Testing **Hy**drogen admixture for **G**as **A**pplications

Long term effect of H2 on appliances tested

Report by GWI and DGC for the THyGA Consortium

Deliverable:	D3.9
Status:	Final, 10^{th} of May 2023
Dissemination level:	PU - Public

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No 874983. This Joint Undertaking receives support from the European Union's Horizon 2020 Research and Innovation program, Hydrogen Europe and Hydrogen Europe Research.

Document classification

Title	Long term effect of H2 on appliances tested
Deliverable	D3.9
Reporting Period	M1-M39
Validation date	M41

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Work package	WP 3
Dissemination	PU = Public
Nature	Technical Report
Version	Final
Doc ID Code	THY_WP3_59
Keywords	Hydrogen, hydrogen tolerance, blends, H2NG, tests, THyGA, natural gas, appliances, LTT, long term tests

Document History

Partner	Remark	Version	Date
DGC	Draft	1	03/03/2023
GWI	Draft	2	12/01/2023
ENGIE	Review	3	24/03/2023
GWI	Review	4	26/04/2023
DGC	Final	5	10/05/2023

Document Review

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List of abbreviations

daf	Dry, air free
GA	Grant Agreement
GAR	Gas Appliances Regulation
H_2NG	Hydrogen / Natural Gas blend
NG	Natural Gas
LTT	Long term test
WP	Work Package

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Introduction

The goals of the long-term tests were to see the impact of blends of hydrogen and natural gas on the technical condition of the appliances and their performance after several hours of operation. To do so, they were run through an accelerated test program, amounting to more than 3000 testing hours for the boilers and more than 2500 testing hours for the cookers. The percentage of hydrogen in the test gas was 30% by volume. Three boilers and two cookers were tested by DGC and two boilers by GWI.

This report describes the test protocol, the results and analysis on the seven appliances tested. Since there were some minor differences in the experimental settings at the laboratories at DGC and GWI, it has been decided to provide the analyses in 3 separate chapters with common conclusions.

Overall introduction

The work described in this report is part of the overall assessment of the impact of hydrogen on gas appliances. It considers the assessment of the long-term impact of hydrogen on appliances, in complement to the "short term test" (see deliverable D3.8[1]).

Seven appliances were tested for this purpose: five boilers and two cookers.

The **LTT (Long Term Test)** test protocol was derived from a similar project's protocol (GASQUAL[2]) and reshaped for the THYGA project together with the manufacturer partners in the project.

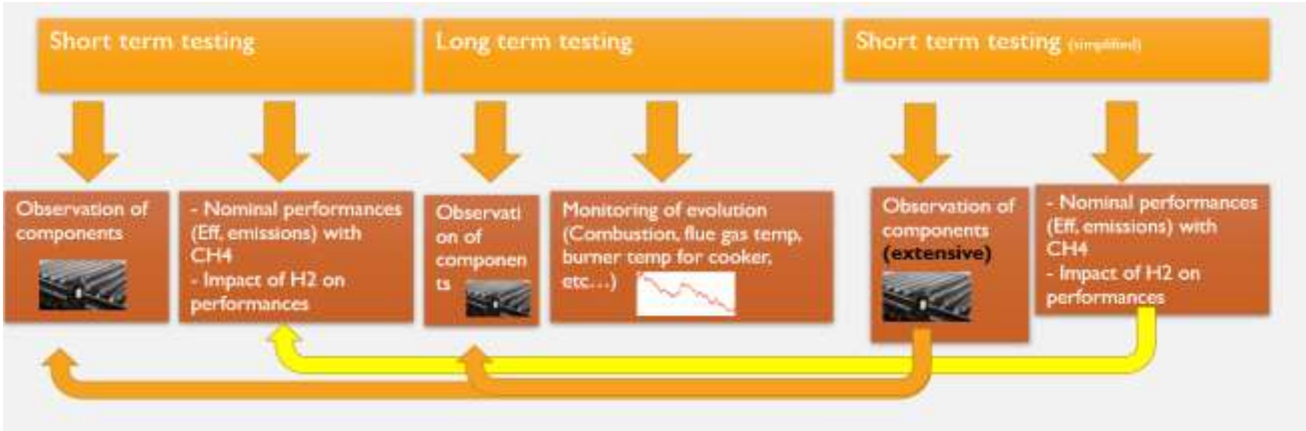


Figure 1: Goals of short- and long-term tests

The appliances tested for the long-term test were also part of the short-term test campaign.

The test consisted in bringing appliances in a situation that was as close as possible to real use situation (with limitations due to testing constrains) and as long as possible period (within the budget allocated). The test included:

- Observation of the appliance including its components before and after the test.
- The monitoring of a possible evolution (continuous measure of combustion parameter).

Figure 1 illustrates the methodology of the exercise. Note that for practical reasons there may be some deviations to the description:

- Components were not necessarily observed before the short-term test as appliances were new).
- The nominal test was not necessarily performed at the end if there was no evolution of the monitored data during while executing the test.

The present LTT report is organized in 3 parts covering three independent campaigns

1. Boiler test at GWI
2. Boiler test at DGC
3. Cooker test at DGC

[1] THyGA report [D3.8) "Segment of technologies by segment report on the impact of the different H2 concentrations on safety, efficiency, emissions and correct operation"

[2] REF /1/ Gasqual D6.1 Standardization in the field of gas qualities. Mandate CE M400. Phase I. Final report. CEN/BT/WG 197

1 GWI test of two boilers

1.1 Design of the Long-Term Tests performed at GWI laboratory within the THyGA project

1.1.1 Test Protocol

The long-term tests of two condensing gas boilers operated with a natural gas / hydrogen blend were designed as follows.

Two 24-hour load profiles were defined to cover the appliance operation on a typical long term test day and on a measurement day, respectively. The standard appliance operation profile is depicted in Figure 2. The appliance is operated using pipeline natural gas (type H) plus 30 vol% of hydrogen all day. For 20 hours per day, it is operated at minimum thermal load Q_{min}. In addition, the appliance is shut off two times and cooled at room temperature for 30 minutes followed by 1 operation hour at maximum thermal load. After that it is shut down for 1 hour followed by a start-up using maximum load for a few minutes and then regulating down to minimum load. This protocol is realised in an automated fashion and repeated every day. Emissions and performance indicators were measured during the operation with 30% H_2 to monitor any sudden changes.

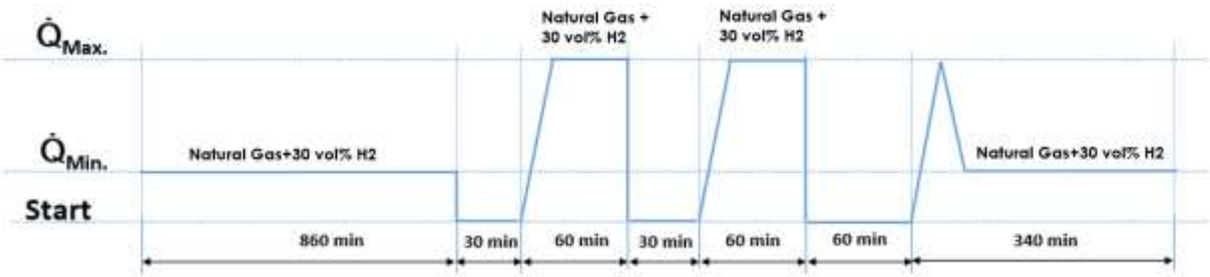


Figure 2: 24-hour load profile applied for long term tests on 6 out of 7 days per week.

The second 24-hour load profile was designed to perform representative and comparable measurements using pure methane as a test gas (G20). This procedure allows to compare the development of measured data over time in order to detect subtle changes which can be compared with the initial new condition of the appliances, tested with the reference gas. Also, the comparability of data from different laboratories is enhanced by crossing out the effect of different natural gas properties in the grids. The corresponding profile is depicted in Figure 3. The diagram indicates at which points in time the gas composition was switched from pipeline gas + 30 vol% H_2 to pure methane. Sufficient time (1h) was granted to allow the appliance to find its dynamical thermal equilibrium at the given boundary conditions, firstly at minimum load and secondly at maximum load. After successful measurements, the gas was switched back to pipeline gas + 30 vol% H_2 and the remaining test program as described for the standard day profile was followed again.

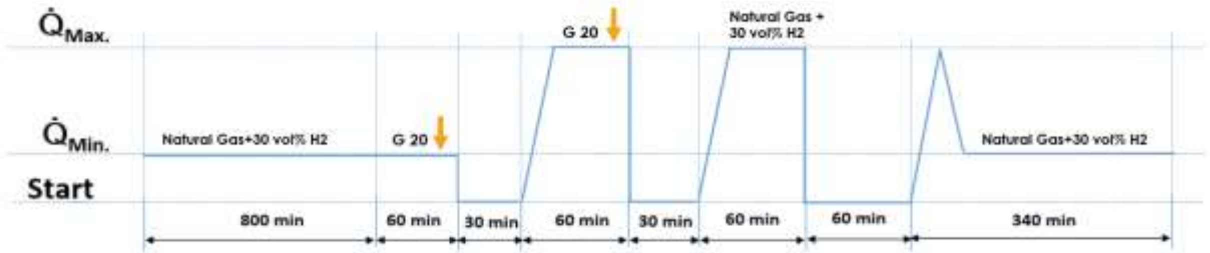


Figure 3: 24-hour load profile applied one day/week to perform reference measurements (yellow arrows) using pure methane (G20)

The temperature spread was chosen to be "60/40", i.e., 60°C outlet water temperature and 40°C inlet water temperature. This temperature spread was maintained whenever the appliances were operated.

For measurements, enough stabilisation time was granted to ensure that the appliance operation reaches a stable state. This is indicated by the yellow arrows in Figure 3,where about half an hour was the minimum waiting time before measurements started. Measurements were taken in a continuous manner once stable state was reached which allowed to measure representative mean values.

The total long term test duration was higher than 3.000 hours of operation time.

1.1.2 Test gases

The long-term tests of the THyGA project were planned with the following test gases. First of all, the standard appliance operation was realised using natural gas H (pipeline gas) with a 30 vol% admixture of hydrogen. At the GWI laboratory, a typical natural gas composition as measured during the long-term tests is given in Table 1. The resulting blend used for the long-term operation of two condensing boilers is given in the right-hand column of Table 1**Error! Reference source not found.**. For comparability between the THyGA labs, pure methane gas (G20) was used for the performance and emission measurements as described above.

Table 1: Test gas compositions for long term tests performed at GWI.

Component			Methane	Natural Gas H	Natural Gas H + 30 vol% H_2
Methane	CH4	vol%	100.0	90.0099	63.0070
Nitrogen	N2	vol%	0	1.0429	0.7300
Carbon dioxide	CO2	vol%	0	1.4789	1.0352
Ethane	C2H6	vol%	0	6.1066	4.2746
Propane	C3H8	vol%	0	1.0194	0.7136
n-Butane	n-C4H10	vol%	0	0.1172	0.0820
2-Methylpropane	i-C4H10	vol%	0	0.1499	0.1050
n-Pentane	n-C5H12	vol%	0	0.0166	0.0116
2-Methylbutane	i-C5H12	vol%	0	0.0263	0.0184
n-Hexane	n-C6H14	vol%	0	0.0322	0.0226
Hydrogen	H2	vol%	0	0.0000	30.00
	sum	**vol%**	**100**	**100**	**100**

Table 2 presents the properties of pure methane (G20) as well as pipeline natural gas H, as taken from the local distribution grid at GWI laboratory. The right-hand column shows the gas properties of the blend used for long term operation.

Table 2: Test Gas properties for long term tests performed at GWI

Gas characteristics following ISO 6976 (2016) Reference Conditions: Combustion: 15°C / Volume: 15°C, p= 1013.25 mbar			Methane	Natural Gas H	Natural Gas H + 30 vol% H_2
Molar mass	M	kg/kmol	16.042	17.904	13.148
Real-gas factor	Z_{15C}	[-]	0.99802	0.99759	0.99901
density	ρ_{15C}	kg/m³	0.67982	0.75902	0.55662
Rel. density	d_{15C}	[-]	0.55472	0.61934	0.45419
GCV (mol)	H_{sm}	KJ/mol	891.51	931.96	738.66
GCV (mass)	H_s	MJ/kg	55.572	52.054	56.180
GCV (vol)	H_{sv}	MJ/m³	37.779	39.510	31.271
GCV (vol)	H_{sv}	kWh/m³	10.494	10.975	8.686
NCV (mol)	H_{im}	KJ/mol	802.65	841.15	661.74
NCV (mass)	H_i	MJ/kg	50.033	46.982	50.329
NCV (vol)	H_{iv}	MJ/m³	34.013	35.660	28.014
NCV (vol)	H_{iv}	kWh/m³	9.448	9.906	7.782
Wobbe index	W_s	MJ/m³	50.724	50.205	46.400
Wobbe index	W_s	kWh/m³	14.090	13.946	12.889
minimum air requirement	Lmin [m_N^3 air/m_N^3 gas]		9.524	10.01	7.71
flue gas (dry, l= 1)	[m_N^3 flue gas/m_N^3 gas]		8.524	9.00	6.89
$CO_{2,max}$	[vol%]		11.732	12.092	11.093

1.1.3 Appliances tested

Appliance 1

Appliance 1 is a full premix condensing boiler. The appliance is capable of modulating, and it is equipped with a combustion control based on ionisation. The latter is based on an air/gas ratio control.

The power input range of the appliance under the gas category I2H is between 4.5 kW and 15.3 kW (net).

The appliance is designed for room-sealed operation (flue type C). In the laboratory, it was operated with 1m pipe length under an air extractor.

The wall hung appliance was manufactured in 2021. It was in new condition before the start of the LTT experiment.

Appliance 2

Appliance 2 is a full premix condensing boiler as well. Its gas-adaptive combustion air control is based on an ionisation current measurement.

The power input range of the appliance under the gas category II2N3P is between 3.9 kW and 19.6 kW (net).

The appliance is designed for room-sealed operation (flue type C). In the laboratory, it was operated with 1m pipe length under an air extractor.

The wall hung appliance was manufactured in 2021. It was in new condition before the start of the LTT experiment.

1.1.4 Data measurement and conversion

During the long-term tests, the following data were measured to describe the boundary conditions: Inlet and outlet water temperatures T_{inlet} and T_{outlet}, mass flow of water m_{water}, flue gas temperature T_{flue}, gas volume V_{gas} (standard volume flow), gas temperature T_{Gas}, gas pressure p_{Gas}, ambient pressure $p_{ambient}$. The emissions were analysed in terms of CO emissions and NOx emissions in ppm (calculated for dry, air free conditions), volume percent of CO_2 in the flue gas and volume percent of O_2 in the flue gas. From the measured values, the thermal output based on the heating of the water (Q_{water}) as well as the power based on the gas consumption (P_{gas}), the efficiency of the boilers (η_{boiler} based on net calorific value, NCV), and the air excess ratio λ were calculated.

The precise composition of the pipeline gas was not measured continuously, therefore P_{gas} was calculated using a representative value for all data points: $P_{Gas} = V_{Gas} \cdot NCV$[2]. The gas volume flow was measured with a bellows gas meter. When converting the operating volume flow V_{gas} to the standard volume flow $V_{15°C,Gas}$, the ambient pressure was determined based on meteorological data published by the German Meteorological Service (DWD) for the location of the Gas- und Wärme-Institut (GWI) in the city of Essen. The thermal output Q_{water} was calculated by multiplying the mass flow of the water with the heat capacity of water $c_{p,m}$ (index m indicates mean value with respect to inlet and outlet temperature) and the temperature spread: $Q_{water} = m_{water} \cdot c_{p,m} \cdot (T_{outlet}-T_{inlet})$.

1.1.5 Deviations from the test protocol and unforeseen events during long term tests

During the long term tests the above presented testing scheme was not changed. Especially the hydrogen admixture level and the operation times per load set point per day as well as the alternation of thermal loads as depicted above were kept constant without exception.

Flexibility for the workflows of the personnel in the laboratory was gained by shifting the day of measurements. The starting point of the fixed test procedure during the measurement days (minute 800 in) was flexibly scheduled to the morning hours or the afternoon to meet organisational demands.

No unforeseen events interfered with the achievement of the testing goals. The appliances operated stable and reliable.

In case of interruption of the long-term tests for external reasons, such as unavailability of the gas mixing station or repairs in the lab, the test cycle was interrupted and restarted at a later point in time.

[2] NCV: Net Calorific Value

1.2 Results part 1: Visual Observations

The appliances were opened before and after testing to document the visual appearance in new condition in comparison with their appearance after long term testing.

As can be seen in Figure 4 and Figure 5, the heat exchanger surfaces show some deposits after the long-term tests. This observation however corresponds well with the experiences from comparable used appliances with natural gas. The same holds true for the visual appearance of the burner surfaces, which are shown in Figure 6 for boiler 2. Minor deposits and discolouration of material are fully in line with expectations in view of the long operation times of the appliances. These findings were accordingly confirmed with the manufacturers.

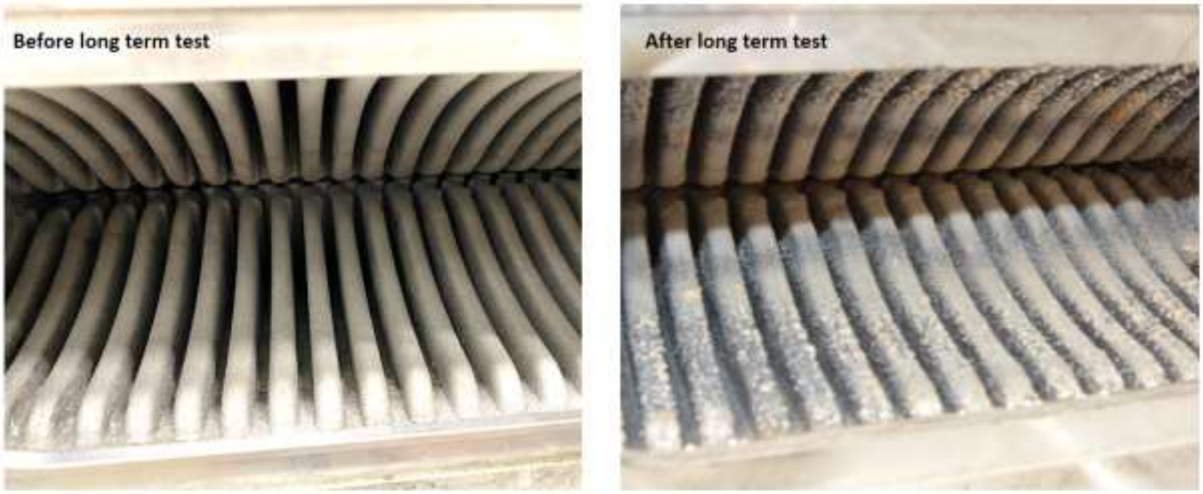


Figure 4: Boiler 1 - Photographs of the heat exchanger before and after long term tests. The observed deposits correspond to typical natural gas operation.

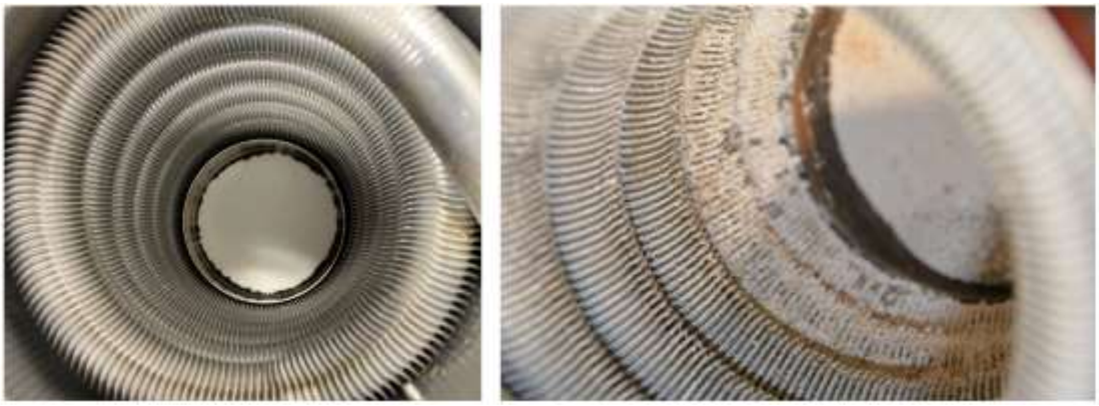


Figure 5: Boiler 2 – Heat exchanger before (left) and after (right) long term test. The observed deposits correspond to typical natural gas operation.

Figure 6: Boiler 2 – Burner before (left) and after (right) long term test

1.3 Results part 2: Measurement Data

1.3.1 Condensing Boiler 1

The data of the weekly measurements are given in Table 3 for minimum load and in Table 4**Error! Reference source not found.** for the maximum load operation.

Table 3: Results for boiler 1 at minimum load. Yellow marked data are calculated from the measurement data.

LONG TERM TEST RESULTS – BOILER 1 @ Q_{MIN} (G 20)

	T_{outlet}	T_{inlet}	m_{water}	T_{flue}	$V_{15°C,gas}$	Q_{water}	P_{Gas}	η_{boiler}	CO_{dry} @ 0 vol% O_2	$NO_{x,dry}$ @ 0 vol% O_2	$CO_{2\ flue}$	$O_{2\ flue}$	Air excess ratio λ	T_{Gas}	p_{Gas}	$p_{ambient}$
	°C	°C	kg/min	°C	m³/h	kW	kW	%	ppm	ppm	vol%	vol%	[-]	°C	mbar	mbar
24.02.2022	60.44	40.89	4.51	49.0	0.648	6.17	6.13	100.6	22.0	21.5	9.20	4.40	1.24	22.3	20.7	1012
03.03.2022	60.45	40.91	4.51	49.0	0.641	6.17	6.06	101.8	20.3	23.8	9.20	4.26	1.23	22.5	20.7	1019
10.03.2022	60.55	40.79	4.51	49.3	0.651	6.23	6.15	101.4	24.5	26.8	9.42	4.30	1.23	20.7	20.6	1023
17.03.2022	60.50	40.80	4.51	49.5	0.644	6.22	6.08	102.2	27.1	30.9	9.20	4.42	1.24	20.4	20.7	1029
24.03.2022	60.62	40.66	4.51	48.1	0.646	6.29	6.10	103.1	22.9	29.6	9.38	4.22	1.23	18.7	20.7	1026
31.03.2022	60.52	40.67	4.51	49.3	0.654	6.26	6.18	101.4	23.6	26.9	9.36	4.16	1.22	19.7	20.7	999
07.04.2022	60.40	40.83	4.51	49.5	0.633	6.17	5.98	103.2	25.9	23.9	9.17	4.31	1.23	21.7	20.6	989
15.04.2022	60.46	40.74	4.51	49.4	0.645	6.22	6.09	102.1	22.6	23.6	9.32	4.18	1.22	20.2	20.6	1027
21.04.2022	60.48	40.75	4.51	49.5	0.648	6.23	6.12	101.7	21.8	23.9	9.28	4.30	1.23	20.8	20.7	1011
05.05.2022	60.47	40.75	4.51	49.5	0.644	6.22	6.08	102.3	22.1	24.7	9.32	4.23	1.23	20.5	20.7	1022
12.05.2022	60.40	40.78	4.51	49.5	0.651	6.20	6.15	100.7	22.7	24.4	9.38	4.17	1.22	21.7	20.7	1018
19.05.2022	60.20	40.87	4.51	49.6	0.634	6.10	5.99	101.8	22.1	25.1	9.39	4.07	1.22	26.4	20.7	1018
26.05.2022	60.35	40.75	4.51	49.6	0.641	6.18	6.05	102.1	23.0	23.2	9.37	4.26	1.23	25.8	20.6	1021
02.06.2022	60.49	40.73	4.51	49.5	0.653	6.23	6.17	101.1	20.5	24.3	9.22	4.45	1.24	21.3	20.8	1020
09.06.2022	60.38	40.77	4.51	49.7	0.642	6.19	6.07	102.0	18.8	19.8	9.31	4.38	1.24	21.8	20.8	1015
23.06.2022	60.18	40.89	4.51	49.9	0.626	6.08	5.91	102.8	21.6	22.4	9.42	4.14	1.22	27.5	20.7	1010
30.06.2022	60.54	40.92	4.51	50.1	0.633	6.19	5.98	103.5	22.4	21.4	9.37	4.26	1.23	27.0	20.7	1011

Table 4: Results for boiler 1 at maximum load. Yellow marked data are calculated from the measurement data.

LONG TERM TEST RESULTS – BOILER 1 @ Q_{MAX} (G 20)

	T_{outlet}	T_{inlet}	m_{water}	T_{flue}	$V_{15°C,Gas}$	Q_{water}	P_{Gas}	η_{boiler}	CO_{dry} @ 0 vol% O_2	$NO_{x,dry}$ @ 0 vol% O_2	$CO_{2\ flue}$	$O_{2\ flue}$	Air excess ratio λ	T_{Gas}	P_{Gas}	$P_{ambient}$
	°C	°C	kg/min	°C	m³/h	kW	kW	%	ppm	ppm	vol%	vol%	[-]	°C	mbar	mbar
24.02.2022	60.49	40.84	9.58	50.6	1.383	13.31	13.07	101.8	41.2	28.5	9.20	4.90	1.27	22.4	20.4	1012
03.03.2022	60.55	40.74	9.67	50.0	1.388	13.40	13.09	102.3	38.5	32.4	9.10	4.80	1.28	20.3	20.4	1019
10.03.2022	60.60	40.72	9.68	50.3	1.379	13.44	13.03	103.1	37.0	31.7	9.31	4.60	1.25	20.3	20.3	1023
17.03.2022	60.52	40.76	9.66	51.0	1.388	13.35	13.11	101.8	40.8	37.8	9.10	4.50	1.24	20.7	20.4	1029
24.03.2022	60.36	40.51	9.49	50.5	1.369	13.18	12.93	101.9	41.9	35.8	9.17	4.39	1.24	20.0	20.7	1026
31.03.2022	60.63	40.65	9.66	50.5	1.400	13.50	13.23	102.1	43.7	32.8	9.24	4.30	1.23	19.8	20.3	1028
07.04.2022	60.51	40.73	9.66	50.6	1.373	13.37	12.97	103.0	38.0	29.1	8.88	4.32	1.23	21.1	20.3	998
15.04.2022	60.49	40.70	9.64	50.6	1.395	13.35	13.18	101.3	41.9	29.8	9.20	4.39	1.24	20.4	20.2	1031
21.04.2022	60.52	40.69	9.64	50.8	1.368	13.37	12.91	103.6	41.3	31.5	9.32	4.21	1.23	20.9	20.4	1006
05.05.2022	60.48	40.59	9.65	50.4	1.379	13.36	13.03	102.5	41.4	24.9	9.22	4.38	1.24	21.0	20.2	1022
12.05.2022	60.41	40.68	9.64	50.6	1.363	13.30	12.88	103.3	40.7	31.4	9.27	4.34	1.23	22.8	20.3	1018
19.05.2022	60.23	40.77	9.62	51.1	1.352	13.10	12.77	102.5	40.2	30.8	9.20	4.30	1.23	25.2	20.4	1021
25.05.2022	60.44	40.63	9.64	51.20	1.367	13.38	12.92	103.4	40.7	30.45	9.25	4.45	1.24	25.8	20.6	1021
02.06.2022	60.75	40.57	9.61	50.80	1.405	13.57	13.27	102.2	39.2	30.1	9.28	4.41	1.24	20.3	20.4	1020
09.06.2022	60.52	40.65	9.63	51.40	1.381	13.38	13.05	102.6	40.0	29.6	9.31	4.36	1.23	22.2	20.4	1015
23.06.2022	60.27	40.52	9.66	52.50	1.372	13.35	12.96	103.0	38.5	28.6	9.24	4.38	1.24	28.5	20.4	1010
30.06.2022	60.38	40.88	9.65	51.00	1.355	13.16	12.80	102.8	37.8	27.2	9.22	4.42	1.24	27.6	20.4	1011

The same data for minimum load are plotted over time in Figure 7 and Figure 8.

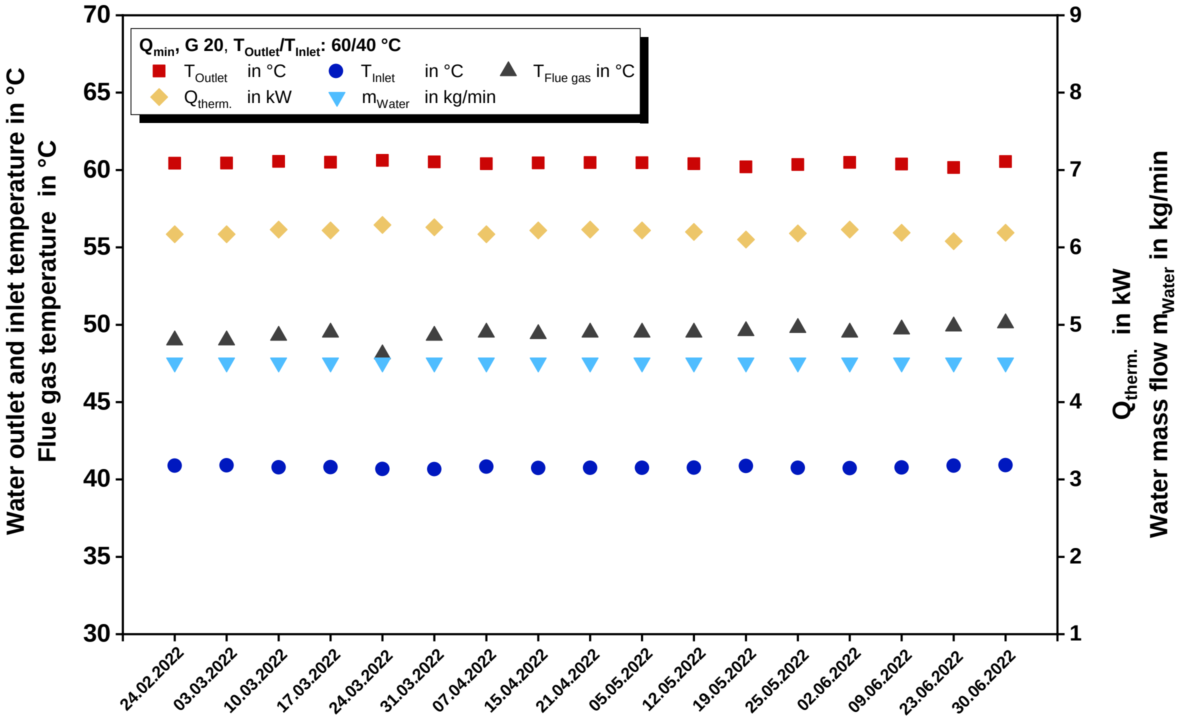


Figure 7: Long term test results for condensing boiler 1 operated at minimum load with pure methane (G20): Outlet, inlet and flue gas temperatures, thermal load and water mass flow.

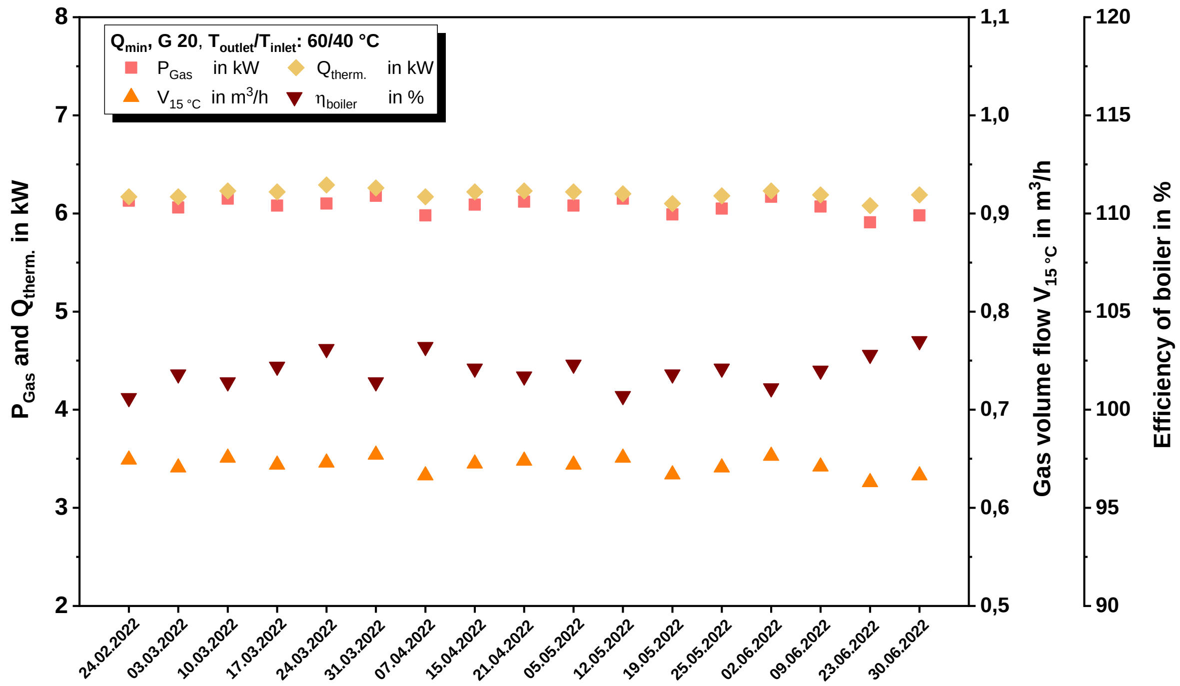


Figure 8: Long term test results for condensing boiler 1 operated at minimum load with pure methane (G20): Output power based on gas consumption P¬Gas (based on NCV), thermal load Qtherm, gas volume flow V15°C, and boiler efficiency ηboiler (NCV).

For maximum load, the data points are presented as a function of time in Figure 9 and Figure 10.

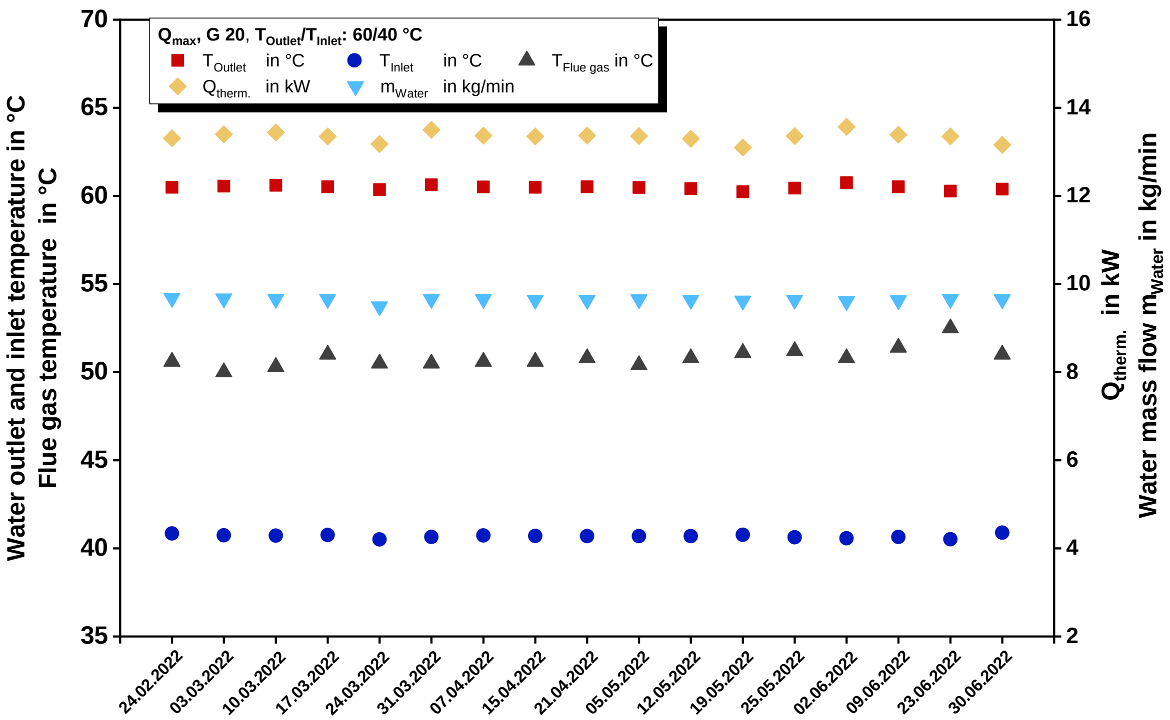


Figure 9: Long term test results for condensing boiler 1 operated at maximum load with pure methane (G20): Outlet, inlet and flue gas temperatures, thermal load and water mass flow., thermal load and water mass flow.

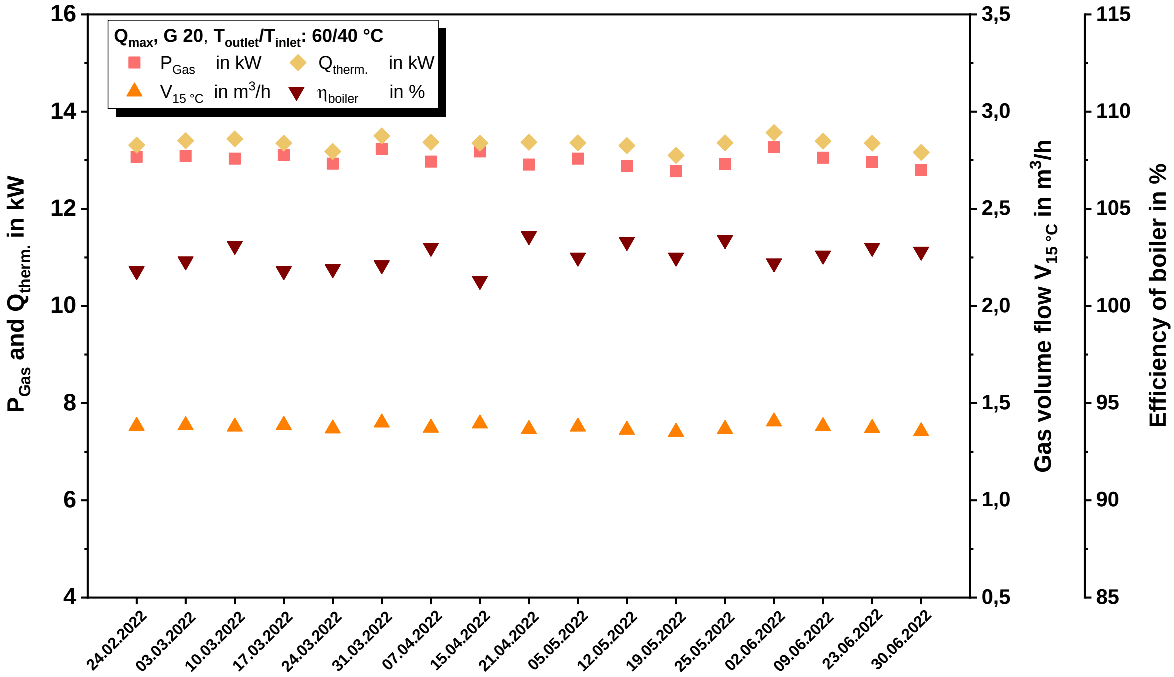


Figure 10: Long term test results for condensing boiler 1 operated at maximum load with pure methane (G20): Output power based on gas consumption P¬Gas (based on NCV), thermal load Qtherm, gas volume flow V15°C, and boiler efficiency ηboiler (NCV).

1.3.2 Condensing Boiler 2

The data of the weekly measurements are given in Table 5 for minimum load and in Table 6 for the maximum load operation.

Table 5: Results for boiler 2 at minimum load. Yellow marked data are calculated from the measurement data.

LONG TERM TEST RESULTS – BOILER 2 @ $Q_{MIN.}$ (G 20)

	T_{outlet}	T_{inlet}	m_{water}	T_{flue}	$V_{15°C,Gas}$	Q_{water}	P_{Gas}	η_{boiler}	CO_{dry} @ 0 vol% O_2	$NO_{x,dry}$ @ 0 vol% O_2	$CO_{2,flue}$	$O_{2,flue}$	Air excess ratio λ	T_{Gas}	p_{Gas}	$p_{ambient}$
	in °C	in °C	in kg/min	in °C	in m³/h	in kW	in kW	in %	in ppm	in ppm	in vol%	in vol%	[-]	in °C	in mbar	in mbar
24.02.2022*	58.51	40.77	5.04	43.0	0.656	6.39	6.20	103.1	2.7	13.5	8.65	5.60	1.33	21.5	19.9	1012
03.03.2022*	58.43	40.98	5.04	43.0	0.631	6.15	5.96	103.2	1.4	8.2	8.85	5.26	1.30	22.5	20.0	1019
10.03.2022*	59.46	40.99	5.04	43.2	0.671	6.54	6.34	103.2	2.5	10.7	9.15	4.66	1.28	19.5	20.1	1023
17.03.2022*	59.65	40.94	5.04	43.3	0.686	6.67	6.48	102.9	3.5	14.0	9.03	4.98	1.27	20.5	20.0	1025
24.03.2022*	58.17	41.07	5.04	43.1	0.617	6.03	5.83	103.4	7.6	10.3	8.73	5.44	1.31	18.7	20.2	1020
31.03.2022*	58.54	41.09	5.04	43.6	0.632	6.15	5.97	103.0	8.5	11.4	8.64	5.17	1.29	15.7	20.2	999
07.04.2022*	58.89	40.99	5.04	43.3	0.648	6.31	6.12	103.1	5.5	17.1	8.91	4.96	1.28	21.7	20.1	989
15.04.2022*	60.08	41.66	5.04	43.4	0.687	6.73	6.49	103.7	8.7	13.3	9.11	4.65	1.25	20.5	20.1	1027
21.04.2022*	60.58	41.03	5.04	44.4	0.708	6.89	6.69	103.0	10.6	16.4	9.09	4.83	1.27	20.9	20.1	1011
05.05.2022*	60.18	41.11	5.04	44.4	0.689	6.72	6.51	103.2	7.2	11.8	8.78	5.21	1.30	20.9	20.0	1022
12.05.2022*	60.72	41.15	5.04	44.6	0.711	6.90	6.72	102.7	10.9	18.1	9.16	4.81	1.26	21.9	20.0	1018
19.05.2022*	60.52	41.21	5.04	44.4	0.697	6.81	6.58	103.5	13.7	15.9	8.98	4.67	1.28	26.5	20.1	1015
02.06.2022*	60.22	41.18	5.03	44.3	0.686	6.68	6.48	103.0						21.3	20.4	1020
09.06.2022*	59.51	41.18	5.04	44.2	0.659	6.44	6.23	103.4	11.5	18.2	9.15	4.72	1.26	21.8	20.3	1015
23.06.2022*	59.68	41.24	5.04	44.6	0.662	6.47	6.26	103.6	9.8	17.3	9.21	4.56	1.26	27.5	20.0	1010
30.06.2022*	59.54	40.98	5.04	44.3	0.674	6.54	6.37	102.8	13.0	15.6	9.08	4.83	1.27	27.0	20.0	1011

Table 6: Results for boiler 2 at maximum load. Yellow marked data are calculated from the measurement data.

LONG TERM TEST RESULTS – BOILER 2 @ Q_{MAX} (G 20)																
	T_{outlet}	T_{inlet}	m_{water}	T_{flue}	$V_{15°C,Gas}$	Q_{water}	P_{Gas}	η_{boiler}	CO_{dry} @ 0 vol% O_2	$NO_{x,dry}$ @ 0 vol% O_2	$CO_{2\ flue}$	$O_{2\ flue}$	Air excess ratio λ	T_{Gas}	p_{Gas}	$p_{ambient}$
	in °C	in °C	in kg/min	in °C	in m³/h	in kW	in kW	in %	in ppm	in ppm	in vol%	in vol%	[-]	in °C	in mbar	in mbar
10.02.2022*	61.71	41.22	15.07	58.2	2.263	21.61	21.38	101.1	42.6	13.1	8.31	6.20	1.37	22.9	19.4	1020
24.02.2022*	61.22	41.12	15.07	57.2	2.212	21.30	20.90	101.5	37.5	15.9	8.22	6.24	1.38	22.5	19.3	1012
03.03.2022*	61.60	41.25	15.07	57.9	2.202	21.38	20.81	102.8	30.7	11.3	8.18	6.13	1.37	20.0	19.4	1019
10.03.2022*	61.63	41.24	15.07	57.6	2.244	21.45	21.20	101.2	47.1	10.0	8.22	6.20	1.38	20.3	19.4	1023
17.03.2022*	61.57	41.21	15.06	57.6	2.211	21.48	20.89	102.8	41.1	14.88	8.20	6.20	1.37	20.6	19.3	1029
24.03.2022*	61.32	41.10	15.07	57.8	2.218	21.23	20.96	101.3	44.9	10.8	7.98	6.55	1.40	20.4	19.4	1028
31.03.2022*	61.38	41.18	15.07	57.7	2.196	21.30	20.75	102.7	48.1	10.7	8.11	6.45	1.40	19.9	19.4	1028
07.04.2022*	60.73	41.24	15.07	57.4	2.148	20.61	20.30	101.5	38.1	10.2	8.16	6.20	1.37	21.0	19.3	998
15.04.2022*	60.74	41.21	15.07	57.2	2.160	20.59	20.41	100.9	49.6	9.9	8.11	6.30	1.39	20.5	19.2	1031
21.04.2022*	61.21	41.21	15.07	57.5	2.211	21.08	20.89	101.0	47.8	10.1	8.20	6.29	1.38	21.1	19.2	1006
28.04.2022*	60.56	41.15	15.07	57.1	2.135	20.47	20.18	101.4	42.5	11.8	8.05	6.48	1.40	21.8	19.2	1027
05.05.2022*	60.92	41.16	15.07	57.1	2.188	20.84	20.67	100.8	43.5	9.8	8.25	6.23	1.38	21.3	19.2	1022
12.05.2022*	61.00	41.18	15.07	56.7	2.192	20.92	20.71	101.2	45.2	11.2	8.04	6.40	1.39	23.0	19.2	1018
19.05.2022*	61.09	41.11	15.07	56.5	2.206	21.07	20.86	101.1	48.8	10.9	8.21	6.13	1.37	21.8	19.1	1018
02.06.2022*	61.43	41.12	15.07	55.5	2.217	21.34	20.95	101.9	51.4	10.7	8.23	6.28	1.38	20.2	19.9	1020
09.06.2022*	61.01	41.11	15.07	56.0	2.158	20.90	20.37	102.6	44.4	9.6	8.08	6.57	1.41	22.2	19.5	1016
23.06.2022*	60.91	41.07	15.07	55.2	2.175	20.92	20.55	101.8	46.8	10.7	8.18	6.24	1.38	28.5	19.0	1010
30.06.2022*	60.85	41.02	15.07	55.9	2.169	20.92	20.49	102.1	47.2	9.8	8.13	6.34	1.39	27.7	19.2	1011

The same data for minimum load are plotted over time in Figure 11 and Figure 12.

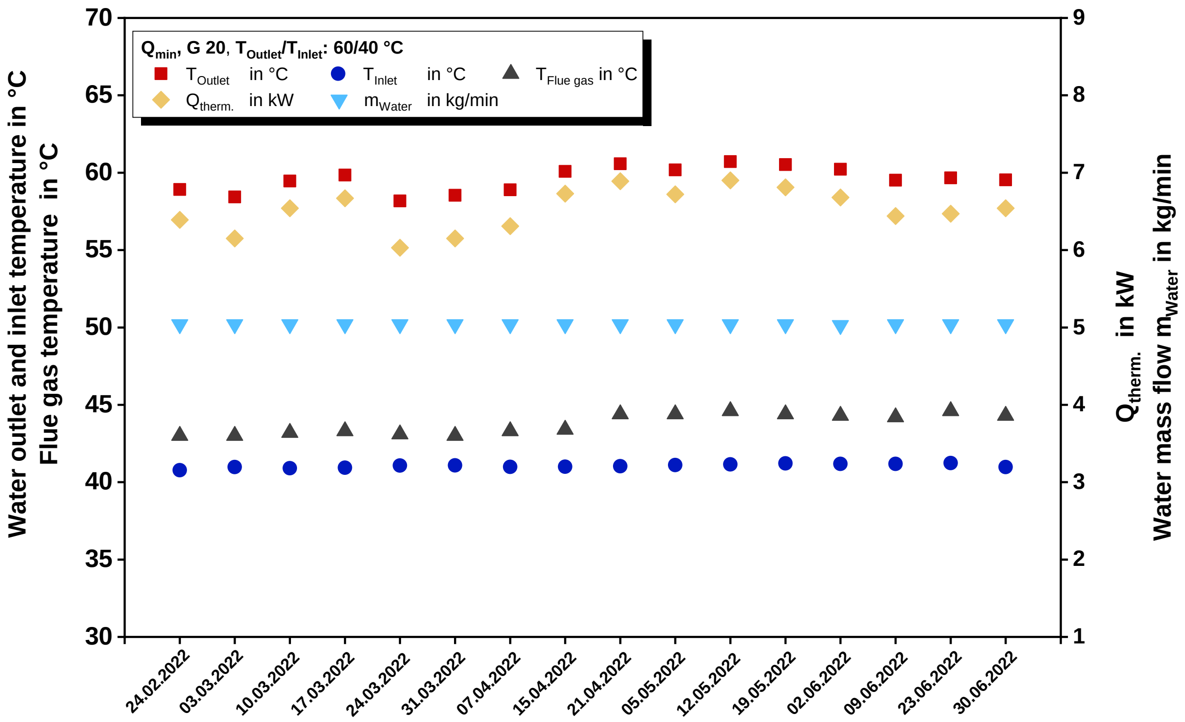


Figure 11: Long term test results for condensing boiler 2 operated at minimum load with pure methane (G20): Outlet, inlet and flue gas temperatures, thermal load and water mass flow.

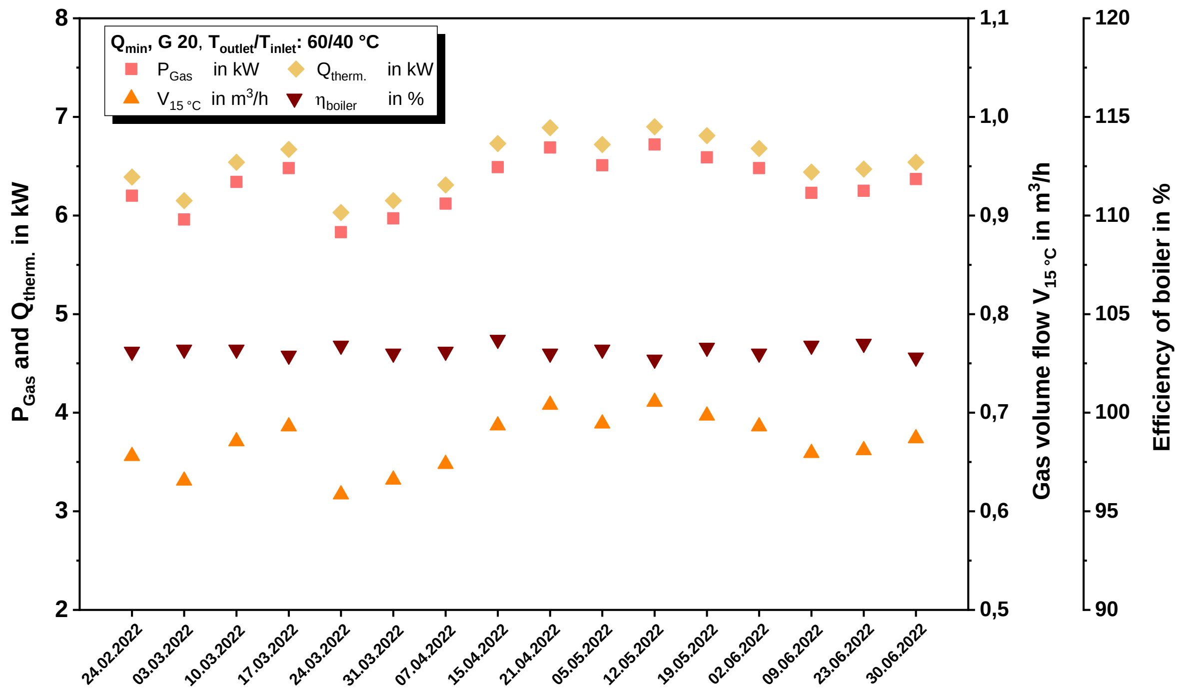


Figure 12: Long term test results for condensing boiler 2 operated at minimum load with pure methane (G20): Output power based on gas consumption P¬Gas (based on NCV), thermal load Qtherm, gas volume flow V15°C, and boiler efficiency ηboiler (NCV).

For maximum load, the data points are presented as a function of time in Figure 13 and Figure 14.

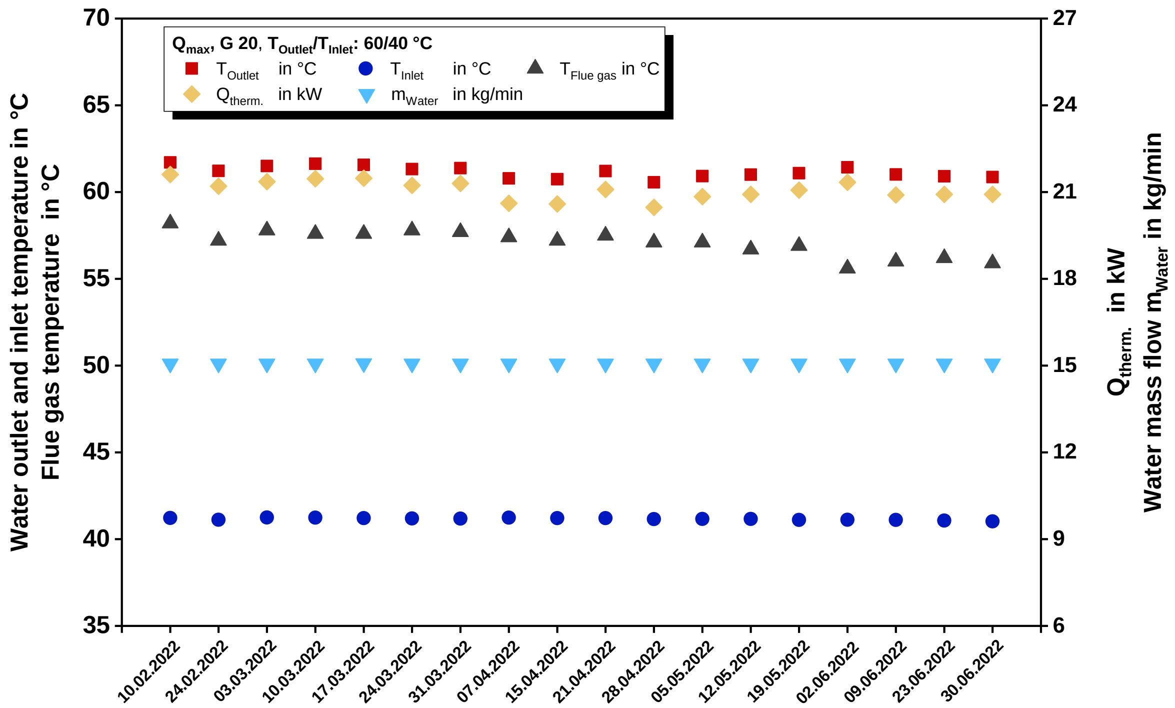


Figure 13: Long term test results for condensing boiler 2 operated at maximum load with pure methane (G20): Outlet, inlet and flue gas temperatures, thermal load and water mass flow.

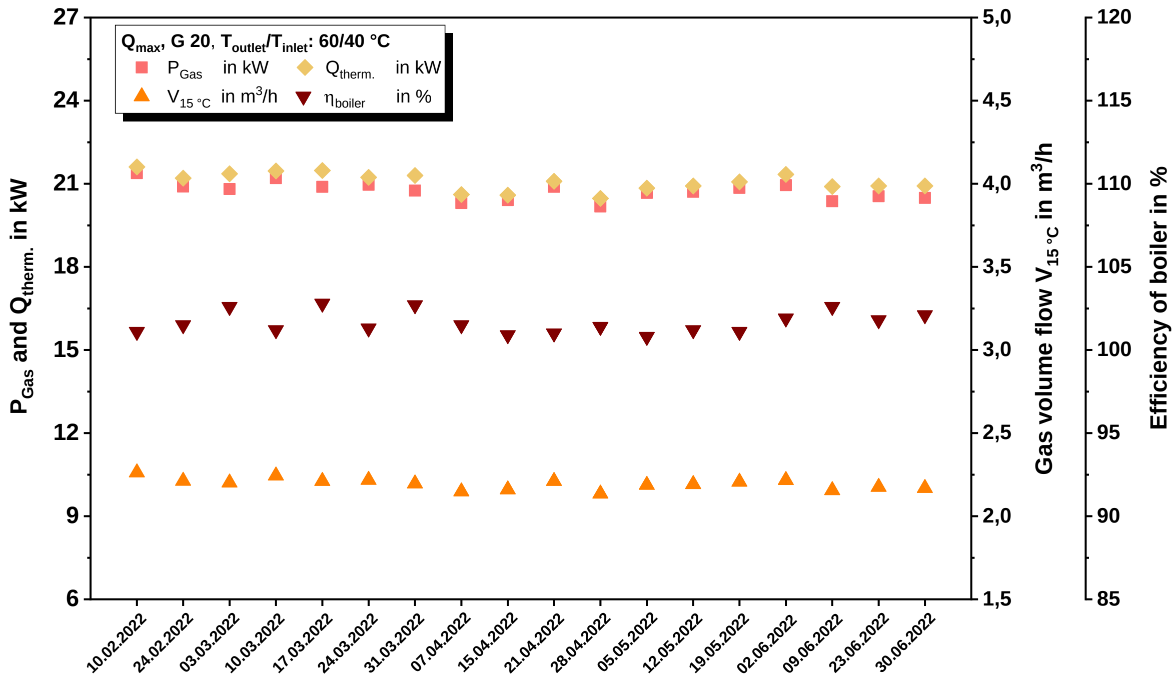


Figure 14: Long term test results for condensing boiler 1 operated at maximum load with pure methane (G20): Output power based on gas consumption P¬Gas (based on NCV), thermal load Qtherm, gas volume flow V15°C, and boiler efficiency ηboiler (NCV).

1.4 Conclusions on the two Long Term Tests on boilers, at GWI

In summary of the two long-term tests performed at GWI laboratory, we conclude that both appliances operated safely and reliably during the >3.000 hour long term test at 30 vol% hydrogen admixture. Both appliances chosen for the experiment are combustion controlled condensing boilers and both were in new condition before start of the tests. Performance data and emissions were monitored as described above. Within the limitations of our measurements, which are given by the gas mixing station, laboratory instruments and other equipment, as well as the change of weather conditions during the months of test duration, we did not observe any degradation, worsening of flue gas emissions, noise emissions or other noticeable behaviour of the appliances. The performance and emission data presented in chapter 3 remained almost constant over the testing period. When opening the appliances after finalisation of the long-term tests, normal amounts of deposits were observed, that correspond well with the experiences from comparable used appliances after natural gas combustion. This interpretation of our findings was confirmed by the manufacturers of both appliances.

2 DGC - test of three boilers

2.1 Protocol description

2.1.1 Test Protocol

The test protocol is similar to what was implemented at GWI, Figure 15 provides an overview of the different phases of operation of the boilers.

<table>
<tr><td colspan="22">normal week</td></tr>
<tr><td colspan="22">30% H2 in NG</td></tr>
<tr><td></td><td></td><td>8:00</td><td>08:30</td><td>09:00</td><td>09:30</td><td>10:00</td><td>10:30</td><td>11:00</td><td>11:30</td><td>12:00</td><td>12:30</td><td>13:00</td><td>13:30</td><td>14:00</td><td>14:30</td><td>15:00</td><td>15:30</td><td>16:00</td><td>16:30</td><td>17:00</td><td>07:30</td></tr>
<tr><td rowspan="2">Day 1 +2</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Qmax</td><td>break</td><td colspan="2">Qmax</td><td colspan="2">break</td><td colspan="4">Q min 30 % H2 + NG</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="5">All burner+ oven Qmin 30 % H2+ NG</td><td>break</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td colspan="4">break</td></tr>
<tr><td rowspan="2">Day 3</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Qmax</td><td>break</td><td colspan="2">part load at high s/s frequencey</td><td colspan="2">break</td><td colspan="4">Q min 30 % H2 + NG</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td>Light back test weekly</td><td>break</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td colspan="4">break</td></tr>
<tr><td rowspan="2">Day 4</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Qmax</td><td>break</td><td colspan="2">Qmax</td><td colspan="2">break</td><td colspan="4">Q min 30 % H2 + NG</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="5">All burner+ oven Qmin 30 % H2+ NG</td><td>break</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td colspan="4">break</td></tr>
<tr><td rowspan="2">Day 5</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Qmax</td><td>break</td><td colspan="2">Qmax</td><td colspan="6">break</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="5">All burner+ oven Qmin 30 % H2+ NG</td><td>break</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td colspan="4">break</td></tr>
</table>

<table>
<tr><td colspan="22">Day 3 + 5 once a month</td></tr>
<tr><td></td><td></td><td>8:00</td><td>08:30</td><td>09:00</td><td>09:30</td><td>10:00</td><td>10:30</td><td>11:00</td><td>11:30</td><td>12:00</td><td>12:30</td><td>13:00</td><td>13:30</td><td>14:00</td><td>14:30</td><td>15:00</td><td>15:30</td><td>16:00</td><td>16:30</td><td>17:00</td><td>07:30</td></tr>
<tr><td rowspan="2">Day 3</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Test with CH4</td><td>break</td><td colspan="2">part load at high s/s frequencey</td><td colspan="2">break</td><td colspan="4">Q min 30 % H2 + NG</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td>Light back test weekly</td><td>break</td><td colspan="2">Test with CH4</td><td>All burner+ oven Qmax 30</td><td colspan="4">All burner+ oven Qmin 30 % H2+ NG</td><td colspan="4">break</td></tr>
<tr><td rowspan="2">Day 5</td><td>Boiler</td><td colspan="8">Q min 30 % H2 + NG</td><td>break</td><td colspan="2">Qmax</td><td>break</td><td colspan="2">Qmax</td><td colspan="6">break</td></tr>
<tr><td>cooker</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="5">All burner+ oven Qmin 30 % H2+ NG</td><td>break</td><td colspan="3">All burner+ oven Qmax 30 % H2+ NG</td><td colspan="3">All burner+ oven Qmin 30 % H2+ NG</td><td>leakage verification</td><td colspan="4">break</td></tr>
</table>

Figure 15: Test protocol

2.1.2 Test gases

Table 7 provides the parameters of the gas distributed and used throughout the testing months in Denmark.

Table 7: Composition of gas throughout LTT

Parameter	Unit	May (avg)	30% H2	June (avg)	30% H2	July (avg)	30% H2	August (avg)	30% H2	September (avg)	30% H2	Global avg	30% H2
Carbon dioxide	% vol	0.74	0.52	1.40	0.98	1.37	0.96	1.28	0.90	1.26	0.88	1.21	0.85
Ethane	% vol	3.71	2.60	5.42	3.79	5.53	3.87	5.46	3.82	5.30	3.71	5.08	3.56
Hexane+	% vol	0.03	0.02	0.03	0.02	0.04	0.03	0.05	0.04	0.05	0.04	0.04	0.03
I-butane	% vol	0.08	0.06	0.13	0.09	0.17	0.12	0.17	0.12	0.19	0.13	0.15	0.10
I-pentane	% vol	0.01	0.01	0.03	0.02	0.03	0.02	0.04	0.03	0.05	0.04	0.03	0.02
Methane	% vol	94.37	66.06	90.82	63.57	90.29	63.20	90.33	63.23	90.39	63.27	91.24	63.87
N-butane	% vol	0.07	0.05	0.15	0.11	0.16	0.11	0.18	0.13	0.23	0.16	0.16	0.11
Nitrogen	% vol	0.55	0.39	0.98	0.69	1.22	0.85	1.16	0.81	1.14	0.80	1.01	0.71
N-pentane	% vol	0.01	0.01	0.02	0.01	0.02	0.01	0.03	0.02	0.04	0.03	0.02	0.02
Propane	% vol	0.44	0.31	1.03	0.72	1.16	0.81	1.30	0.91	1.36	0.95	1.06	0.74
Hydrogen	% vol	0.00	30.00	0.00	30.00	0.00	30.00	0.00	30.00	0.00	30.00	0.00	30.00
TOTAL	% vol	100.01	100.01	100.01	100.01	99.99	99.99	100.00	100.00	100.01	100.01	100.00	100.00
Gross Calorific Value	kWh/Nm³	11.36		11.52		11.55		11.60		11.62		11.61	
Gross Calorific Value	MJ/Nm³	40.90		41.49		41.58		41.75		41.83		41.79	
Net Calorific Value	kWh/Nm³	10.25		10.41		10.44		10.48		10.50		10.49	
Net Calorific Value	MJ/Nm³	36.91		37.47		37.57		37.72		37.79		37.76	
Wobbe Index	kWh/Nm³	14.79		14.70		14.69		14.74		14.76		14.75	
Wobbe Index	MJ/Nm³	53.26		52.92		52.88		53.06		53.13		53.09	

2.1.3 Appliances tested

Boiler 1 (D4) is a wall hung full premix condensing boiler, manufactured in 2020. The boiler has a modulating burner and is equipped with a pneumatic based combustion control (gas volume modified as function of the air flow, not dependant on gas quality). The power input is between 5 kW and 20 kW (net). The gas category is II 2H3B/P.

Boiler 2 (D5) is a wall hung full premix condensing boiler, manufactured in 2020. The boiler has a modulating burner and is equipped with an ionisation-based combustion control. The power input is between 4.3 kW and 20.8 kW (net). The gas category is II 2H3B/P.

Boiler 3 (D6) is a wall hung full premix condensing boiler. The boiler has a modulating burner and is equipped with an ionisation-based combustion control. The power input is between 2.5 kW and 22 kW (net). The gas category is II 2H3B/P.

All boilers have been tested for THyGA "short term" before being tested again for this long-term test.

2.1.4 Data measurement and conversion

The following data was measured:

- CO emissions in flue (in ppm daf)
- O2 in %
- Gas consumption (nm3/h)
- Water flow (kg/h)
- Heat input (kW)
- Return temperature (°C)
- Flow temperature (°C)
- Flue gas temperature (°C)
- Temperature at the gas valve (°C)
- Fan temperature (°C)
- Pgas (mbar)

2.1.5 Deviations from the test protocol and unforeseen events during long term tests

A few unforeseen events and deviations took place:

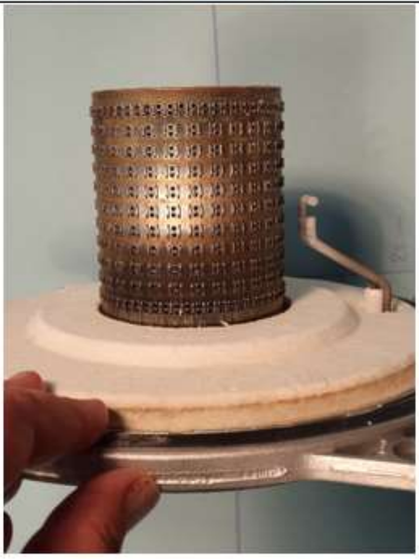
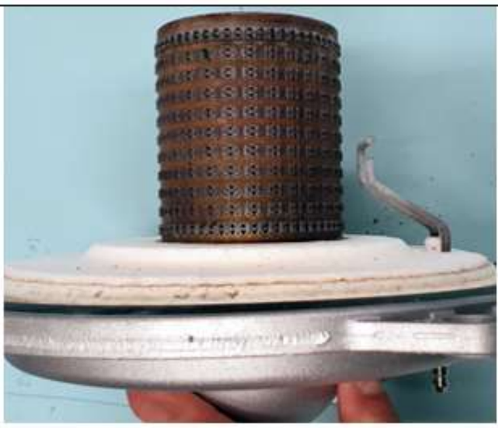
- Data acquisition was interrupted on the 4th of September due to a data connection error.
- Boilers were set only at Qmin due to noise measurements at DGC lab on the 6th and 7th of September.
- There were data acquisition breaks due to a faulty file (on 19th & 20th August and on 8th September).
- No measurement of emissions on the 1st of August due to calibration/linearization of equipment.

2.1.6 Testing time

The 3 boilers were tested each for a total of 4195 hours.

2.2 Visual Observations

2.2.1 Boiler 1 (D4) Burner

Ref	Before	After
1.1		
1.2		

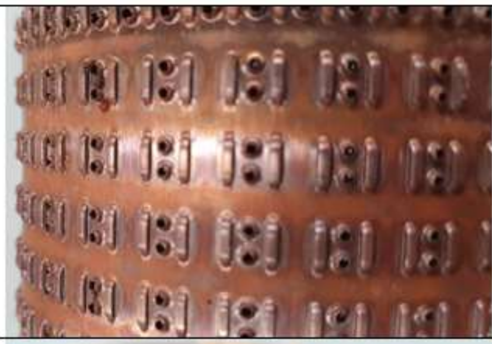
1.3		
1.4		

Figure 16: Pictures of boiler 1 Burner (D4)

Figure 17: Front and closeup view of boiler 1 heat exchanger (D4)

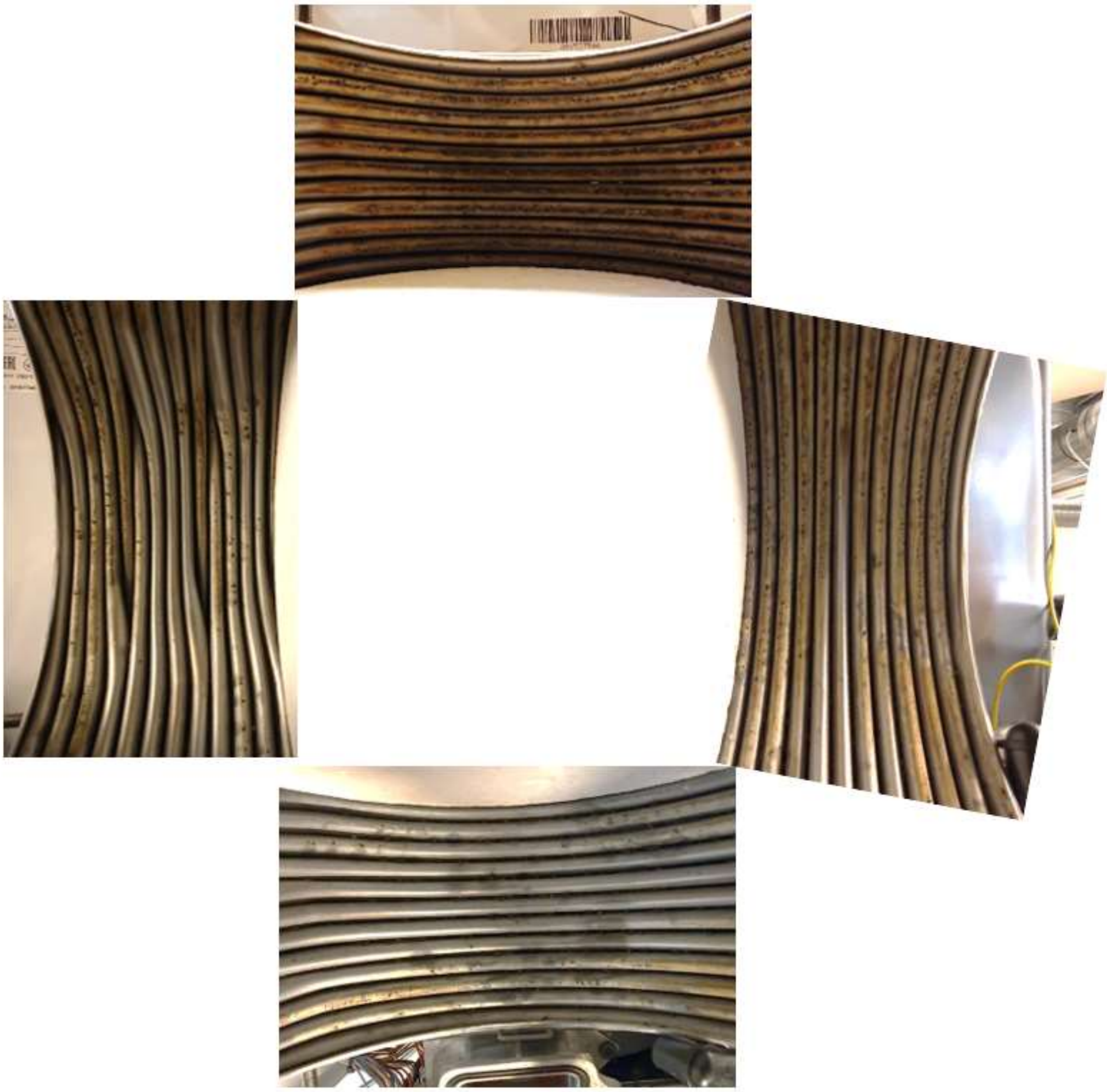


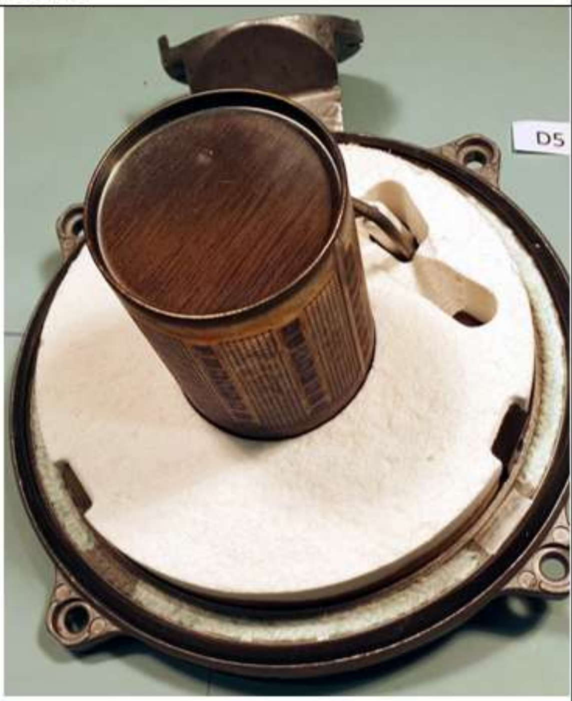
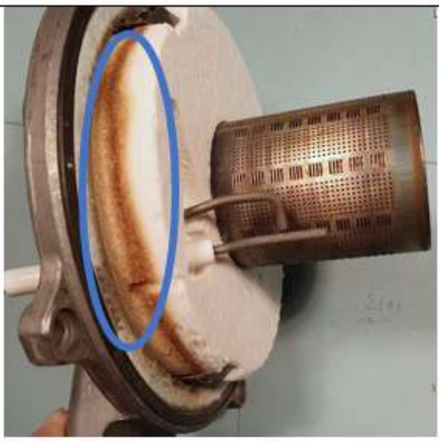
Figure 18: Overall view of boiler 1 (D4)

Figure 19: Deposit in boiler 1 (D4) spread on paper on the left, deposit in the boiler ("condensate reservoir") on the right.

The burner itself is more orange and there is deposit around the heat exchanger. Following discussion within WP3 and manufacturers, it was concluded that this is due to air pollution that remains attached to the coils at high temperature. It is a normal behaviour also with NG or LPG and is not linked to H2. Bigger is the pollution or the quantity of dust in the air and bigger is this black/brown deposit in the exchanger.

We observe more deposit on top. Some examples of such deposits on boilers operating with natural gas can be seen in the conclusion of this section

2.2.2 Boiler 2 (D5)

Ref	Before	After
2.1		
2.2		

2.3		
2.4		
2.5		

2.6		

Figure 20: Pictures of boiler 2 (D5)

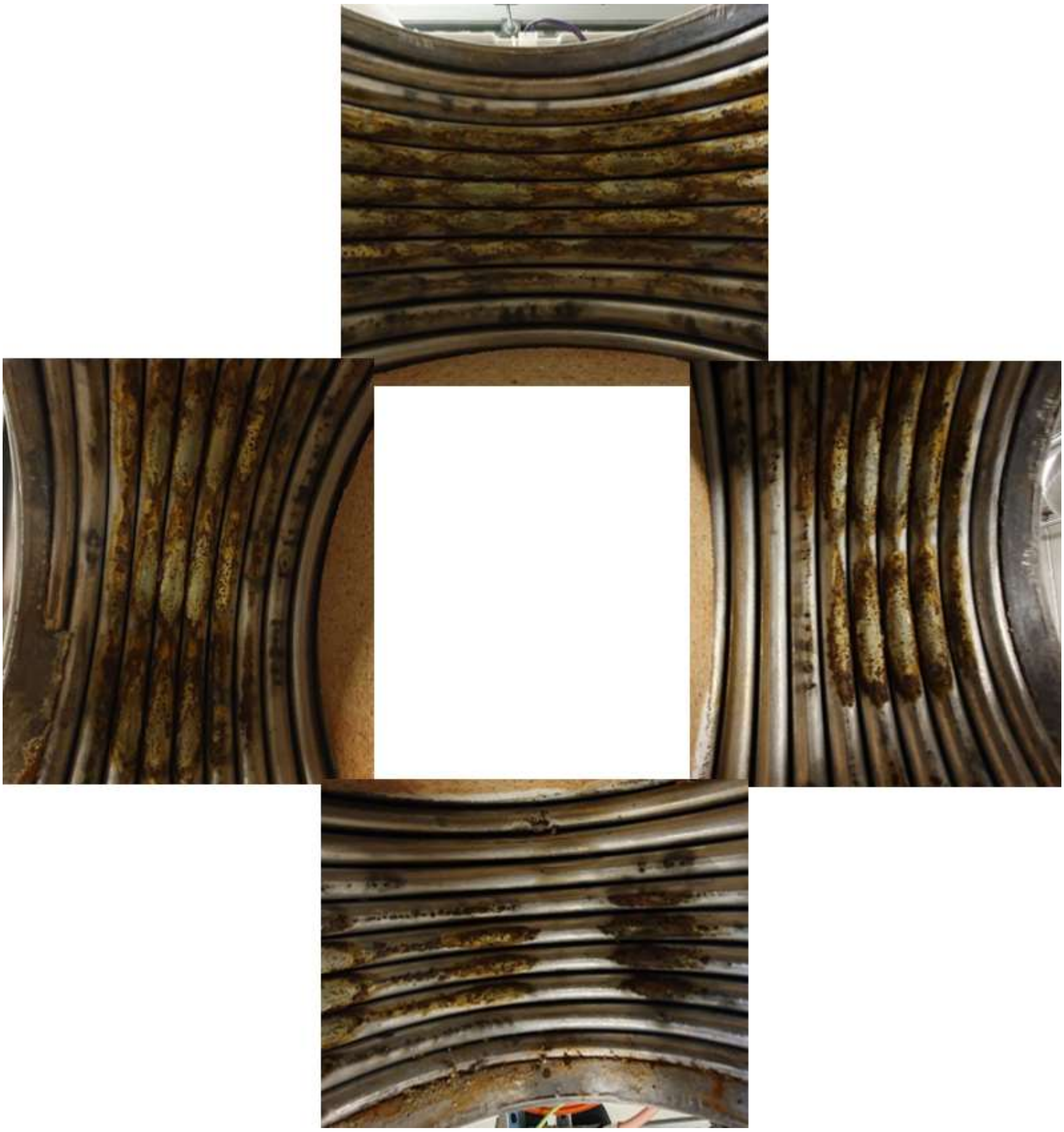


Figure 21: Overall view of boiler 2 (Burner and heat exchanger) (D5)

Figure 22: Closeup of isolation of boiler 2 (D5)

Little difference on the heat exchanger itself. We also observed a heavy deposit inside, probably also due to air pollution. Deposit alternates green circles and rust, corresponding to the burner structure (picture 2.4) with the little holes of the burner that are separated by bigger ones (yellow circles on pictures 2.4, 2.5 and 2.6). There is still more rust on top.

Picture 2.6 of shows green deposit in the top red circle, which is due to the lining on the Figure 22.

The insulation material is chipped (Figure 20, picture 2.2).

Comments received from the manufacturer: the results presented have been discussed with the manufacturer of the boiler and the conclusions are made considering the information we have received.

2.2.3 Boiler 3 (D6)

Ref	Before	After
3.1		
3.2		

3.3		
3.4		
3.5		

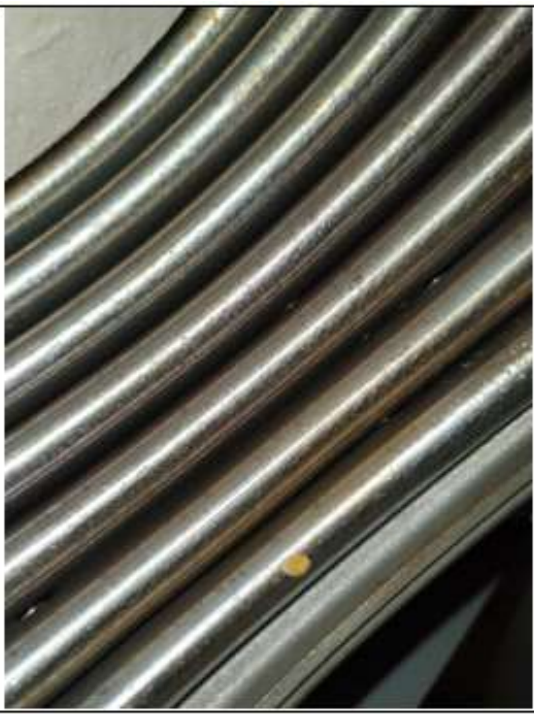
3. 6		

Figure 23: Pictures of boiler 3 (D6)

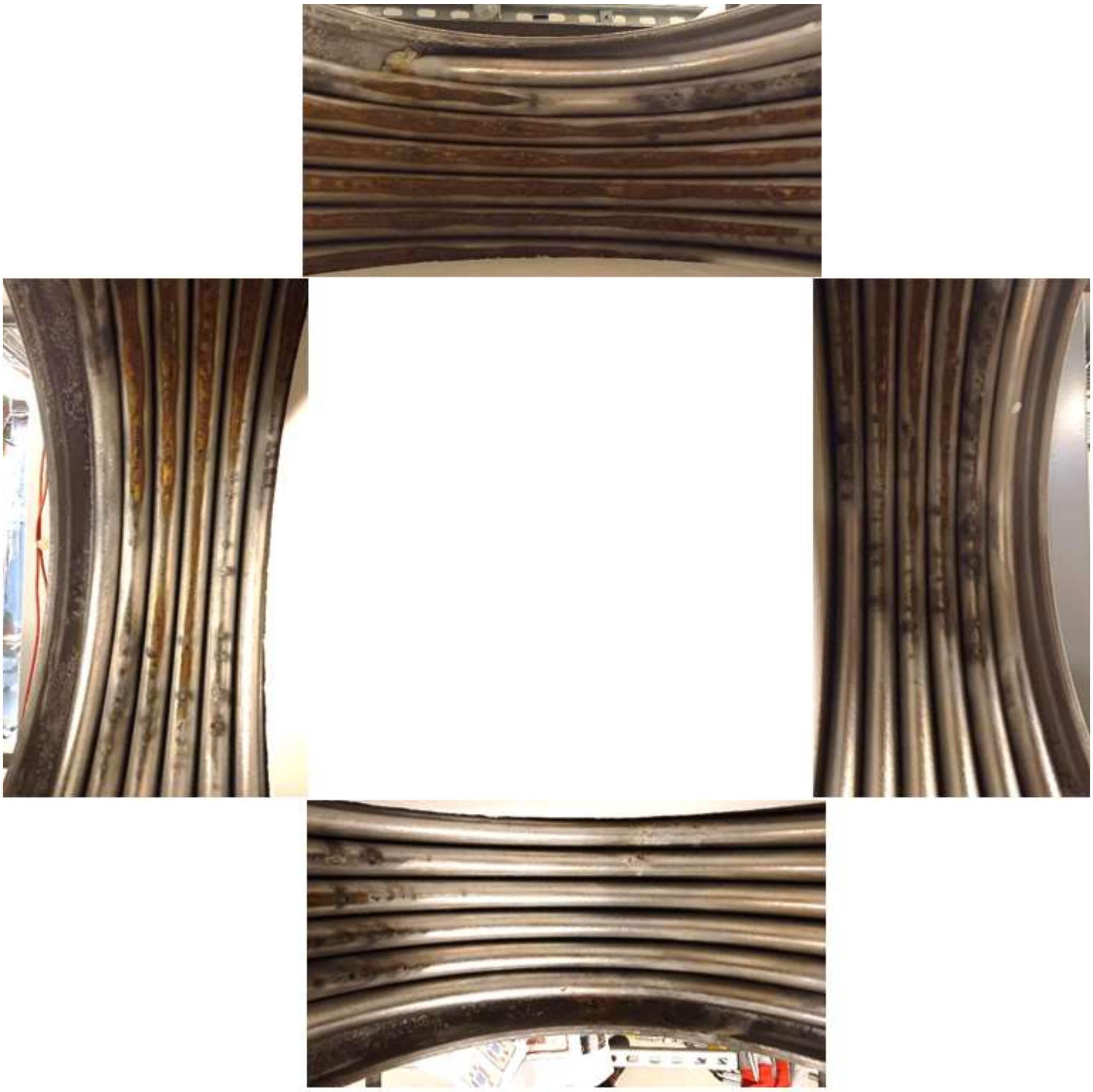


Figure 24: Overall view of boiler 3 (D6)

There is more rust on the burner (picture 3.3) and deposit around. This time it seems to be corroded. We can see on picture 3.5 that the corrosion is not all around, just on specific portions of the cylinder (mostly the top). The reason is unclear so far.

Comments received from the manufacturer: the results presented have been discussed with the manufacturer of the boiler and the conclusions are made considering the information we have received.

2.2.4 Conclusion

All boilers have a certain amount of deposit/rust. The deposit seems to come from air pollution and is normal (see screenshot from the video of maintenance underneath).

Most of that deposit is on the top of the boilers. This is probably due to the evacuation of the flue gas that happens at the top.

Figure 25: Screenshot from maintenance video of a similar boiler operating with natural gas in field – source: You Tube

2.3 Test Data measured

2.3.1 CO evolution

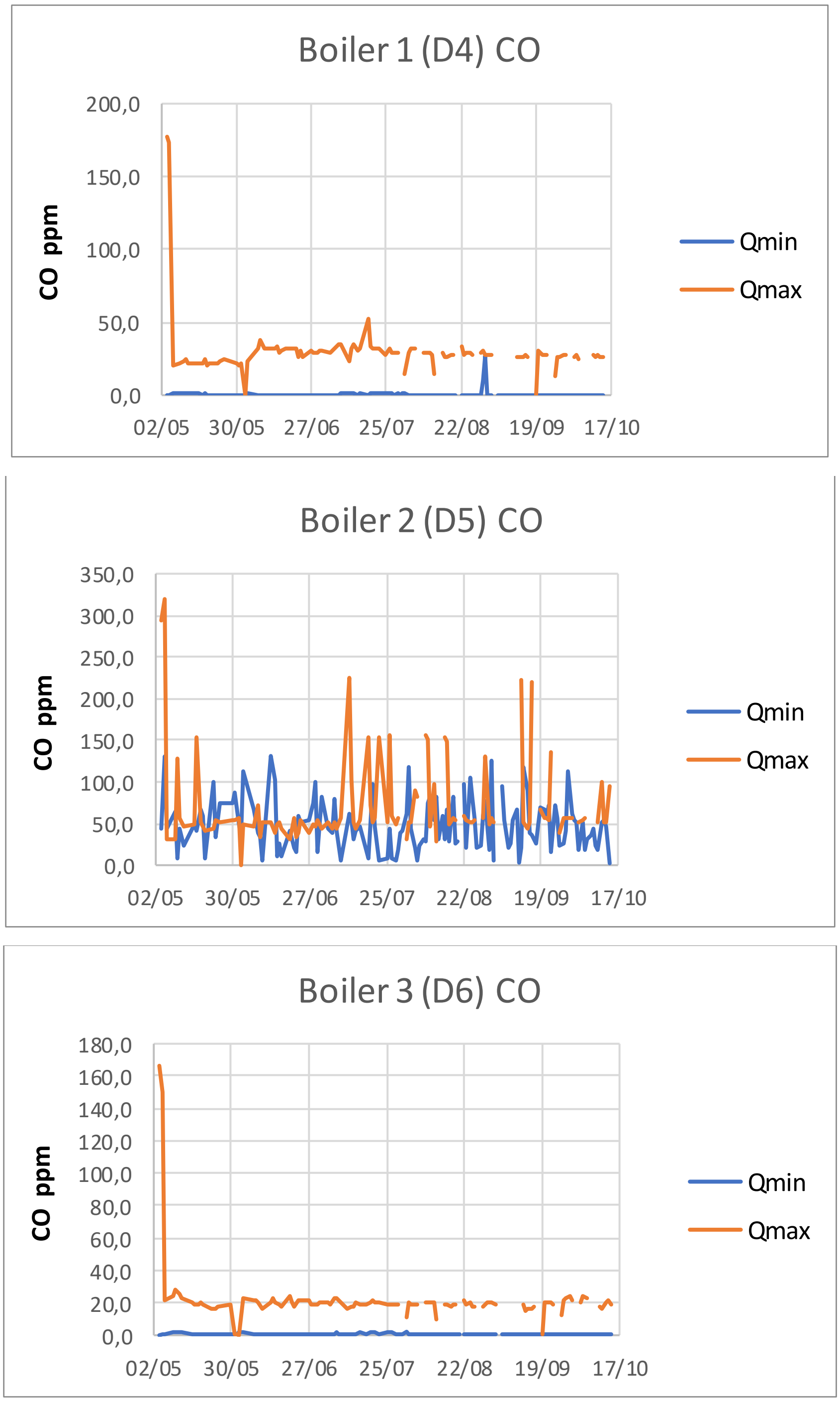
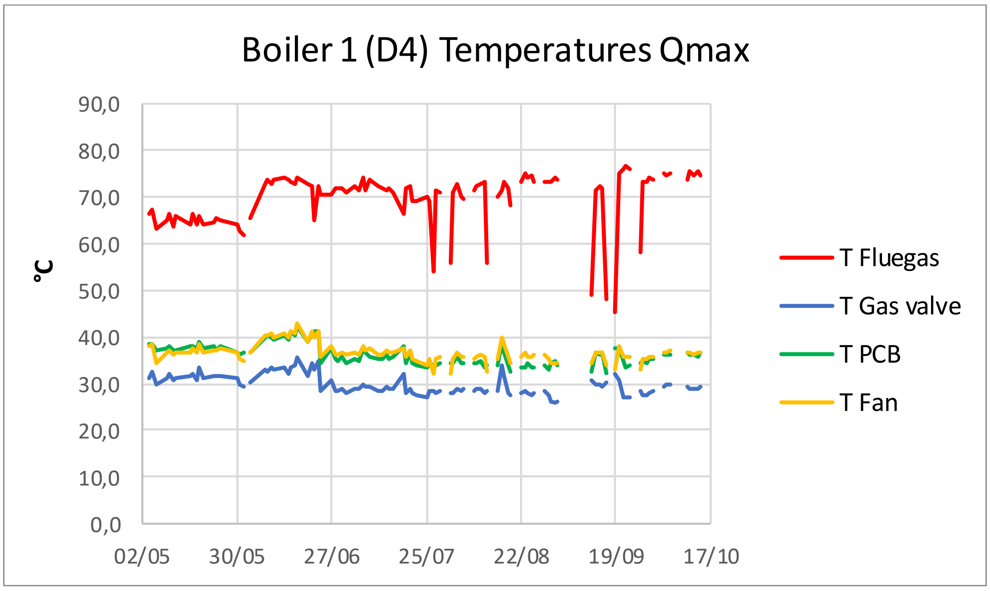


Figure 26: CO emissions for the 3 boilers tested at DGC

We don't see an evolution of the CO during the duration of the test. Peaks for boiler 2 are linked to the boiler operation.

2.3.2 Temperature evolution



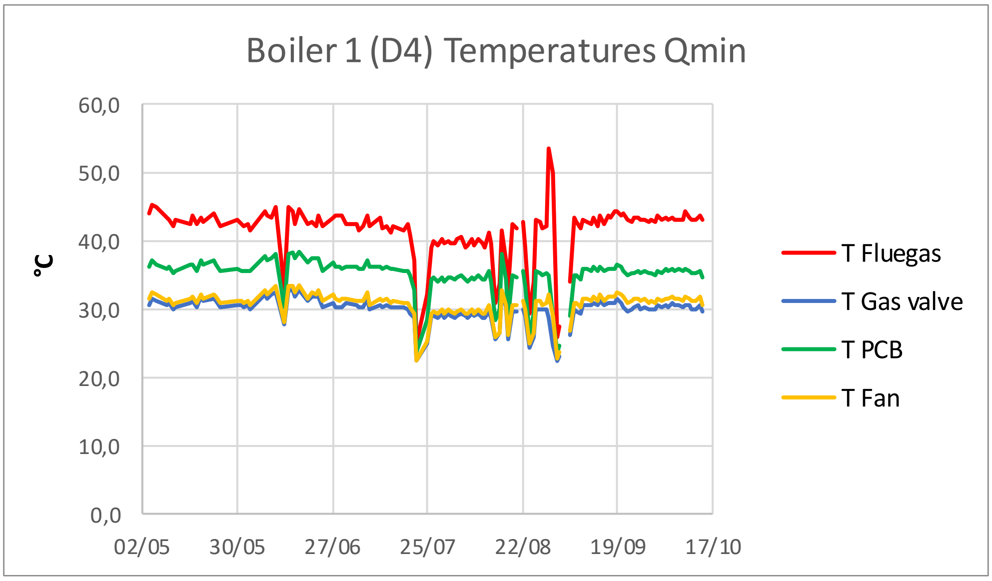
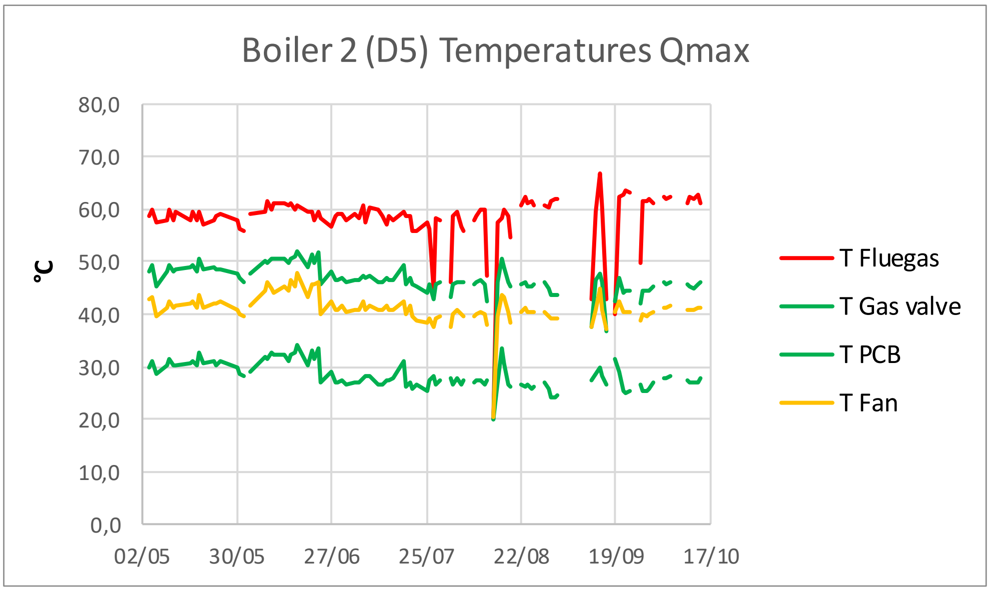


Figure 27: Temperatures evolutions for boiler D4 tested at DGC

For this boiler, we see a sudden increase of the flue gas temperature (about 10 °C) **at Qmax** during the duration of the test (around the 30/05). This is correlated with the increase of heat input, which was changed because the appliance was not actually operating at the nominal Qmax before that date. So the heat input was adjusted by the laboratory to correct from this. This has not impacted the result.



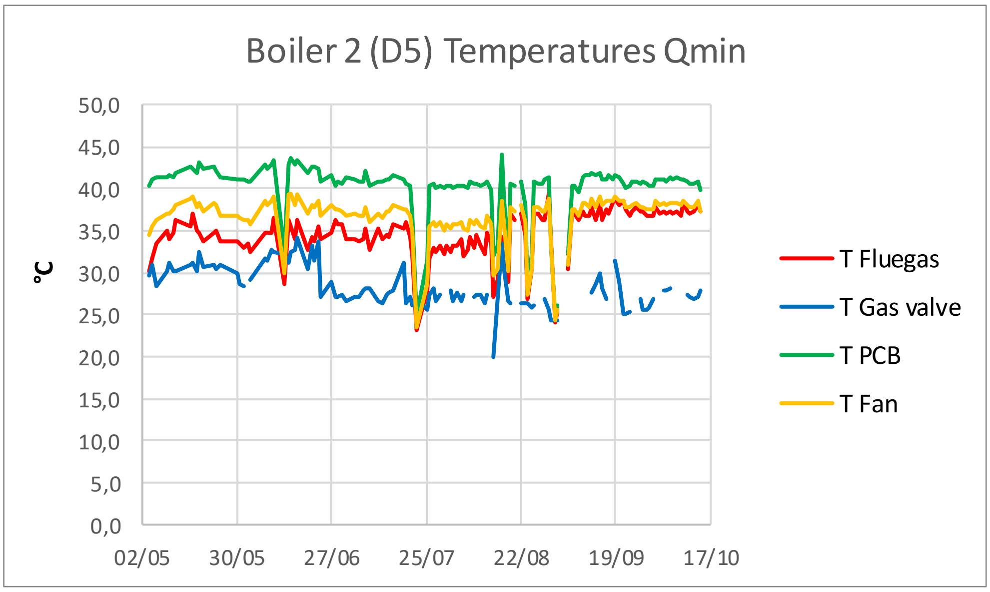
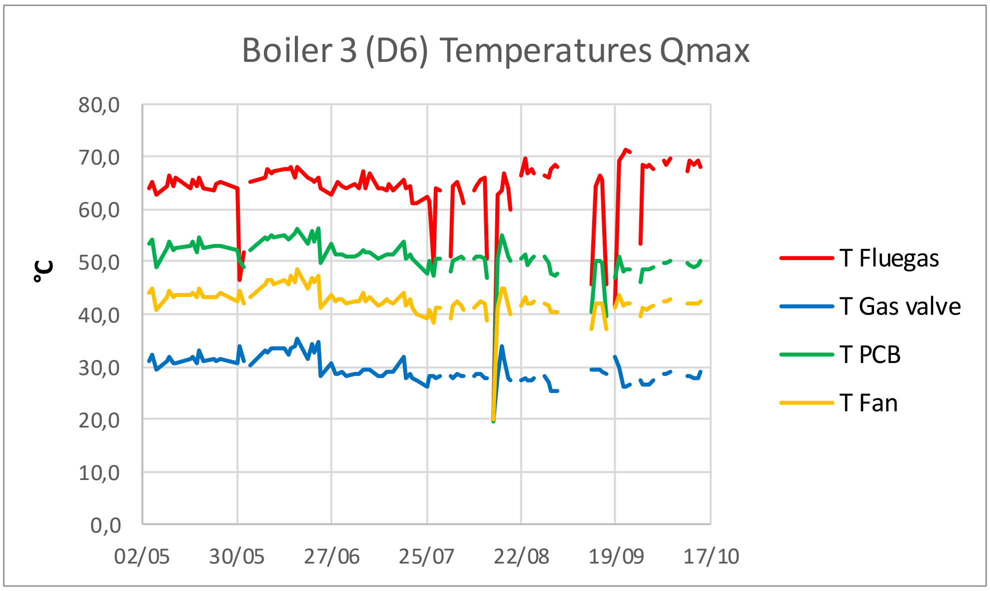


Figure 28: Temperatures evolutions for boiler D5 tested at DGC

We don't really see trends here, appart a slight drecrease of the gas valve temperature. We dont have an explanation for that.



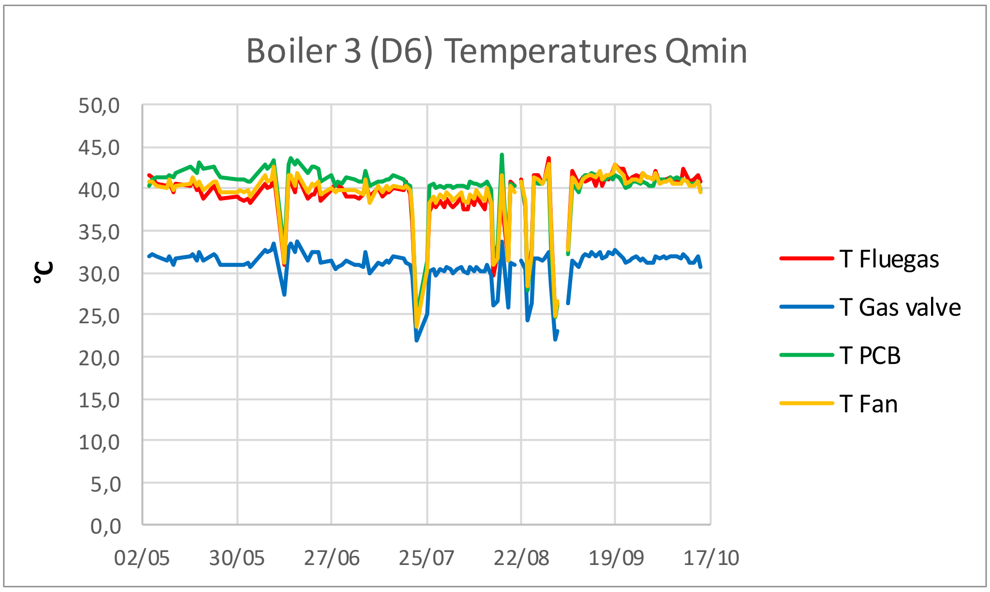


Figure 29: Temperatures evolutions for boiler D6 tested at DGC

We don't really see trends here.

2.3.3 Gas consumption evolution

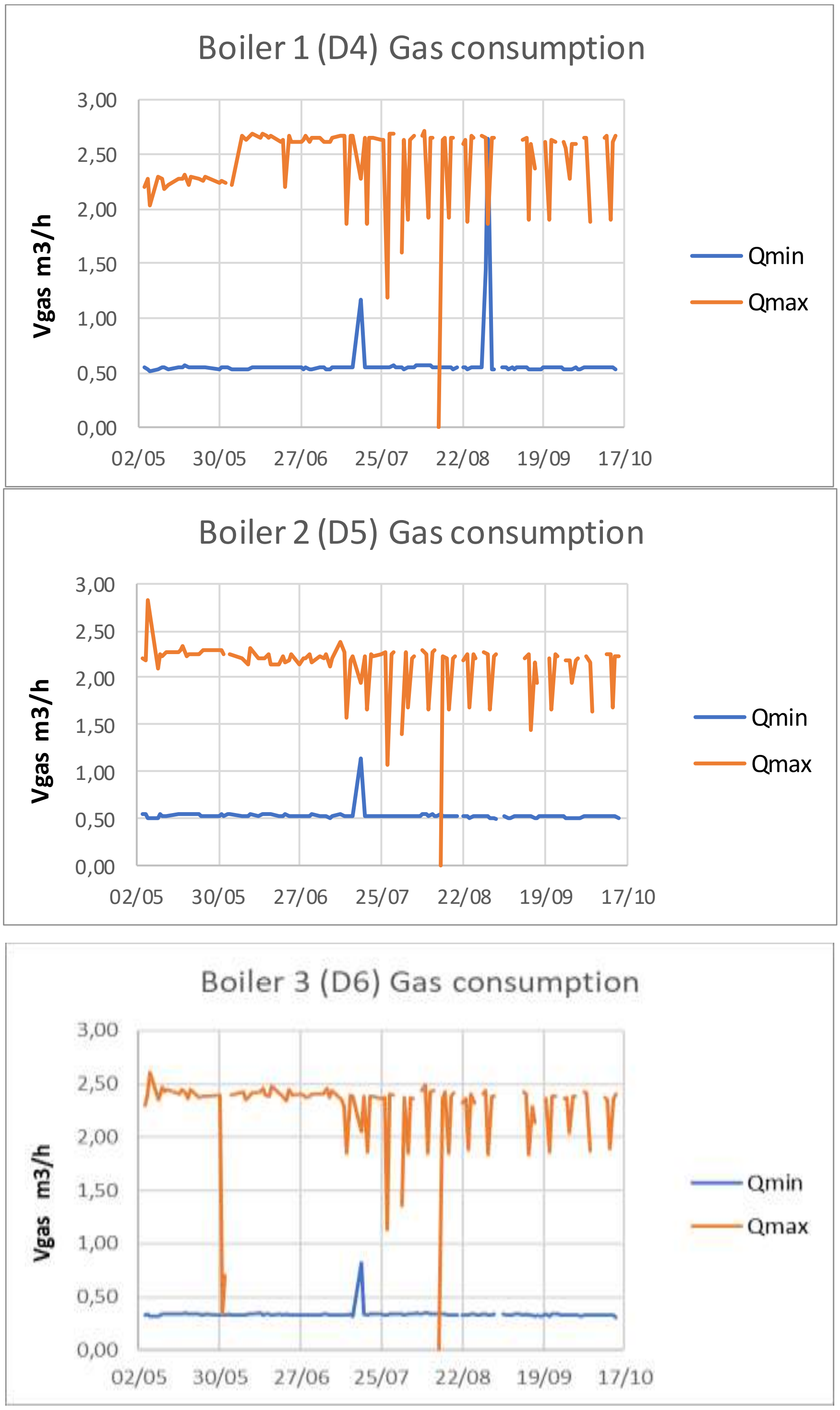


Figure 30: Gas consumption evolutions for the 3 boilers tested at DGC

There is a sudden change in gas consumption for boiler 1 at Qmax because the boiler was previously not functioning at Qmax but at a lower power (wrong setting by mistake).

The peaks on the figures are not reflecting physical changes of heat input but just measurement signals alteration between the measurements of two different appliances (Since an appliance is measured for 10 minutes and then another one is, there are peaks in-between).

2.3.4 O2

Slight decrease in O2 for D5, otherwise the levels remained stable.

Figure 31: O2 levels in the exhaust fumes evolutions for the 3 boilers tested at DGC

2.3.5 Conclusion

No evolution in the parameters, except boiler 1 (D5) with an increase in gas consumption and temperature on the 8th of June.

2.4 Conclusion on LTT based on data & observation of the components

All boilers have a certain amount of deposit/rust. The deposit seems to come from air pollution and is normal. Most of that deposit is on the top of the boilers. This is probably due to the evacuation of the flue gas from the top of the appliance. No evolution in the parameters, except boiler 1 (D4) with an increase in gas consumption and temperature in the beginning of June. This is because it was not previously run at Qmax (manipulation error).

As a result, after discussion with the manufacturers, our conclusion is that boilers tested in DGC for 4195 hours with 30 % of H2 according to our test protocol do not show particular differences as if operated with natural gas.

3 DGC test of two cookers

3.1 Protocol description

3.1.1 Test protocol

Figure 32 provides an overview of the different phases of operation of the cookers.

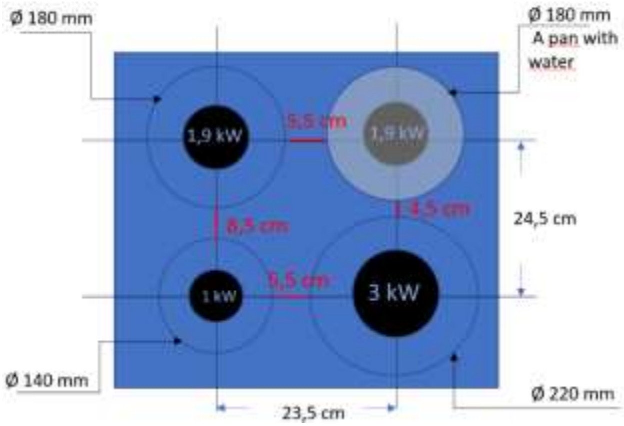
normal week																					
30% H2 in NG																					
		8:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	07:30
Day 1 +2	Boiler	Q min 30 % H2 + NG								break	Qmax		break	Qmax		break		Q min 30 % H2 + NG			
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG						break	All burner+ oven Qmax 30 % H2+ NG			All burner+ oven Qmin 30 % H2+ NG				break			
Day 3	Boiler	Q min 30 % H2 + NG								break	Qmax		break	part load at high s/s frequencey		break		Q min 30 % H2 + NG			
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG					Light back test weekly	break	All burner+ oven Qmax 30 % H2+ NG			All burner+ oven Qmin 30 % H2+ NG				break			
Day 4	Boiler	Q min 30 % H2 + NG								break	Qmax		break	Qmax		break		Q min 30 % H2 + NG			
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG						break	All burner+ oven Qmax 30 % H2+ NG			All burner+ oven Qmin 30 % H2+ NG				break			
Day 5	Boiler	Q min 30 % H2 + NG								break	Qmax		break	Qmax		break					
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG						break	All burner+ oven Qmax 30 % H2+ NG			All burner+ oven Qmin 30 % H2+ NG				break			
Day 3 + 5 once a month																					
		8:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	07:30
Day 3	Boiler	Q min 30 % H2 + NG								break	Test with CH4		break	part load at high s/s frequencey		break		Q min 30 % H2 + NG			
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG					Light light back test weekly	break	Test with CH4		All burner+ oven Qmax 30	All burner+ oven Qmin 30 % H2+ NG				break			
Day 5	Boiler	Q min 30 % H2 + NG								break	Qmax		break	Qmax		break					
	cooker	All burner+ oven Qmax 30 % H2+ NG		All burner+ oven Qmin 30 % H2+ NG						break	All burner+ oven Qmax 30 % H2+ NG			All burner+ oven Qmin 30 % H2+ NG			leakage verification	break			

Figure 32: Test protocol

Some comments:

- The monthly tests with G20 were done twice. No issues were observed.
- There are 4 temperature probes available by appliance, one for each burner.
- The cycle for measuring temperatures in the flue gas is 10 minutes.
- Leak verification was done with a leak detector and no leaks were detected.
- A stress test was performed with plates sent by a manufacturer. It consisted of using plates to overheat the burner underneath them. The test was conducted during the whole period of the long-term test. When emissions were measured, the pot with water was used, otherwise it was the plates. No issues observed.

Figure 33: Plates setup above, temperature probes setup underneath



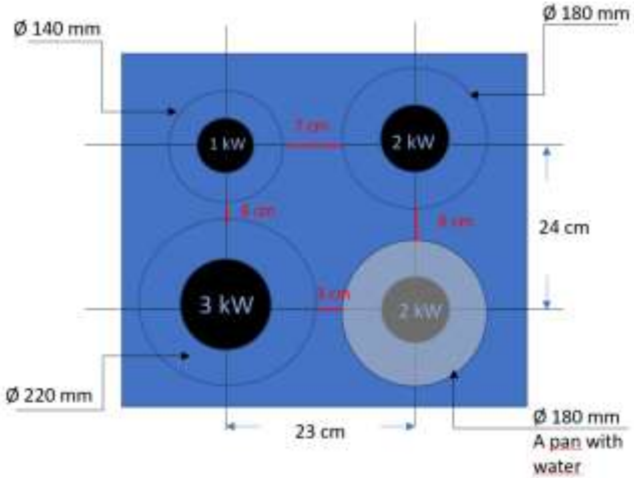


Figure 34: Cookers dimensions

3.1.2 Test gases

Table 8 provides the parameters of the gas distributed and used throughout the testing months in Denmark.

Table 8: Gas composition over the duration of the test

Parameter	Unit	May (avg)	30% H2		June (avg)	30% H2		July (avg)	30% H2		August (avg)	30% H2		September (avg)	30% H2		Global avg	30% H2
Carbon dioxide	% vol	0.74	0.52		1.40	0.98		1.37	0.96		1.28	0.90		1.26	0.88		1.21	0.85
Ethane	% vol	3.71	2.60		5.42	3.79		5.53	3.87		5.46	3.82		5.30	3.71		5.08	3.56
Hexane+	% vol	0.03	0.02		0.03	0.02		0.04	0.03		0.05	0.04		0.05	0.04		0.04	0.03
I-butane	% vol	0.08	0.06		0.13	0.09		0.17	0.12		0.17	0.12		0.19	0.13		0.15	0.10
I-pentane	% vol	0.01	0.01		0.03	0.02		0.03	0.02		0.04	0.03		0.05	0.04		0.03	0.02
Methane	% vol	94.37	66.06		90.82	63.57		90.29	63.20		90.33	63.23		90.39	63.27		91.24	63.87
N-butane	% vol	0.07	0.05		0.15	0.11		0.16	0.11		0.18	0.13		0.23	0.16		0.16	0.11
Nitrogen	% vol	0.55	0.39		0.98	0.69		1.22	0.85		1.16	0.81		1.14	0.80		1.01	0.71
N-pentane	% vol	0.01	0.01		0.02	0.01		0.02	0.01		0.03	0.02		0.04	0.03		0.02	0.02
Propane	% vol	0.44	0.31		1.03	0.72		1.16	0.81		1.30	0.91		1.36	0.95		1.06	0.74
Hydrogen	% vol	0.00	30.00		0.00	30.00		0.00	30.00		0.00	30.00		0.00	30.00		0.00	30.00
TOTAL	% vol	100.01	100.01		100.01	100.01		99.99	99.99		100.00	100.00		100.01	100.01		100.00	100.00
Gross Calorific Value	kWh/Nm³	11.36		11.52		11.55		11.60		11.62		11.61						
Gross Calorific Value	MJ/Nm³	40.90		41.49		41.58		41.75		41.83		41.79						
Net Calorific Value	kWh/Nm³	10.25		10.41		10.44		10.48		10.50		10.49						
Net Calorific Value	MJ/Nm³	36.91		37.47		37.57		37.72		37.79		37.76						
Wobbe Index	kWh/Nm³	14.79		14.70		14.69		14.74		14.76		14.75						
Wobbe Index	MJ/Nm³	53.26		52.92		52.88		53.06		53.13		53.09						

3.1.3 Appliances tested

Cooker 1 is free-standing cooker with “partially aerated ribbon burner” (oven) and an “atmospheric partially aerated single ring burner” (hob). The gas category is II 2H3B/P.

It has four hob burners and one oven:

- D1 is the big burner, its power input varies between 0,76 and 3 kW for G20.
- D2 is the small burner, its power input varies between 0,48 and 1kW for G20.
- D3 is the oven, its power input varies between 1 and 2,5 kW for G20.
- G1 and G2 are the medium burners, their power input varies between 0,48 and 1,9 kW for G20.

Cooker 2 is a free-standing cooker. The gas category is II 2H3B/P.

It has four hob burners and one oven:

- D7 is the big burner, its power input varies between 0,72 and 3 kW for G20.
- D8 is the small burner; its power input varies between 0,35 and 1 kW for G20.
- D9 is the oven, its power input varies between 0,9 and 2,7 kW for G20.
- E1 and E2 are the medium burners, their power input varies between 0,43 and 2 kW for G20.

These 2 cookers have been tested for THyGA “short term” tests before being tested for the long-term test.

3.1.4 Data measurement and conversion

The following data was measured:

- Gas consumption (Nm3/h)
- Heat input (kW)
- Temperature different burners and oven (°C)
- Flame safety device signal (mV) (only on big burner D7 and small burner D8 for cooker 2, special arrangement advised by manufacturer).

3.1.5 Deviations from the test protocol and unforeseen events during long term tests

A few unforeseen events took place or deviations from protocol took place:

- No measurements due to photo/video documentation sessions on the 24th of June and on 25th July.
- No emission measurements due to calibration/linearization on the 1st of August.
- Cooker 1's oven is thermostat regulated. When switching from Qmax to Qmin, it would turn off because the temperature would already be high enough. Therefore, no measures at Qmin for D3.
- Cooker 2's oven's flame supervision device also had issues (starting 08/07), making it turn off after some time at Qmin and not turn back on. It stopped being tested at Qmin from 02/08.

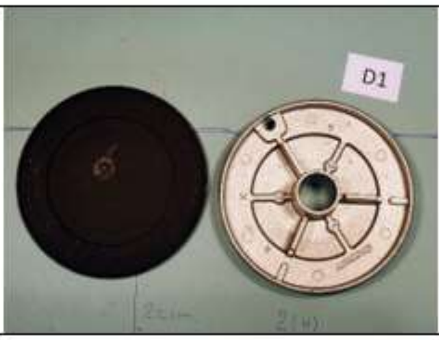
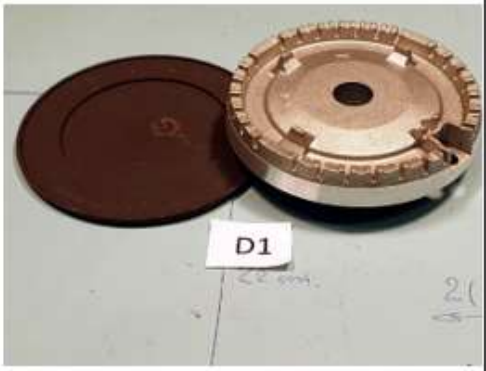
3.1.6 Testing time

Cooker 1 was tested for 2553 hours and cooker 2 for 2803 hours (sum of all cookers + oven).

3.2 Visual Observations

3.2.1 Cooker 1

3.2.1.1 D1, big burner

Ref	Before	After
D1.1		
D1.2		
D1.3		

D1.4		
D1.5		
D1.6		

Figure 35: Pictures from cooker 1, burner D1 N°1

Figure 36: Pictures from cooker 1, burner D1 N°2

Overall, marks of wear can be seen, especially on the burners. Picture D1.2 and Figure 36 show a sort of “petrol” reflection on the metal. Black marks on the sides and on top.

Some water was lost during the operations (from the pot), making the screws rust. The rust on the screws surrounding the ignition pit is uneven.

3.2.1.2 D2, small burner

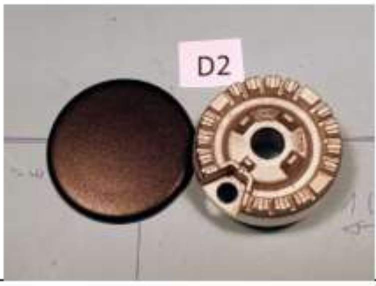
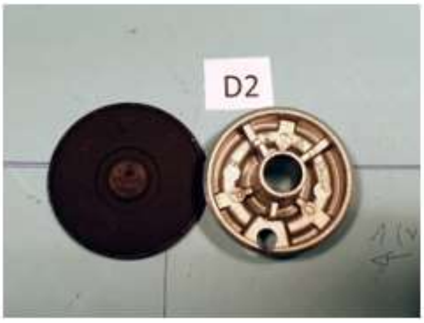
Ref	Before	After
D2.1		
D2.2		
D2.3		
D2.4		

Figure 37: Pictures from cooker 1, burner D2 N°1

Figure 38: Pictures from cooker 1, burner D2 N°2

Overall, marks of wear can be seen, especially on the burner itself. Unidentified black marks on side and on top. This is not soot because it does not leave when touched, could it be the coating changing/reacting?

3.2.1.3 D3, oven

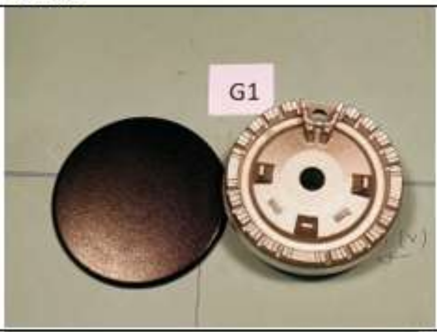
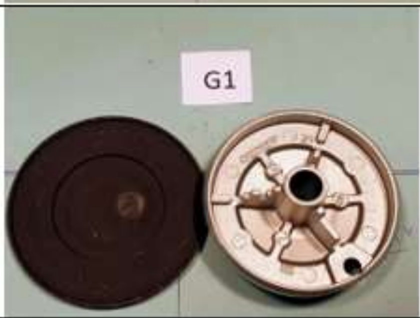
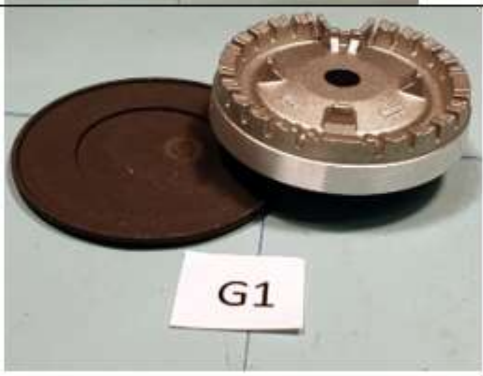
Ref	Before	After
D3.1		
D3.2		
D3.3		

Figure 39: Pictures from cooker 1, burner D3 N°1

Figure 40: Pictures from cooker 1, burner D3 N°2, tray above the burners

We do notice more deposit around the burner in all the photos after the long-term test, but it has not been possible to determine what was this deposit, where it came from (some coating using elements that could react with water and form deposit?).

3.2.1.4 G1, medium burner

Ref	Before	After
G1.1		
G1.2		
G1.3		
G1.4		

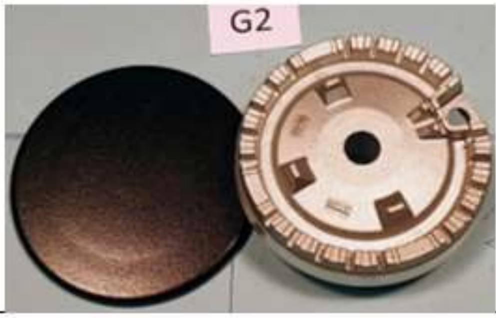
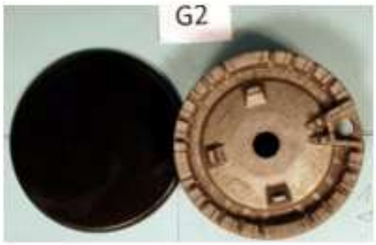
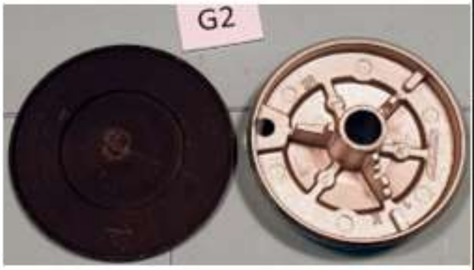
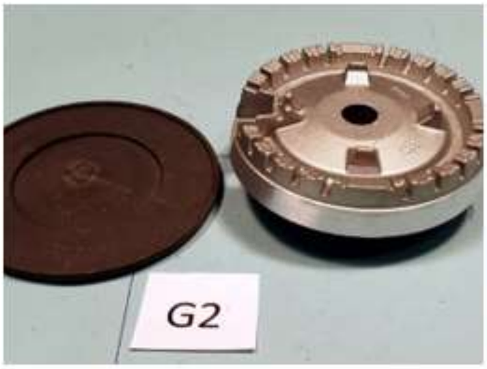
G1.5		
G1.6		

Figure 41: Pictures from cooker 1, burner G1 N°1

Figure 42: Pictures from cooker 1, burner G1 N°2

More deposit can be seen inside. The appearance is one of a used burner (as it would be with natural gas), especially on the sides. The deposit comes from spilled water.

3.2.1.5 G2, medium burner

Ref	Before	After
G2.1		
G2.2		
G2.3		
G2.4		

G2.5		

Figure: Pictures from cooker 1, burner G2 N°1

Figure 43: Picture from cooker 1, burner G2 N°2

The burner just looks generally used, especially on the sides.

3.2.2 Cooker 2

3.2.2.1 D7, big burner

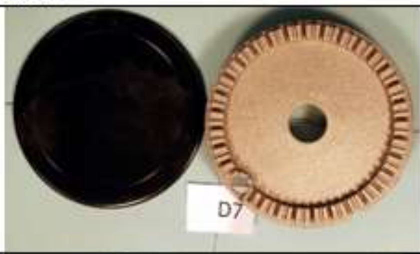
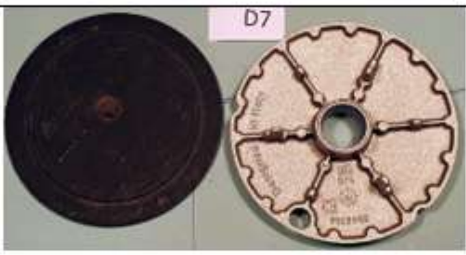
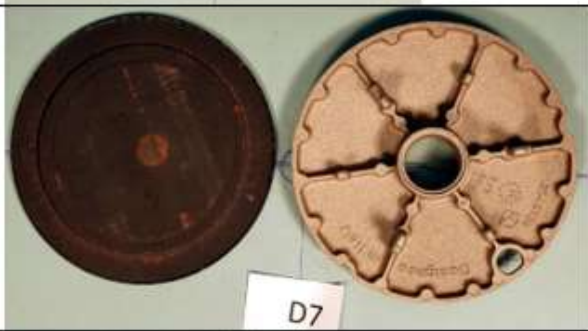
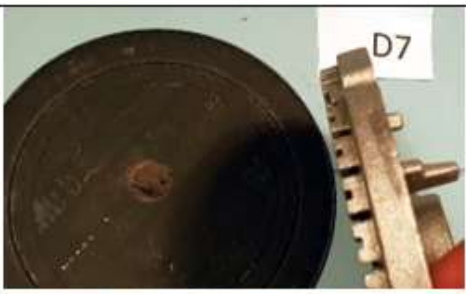
Ref	Before	After
D7.1		
D7.2		
D7.3		
D7.4		
D7.5		

Figure 44: Pictures from cooker 2, burner D1 N°1

Figure 45: Pictures from cooker 2, burner D1 N°2

There is no mark of wear and tear on the burner, but some deposit in the ignition pit and we observe more rust on the bottom of the burner cap, thin white cracks (see figure above), and deposit mark on its top. Nothing out of the ordinary.

3.2.2.2 D8, small burner

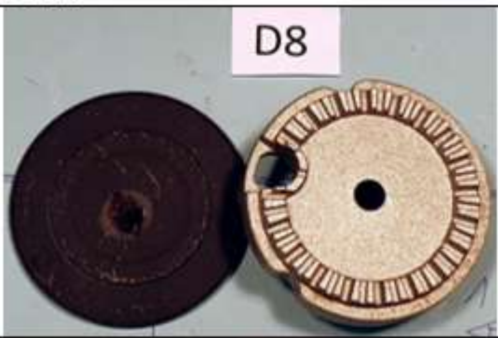
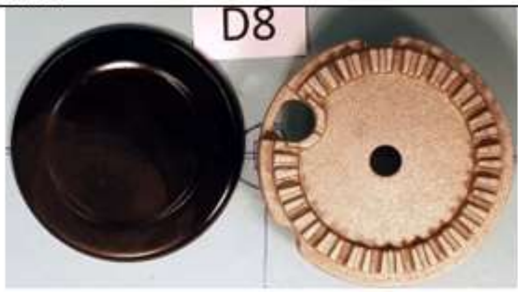
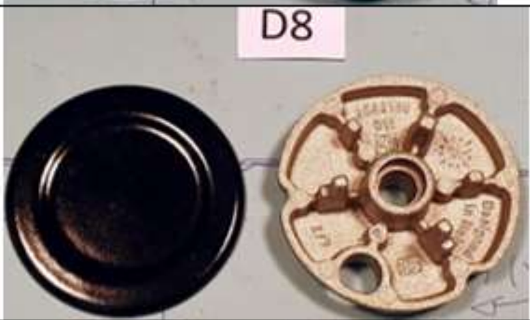
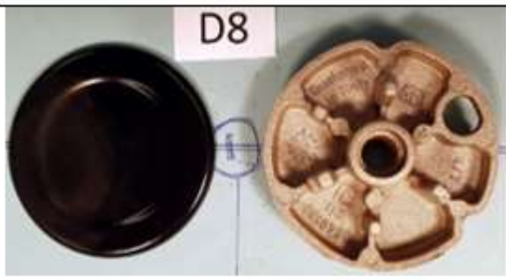
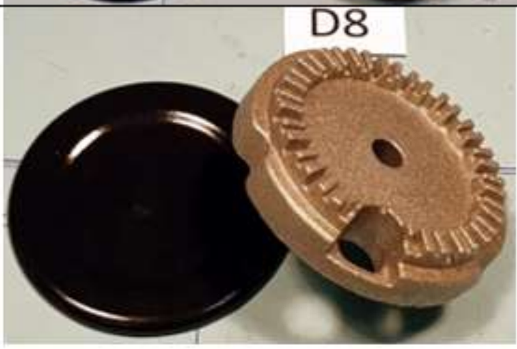
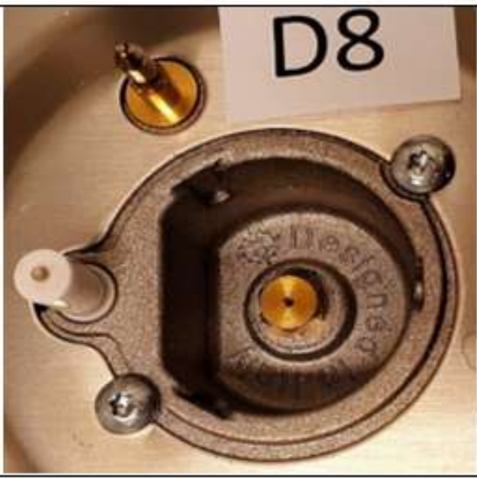
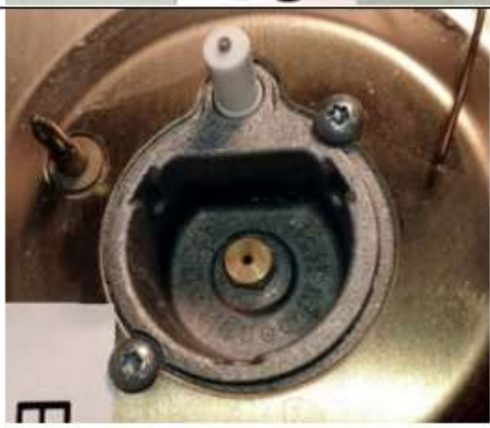
Ref	Before	After
D8.1		
D8.2		
D8.3		
D8.4		

Figure 46: Pictures from cooker 2, burner D8 N°1

Figure 47: Pictures from cooker 2, burner D8 N°2

No mark of wear and tear on the burner, deposit in the ignition pit but there are some white traces on the burner caps.

3.2.2.3 D9, bottom of the oven

Ref	Before	After
D9.1		
D9.2		

Figure 48: Pictures from cooker 2, burner D9 N°1

Small amount of deposit is seen, due to humidity of the combustion process but negligible.

Figure 49: Pictures from cooker 2, burner D9 N°1, tray above the burner

3.2.2.4 D10, top of the oven

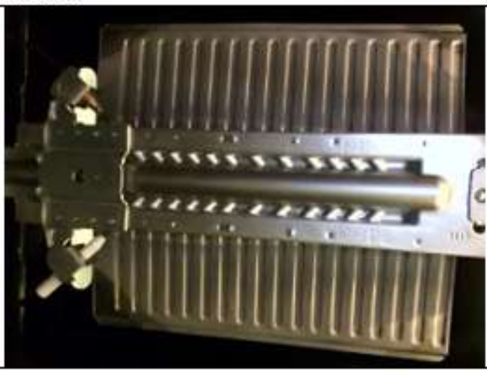
Ref	Before	After
D10.1		

Figure 50: Pictures from cooker 2, burner D10

No sign of wear and tear, deposit on the side grills. The deposit could come from pollution in the air or dust.

3.2.2.5 E1, medium burner

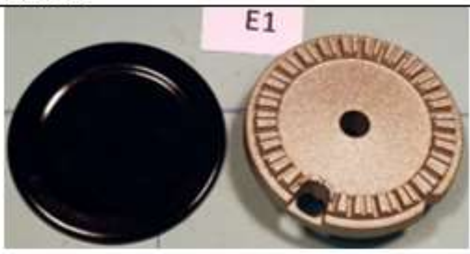
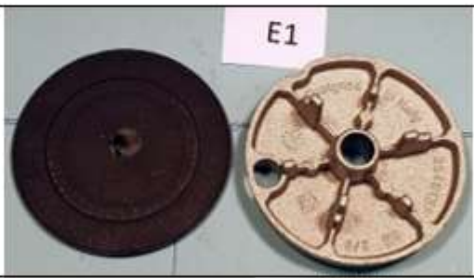
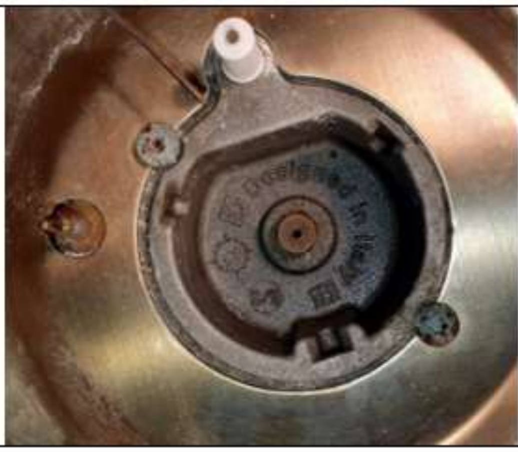
Ref	Before	After
E1.1		
E1.2		
E1.3		
E1.4		

Figure 51: Pictures from cooker 2, burner E1

No mark of wear and tear on the burner, limestone deposit in the ignition pit. Deposit traces on the top side of the burner caps and more rust on the bottom side.

3.2.2.6 E2, medium burner

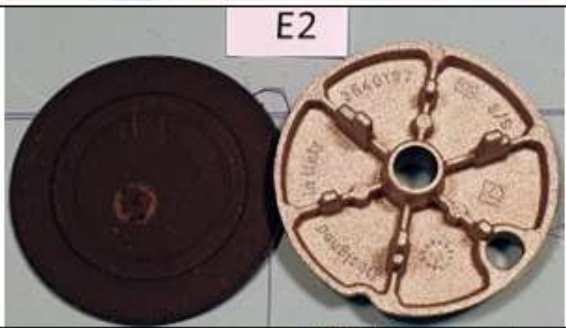
Ref	Before	After
E2.1		
E2.2		
E2.3		
E2.4		

Figure 52: Pictures from cooker 2, burner E2

No mark of wear and tear on the burner, limestone deposit in the ignition pit. White traces (could be limestone) on the top side of the burner cap and more rust on the bottom.

3.3 Comparison between new and used parts

3.3.1 Cooker 1

Figure 53: Comparison of parts before/after tests for cooker 1

On the left, the new parts and on the right, the used ones. We can see that there is a drastic change in color between the burners. It seems that the used one is less “grainy”. The burner cap has more rust on the bottom and deposit on top. There is no visible deformation after use.

3.3.2 Cooker 2

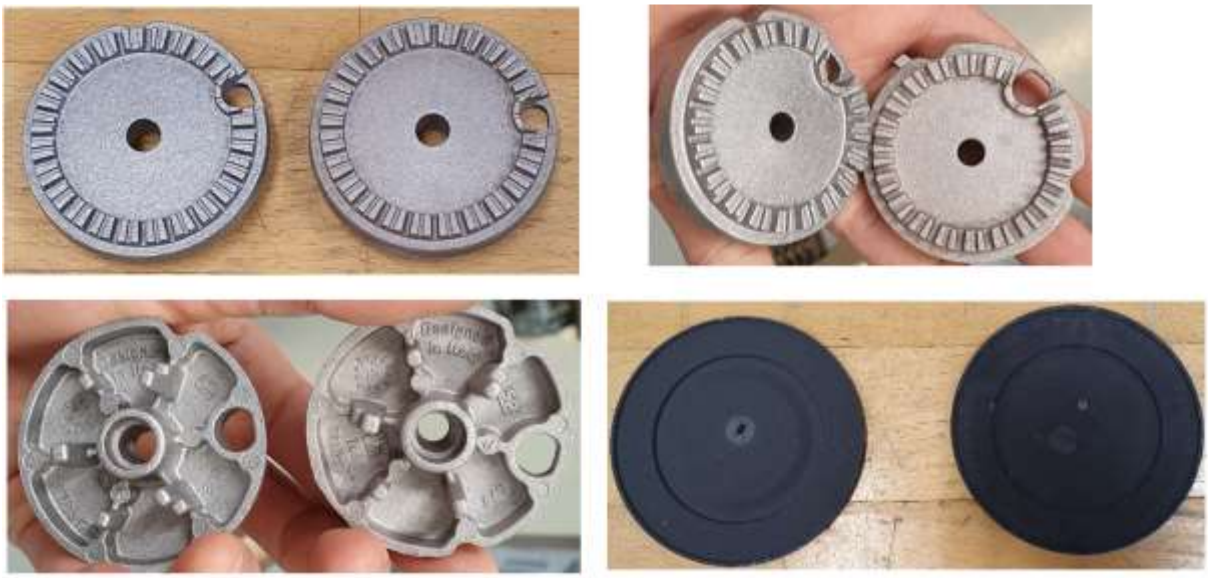


Figure 54: Comparison of parts before/after tests for cooker 2

On the left, the new pieces and on the right the used ones. We notice that the color of the burner changed, becoming more yellowish, (presumably like a behavior with natural gas). The burner cap only has some markings due to deposit and wear (the white ring around the edge on the last photo).

There is no visible deformation after use.

Comments received from the manufacturer:

The results presented have been discussed with one of the manufacturers and the conclusions are made considering the information we have received.

3.3.3 Overall conclusion

The Cooker 1 oven shows signs of usage, in the form of black marks (not soot, it does not mark the finger) on the burners and oily reflections. The oily reflections are normal for aluminium and depend on the alloy. The black marks could come from the migration of metals inside the burner to its surface.

The cooker 2 oven shows no sign of wear, except for more limestone deposit in the ignition pit (due to spilled water) and on the burner caps. The burner caps also have more rust. As for why there is no marks or oily reflections, the coating might be different on the second appliance. It is a bit more yellowish but not in a problematic way. It seems less grainy, which shouldn’t change. This could be due to the higher temperature of the flame with hydrogen.

In general, the screws near the ignition pit do not have the same quantity of rust and limestone deposit. The smaller burners (D2, D8) seem to be the least touched (logical), whereas the bigger ones rust more. In the case of D1, the rust is uneven on the two screws, possibly a geometry problem?

There is a deposit in the oven, we do not know where it comes from.

3.4 Test Data measured

This test is done with CH4 to check if there is a difference in emission levels from before to after the long-term test.

Table 9: Difference in emissions before/after Long Term Test

		Flue Gas (Measured)					Flue Gas (Calculated)				
		CO [ppm]	NO_x [ppm]	NO_2 [ppm]	CO_2 [%]	O_2 [%]	CO ref [ppm]	NOx ref [ppm]	CO ref mg/kWh	NOx ref mg/kWh	Air excess lambda
D1	BEFORE	57	24	6	3.6	14.5	185	79	198	139	3.2
	AFTER	79	24	7	4.0	13.8	233	69	249	122	2.9
D2	BEFORE	8	12	3	1.9	17.5	49	74	53	130	6.1
	AFTER	14	13	3	2.2	17.0	74	67	79	117	5.3
D3	BEFORE	27	17	12	2.6	16.4	125	78	134	137	4.6
	AFTER	26	18	5	2.7	16.1	108	74	115	131	4.3
D7	BEFORE	367	29		4.7	12.7	909	72	972	127	2.5
	AFTER	232	28	11	4.6	12.7	583	70	624	123	2.5
D8	BEFORE	89	13	5	2.2	17.1	471	69	504	121	5.4
	AFTER	137	13	6	2.3	16.8	688	66	736	116	5.0
D9	BEFORE	25	13	9	2.0	17.5	145	76	156	133	6.0
	AFTER	23	12	8	1.9	17.6	143	72	153	127	6.1

	Difference after/before									
	CO [ppm]	NO_x [ppm]	NO_2 [ppm]	CO_2 [%]	O_2 [%]	CO ref [ppm]	NOx ref [ppm]	CO ref mg/kWh	NOx ref mg/kWh	Air excess lambda
D1	22	-1	1	0.4	-0.7	48	-10	52	-17	-0.3
D2	6	0	0	0.3	-0.5	25	-7	26	-13	-0.8
D3	-1	1	-7	0.1	-0.3	-17	-4	-18	-7	-0.3
D7	**-135**	-1	11	-0.1	0.0	**-326**	-2	**-348**	-4	0.0
D8	48	0	1	0.1	-0.3	**217**	-3	**233**	-5	-0.4
D9	-2	-1	-1	-0.1	0.1	-3	-4	-3	-6	0.1

A test done later with cooker 2 (D7, D8 and D9) showed that the injector was not well screwed in, causing high CO emissions.

The emission levels are pretty much the same, with no tendency to go up or down (D8 shows an increase in CO while D7 a decrease).

3.5 Conclusion on LTT based on data & observation of the components

It seems that both cookers tested with 30% H2 are not impacted by the use of H2NG blends compared to a typical use with natural gas.

There are differences in the aspect of burners after 2553 hours of testing for cooker 1 and 2803 hours of testing for cooker 2, but exchanges with manufacturers suggest that the same would have been observed with natural gas.

The change in aspect, especially for cooker 1, could be due to an increase in material temperatures due to a flame position closer to the burner when admixing hydrogen.

The emission levels are pretty much the same, with no tendency to go up or down (D8 shows an increase in CO, while D7 shows a decrease).

In conclusion, the data measured before and after the long-term tests do not show any visual signs that suggest that the long-term test has impacted the tested appliances negatively.

4 Conclusion

The tests carried out with a blend of natural gas with 30% hydrogen under the test conditions and duration given have not shown any particular impact on the performances and operation of the appliances.

The signs of wear and tear that were observed for boilers would have also been observed using pure natural gas and there is no visible additional impact due to the presence of hydrogen.

For one of the cookers tested – probably due to a higher temperature - the appearance of the burner surface did change but without impacting the performances. The quality of the material / alloys used for the burner is certainly playing an important role.

Those results are positive but cannot be extrapolated to the Millions of appliances on the market due to obvious limitations of our test campaign which most importantly are:

- The high diversity of appliances types, and materials used for the > 200 millions of appliances installed in the EU.
- The shorter testing time compared to the appliance's normal lifetime.

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