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

Test report on mitigation solutions for residential natural gas appliances not designed for hydrogen admixture

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Executive summary

Adding hydrogen into the gas grid will have a beneficial effect on CO_2 emissions and will contribute to reduce our dependency on fossil fuels. However, due to physico-chemical properties different from those of natural gas, hydrogen, even mixed at low proportion to natural gas, may alter the proper functioning of some gas appliances. This was previously discussed in THyGA's reports combustion-theoretical report D2.2 and the appliance-focussed report D2.3 [1,2].

Thanks to its extensive testing programme, the THyGA project provides information on the extend of perturbations that hydrogen could cause to gas appliances [3]. This work has confirmed that **field adjustment** of gas appliances can be an issue if current practices are not updated. For some appliances, when they are adjusted with a low Wobbe Index gas mixed with 20% hydrogen and used afterwards with a high Wobbe Index gas without hydrogen, it can produce high amounts of CO emissions. Several mitigation solutions have been studied. Among them, we can underline:

- Appliance adjustment should be based on O_2 values, rather than CO_2 values.
- The authors suggest going further, and to forbid field adjustment or to re-adjust all appliances back to G20 prior to injecting hydrogen in the natural gas grid.
- It is preferable to use combustion-controlled boilers that keep the air/fuel ratio constant (via ionization probe or CO sensor).

However, concerning the last bullet point, more investigations should be performed to clarify if flashback occurs during auto-calibration periods, when the boiler operates for a few seconds in near-stoichiometric conditions.

Some directions for other potential mitigation measures are also suggested in this report.

Moreover, test results show that the CO_2 (or O_2) range of adjustment suggested by manufacturers on some appliances may have to be updated in order to take into account adjustment from low Wobbe Index and use with high Wobbe Index gases. This is especially required for appliances that operate with a very low air excess.

Concerning existing appliances, the previous report [4] mentioned a **grey area concerning natural draught for exhaust fumes**: the increase of air excess caused by the introduction of hydrogen could lower flue gas temperature, thus causing draught problem on appliances with no fan.

Up to 20% H_2, natural draught is almost not impacted by H_2 admixture. In most cases, the flowrate of the flue gas was reduced or remained constant when hydrogen was added. Relative density of flue gas at maximum heating power is higher than at minimum heating power and will not cause any trouble. Relative density of flue gas ($\varrho_{flue}/\varrho_{air}(15°C)$) at Qmin is always below 0.83 up to 40% H_2. Its variation is lower than 1% between 0% H_2 and 40% H_2. As a consequence, no natural draught problems are expected in the range 0-40% H_2.

Also, the increase of the proportion of water vapour in the flue gas could cause problems of **condensation in flue pipes not designed for**. The impact of this phenomenon was checked experimentally to investigate if mitigation measures are required.

Up to 20% H_2, extra condensation is not expected to appear for non-condensing boilers, as several physical effects compensate each other. The more difficult configuration occurs at minimum heating power where flue gas temperature is lower. Even with 40% H_2, the minimum temperature difference between flue gas temperature and dew point temperature leaves some safety margin.

Concerning the **acidity of the condensates**, it has been checked that it does not increase with rising hydrogen concentration. It is known that hydrogen has a higher adiabatic flame temperature than natural gas. Flame temperature has an impact on the production of thermal NOx. NOx tends to dissolve in condensed water of condensing appliances and form nitric acid leading to acidity of the condensates. As a consequence, the impact of hydrogen on condensates was experimentally investigated. Condensates acidity was measured on several boilers. Acidity decreases with increasing hydrogen concentrations in the fuel gas. This is caused by the decrease of NOx concentration in flue gas.

For partially premixed appliances, such as cookers, hydrogen addition has two impacts: it increases the flame velocity by increasing the rate of combustion chemical reactions and it increases the primary fuel/air ratio which also increases flame velocity. A potential solution would be to change gas injectors of cooktop tables to make the primary air/fuel ratio a little bit poorer. This was also tested within the THyGA project.

A 2.75 kW cooktop burner was operated with no flashback up to 80% H_2. However, CO emissions DAF were close to 1000 ppm when the burner was used with pure methane. The modification works well if the hydrogen level is kept above 20% but is not adequate for H2NG when the hydrogen concentration varies between 0 and 20%.

List of abbreviations

ACCF	Adaptative Combustion Control Functions
AP	Advisory Panel Group
CARI	Combustion Air Ratio Index
CH_4	Methane
C_3H_8	Propane
CHP	Combined Heat and Power
CO	Carbon monoxide
DAF	Dry Air Free
EU	European Union
GA	Grant Agreement
GAD	Gas Appliances Directive
GAR	Gas Appliances Regulation
H_2	Hydrogen
H_2NG	Hydrogen / Natural Gas blend
HCV	Higher Calorific Value
Lambda	Air excess
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
N_2	Nitrogen
NG	Natural gas
ρ	density
Qflue	Exhaust fumes flowrate
Qmax	Maximum heating power
Qmin	Minimum heating power
S_L	laminar flame velocity
Tad	Adiabatic Temperature of combustion
TC	CEN/CENELEC Technical Committee
Ws	(Superior) Wobbe Index (MJ/m3 at 15/15)
λ	Air-fuel equivalence ratio

Note that this document uses reference temperatures at (15°C/15°C) for heating power and Wobbe Index.

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Introduction

Adding hydrogen into the gas grid will have a beneficial effect on CO2 emissions and will contribute to reduce our dependency on fossil fuels in various energy sectors [5], among others, in the heating and cooking sectors. However, due to physico-chemical properties different from those of natural gas, hydrogen, even mixed at low proportion to natural gas, may disrupt the proper functioning of some gas appliances. This was previously discussed in THyGA's reports on combustion theory D2.2 and on the appliance-focussed report D2.3 [1,2]. Thanks to an extensive testing programme, the THyGA project has provided information on the extend of perturbations that hydrogen could cause to gas appliances [3]. Some of the test results show that, when an appliance is adjusted with a low Wobbe Index gas mixed with 20% hydrogen and used afterwards with a high Wobbe Index gas without hydrogen, it can produce high amounts of CO emissions. To mitigate this problem, the option of performing appliance adjustment based on O2 measurement rather than CO2 measurement was explored as well as other options.

Another approach to adjustment, for new appliances, is to use adaptive combustion control function (ACCF) or 'combustion control'. Currently, ACCF is mainly based on ionization sensors which fail to detect the presence of hydrogen in the fuel. An alternative technology, based on a CO sensor, has been tested to check if it brings improvements or not.

Concerning existing appliances, the previous report mentioned a grey area concerning natural draught: the increase of air excess caused by the introduction of hydrogen could lower flue gas temperature, thus causing a draught problem for ducts not designed for operation with pressure. Also, the increase of the proportion of water vapour in the flue gas could cause problems of condensation in flue pipes not designed for. The impact of these phenomena was checked experimentally, to investigate if mitigation measures are required.

It is also known that hydrogen has a higher adiabatic flame temperature than natural gas. Flame temperature has an impact on the production of thermal NOx. NOx tends to dissolve in condensed water of condensing appliances and form nitric acid. As a consequence, the impact of hydrogen on condensates was experimentally investigated.

For partially premixed appliances, such as cookers, hydrogen addition has two impacts: it increases the flame velocity by increasing the rate of combustion chemical reactions and it increases the primary fuel/air ratio which also increases flame velocity. One potential solution could be to change gas injectors of a cooktop table burner to make the primary air/fuel ratio a little bit poorer to make cooking burners more resilient to flashback. Tests results will be presented in this report.

1. Adjustment

1.1 Context

Europe is currently facing a technical challenge concerning the impact of gas sources on the Wobbe Index range of delivered gases. In one hand, the European goal is on its way to switch from fossil gases to renewable energies such as low Wobbe Index biomethane. On the other hand, the geopolitical context is in favour of high Wobbe Index LNG imports to replace Russian gas transported by pipe. Thus, more and more customers will encounter a wide range of Wobbe Indexes in the transition period between now and 2050 (Figure 1).

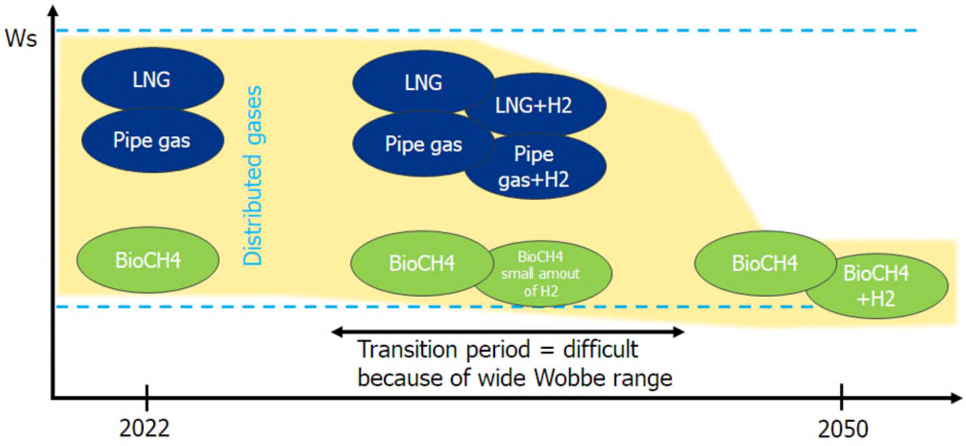

Figure 1: Probable evolution of gas sources over the period 2022-2050

Although gas appliances are tested and certified with a range of limit gases wider than the normally delivered gases in Europe [6], it is a common practice to adjust them to the local gas during installation in order to optimize their performances and reduce their emissions. However, this practice may lead to adverse effects when gas quality changes.

In the past, the European project GASQUAL has studied the impact of adjustment when gas quality varies [7]. The work performed in GASQUAL consisted in testing mostly new appliances (about 100) conform to the Gas Appliance Directive. Appliances were adjusted with G20 (reference gas, WI=50.72MJ/m3 at 15/15), G23 (45,67MJ/m3), G21 (54.76MJ/m3). The impact on different aspects were assessed:

- CO emissions
- Other safety issues
- Operational aspects

The main conclusions of the project were:

- About 5 % of appliances have issues all over the range of Wobbe Index. Those appliances are all from full premixed boilers that are adjusted with G23. Those in the same segment that are adjusted with G20 can cope with the entire Wobbe Index range.
- About 95 % have no or only low impact of gas quality over the range of Wobbe 46 to 50,8 MJ/m3 (ΔWs=4.8 MJ/m3)
- About 50 % have no or only low impact of gas quality over the whole range of Wobbe 46 to 54,7 MJ/m3 (ΔWs=8.8 MJ/m3)

At the beginning of the THyGA project, it was decided to study adjustments based on European distributed gases [8] and to test adjustments based on a Wobbe range between 47,63 MJ/m3 (EUlow) and 52,78 (EUhigh) MJ/m3 (15/15) (ΔWs= 5,15 MJ). As EUlow[1] mixed with 20%H2 has a Wobbe Index of 45.6 MJ/m3, the Wobbe range covered by the tests is close to the one of the GASQUAL project, at ΔWs=7.18 MJ/m3.

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[1] EUlow : lower distributed Wobbe Index in Europe

1.2 Theory behind adjustment on O2 and CO2 values

Some equations are needed to have a better knowledge on why O2 adjustment is better than CO2 adjustment. They are described in this section.

By definition of air-fuel equivalence ratio λ:

(Eq 1.) $$\lambda = \frac{V_a+V_{ae}}{V_a}$$

With

Va	Volume of air required to burn 1m^3 of gas (m^3 of air/m^3 of gas)
Vae	Volume of air in excess (m^3 of air/m^3 of gas)
Vf0	Volume of dry burnt gases generated by the combustion of 1 m3 of gas (m^3 of flue gas/m^3 of gas)
λ	Air–fuel equivalence ratio

(Eq 2.) $$\%CO_{2\,max} = \frac{VCO_{2\,max}}{V_{f0}}$$

With:

$VCO_{2\,max}$	Stoichiometric volume of CO2 produced by combustion
$\%CO_{2\,max}$	The stoichiometric percentage of CO2

(Eq 3.) $$\%CO_2 = \frac{VCO_{2\,max}}{V_{f0}+V_{ae}}$$

Combining the two previous equations

(Eq 4.) $$V_{ae} = V_{f0}\,\frac{(\%CO_{2\,max}-\%CO_2)}{\%CO_2}$$

By combining the previous equation with the definition of Air–fuel equivalence ratio, we can write the equation linking the dry %CO2 measured during adjustment and the air excess:

(Eq 5.) $$\lambda = 1 + \frac{V_{f0}}{V_a}\,\frac{(\%CO_{2\,max}-\%CO_2)}{\%CO_2}$$

Now, let’s establish the relation between %O2 measured and λ.

By definition:

(Eq 6.) $$\%O_2 = \frac{21\%\,V_{ae}}{V_{f0}+V_{ae}}$$

Where 21% Is the percentage of O2 in air.

So:

(Eq 7.) $$V_{ae} = V_{f0}\,\frac{\%O_2}{21\%-\%O_2}$$

By introducing previous equation into the air–fuel equivalence ratio definition (Eq 1.), we can write the relation between λ and %O2.

(Eq 8.) $$\%O_2 = \frac{21\%}{1+\frac{V_{f0}}{V_a(\lambda-1)}}$$

By combining the two previous framed equations, the relation between %C02 and %O2 is deduced:

(Eq 9.) $$\%O2 = 21\% - \frac{21\%}{\%CO2_{max}}\,\%CO2$$

(Eq 9.) is the relation between the %CO2 used for adjustment and the %O2 used in THyGA’s tests of adjustments. This relation shows why CO2 adjustment is not optimum: if an appliance is adjusted with

%CO2, then the %O2 available for combustion depends on the nature of the fuel through the value of $\%CO2_{max}$ (%CO2 in flue gas in stoichiometric conditions).

It is also possible to calculate %CO2 from the λ value:

$$\%CO2 = \frac{\%CO2_{max}}{1+\frac{V_a(\lambda-1)}{V_{f0}}} \quad \text{(Eq 10.)}$$

1.3 Adjustment on CO2, why it doesn't work well

For premix air-tight appliances, it is usually considered that CO emissions are correlated to the air excess.

- If there is not enough air, then combustion is too rich. CO molecules can't find O2 molecules to be oxidized to CO2, which lead to high CO emissions.
- On the contrary, if there is too much air, combustion becomes unstable and lead to an increase of CO emissions.

These phenomena are usually put in evidence by tracing CO emissions as a function of %O2 in flue gas, as on Figure 2.

It is well known that different gases have different combustion air quantity requirements. Depending on the initial adjustment of an appliance, variation of gas quality could lead to an increase of CO emissions by lack or by excess of air, as also shown on Figure 2.

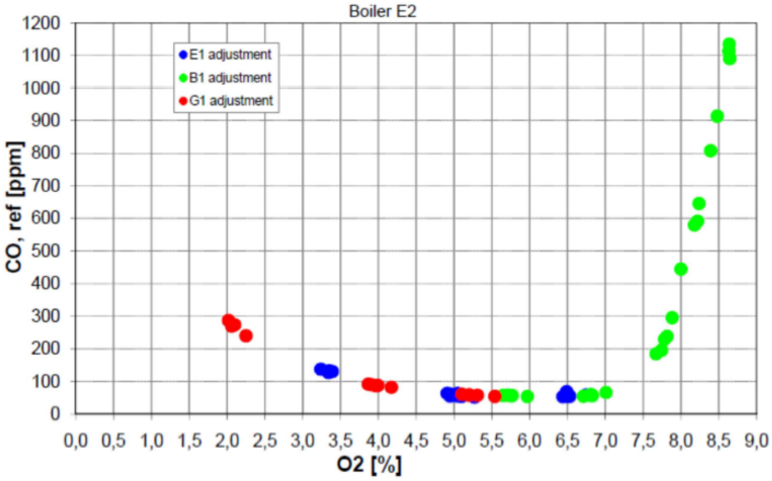

Figure 2: Impact of air excess on CO emissions (Source: [7])

The most difficult adjustment test performed during the THyGA project is adjustment "G" [8], when the appliance is adjusted at EUlow+20%H2 and then used with EUhigh[2] (Figure 3). During this test the appliance is adjusted to the lowest Wobbe index gas (EUlow+20%H2) and used afterwards with the highest Wobbe Index gas (EUhigh).

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[2] EUhigh : Natural gas distributed in Europe with a typical high Wobbe Index

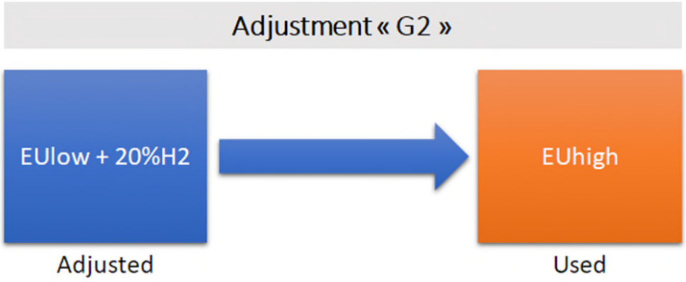


Figure 3: Adjustment test "G2" is the most difficult adjustment test within the THyGA project.

During THyGA's tests, it has been observed, on a several appliances, that operating the appliance at EUhigh after adjusting the appliance at EUlow+20%H2 can lead to high CO emissions (Figure 4 is one example of what could happen).

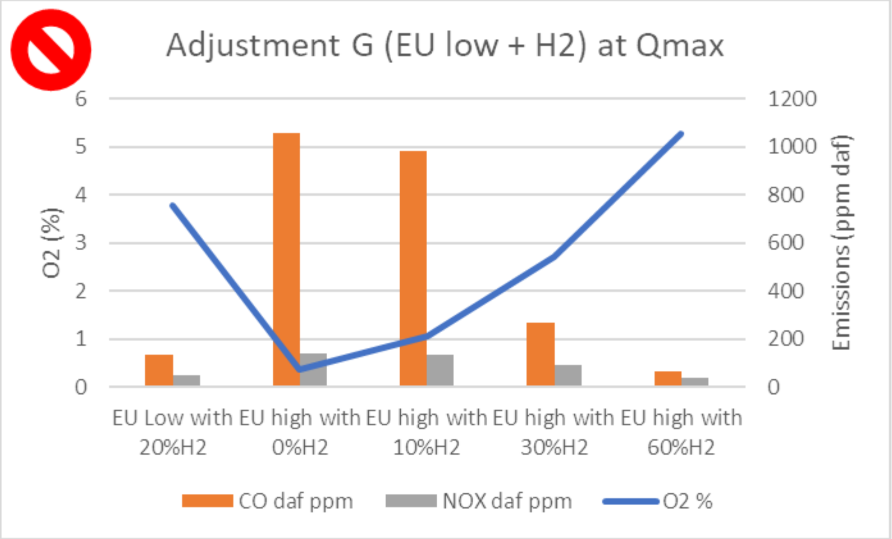


Figure 4: Example of high CO emissions caused by adjustment and gas change in an extreme case.

There are two reasons that cause appliances to emit more CO in this test:

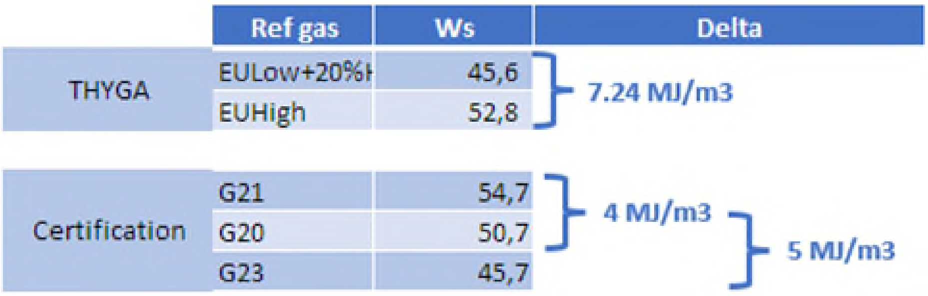
- The first one is the high value of the Wobbe index difference between EUlow+20%H2 and EUhigh (+7.24 MJ/m3).
- The second one is that the relationship between CO2 and λ, which was valid for natural gases, is no longer valid with hydrogen. This leads to a misadjustment (adjustment at the wrong λ).

This will be explained in detail in the next sections.

1.3.1 The Wobbe index step

Going from EUlow+20%H2 to EUhigh corresponds to an increase of the Wobbe index by 7.24 MJ/m3.

By comparison, the H category of the second family has a Wobbe index range of 9 MJ/m3 but, considering that appliances are factory-adjusted for G20, the maximum jump of Wobbe index is reduced to 5 MJ/m3 for certification tests (Table 1).



	Ref gas	Ws	Delta
THYGA	EULow+20%	45,6	7.24 MJ/m3
	EUHigh	52,8	
Certification	G21	54,7	4 MJ/m3
	G20	50,7	5 MJ/m3
	G23	45,7	

Table 1: Variations of Wobbe Index during adjustments.

1.3.2 Difference between adjustment using CO2 and O2 values

The goal of adjustment is to make the appliance operate with maximum performance at a specific air–fuel equivalence ratio λ. Currently, adjustment in the field is typically based on the measurement of the CO2 concentration in the flue gas. The technician compares the values to the default value or value range as defined by the manufacturer and adjusts the appliance until it meets this specification.

The relation between %CO2 and λ is given by (Eq 10.). Nowadays, this relation is correct because, for natural gas, the value of %CO2max does not change much from one natural gas to another. However, it will no longer be the case in the future, if notable amounts of hydrogen are admixed to natural gas.

Table 2 shows what happens when an appliance is adjusted at 8.8% of CO2 in the flue gas with different kinds of possible distributed gases:

- If the appliance is fed with G20 during adjustment (CO2=8.8%), the air/fuel equivalence ratio λ is set to its nominal value of 1.3
- If the appliance is fed with EUlow or EUhigh and the appliance is again adjusted to 8.8% of CO2, it is adjusted to a λ value close to 1.3. It is indeed slightly different, about 1.29 for EUlow and 1.33 for EUhigh.

Reference gas	Va	Vf0	%CO2max	Lambda
G20	9,56	8,56	11,70%	1,30
EUlow	9,14	8,23	11,62%	1,29
EUhigh	10,52	9,45	12,00%	1,33
G20+20%H2	7,79	6,96	10,99%	1,22

Table 2: Impact of gas composition on λ, for an appliance adjusted for G20, for an adjustment based on CO2 (8.8%CO2).

However, when G20 is mixed with 20%H2, the %CO2max value drops to 10.99% instead of 11.70% and the appliance is adjusted to a λ value lower than the target value of 1.30 (λ=1.22). In other words, after the procedure with admixed hydrogen, the appliance operates in richer conditions, closer to the stoichiometric value.

If, one day, the very same appliance is fed with a gas with a high Wobbe Index (ex: EUhigh), then the air/fuel ratio will decrease to a richer value, close or below stoichiometry and will cause the flame to emit CO above the usual limits due to a lack of oxygen available in the fuel/air mix for CO2 formation.

Ref gas	Va	Vf0	Vf0/Va	Lambda
G20	9,56	8,56	0,90	1,30
EUlow	9,14	8,23	0,90	1,30
EUhigh	10,52	9,45	0,90	1,30
G20+20%H2	7,79	6,96	0,89	1,30

Table 3: Impact of gas composition on λ for an adjustment based on O2 (5.3%O2)

When an appliance is adjusted based on O2 measurement instead, only Vf0/Va is involved in the mathematical relation between O2 and λ (Eq 6.). This value is quite constant for natural gases and does not vary much for G20+20%H2**. As a consequence, adjustment based on O2 leads to the expected value of λ** (see Table 3).

The impact of the choice of O2 vs CO2 adjustment can be estimated from CO and O2 measurement in the flue gas. CO emissions of an appliance can be deduced from %O2 in flue gas thanks to a mathematical correlation (Figure 5). Variations of λ, when switching from one gas to another are calculated by using the Combustion Air Ratio Index (CARI) of each gas. %CO2 and %O2 are calculated using equations presented in section 1.2.

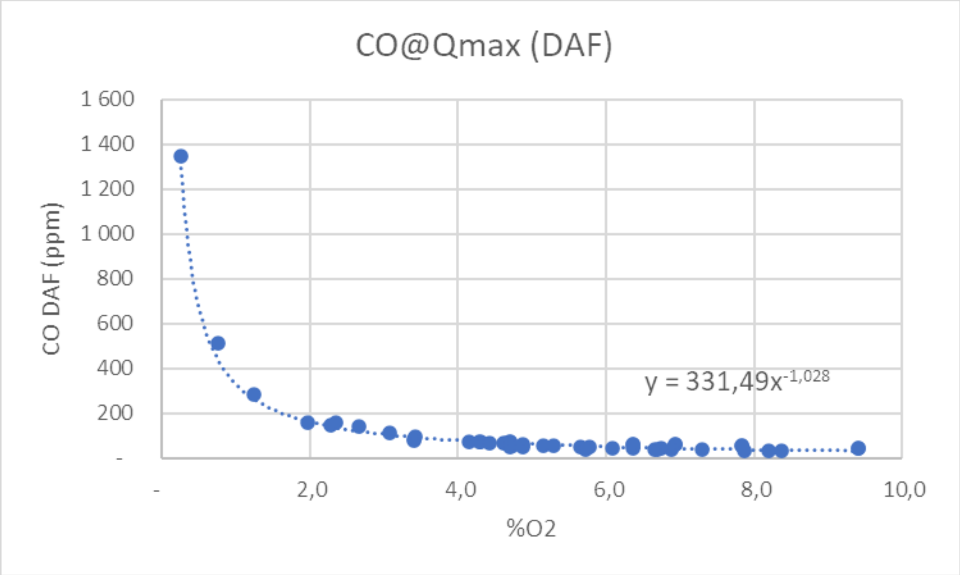


Figure 5: CO emissions vs %O2 in flue gas for appliance GW08.

Table 4 shows the simulated impact of CO2/O2 adjustment. The first table shows the reference adjustment for G20 at 7.8% of CO2, which corresponds to a %O2 of 6.9%.

The second table shows what happens when the appliance is adjusted at 7.8 % of CO2 when it operates with EUlow+20%H2. When the gas is changed to EUhigh, CO emissions are estimated to be 1940 ppm.

The third table shows what happens when the appliance is adjusted, with EUlow+20%H2, at 6.9 % O2. When the gas is switched to EUhigh, calculated CO emissions are largely below 1000 ppm, at a level of only 228 ppm.

Reference adjustment (G20)

Ref gas	Va	Vf0	%CO2max	CARI	Lambda	%CO2	%O2	Estimated CO (ppm)
G20	9,14	8,23	11,62%	12,08	1,44	**7,8%**	**6,9%**	48

Adjustment with CO2

Ref gas	Va	Vf0	%CO2max	CARI	Lambda	%CO2	%O2	Estimated CO (ppm)
Eulow+20%H2	7,79	6,96	11%	11,34	1,36	7,8%	6,0%	55
EUHigh	10,52	9,45	12%	13,36	1,01	11,9%	0,2%	**1 940**

Adjustment with O2

Ref gas	Va	Vf0	%CO2max	CARI	Lambda	%CO2	%O2	Estimated CO (ppm)
Eulow+20%H2	7,79	6,96	11%	11,34	1,44	7,4%	6,9%	48
EUHigh	10,52	9,45	12%	13,36	1,07	11,2%	1,4%	228

Table 4: Simulated impact of O2 and CO2 adjustment at Qmax.

Next chapter will show tests carried out on adjustable gas appliances.

1.3.3 Test results

The impact of CO2 and O2 adjustments on a boiler are shown on Figure 6. This case was chosen because it clearly shows the reason of the high CO emissions with CO2 adjustment and the improvements brought by O2 adjustment.

The manufacturer’s range of O2 (calculated from CO2) adjustment is also reported on Figure 6. It can be observed that, when the appliance is fed with EUlow+20%H2 and adjusted with CO2 (black triangles), the air excess is no longer in the range specified by the manufacturer for adjustment and the %O2 in flue gas is already below the %O2 limit during adjustment.

On the contrary, with the same gas, but with adjustment based on O2 (red circles), the boiler operates within the limits defined by the manufacturer. Moreover, the mixture is leaner than with CO2 adjustment. These differences lead to lower CO emissions when the Combustion Air Ratio Index (CARI) of the gas increases due to the replacement of EUlow+20%H2 by EUhigh.

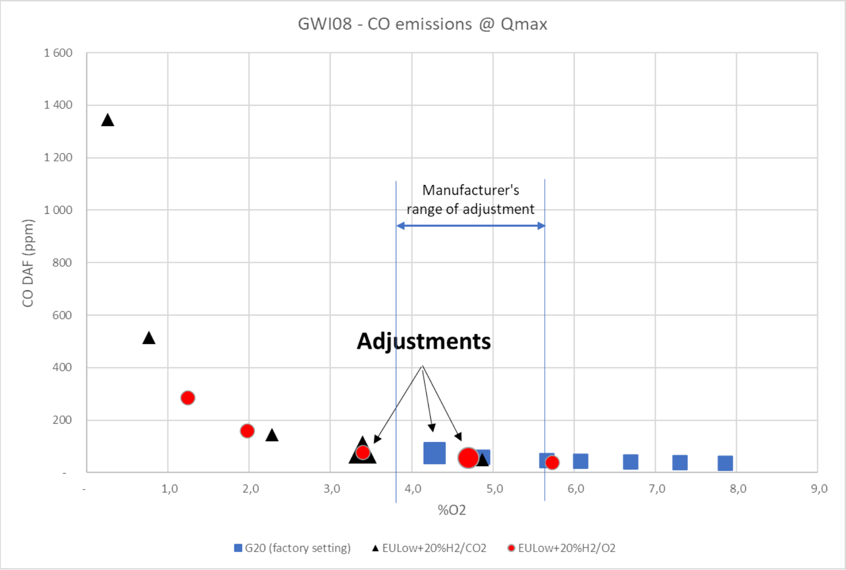


Figure 6: CO emissions as a function of the %O2 in flue gas (GW08@Qmax).
Bigger signs show where the appliance was adjusted (G20 for squares, and EUlow+20%H2 for circles and triangles).

Table 5 sums up the effects of CO2 and O2 adjustment on CO emissions at maximum heating power for boilers GW08, EN01 and EN02. **A substantial CO decrease is observed when O2 adjustment is used**.

Boiler	Qcal	Adjustment	CO DAF (ppm)@EUlow+20%	CO DAF (ppm)@EUhigh
GW08	Qmax	CO2	87	1347
GW08	Qmax	O2	53	285
EN01	Qmax	CO2	93	664
EN01	Qmax	O2	60	288
EN02	Qmax	CO2	9	41
EN02	Qmax	O2	7	22

Table 5: Comparison of CO emissions at EUhigh after adjustment at EUlow+20%H2 with O2 and CO2 adjustment at Qmax for 3 different boilers.

At minimum heating power, the use of O2 adjustment has almost no impact on CO emissions (Table 6) which is low both for CO2 and O2 adjustment. The difference between CO2 and O2 adjustment is only a few ppm in this case. All CO DAF concentrations measured are largely below the limit of 1000 ppm used as a safety threshold in European standards.

Boiler	Qcal	Adjustment	CO DAF (ppm)@EUlow+20%	CO DAF (ppm)@EUhigh
GW08	Qmin	CO2	64	45
GW08	Qmin	O2	62	43
EN01	Qmin	CO2	5	5
EN01	Qmin	O2	7	9
EN02	Qmin	CO2	14	2
EN02	Qmin	O2	18	6

Table 6: Comparison of CO emissions with O2 and CO2 adjustment at Qmin for 3 different boilers.

This is due to the fact that, at Qmin, CO emissions are reduced by the higher air excess. In the CO/%O2 diagram, CO curves are on the flat part of the U curve. Thus, changing the λ has less impact on CO emissions at Qmin than at Qmax.

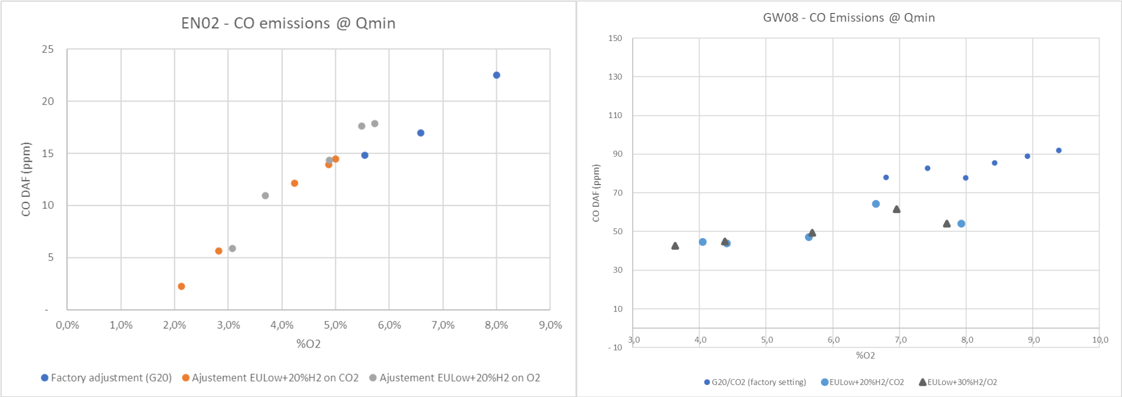


Figure 7: CO emissions as a function of %O2 in flue gas at Qmin. The CO emissions remain at low levels (gas used: G20, EUlow+20%H2, EUhigh, EUhigh+20%H2, EUhigh+40%H2 and EUhigh+60%H2).

Concerning NOx emissions, the tendency is the same as for CO emissions:

- At Qmax, lower NOx emissions when the appliance is adjusted with O2 compared to CO2 adjustment (Table 7).
- At Qmin, lower (but not always) value of NOx in flue gas (Table 8).

Boiler	Qcal	Adjustment	NOx DAF (ppm)@EUlow+20%	NOx DAF (ppm)@EUhigh
GW08	Qmax	CO2	68	147
GW08	Qmax	O2	32	134
EN01	Qmax	CO2	61	225
EN01	Qmax	O2	39	155
EN02	Qmax	CO2	64	237
EN02	Qmax	O2	39	185

Table 7: Comparison of NOx emissions with O2 and CO2 adjustment at Qmax.

Boiler	Qcal	Adjustment	NOx DAF (ppm)@EUlow+20%	NOx DAF (ppm)@EUhigh
GW08	Qmin	CO2	12	25
GW08	Qmin	O2	11	27
EN01	Qmin	CO2	16	56
EN01	Qmin	O2	21	69
EN02	Qmin	CO2	42	36
EN02	Qmin	O2	12	30

Table 8: Comparison of NOx emissions with O2 and CO2 adjustment at Qmin for 3 different boilers.

On boiler GW08, it has also been checked that O2 adjustment does not introduce any new problem. Adjustments/operations with other gases were performed for different gases combinations. Adjustment gases / operation gases tested are summed up in Table 9.

Adjustment gas/method	Operation gas	Delta WS (MJ/m3)
G20	G20+60%H2	-7,1
EUhigh/CO2	EUlow+60%H2	-12,1
EUlow/CO2	EUhigh	4,8
EUhigh+20%H2/CO2	EUlow+60%H2	-8,5
EUlow+20%H2/CO2	EUhigh	6,9
EUhigh/O2	EUlow+60%H2	-11,2
EUlow/O2	EUhigh	4,9
EUhigh+20%H2/O2	EUlow+60%H2	-8,2
EUlow+20%H2/O2	EUhigh	6,9

Table 9: List of O2 and CO2 adjustment tests performed on boiler GW08.

During these tests, the boiler operated properly, but with high emissions of CO during the adjustment on CO2 at EUlow+20%H2 and used at EUhigh (as stated before). With O2 adjustments for other gases and Wobbe Index changes, no new problem was observed, and CO emissions remained under control.

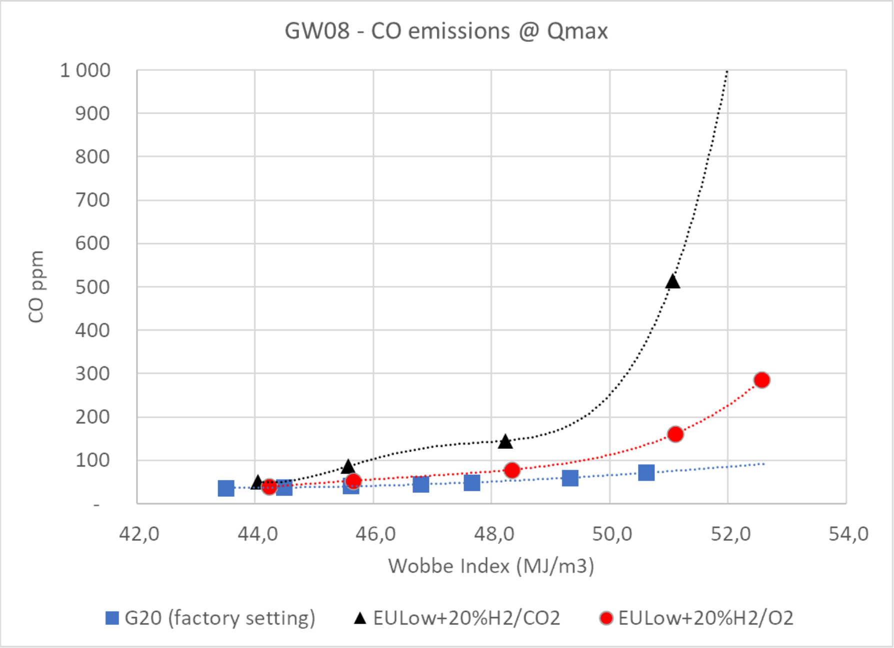


Figure 8: CO emissions of boiler GW08 at Qmax, with CO2 and O2 adjustments and various adjustment gas compositions.

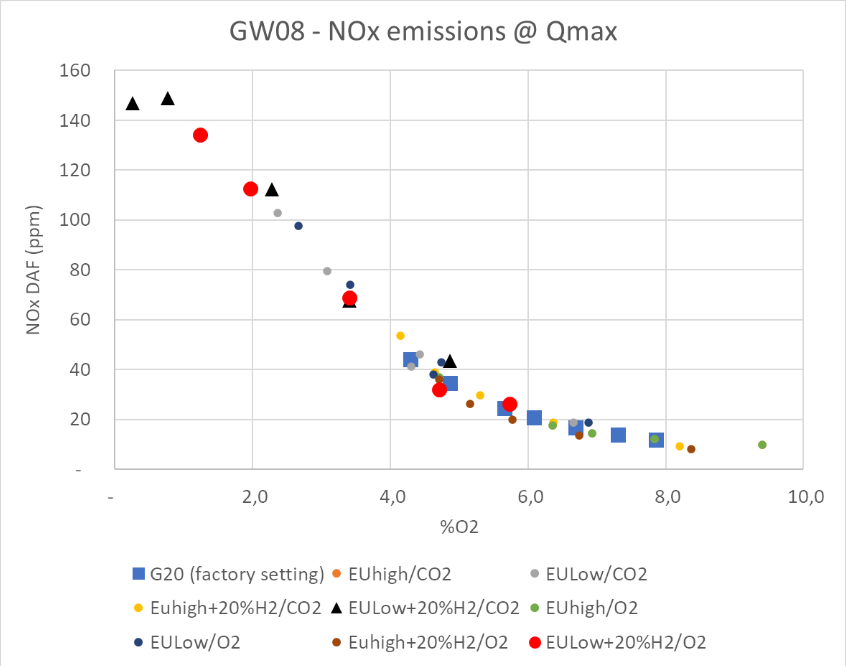


Figure 9: NOx emissions of boiler GW08 with CO2 and O2 adjustments and various adjustment gas compositions.

It should be noted that, on some boilers, even if O2 adjustment can help decrease the amount of CO emission in the worst adjustment configuration, CO levels can stay above 1000 ppm.

An example was found during the test of appliance GA11. Manufacturer adjustment range for CO2 is [9.2% - 10.5%]. Converted to O2 adjustment, the %O2 range is [2.1% - 4.5%]. Adjustments with O2 were tested for these two limits. Results are listed in Table 10.

Adjustment	Adjustment λ	CO EUlow+20% (ppm)	CO EUhigh (ppm)	EUhigh λ
G20 (O2=4.5%)	1,24	13		1,20
EULow+20%H2 (O2=4.5%)	1,24	49	332	1,06
EULow+20%H2 (O2=2.1%)	1,10	196	10 268	0,93
EULow+10%H2 (O2=2.1%)	1,10	204	2 586	0,96

CO2 adjustment range (manufacturer): 9.2%-10.5%
O2 adjustment range (calculated): 2.1%-4.5%

Table 10: O2 adjustment tests and resulting CO emissions of boiler GA11 tested on limit values of the adjustment range.

When the appliance is adjusted on EUlow+20%H2 at the maximum %O2 (4.5%) and used with EUhigh, CO emissions stay below 1000 ppm. On the contrary when %O2 is set to the lower limit of the adjustment range, the same operation leads to CO emissions above 10 000 ppm, even when O2 adjustment is performed. This is due to the fact that, at the lower O2 limit, the λ is only 1.1. When the gas is changed to EUhigh, λ drops down to 0.93, which is on the rich side of stoichiometry.

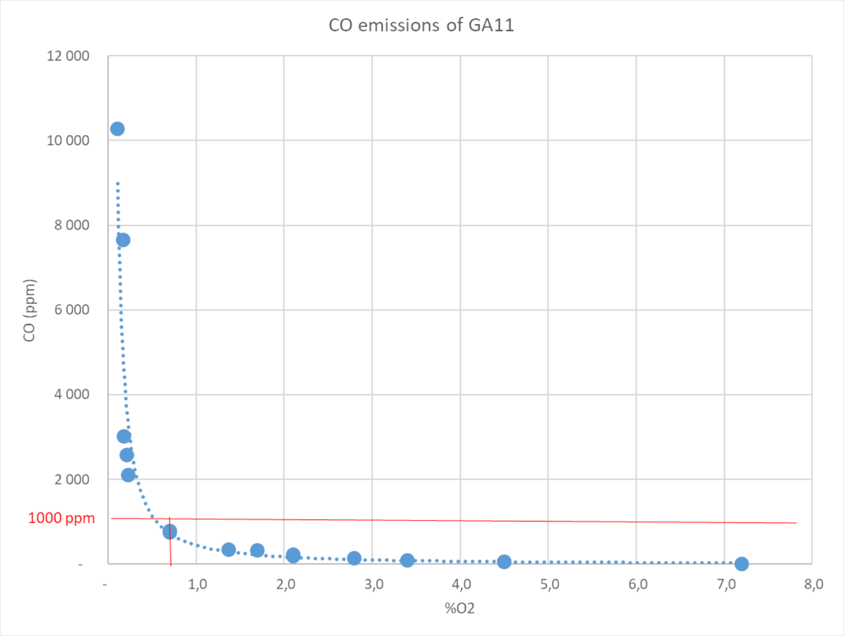


Figure 10: CO emissions / %O2 curve for tested boiler GA10.

This problem could be corrected by implementing and applying the following simple rule: For this specific boiler model, an adjustment for EUlow+20% EUhigh should not lead to an O2 concentration lower than 1% when burning EUhigh (based on Figure 10, with a safety margin). For this specific appliance, this corresponds to a minimum O2 value of about 4.1%.

So, among the mitigation measures to be taken for H2NG, re-examination and redefinition of the current manufacturer-defined adjustment ranges must be carried out when taking into account potential field adjustment at EUlow+20%H2 and later use with an EUhigh gas with no hydrogen admixture. Some appliances may have to operate in leaner conditions than with natural gas on H2NG networks (this can slightly impact both efficiency and emissions). For example GA11 tested above has a CO2 adjustment range of 9.2%-10.5%. It should be noticed that 10.5% is too close to stoichiometry from the start, anyway (maximum %CO2 for G20 is 11.68% at stoichiometry). However, it should be noticed that %CO2 values for adjustment are rarely seen above 10%. So, the modification of CO2 range for adjustment will probably be required only for a few boilers.

1.3.4 Combustion analysers

Nowadays, most gas appliance adjustment rely on adjusting the measured CO2 value in flue gas to a CO2 range given by the manufacturer.

Portable combustion gas analysers used during statutory inspections and assessments are certified according to standard EN 50379 [9]. There are currently two kinds of portable analysers:

1. The one using a CO2 sensor.
2. The one relying on an O2 sensor. CO2 concentration is extrapolated from O2 measurement considering a priori properties of the fuel used.

For O2 adjustment, the first one cannot be used, even if there is a conversion algorithm to estimate O2 from CO2 measurement. This calculation relies on hypothesis on the fuel (considered as a natural gas) that are not valid for H2NG mixtures (see Section 1.3.2).

The second one can be used if there is a possibility to display the O2 content of the flue gas.

Note: Some portable combustion analysers are equipped with an O2 sensor, and they calculate CO2 concentration with an internal algorithm. As a consequence, they provide a CO2 value different from CO2 analysers used in laboratories which measure CO2 concentration directly. The impact of the indirect measurement used in portable combustion analysers has not been assessed during the THyGA project.

1.3.5 Conclusions

Adjustment tests performed on several gas appliances have shown that:

- O2 adjustments enable the installer to adjust the appliance to the proper lambda whatever the amount of hydrogen.
- O2 adjustments lead to lower CO and NOx emissions at maximum heating power and keep them at low levels at minimum heating power.
- No malfunctions were produced by O2 adjustments.

Moreover, the adjustment range must be checked in order to verify that, in the richer condition of this range, an adjustment at EUlow+20%H2 does not lead to excessive CO emissions.

1.4 Heating power limitation

When the gas used during adjustment contains hydrogen and the appliance is used, afterwards, with a gas of higher Wobbe Index without hydrogen, there is a risk that the appliance operates at a higher heating power than the range defined by the manufacturer. This configuration is illustrated on Figure 11.

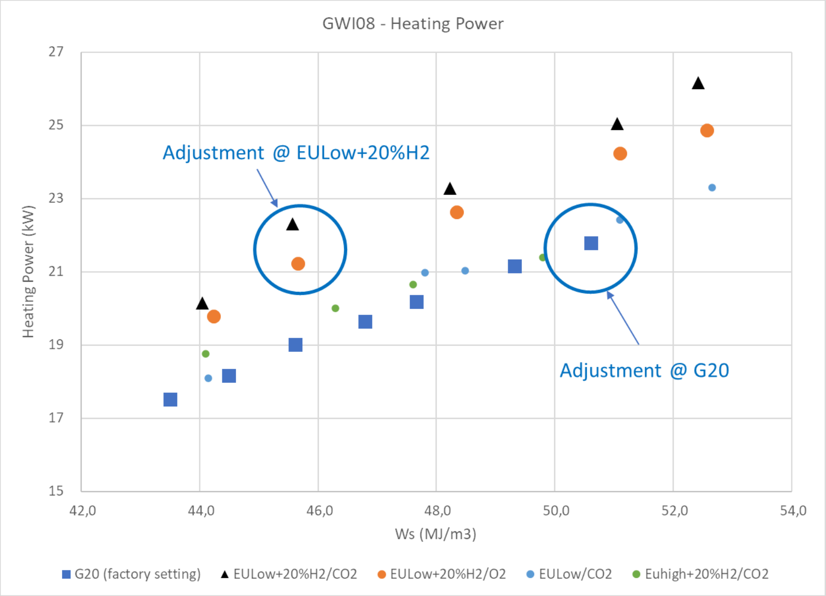


Figure 11: Impact of adjustment on heating power for tested boiler GW08.

A mitigation measure to limit the heating power of a gas appliance would be to re-design the injector in order to **assure the right heat input for G20 gas with the throttle screw of the gas valve completely open or nearly completely open**. In case the gas during the setting of the boiler contains H2, the O2 value will be above the manufacturer specifications without any possibility to increase the gas flowrate, thus avoiding any overload when the H2 is no longer present in the gas mixture.

1.5 Alternative adjustment methods

It has been shown that adjustment based on CO2 should be replaced by adjustment on O2 because it is the best way to guarantee that the λ value of the appliance is conform to manufacturer's requirements.

Other options should also be considered. They are described in this section.

1.5.1 Alternative method #1: Forbid adjustment

One option for manufacturer would be to consider that factory adjustment is the best way to cover the full Wobbe range with their appliance. In that case, **forbidding field adjustment if the gas composition is not known** seems the best option to ensure proper operation of the appliance during its lifetime.

This approach is corroborated by previous studies like the GASQUAL project [7] or THyGA WP3 results [10].

1.5.2 Alternative method #2: Adjustment based on %H2

The goal of this alternative method is to adjust the appliance to G20 even if there is already some hydrogen present in the gas pipe. This approach has already been performed in Denmark, for natural gas, where appliances were re-adjusted to G20 when knowing the Wobbe Index.

When hydrogen is mixed to natural gas, the air excess of premixed gas appliances without combustion control increases with %H2. So, if an appliance is adjusted to the manufacturer's specifications when hydrogen is present in the gas, the air excess will be below the specifications when hydrogen is no longer present.

If the %H2 in the gas is known roughly, by steps of 5%, for example, it is possible to correct the manufacturer's O2 specification according to the %H2 in order to have the right %O2 value for G20. Table 11 shows the impact of hydrogen admixture on flue gas O2 concentration. The correction is calculated by subtracting the G20 %O2 value to the mean %O2 value of the considered %H2 range.

%H2	CARI	Lambda	%O2	Correction to apply to %O2
0%	12,84	1,30	5,25%	0,1%
5%	12,64	1,32	5,51%	0,4%
10%	12,43	1,34	5,77%	0,6%
15%	12,23	1,36	6,02%	0,9%
20%	12,02	1,39	6,38%	

Table 11: %O2 change when hydrogen is mixed to CH4 and correction to apply.

So, for example:

- If %H2 is in the range 0%-5% → the correction value to O2 should be 0.1% (or keep the nominal value as the correction is small)
- If %H2 is in the range 6-10% → the correction value to O2 should be 0.4%
- If %H2 is in the range 11-15% → the correction value to O2 should be 0.6%
- If %H2 is in the range 16-20% → the correction value to O2 should be 0.9%

1.5.3 Factory adjustment on CH4+10%H2

For appliances dedicated to operate on a gas network where the %H2 can vary from 0% to 20%, adjustment with G20 or with local gas may not be the optimum solution. Instead, a "factory adjustment" with a gas mixture of CH4+10% H2 could lead to better mean performances as it corresponds to the future use of the appliance. This factory adjustment is investigated in this section.

Specific tests for this adjustment were not performed during THyGA project but based on test results of the boiler GW08, it is possible to estimate the impact of this adjustment on CO and NOx emissions.

The procedure used to estimate the impact of G20+10%H2 adjustment is the following:

1. From GW08 test results, calculate the correlation of %CO and %NOx as a function of %O2.
2. Get the maximum allowed %CO2 for adjustment from the manufacturer's installation manual (9.6%). Calculate the corresponding %O2 (3.74%) value and λ (1.19).
3. Consider factory adjustment with G20 and G20+10%H2 → estimate the λ shift when the boiler is used with:
    a. EUhigh
    b. EUhigh+10%H2
    c. G20
    d. G20+20%H2
    e. EUlow
    f. EUlow+20%H2
4. Calculate CO and NOx emissions with the correlations of step 1.
5. Estimate the impact on flame velocity.

CO and NOx correlations were respectively extracted from the curves Figure 12 and Figure 13.

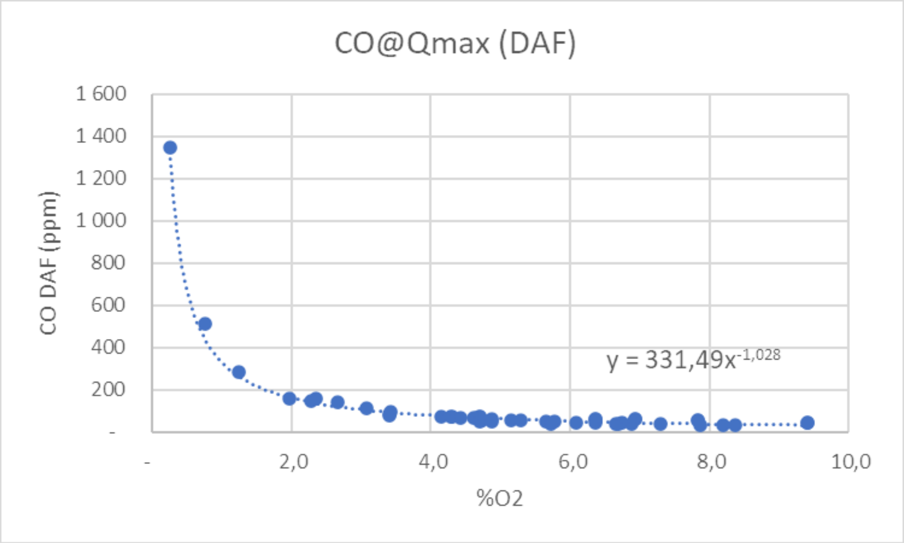


Figure 12: CO vs O2 curve for boiler GW08 at Qmax.

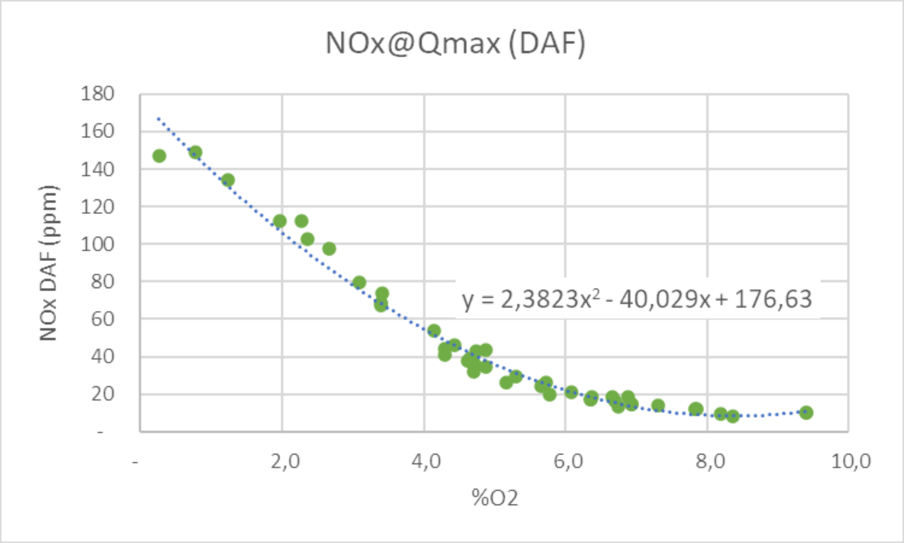


Figure 13: NOx vs O2 curve for boiler GW08 at Qmax.

The simulated adjustment was considered to be an O2 adjustment because it has been demonstrated previously that this approach enables the boiler to be adjusted at the lambda prescribed by the manufacturer. For G20, an adjustment of 9.6% of CO2 corresponds to λ=1.19 and an O2 value of 3.74%.

CO2 concentrations for adjustment are different for G20 and G20+10%H2 due a different gas composition (Table 12). Of course, Wobbe Index of adjustment gases are also different.

Adjustment with:	Ws (kWh/m3)	CO2	O2	Lambda
G20	14,09	9,60	3,74	1,19
G20+10%H2	13,75	9,37	3,74	1,19

Table 12: Differences between adjustment on G20 and G20+20%H2.

The %O2 in flue gas was calculated for different natural gases and H2NG mixtures (Figure 14) Adjustment with G20+20%H2 leads to a lower value of %O2 in flue gas (richer combustion). Based on the correlations of Figure 12 and Figure 13, CO and NOx emissions were estimated. Both for CO and NOx, emissions are higher when the appliance is adjusted with G20+10%H2. Moreover, the richer air/fuel mixture leads to an increase of flame velocity (Figure 16) which could have adverse consequences on burner overheating and flashback.

Figure 14: Simulated %O2 in flue gas for an appliance adjusted with G20 and G20+10%H2.

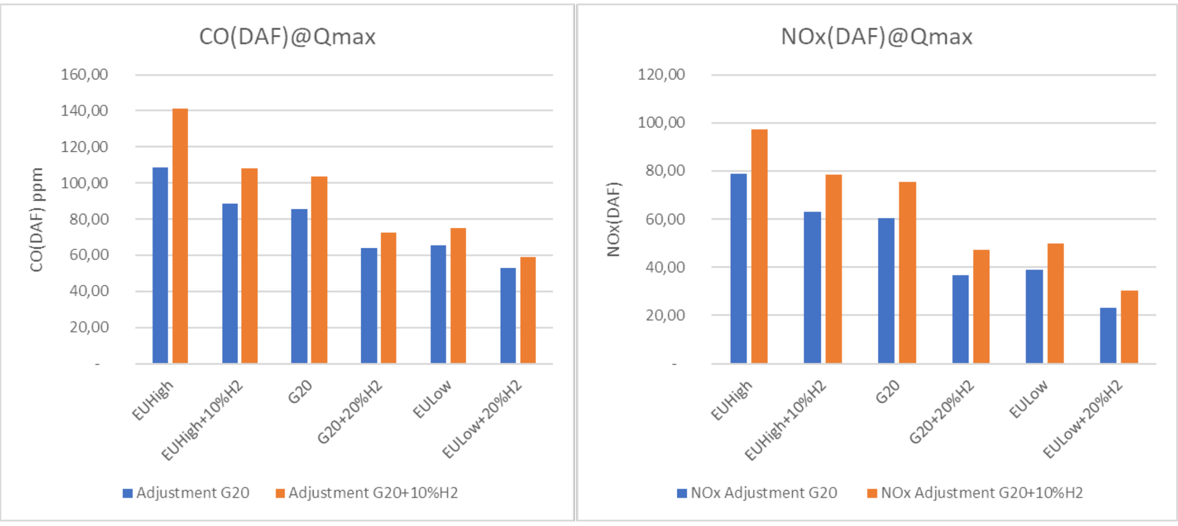


Figure 15: Simulated CO and NOx concentration in flue gas for an appliance adjusted with G20 and G20+10%H2.

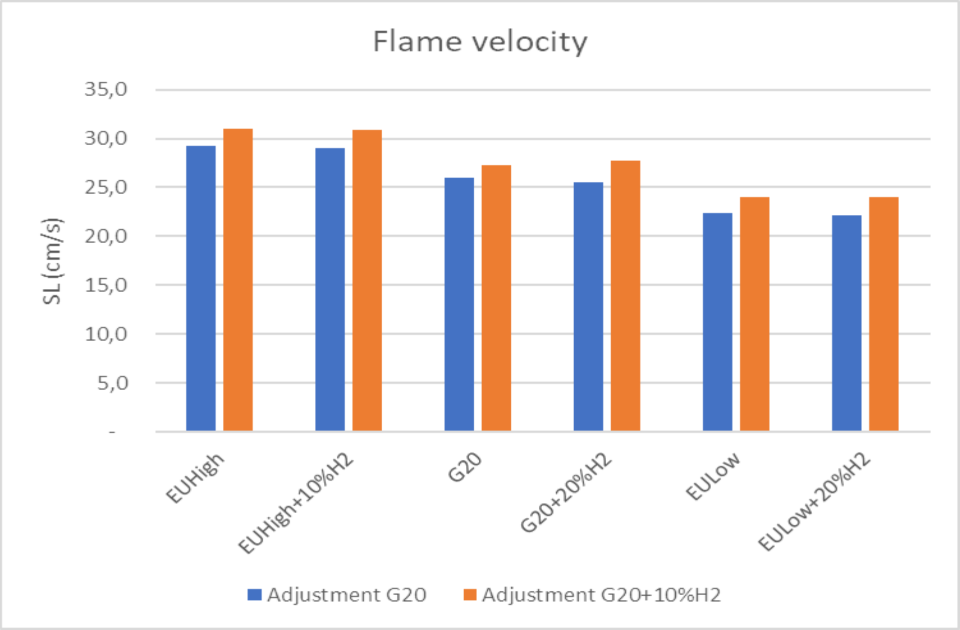


Figure 16: Simulated flame velocity for an appliance adjusted with G20 and G20+10%H2.

Conclusion: Adjusting appliances with G20+10%H2 seems a proper way to adjust appliances fed with a H2NG mixture that could include up to 20%H2. However, it could both increase pollutant emissions (NOx) and CO emissions, and lead to an increased risk of flashback and burner overheating, so it is not advised to adopt a factory adjustment with G20+10%H2.

1.5.4 Alternative Mitigation solution #3: limited gas range

Even with O2 adjustment, the change from EUlow+20%H2 gas to EUhigh gas (+15.9% on Ws) could be a very severe scenario for some appliances. With such a high Wobbe Index variation, it might not be possible to optimize appliance performances (efficiency & emissions) over the full gas range.

Defining a restricted range of Wobbe Index that could allow appliances to operate properly and without risk when %H2 in the gas varies from 0% to 20% is an option that should be studied.

A first attempt to define new ranges of Wobbe Index for H2NG mixtures was reported on CEN document [11]. This document specified two gas classes to corresponding to Wobbe Index Range at the exit point of gas network.

- One was named “Class Specified” and limits the Wobbe Index bandwidth to 3.7 MJ/m3.
- On was named “Class Extended” and covers all other cases.

The class specified is very restrictive and it seems difficult to apply such a restricted range of Wobbe Index in Europe while, the increasing imports of LNG due to the political context and the increasing proportion of biomethane tend to increase the Wobbe Index Range in the gas network.

The question of the Wobbe Index range allowed in gas networks should be treated anyway. In particular, concerning the lower limit. In 2050, the only gases that should be present in gas networks are renewable methane with some inert gases, an unknown proportion of hydrogen, but without any of the higher hydrocarbons. In that configuration, a new limited Wobbe Index range for these green gases should be defined.

2. Adaptative combustion control functions

In contrast to the technical details and potential mitigation measures discussed above, we see a completely different picture for modern gas appliances that contain combustion controls. These appliances do not need to be manually adjusted in the field but adjust themselves automatically to the natural gas burnt. In case of H2NG distribution, these modern appliances solve several impacts of the hydrogen admixture, but since they were not designed to expect hydrogen in the gas mix, their combustion control functions may also fail in the presence of high hydrogen concentrations. This chapter presents typical manufacturer solutions and explains the impact of H2NG.

2.1 Ionization probe sensor

Nowadays, most combustion-controlled boilers rely on the ionization probe to operate at the optimum air excess. Details of this technology can be found in the report [12]. Results of the same report show that this sensor technology is able to compensate for gas quality variations only for hydrocarbons. If hydrogen is added to the gas, the boiler behaves as a standard boiler: air excess increases in proportion to the hydrogen mixed to the gas (Figure 17).

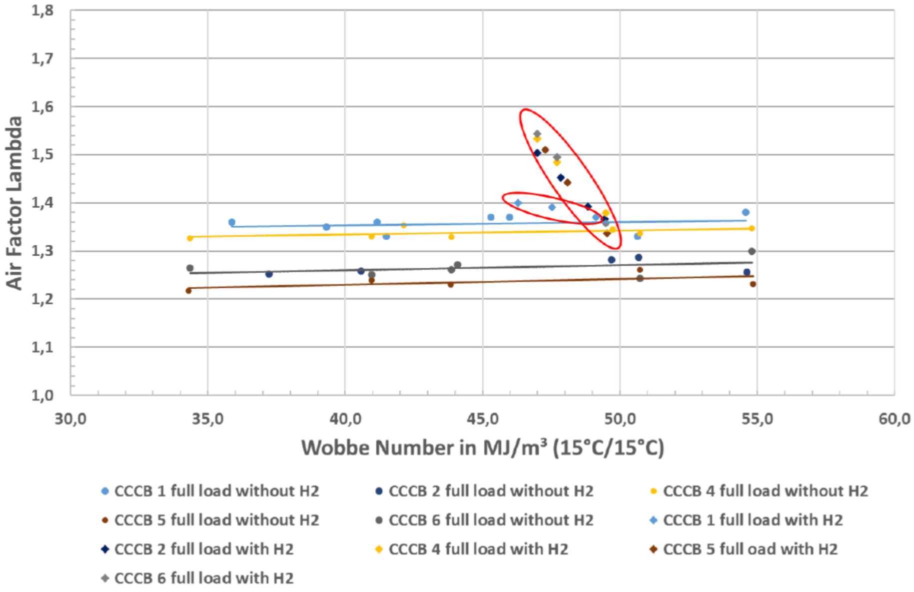


Figure 17: Impact of Wobbe Number variations on Lambda. Gas containing hydrogen (source: [12]).

This behaviour is usually considered as an advantage because the increase of air excess compensates for the increase of fundamental flame velocity due to hydrogen.

In the following sections, an alternative to the ionization probe sensor is tested.

2.2 Vaillant CO sensor

Most combustion controlled condensing boilers rely on the ionization probe to adjust the air/fuel ratio to an optimum value [12]. Its working principle is based on the ionisation of the hydrocarbons during combustion, i.e. the formation of free electrons and remaining ionised atoms and molecules. Using a collector electrode close to the position of the flame, a small electrical current can be measured. This signal is used by control electronics to (1) simply detect the presence of the flame / confirm successful ignition and (2) to produce a signal which is proportional to the concentration of hydrocarbons in the gas mix. The latter signal can be used to control the gas/air mix e.g. in terms of adding more or less air, in other words to adjust the lambda value to a default.

If we add hydrogen to the fuel gas, we add a gas that does not contain hydrocarbons. Thus, the amount of ions in the flame is reduced and the change in air excess which goes along with hydrogen admixture may not be fully detected. As a consequence, with increasing proportion of hydrogen, there is a deviation of λ from the theoretical optimum value and as a result, combustion-controlled boilers may show a tendency to behave as conventional boilers. In that case, their strength of adapt to hydrogen addition might be lost, at least when admixing very high levels of hydrogen.

The behaviour of these boilers was already studied in [12].

As a consequence, it was decided to test a boiler equipped with an alternative combustion control technology. Vaillant boilers were mentioned for using a CO sensor (Figure 18) to perform combustion control [12].

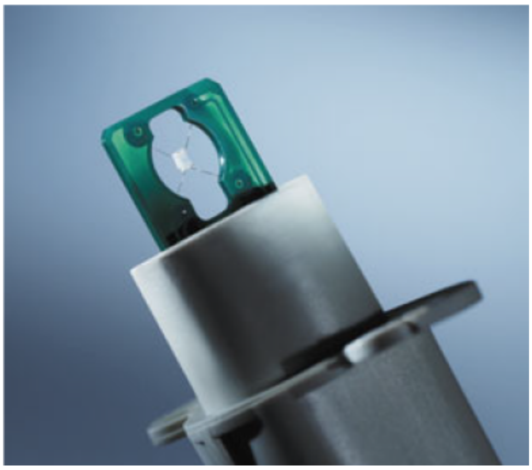


Figure 18: Vaillant CO sensor for combustion control (Source: [13]).

The CO sensor is positioned in the flue gas. It corrects the λ value in order to keep CO emissions at a minimum level. According to [13], the advantages claimed for this technology are :

1. Ability to adapt to different gas qualities or air pressure.
2. Optimal adjustment in terms of pollutants and efficiency
3. The sensor does not have to provide the exact measured value. Any cross sensitivities or aging of the sensor have no negative effects.
4. Optimum operating point (in terms of λ) is not an absolute value. It can depend on the burner or the ageing of the boiler. The CO sensor is able to adapt.

It has been shown in a previous chapter that, up to 40% H2, the U curve of a boiler (CO as a function to %O2 in flue gas) is not changed by H2 addition in the fuel gas (Figure 8) : gases with H2 and gases without H2 stay on the same %O2/CO curve. As a consequence, relying on this curve, the CO sensor should be able to adapt correctly to H2NG.

2.3 Test results

The boiler EN 21has been tested under two different conditions:

1. Adjustment at EUlow+20%H2 and used with gases of higher Wobbe Index (up to EUhigh) without any change.
2. Auto-adjustment of the boiler for each new gas composition.

The impact of auto-adjustment, based on the CO sensor can be observed on Figure 19 and Figure 20. When the boiler is adjusted with a low Wobbe Index gas like EUlow+20%H2 and used with EUhigh, it is obvious that λ control with a CO sensor decreases CO emissions. In that configuration, CO emissions were halved for EUhigh.

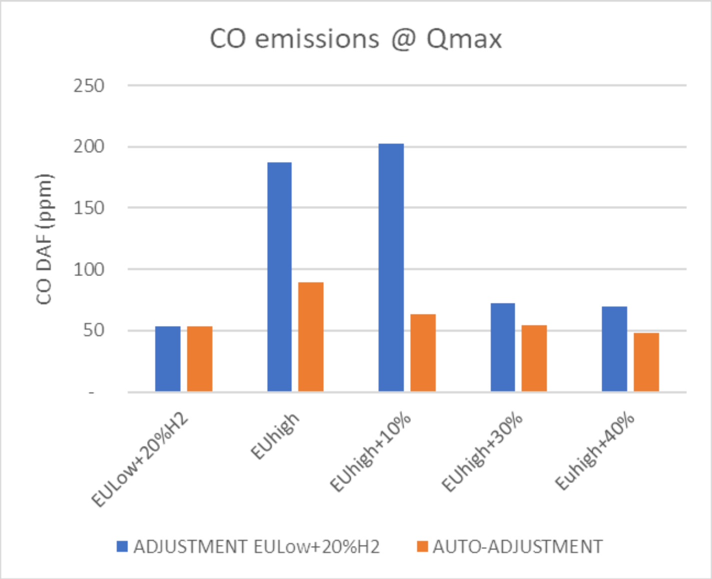


Figure 19: Impact of auto-adjustment function of boiler EN21 on CO emissions at Qmax.

It is also interesting to consider the impact of auto-adjustment on NOx: under the same conditions (EUhigh), NOx emissions (Figure 20) were halved thanks to the use of combustion control.

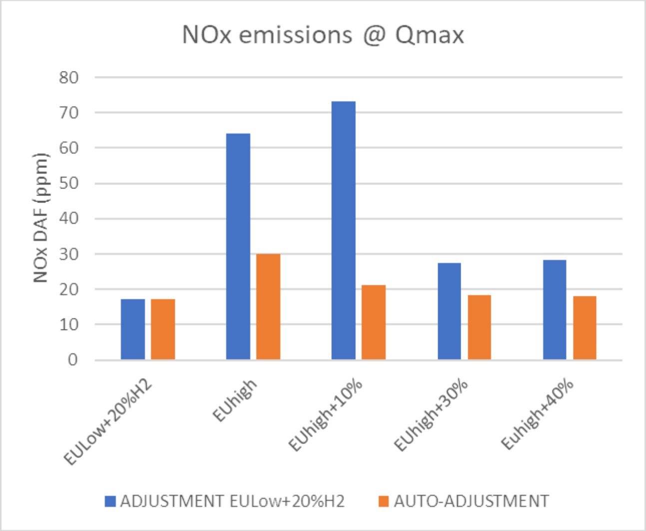


Figure 20: Impact of auto-adjustment function of boiler EN21 on NOx emissions at Qmax.

In Figure 21, CO emissions are plotted as a function of %O2 in the flue gas. Two interesting results can be observed on this figure:

1. CO emissions are lower when auto-adjustment is used (orange points), as mentioned above.
2. smaller air excess variation range (%O2) with auto-adjustment.

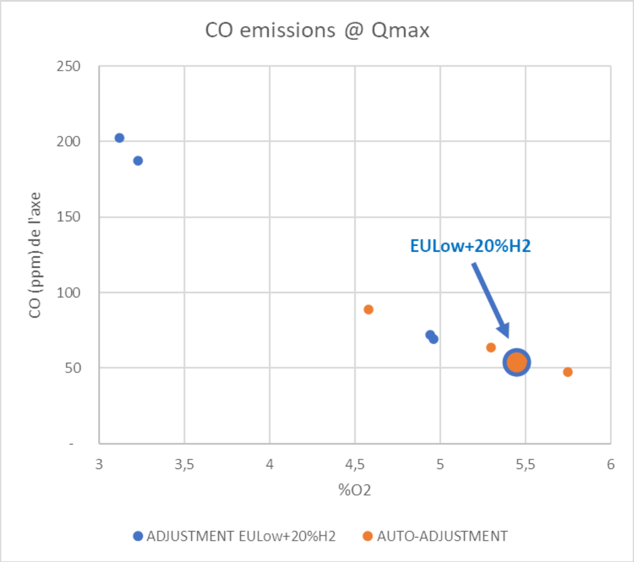


Figure 21: CO emissions as a function of %O2 at Qmax.

It is usually considered that keeping a constant lambda when H2 is mixed to the fuel could lead to an increased risk of flashback because, for standard boilers, the lambda increases with %H2 and the increase of fundamental flame velocity is balanced by the increase of air excess [1].

In the present case, the air excess increases slightly when hydrogen in mixed with the gas (Figure 22). It can be calculated that this increase of air excess compensates the increase of fundamental flame velocity induced by the presence of hydrogen (Figure 23). As a consequence, flashback risk is not increased by auto-adjustment.

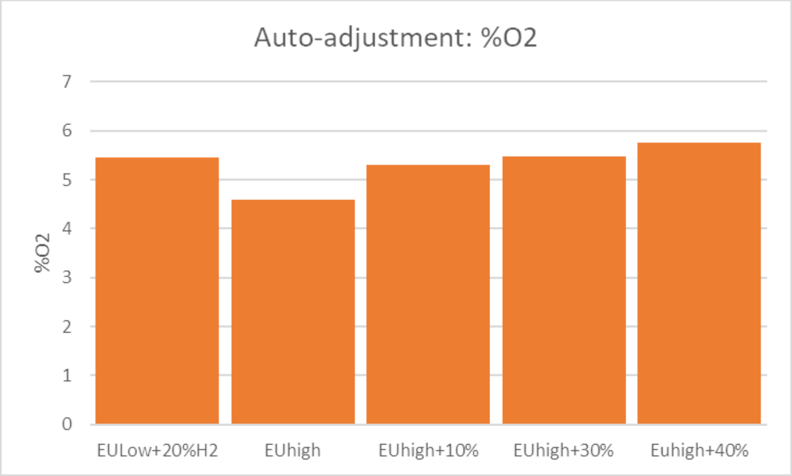


Figure 22: O2 concentration in flue gas after auto-adjustment (Qmax).

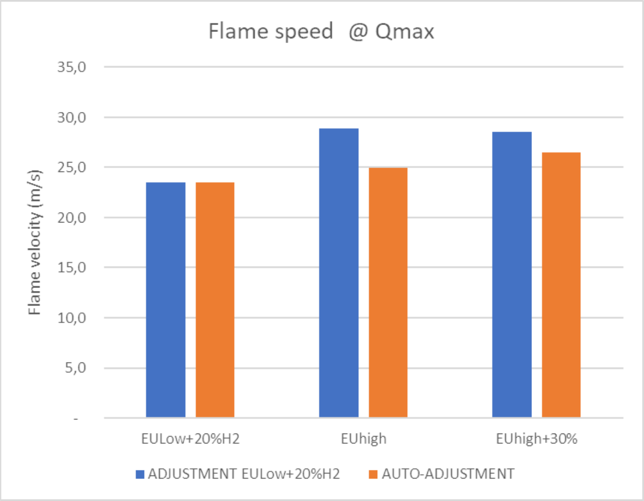


Figure 23: impact of auto adjustment on flame velocity in the case of an adjustment to EUlow+20%H2.

At Qmin, CO emissions are kept below 14 ppm on both cases and NOx emissions stay below 10ppm, but the impact of auto-adjustment is not always beneficial (Figure 24).

Flame speed was not investigated for Qmin as %O2 was higher at Qmin than at Qmax.

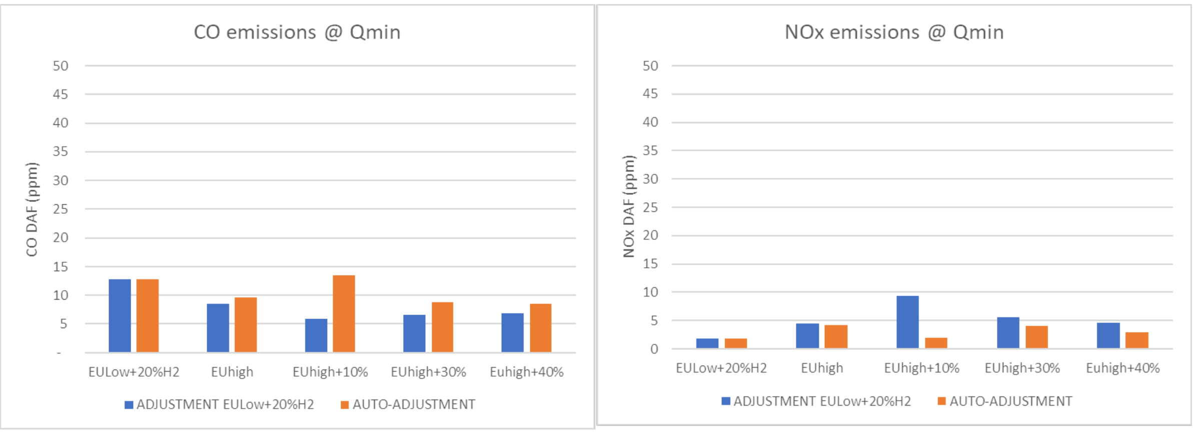


Figure 24: impact of auto-adjustment on CO and NOx emissions at Qmin.

Note: *on Figure 24, results for EUhigh+10%H2 should be taken with care as they show a very different behaviour of EUhigh and EUhigh+30%. In that case, the O2 concentration in flue gas was 8% versus 6% for EUhigh and EUhigh+30%. Thus, this value is considered too high by the authors.*

2.4 Conclusions

The adjustment that leads to the higher CO emissions has been used as a test reference in this chapter (EUlow+20%H2 → EUhigh). The boiler equipped with CO sensor does not suffer from high CO emissions when it is auto-adjusted to EUlow+20%H2 and used with EUhigh. CO and NOx emissions are strongly decreased.

In the future, it would be interesting to perform a more detailed analysis of the interactions between adjustment, non-adjustment, auto adjustment (with ionization probe, CO sensor or O2 sensor) in order to have a better view on the benefits and disadvantages of each option.

On Figure 17, one boiler performed better than the others to keep the λ constant. This leads to the question if some ionisation system can, maybe, also be used with acceptable results.

One more specific point should be studied: the auto-calibration period should be investigated more closely because during this period, the air/fuel ratio of the boilers can become nearly stoichiometric for a few seconds. This could cause an increase of flame velocity high enough to cause flashback. Therefore, flashback tests during auto-calibration should be performed at different %H2 admixture levels and on several boilers in order to check if there is flashback in these conditions.

3. Natural draught

In modern condensing boilers, a fan is used to feed the appliance with air or to extract flue gas from the combustion chamber to the flue pipe. On older appliances, the flows of air and flue gas rely only on the Archimedes principle: hot gases are drawn upward by buoyancy. No fan is used to ensure proper operation.

A question was raised during the THyGA project concerning the impact of hydrogen on natural draught: **does hydrogen addition help or refrain natural draught?**

This question is studied in this section.

3.1 Principle

In the case of gas appliances, two phenomena must be considered to estimate the impact of hydrogen on natural draught:

1. Buoyancy
2. Flue gas flowrate (and its impact on pressure drop)

Buoyancy

Buoyancy is the Archimedes principle applied to gases. At a pipe exit, when the density of gas A is lower than gas B, gas A goes up, natural draught operates properly.

For gas appliances:

- When $\rho_{FlueGases} < \rho_{Air}$ → flue gas goes up 👍
- When $\rho_{Air} < \rho_{FlueGases}$ flue gas can't go up → no natural draught 👎

Flue gas flowrate evolution

Also, it should be checked that flue gas flowrate do not increase in such a way that the flue pipe is not large enough to let all the gases pass through and generates an increase of pressure losses.

Flue gas flowrate

- if Qflue(H2NG) <= Qflue(natural gas) → no problem 👍
- if Qflue(H2NG) > Qflue(natural gas) → increase of pressure drop → requires attention 🤔

3.2 Impact of H2

Hydrogen addition to natural gas has several impacts on flue gas flowrate and density (see also [1]). Unfortunately, these impacts do not go in the same direction:

- It has been shown previously [1] that hydrogen addition to natural gas **increases the fuel gas flowrate** for atmospheric appliances.
- The decrease of fuel gas density when adding hydrogen has an impact on the air **excess λ which increases with %H2**.
- **Air excess increases**, which impacts the volume of flue gas produced.
- However, the volume of flue gas produced by 1m^3 of fuel gas decreases when the proportion of H2 increases.
- Hydrogen has also an impact on flue gas composition (less CO_2, more H_2O), especially on its density.
- Adiabatic flame temperature of hydrogen is higher than the one of natural gas (which decreases density)
- Efficiency evolution of the heat exchanger is a priori unknown. It has an impact on flue gas temperature.

All these contradictory effects are resumed in Table 13

	Impact on density	Impact on wet flue gas flowrate
Increase of fuel gas flowrate	-	Increase
Decrease of flue gas produced by 1m3 of fuel gas (Vf'0)	-	decrease
Air excess increase	Increase (lower temperature)	Increase
Flue gas composition	Decrease (CO2 replaced by H2O)	Increase (density decrease)
Flue gas temperature after heat exchanger	Unknown	Unknown
Adiabatic flame temperature	Increase	Increase
All phenomena combined	Unknown	Unknown

Table 13: impact of hydrogen proportion in the fuel on flue gas.

As the effects of some parameters can compensate others, it is not possible to estimate a priori the impact of hydrogen in fuel mixtures by calculation only. Experimental investigations are required in order to measure the combined impact of all the effects mentioned above.

3.3 Test & calculation results

The results presented here are based on tests carried out during the THyGA project on four natural draught, non-condensing, B_{11} boilers.

- EB02 (12.0-26.5 kW) / 2019
- GW2 (8.9-22.0 kW) / 2005

- GA1 (11.0-25.8 kW) / 2016
- EN03 (35kW) / 1997

The following data were measured on these boilers:

- Boiler inlet: fuel gas flowrate and composition
- Boiler outlet: flue gas temperature, %CO2, %O2

From these measurements, the following data were deduced:

- λ: calculated from %CO2+fuel gas composition (and/or %O2)
- Wet flue gas composition: calculated from fuel gas composition and λ
- Flue gas flowrate: calculated from fuel gas flowrate and composition and λ
- Flue gas relative density: calculated from flue gas composition and temperature

Major impacts of %H2 are shown below.

3.3.1 Impact on air excess

As it was observed on other gas appliances, the increase of the proportion of H2 in the fuel gas causes an increase of the air excess in the flue gas (Figure 25).

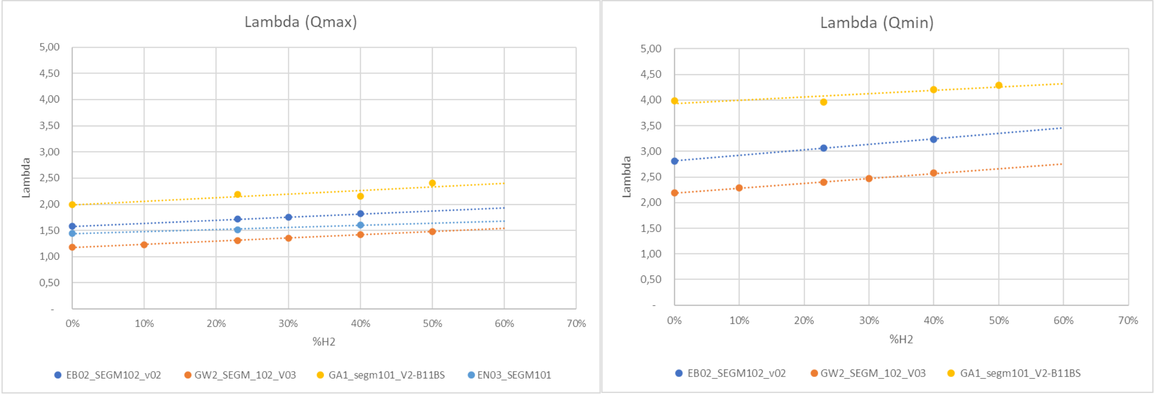


Figure 25: Increase of λ with %H2.

3.3.2 Impact on flue gas temperature

Temperature measured after the heat exchanger shows that flue gas temperature decreases in most cases or remains stable (in one case at Qmin) (Figure 26).

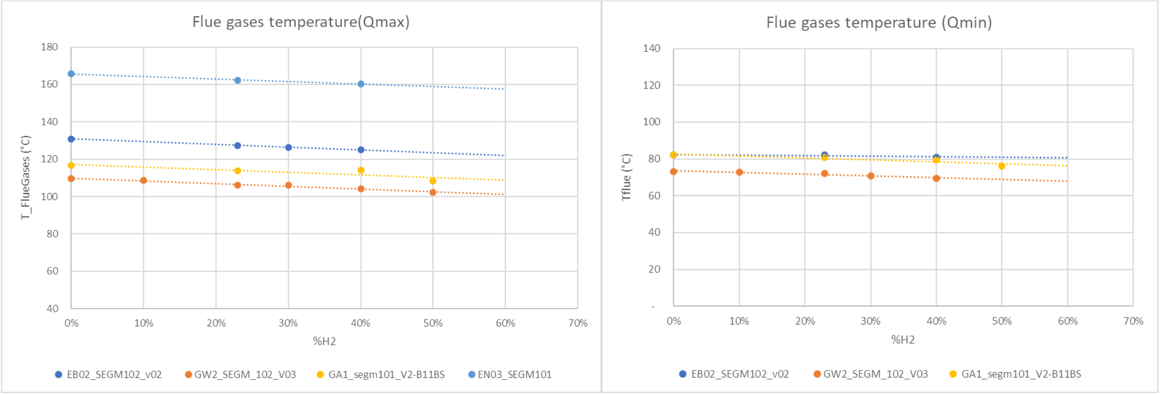


Figure 26: Flue gas temperature evolution with %H2 (atmospheric boilers)

3.3.3 Flue gas flowrates

Concerning gas flowrates, the three boilers have different behaviour:

- The flue gas flowrate of EB02 decreases at Qmax but increases at Qmin.
- The flue gas flowrate of GW02 increases at Qmax but remains stable at Qmin.
- There is a strong decrease of the flue gas flowrate of GA1 both at Qmin and Qmax

However, it can be noticed that the flue gas flowrate, when it increases, does not vary much when hydrogen is added, so the variations of the flue gas flowrate should not be a problem when hydrogen is added.

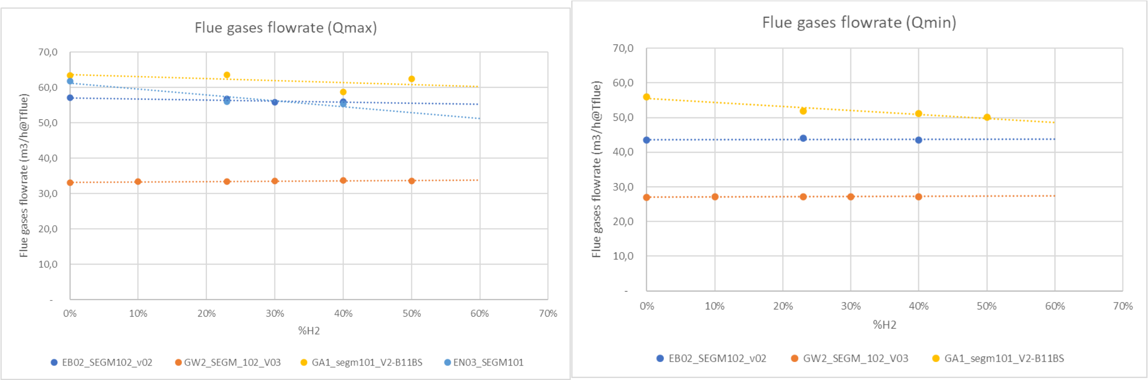


Figure 27: Flue gas flowrate evolution with %H2 (atmospheric boilers)

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3.3.4 Relative density

For all three boilers, the relative density of flue gas remained stable or increased. The good point is that, even with H2 concentrations in fuel gas as high as 50%, the relative density $\rho_{gas}(Tflue)/\rho_{Air}(15°C)$ remains far below the physical limit of 1.

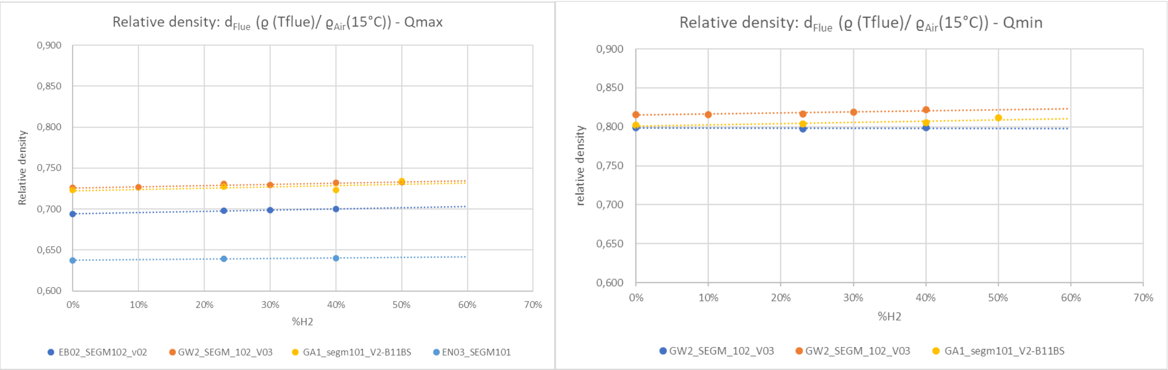

Figure 28: Relative density of flue gas (ref: air at 15°C).

In order to estimate what could happen if the boiler is used in the most extreme conditions, air temperature was raised to 35°C. Even in that case, it is calculated that the relative density of flue gas would remain below 0.9 when 60% of fuel is added to CH4. For 23%H2, the rise of relative density does not appear to be high enough to cause trouble to natural draught.

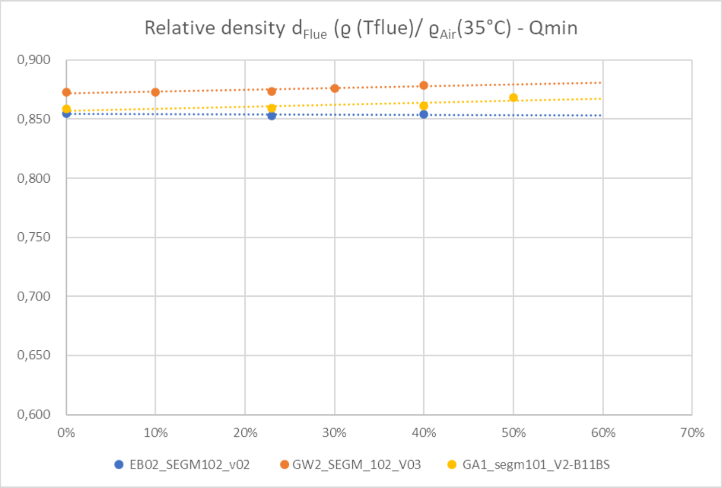

Figure 29: relative density of flue gas at Qmin (ref: air at 35°C)

3.4 Conclusions concerning natural draught

From the tests carried out on four natural draught boilers, it can be concluded that hydrogen addition to natural gas should not cause any problem:

- At Qmin and Qmax, the flue gas flowrate showed either a small increase or decrease (or remained stable), but the maximum variation was +1.4% at 50%H2. So, the volumetric flowrate of flue gas is not considered as problematic.
- Concerning the density ratio between flue gas and ambient air, no problem should be observed at Qmax, as the calculated relative density $\rho_{gas}(Tflue)/\rho_{Air}(15°C)$ is below 0.75. At Qmin, the relative density does not vary much and remains below 0.85. When considering ambient air at 35°C, it still remains below 0.9 at Qmin. However, with such temperatures, the boiler should only operate for hot water production ad so, at Qmax only. So, no natural draught problem should occur because of the lower relative density of flue gas at Qmax.

4. Extra condensation in existing flue ducts?

A risk that could occur when hydrogen is blended to natural is the appearance of condensation in a flue duct not designed to: the presence of water could lead to the deterioration and finally destruction of materials in the flue pipe.

Condensation is intimately linked to two parameters:

1. Flue gas temperature
2. The concentration of water (%H2O) in flue gas

The stoichiometry of combustion indicates that with a constant air excess, %H2O in flue gas increases when the gas is mixed with hydrogen.

Table 14 shows the evolution of %H2O in flue gas for methane with a constant lambda of 1.3.

%H2 in fuel (CH4/H2)	Constant Lambda	%H2O in exhaust gases
0%	1,30	14,9%
20%	1,30	15,7%
40%	1,30	16,8%
60%	1,30	18,6%
80%	1,30	21,5%
100%	1,30	27,7%

Table 14: Evolution of %H2O in exhaust gases with %H2, and constant Lambda

However, it has been demonstrated that, in atmospheric appliances, air excess increases with %H2 (according to the ratio of gases CARI). In that case, %H2O is relatively stable up to 60% of H2 (Table 14).

%H2 in fuel (CH4/H2)	Lambda varying (atmospheric appliance)	%H2O in exhaust gases
0%	1,30	14,9%
20%	1,39	14,8%
40%	1,50	14,8%
60%	1,63	15,1%
80%	1,78	16,2%
100%	1,84	20,4%

Table 15: %H2O in flue gas according to %H2 (Lambda variable with %H2).

This tendency was verified at the maximum heating power (Qmax) during the tests carried out during the THyGA project (Figure 30). At minimum heating power, two appliances showed a decrease of %H2O and two appliances showed an increase of %H2O, however small on the 0-20%H2 range.

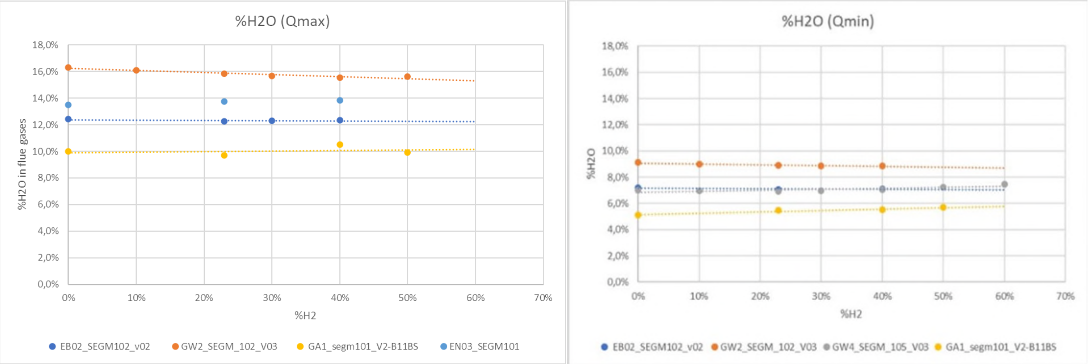

Figure 30: Proportion of H2O in flue gas (non-condensing boilers)

The water dew point can be calculated from %H2O using empiric formulas such as Antoine equation [14]. Figure 31 and Figure 32 compare flue gas and dew point temperature at Qmax and Qmin. Temperature difference at Qmax is about 50°C whereas it is only 30°C for Qmin. Therefore, Qmin is more critical considering condensation than Qmax.

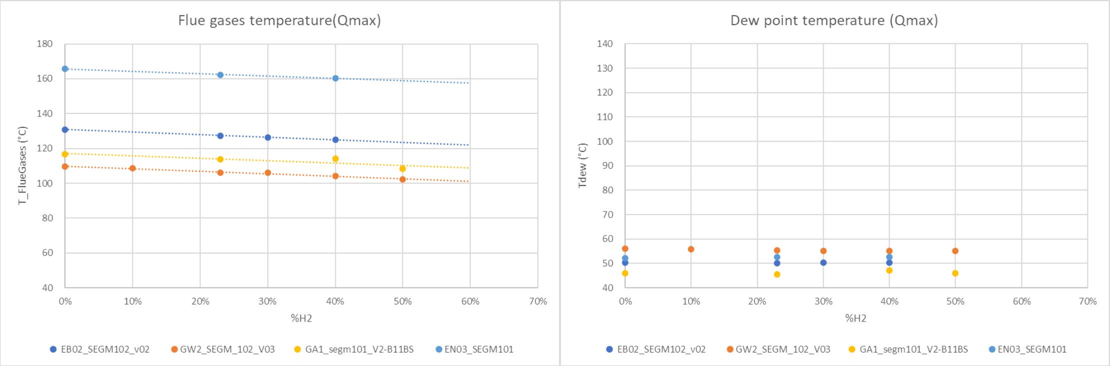

Figure 31: Evolution of flue gas temperature and dew point temperature when H2 is added to the gas (Qmax) (*note: dewpoint temperatures can be considered constant as they only vary by ±1°C*).

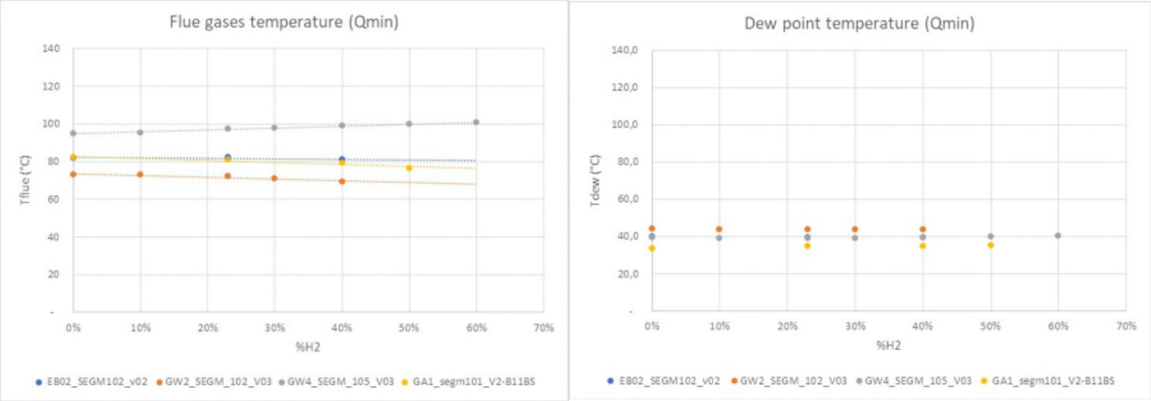

Figure 32:Evolution of flue gas temperature and dew point temperature when H2 is added to the gas (Qmin) (*note: dewpoint temperatures can be considered constant as they only vary by ±1°C*)

At Qmin, the difference measured between measured flue gas temperature and dew point temperature does not vary much (Figure 33) and should not have a sensible impact for most cases. The most critical appliance is GW2 as the initial temperature difference is 28.8°C (CH4) only. For 40%H2, the temperature difference decreases down to 25.5°C, thus leaving less safety margin for that appliance.

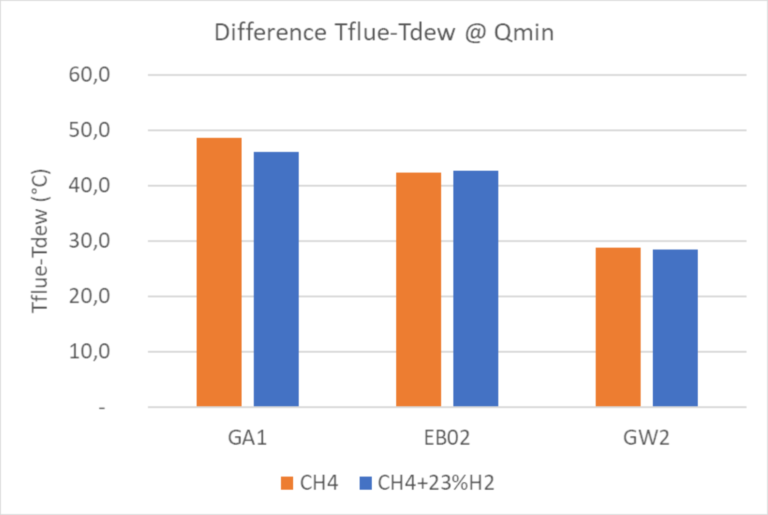

Figure 33: Temperature difference between flue gas and dew point (Qmin).

Conclusion

For most non-condensing boilers, adding H2 to the fuel gas will not cause extra condensation problems up to 20%H2 as the temperature difference between flue gas and dew point is and remains clearly above 40°C at Qmin.

For boilers with less safety margin on temperature difference between flue gas and dew point, it could be wise to increase flue gas temperature by any means (increase heating power, decrease air excess, decrease water flowrate in the heat exchanger… if possible) or to replace the exhaust pipe and possibly the boiler.

5. Condensing boilers: condensates volume and acidity

Concerning condensates, hydrogen can have two kinds of impacts: it could cause an increase of the condensate flowrate (more water in flue gas, increase of heat exchanger efficiency, …) but it can also, potentially, change the acidity of condensates which could have an impact on the lifetime of heat exchangers.

5.1 Condensate flowrate

In this document, condensation tests were performed at a 60/40 regime (water flows from the boiler at 60°C and returns at 40°C).

At minimum heating power Qmin, a stable or increasing flowrate of condensate was measured. This is attributed to an increase of the efficiency of the heat exchanger, as the heating power of the boiler decreases with increasing proportion of %H2 in the fuel gas.

The measured temperature of flue gas is quite constant at Qmin when %H2 varies for the boilers analysed in the following diagram. The volume of flue gas decreases by 1% to 5% between 0% and 60%H2. When combined, these phenomena decrease the flue gas velocity which has a positive impact on heat exchanger efficiency.

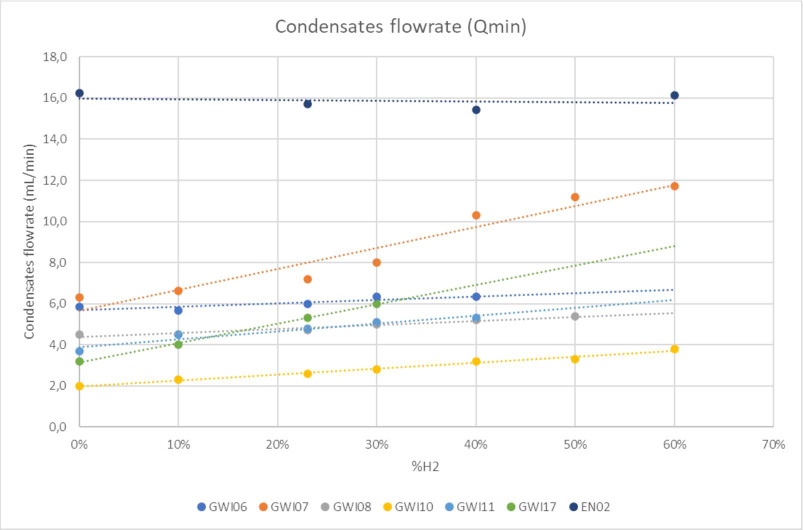

Figure 34: Condensates flowrate (Qmin)

At Qmax, no clear tendency was found by the measurements. Boilers can have a decreasing, increasing or stable condensate flowrate (see Figure 35).

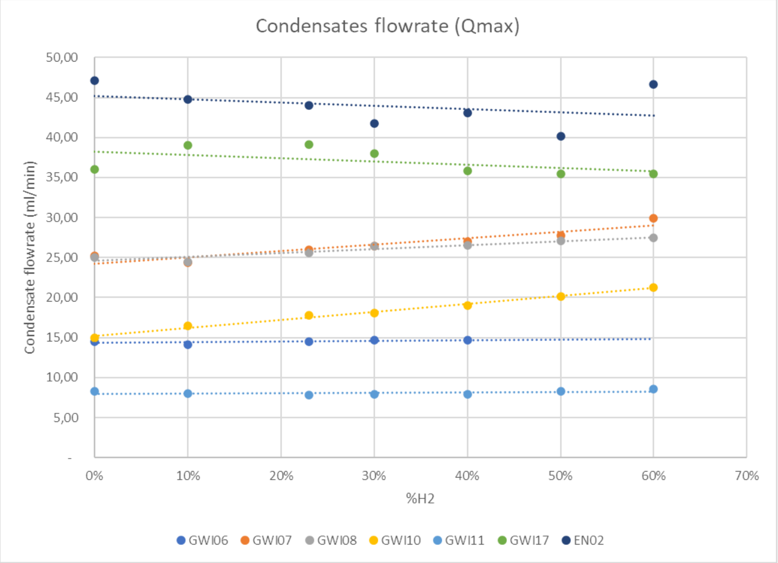

Figure 35: Condensate flowrate (Qmax)

The increase of condensate flowrate is mainly caused by a decrease of the heating power of the boilers (Figure 36) which has a positive impact of heat exchanger efficiency (by increasing flue gas residence time). The efficiency of the condenser, defined by the measured condensate flow divided by the maximum theoretical water flow in flue gas, is represented in (Figure 37).

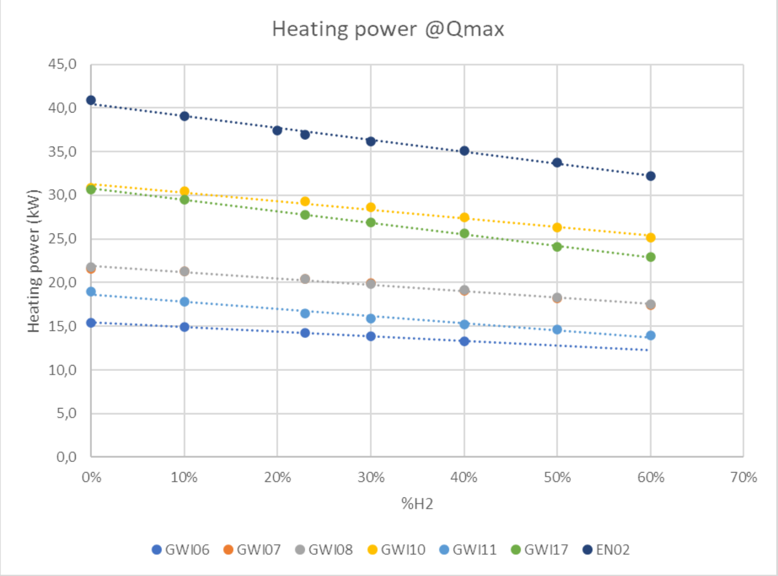

Figure 36: Heating power at Qmax.

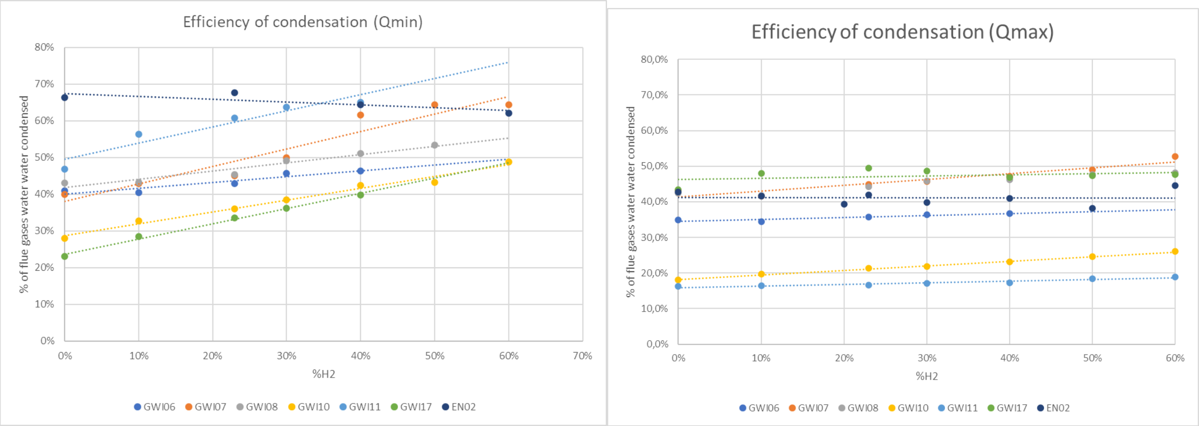

Figure 37: Efficiency of the condenser.

Conclusions

During tests carried out in the THyGA project, no malfunction related to the variation of condensates was identified. Thus, it is considered that no corrective action is required for existing appliances in the case of hydrogen admixture. However, discrepancies concerning the proportion of water condensed were measured between appliances. The variation of condensate flowrate differed slightly between appliances (Figure 38). When designing a new appliance suitable for high proportions of H2 in H2NG, a change of the condenser design should be studied in order to achieve maximum performances.

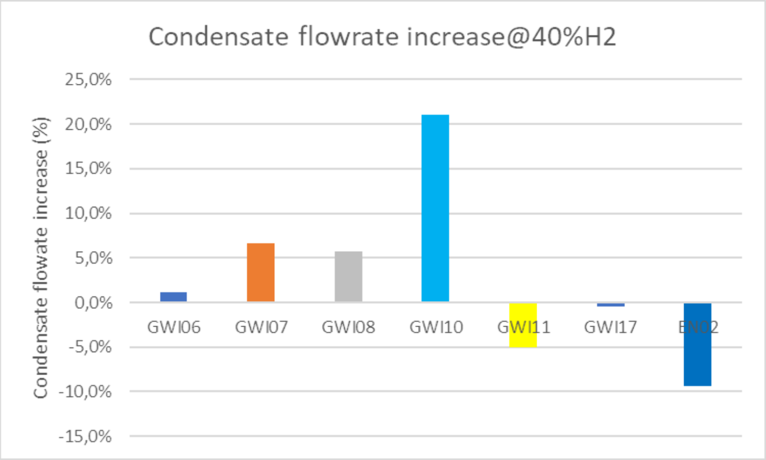

Figure 38: condensate flowrate variations between 0% and 40% H2.

5.2 Does H2 increase the acidity of condensates?

When the water of the flue gas condensates in the heat exchanger, some minor gaseous compounds found can be dissolved in the process. Among them, it is well known that SO_2, NO_2 and CO_2 can produce acidic compounds in water:

- $NO_2 + H_2O \rightarrow HNO_3$
- $CO_2 + H_2O \rightarrow H_2CO_3$
- SO_2/SO_3 diluted in water produce sulfuric compound H_2SO_4

Although some sulphur compounds can be found in natural gas, they are limited to traces elements and are not considered as responsible to the acidification of condensates. Moreover, tests performed within the THyGA project were carried out with high purity and unodorised bottled gases. As a consequence, no sulphur components were present during tests.

H_2CO_3 did not affect much condensates acidity during the tests. Carbonates were measured by an independent lab. Both hydrogenocarbonates (HCO_3) and carbonates (CO_3) stayed under detection limits (resp. 5 mg/L and 1 mg/L).

Acidity of condensate is mainly caused by nitric acid. Analysis of condensates revealed the presence of nitrate and nitric ions. Their amount decreased with %H2 in the fuel gas.

Table 15 shows the evolution of pH when %H2 is increased. With G20, condensates are acidic, with a pH of 3.5. When hydrogen is added, the pH increases slightly. This is caused by the decrease of NOx in flue gas: there is less NOx available to be diluted in condensing water. As a consequence, water acidity decreases.

%H2	pH (Qmax)	NOx (Qmax)	pH (Qmin)	NOx (Qmin)
0%	3,5	48	4,1	14
23%	3,6	21	4,2	9
40%	3,7	12	4,3	4

Table 16: pH and NOx evolution with %H2 in fuel gas.

These results cannot be directly extrapolated to all condensing gas appliances. However, for most condensing boilers, NOx concentration in flue gas will decrease [10]. So, less NOx will dissolve into the condensates.

The consequence is that condensate pH will probably increase or remain stable. So, no mitigation measure will be required.

6. Cooking burners

6.1 Theory

6.1.1 Laminar flame velocity / impact of H2

As detailed in a previous report [2], cooking burners are based on a partially premixed flame technology. A primary amount of air is mixed with the fuel gas inside the burner and the rest (secondary air) comes to the flame outside the burner to achieve the combustion. At the first stage, only 40% to 60% of the air required for combustion is mixed with the fuel gas. This mixture usually burns as a stable premixed flame at the exit of the burner port. However, if the conditions are met, this flame can enter the burner and cause flashback. This phenomenon appears when the flame velocity becomes greater than the exiting fresh gas velocity, enabling the flame to move upstream until it enters the burner.

On top of gas composition and temperature, the air-fuel equivalence ratio λ has a key influence on flame velocity [1].

If an appliance can maintain its primary λ constant while %H2 increases in the fuel gas, the increase of flame velocity (SL) remains low for primary λ below 0.6 (blue, orange and grey curves on Figure 39).

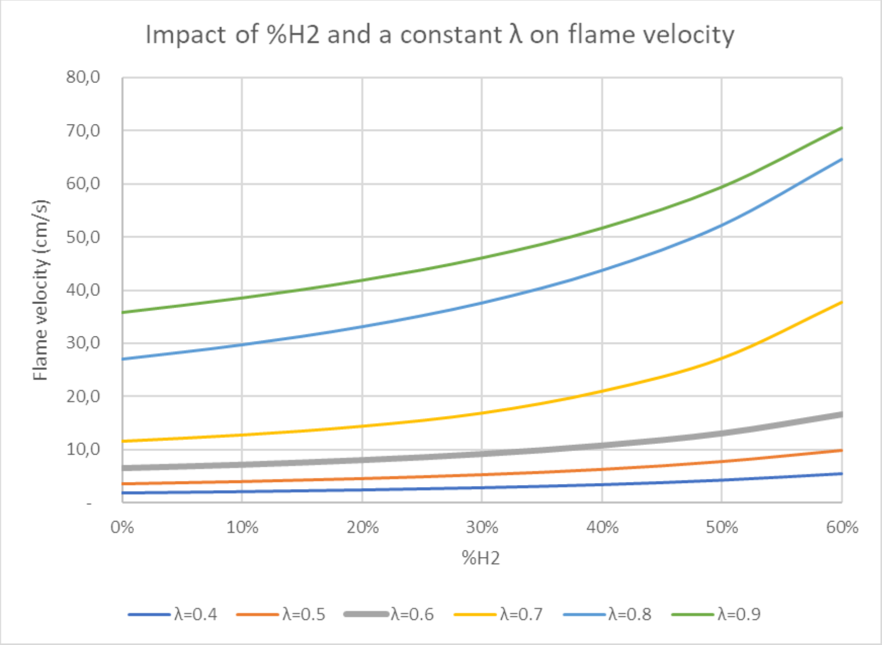

Figure 39: Impact of %H2 on flame velocity with a constant λ.

However, on most -if not all- partially premixed burners, adding hydrogen to natural gas increases the primary λ value proportionally to 1/CARI (Combustion Air Ratio Index) [1]. As a consequence, for partially premixed burners, the impact of hydrogen addition on flame velocity is quite high (Figure 40) which makes partially premixed burners more sensible to flashback than fully premixed burners.

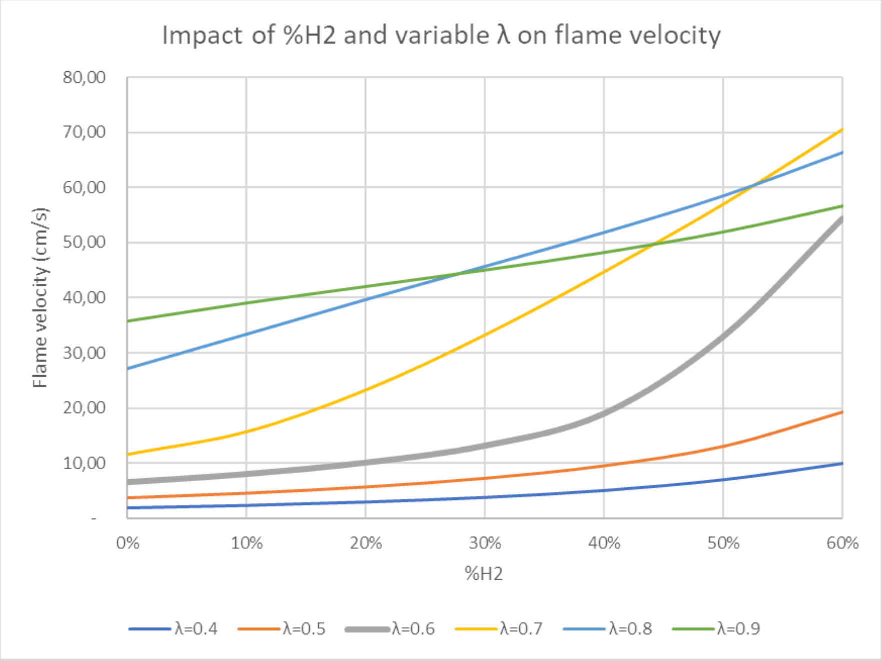

Figure 40: Impact of %H2 on flame velocity with λ proportional to 1/CARI.

It should be noted that, **the lower the initial λ, the lower the impact of H2 on flame speed**. So, a potential mitigation measure could be to change the gas injector in order to lower the primary λ value. If so, care should be taken not to make the primary air/fuel ratio too rich because it would cause some yellow tipping flame (soot in flame) and/or increase in CO emissions. Also, a change of injector size without changing the gas pressure will change the heating power of the burner.

6.1.2 Primary air/fuel ratio control

Changing the injector size of a burner is the way to change the primary air/fuel ratio.

Let's consider that, at an injector outlet, the momentum of the gas is entirely transmitted to the air:

(Eq 11.) $$\boldsymbol{Q_{mg}.U_g = Q_{ma}.U_a}$$

Where Q_{mg} and Q_{ma} are, respectively, the mass flowrate of gas and air and Ug and Ua their corresponding velocity.

The mass flowrate Q_{mg} is linked to the volume flowrate Q_g by the following equation (as for air):

(Eq 12.) $$\boldsymbol{Q_{mg} = \rho_g.Q_g}$$

(Eq 13.) $$\boldsymbol{Q_{ma} = \rho_a.Q_a}$$

Gas velocity Ug is linked to the volume flowrate by relation (as for air):

(Eq 14.) $$\boldsymbol{U_g = \frac{Q_g}{s}}$$

(Eq 15.) $$\boldsymbol{U_a = \frac{Q_a}{S}}$$

Where **s is the surface area of the injector** (m^2), and S is the surface area of the air pipe (m^2).

(Eq 11.), (Eq 12.) and (Eq 14.) combination lead to the following equation:

(Eq 16.) $$\boldsymbol{\frac{Q_a}{Q_g} = \sqrt{\frac{\rho_g}{\rho_a}.\frac{S}{s}}}$$

Air/gas ratio r is defined as:

(Eq 17.) $$r = \frac{Q_a}{Q_g} = \sqrt{\frac{\rho_g}{\rho_a}.\frac{S}{s}}$$

By definition, the air fuel equivalence ratio is calculated by the following formula:

(Eq 18.) $$\boldsymbol{\lambda = \frac{r}{Va/_1} = \frac{\sqrt{d}}{Va}.\sqrt{\frac{S}{s}}}$$

(Eq 18.) shows two ways to reduce the value of λ in order to limit the impact of hydrogen on flame velocity:

1. Reduce the air inlet section.
2. Increase injector diameter.

It should be noticed that option 1 does not have any impact on heating power. This is the reason why this technique is used on some catering equipment in order to adjust combustion air/fuel ratio.

On the contrary, option 2 increases the heating power of the burner. It is interesting for constant composition H2NG mixtures because it can compensate the decrease of heating power, but it could lead to overheating when used with pure natural gas.

6.2 Test results

A domestic cooking burner has been tested with two different gas injectors. The original one, which has a diameter designed for a heating power of 3.05 kW for G20 and a bigger one, with a heating power of 3.35 kW for G20. For the second injector, the heating power for G20+20%H2 is 2.95 kW.

By using a bigger injector, the air/fuel stoichiometric ratio is decreased, and the burner is supposed to be more resilient to flashback.

With the bigger injector, the burner was operated at Qmin up to 80%H2 with a water pot, without any occurrence of flashback.

However, the measurement of pollutant emissions shows an increase of CO emissions with G20: by changing the injector CO emissions at Qmax with G20 are doubled, increasing from 428 to 838 ppm (Figure 41). CO emissions also increase at Qmin, but in a lower extent. NOx emissions with both injectors do not vary much.

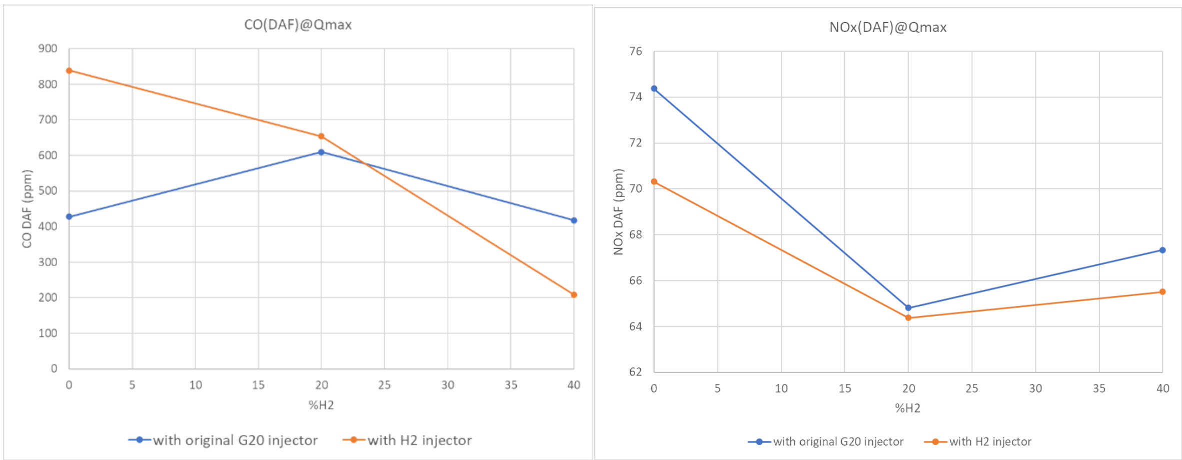

Figure 41: Comparison of CO and NOx emissions for two injector size at Qmax.

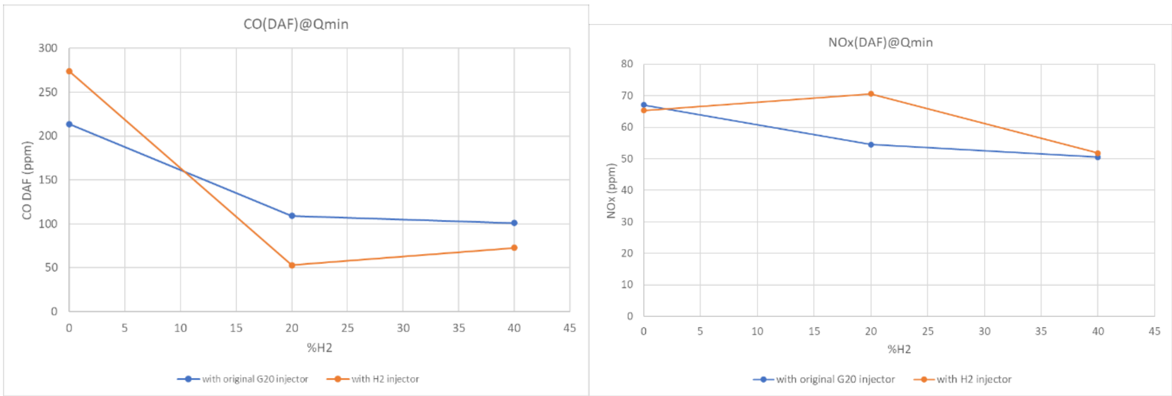

Figure 42: Comparison of CO and NOx emissions for two injector size at Qmin.

6.3 Conclusions on injector change

An increase of injector diameter of a cooking burner offers an increase protection of the burner to the phenomena of flashback and allows to reach the power for which the burner was initially designed for with G20.

However, when the burner is used with G20, CO emissions are doubled, so it cannot be considered to be a mitigation measure if the %H2 varies from 0 to 20% or above.

On the contrary, if the bigger injector is used with a minimum percentage of hydrogen of 20%, this modification brings flashback resistance and pollutant emissions close to the original one.

7. CONCLUSIONS

One of the main issues underlined by the extensive tests performed during THyGA project is the risk of high CO emissions due to adjustment with a low Wobbe Index gas containing hydrogen and the use with a high Wobbe Index gas without hydrogen. Several mitigation solutions have been studied. Among them, we can underline:

- Appliance adjustment should be based on O_2 values, rather than CO_2 values.
- the authors suggest only allow adjustment (or re-adjustment) of appliances to G20 if the gas composition or Wobbe is known. A specific procedure to do that would need to be developed.
- Set points for the initial adjustments with G20 could be revised toward lower CO2 or higher O2 at least for the appliances on the market with too close to stoichiometry set points.
- It is preferable to use combustion-controlled boilers that keep the air/fuel ratio constant (via ionization probe or CO sensor).

However, concerning the last bullet point, more investigations should be performed to clarify if flashback occurs during auto-calibration periods, when the boiler operates for a few seconds in near-stoichiometric conditions.

Some directions for other potential mitigation measures are also suggested in this report.

Moreover, test results show that the CO_2 (or O_2) range of adjustment suggested by manufacturers on some appliances may have to be updated in order to take into account adjustment from low Wobbe Index and use with high Wobbe Index gases. This is especially required for appliances that operate with a very low air excess.

Some questions were asked, during the lifetime of the project, about the impact of hydrogen on condensates, natural draught and potential condensation in flue ducts downstream of a non-condensing boiler.

Condensates acidity was measured on several boilers. Acidity **decreases with increasing %H2** in the fuel gas. This is caused by the decrease of NOx concentration in flue gas.

Up to 20%H2, extra condensation is not expected to appear for non-condensing boilers because several physical effects compensate each other. The more difficult configuration is at minimum heating power. However, even at 40%H2, the minimum temperature difference between flue gas temperature and the dew point was 28.8°C, thus leaving some safety margin.

Up to 20%H2, natural draught is almost not impacted by H2 admixture. In most cases the flowrate of the flue gas was reduced or remained constant when hydrogen was added. Relative density of flue gas at maximum heating power is higher than at minimum heating power. Relative density of flue gas ($\varrho_{flue}/\varrho_{air}$(15°C) at Qmin is always below 0.83 up to 40%H2. Its variation is lower than 1% between 0%

and 40%H2. As a consequence, no problems natural draught problems are expected in the range 0-40%H2.

Concerning cooking hobs, an attempt was made to change the injector size of a 2.75 kW burner in order to make it more resilient to flashback by decreasing the primary air/fuel ratio. The burner operated with no flashback up to 80%H2. However, CO emissions DAF were close to 1000 ppm when the burner was used with pure methane. The modification works well if %H2 is kept above 20%H2 but is not adequate for H2NG where %H2 varies from 0 to 20%.

Delayed ignition is also a subject of interest when hydrogen is mixed with natural gas. THyGA WP3 test report [10] includes tests results for room sealed and partially premixed boilers, as well as for decorative gas fire. Mitigation measures to prevent delayed ignition includes an adjustment that takes into account the presence of H2 in the fuel gas, reduce ignition safety time by replacing the burner control device.

List of Illustrations

List of tables

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