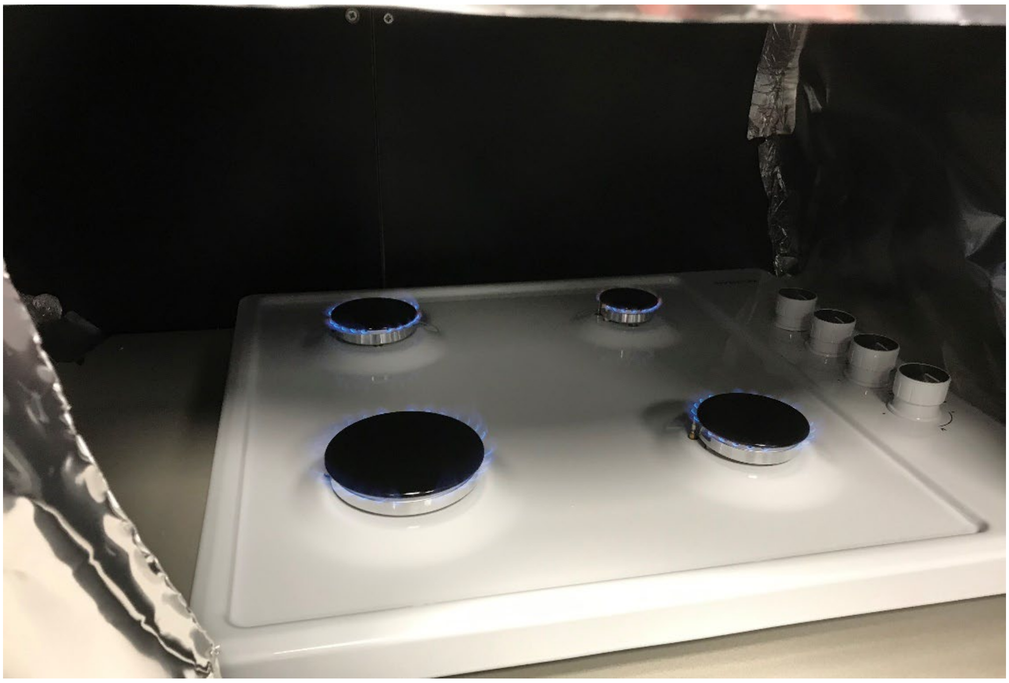

Figure 20 Gas hob 5, 100% natural gas.

Figure 21 Gas hob 5, 70% natural gas - 30% hydrogen. Right front and left back orange flame. Note: of the 60% natural gas - 40% hydrogen is no photo available.

Figure 22 Gas hob 5, with 4 pots of water, 100% natural gas.

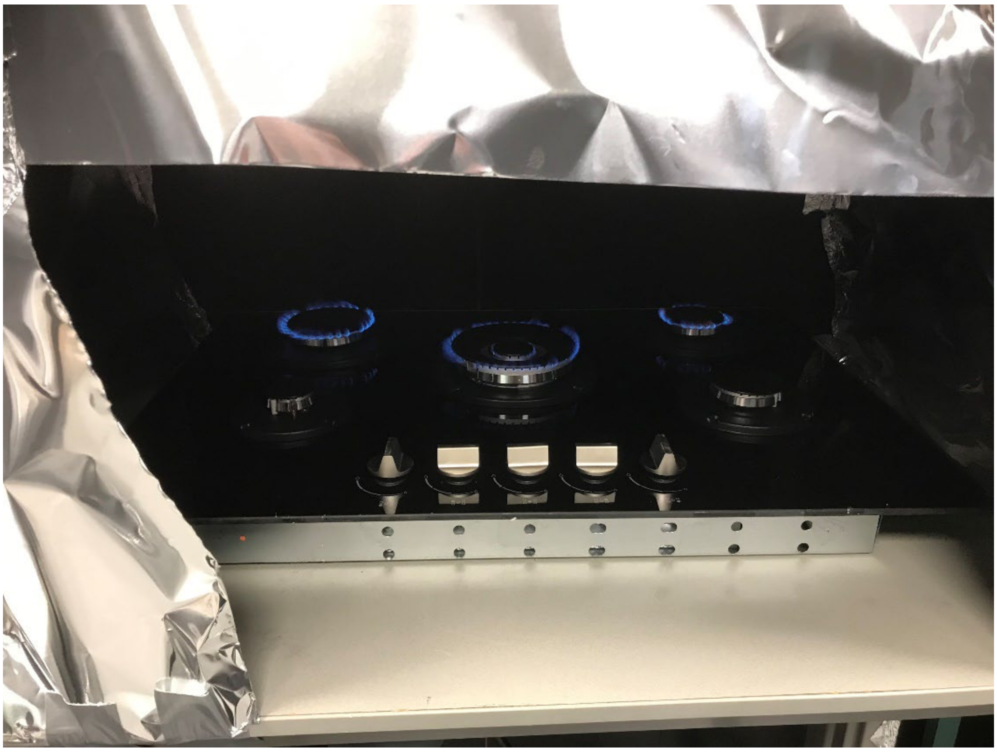

Figure 23 Gas hob 6, 100% natural gas.

Figure 24 Gas hob 6, 60% natural gas - 40% hydrogen.

Figure 25 Induction hob 7 with 4 pots of water.

Figure 26 Ceramic hob 8 with 4 pots of water.