Combustion control in domestic gas appliances

Fuel gases containing hydrogen

Project report
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REPORT

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Summary

Several European manufacturers are today offering domestic gas boilers that are able to burn gases of different compositions with automatic adjustment of the excess air ratio. This study was initiated by test results from E.ON in Germany, which showed that the automatic adjustment did not operate as planned when hydrogen was added to natural gas.

This report contains a description of the combustion control systems used in some European residential condensing gas boilers with fully premixed burners. Combustion control systems are based either on flame ionisation or flue gas analysis to evaluate the combustion. No publically available detailed tests have investigated the sensitivity to hydrogen addition in these burners. A general discussion of the detection principles supported by German test in similar burners gave the following conclusions.

Flame ionisation is used by Weishaupt and Viessmann. Flame ionisation is used for combustion of hydrocarbons and may be a weakness when hydrogen is added to natural gas. The concentration of ions for a hydrocarbon-hydrogen mixture is lower than for the hydrocarbon fuel alone and may disturb the system. Another source is the location of the electrode. The flame position may change the ionisation signal. Both sources are suggested as explanation of the lack of compensation for hydrogen addition in appliances using combustion control observed in E.ON Ruhrgas tests.

Flue gas analysis is used by Vaillant. A CO detector is used and adjusts the gas and air flow to an operating point between the large CO gradients at low and high excess air ratios. It seems that flue gas analysis using a CO detector is not as sensitive to a moderate hydrogen addition to natural gas as the flame ionisation technology. However, no tests were available to verify this.

The study was ordered by the Danish gas companies’ Technical Committee on Gas Utilisation and Installations (FAU GI) Quality assurance was made by Leo van Gruijthuijsen.

1 Introduction

This study focuses on combustion controls used in some condensing boilers with fully premixed burners. This chapter describes the influence on the combustion when hydrogen is added to natural gas.

Hydrogen is not a naturally occurring component in natural gas. If hydrogen is present it originates from either gasification (either of biomass or fossil fuels) or from electrolysis. Hydrogen based on biomass gasification, electrolysis or renewable electricity/power reduces the overall carbon footprint of the natural gas used by the end user.

In a German work /1/ the influence of hydrogen containing natural gas on appliance performance was studied. It was observed that combustion control supposed to compensate for changes in gas composition did not operate as expected regarding the ability to compensate the combustion for changes in gas quality. No safety risks were observed in the tests. The German study initiated this study, the purpose of which is to find an explanation for the German observation.

The present interest for Power-to-gas and hydrogen production and injection into the natural gas grid has also raised the question regarding the appliance and burner sensitivity to changes in gas quality. It is often mentioned that it is possible to use up to 10% hydrogen content in the natural gas. The German study mentioned previously observed problems with the combustion control at this hydrogen content. A recent GERG project included aspects of hydrogen addition to natural gas from transmission and storage to the combustion. The results are summarised in a paper /2/.

1.1 Hydrogen influence on natural gas combustion

Hydrogen has significantly different properties compared to the hydrocarbons normally present in natural gas. The heating value, Wobbe number and laminar flame velocity are a few examples. Table 1 shows these differences in various gas properties.

Table 1 Hydrogen and methane properties (25/0°C) [1]

Property	Hydrogen	Methane
Lower heating value, H_i (MJ/m^3)	10.778	35.808
Higher heating value, H_s (MJ/m^3)	12.752	39.735
H_s/H_i (-)	1.183	1.110
Density (kg/m^3)	0.0898	0.7175
Relative density (-)	0.0695	0.5548
Lower Wobbe number (MJ/m^3)	40.8833	48.0714
Upper Wobbe number (MJ/m^3)	48.3711	53.5434
Air requirement (m^3/m^3)	2.409	9.671
Laminar flame speed (m/s)	346	43

Figure 1 shows the influence of hydrogen addition to methane and natural gas (Danish natural gas, average Sep. 2013). The graph shows that hydrogen reduces both the heating value and the Wobbe number in a mix containing up to approximately 80 % (vol).

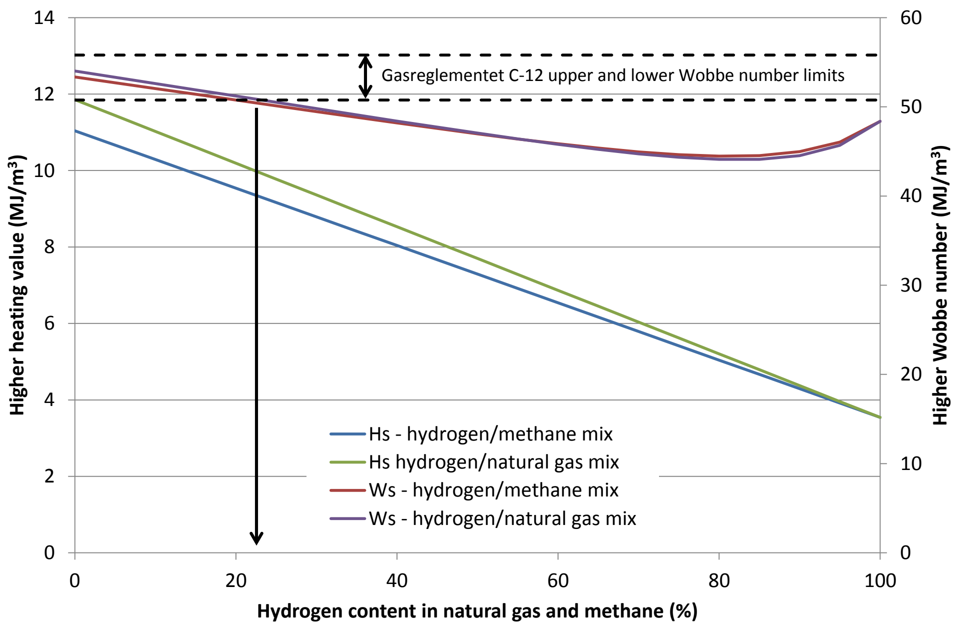

Figure 1 Heating value and Wobbe number for methane and natural gas with added hydrogen

Figure 1 shows that the maximum hydrogen content in the mix is approximately 20% to fit the Danish Wobbe number limit set in the Danish Gas Regulations (Gasreglementet), section C-12.

When hydrogen is added to a gas burner adjusted for natural gas, both the operating point and combustion characteristics will change. The burner in-

[1] Sources: Heating values from ISO 6976, densities from NIST Webbook, and air requirement and flame speed from /1/.

put will be reduced due to the lower Wobbe number. If the combustion air flow is forced, i.e. a burner fan, and not corrected to changed gas composition, the air factor will also be changed. In case of moderate hydrogen addition the air factor will increase. The flame speed will also be affected and this can potentially cause flame instability. Addition of rapidly burning hydrogen may cause flame flashback. Figure 2 illustrates the situations for both fully premixed combustion (lean premix) and partially premixed combustion (rich premixed). An atmospheric burner has typically a partial premixed combustion found in the left part of the graph while the right part of the graph represents the combustion in fully premixed burners. Combustion control is only used in fully premixed burners. No observations of flashback in these burners have been found when hydrogen concentrations are limited to 10-20 %. Some concern regarding overheating in premixed burners have been raised, but no study or test confirming this has been found.

In burners with air ratio $\lambda<1$ the air ratio will increase if hydrogen is added due to reduced load and constant primary air flow. The laminar flame velocity increase caused by the hydrogen content is amplified by the shift in air ratio towards stoichiometric conditions. In burners with air ratio $\lambda>1$ the laminar flame velocity will also increase due to the hydrogen content, but as the air ratio shifts to a higher value the laminar flame velocity will not be as affected.

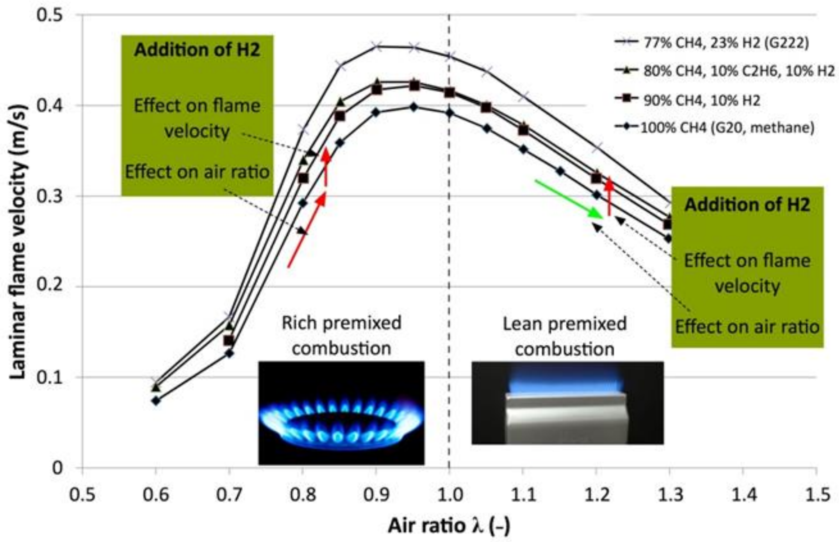

Figure 2 Laminar flame velocity change when hydrogen is added to natural gas

The main observations in /1/ for a condensing boiler with and without combustion control are shown in Figure 3. The two left graphs show test results with SCOT combustion control compared to test results without combustion control (right graphs). It is clear that the burner input and excess air ratio changes are similar for both boilers. The combustion control should normally adjust the burner to a constant excess air ratio. The emissions also show similar behaviour with equal or reduced levels as the hydrogen addition increases.

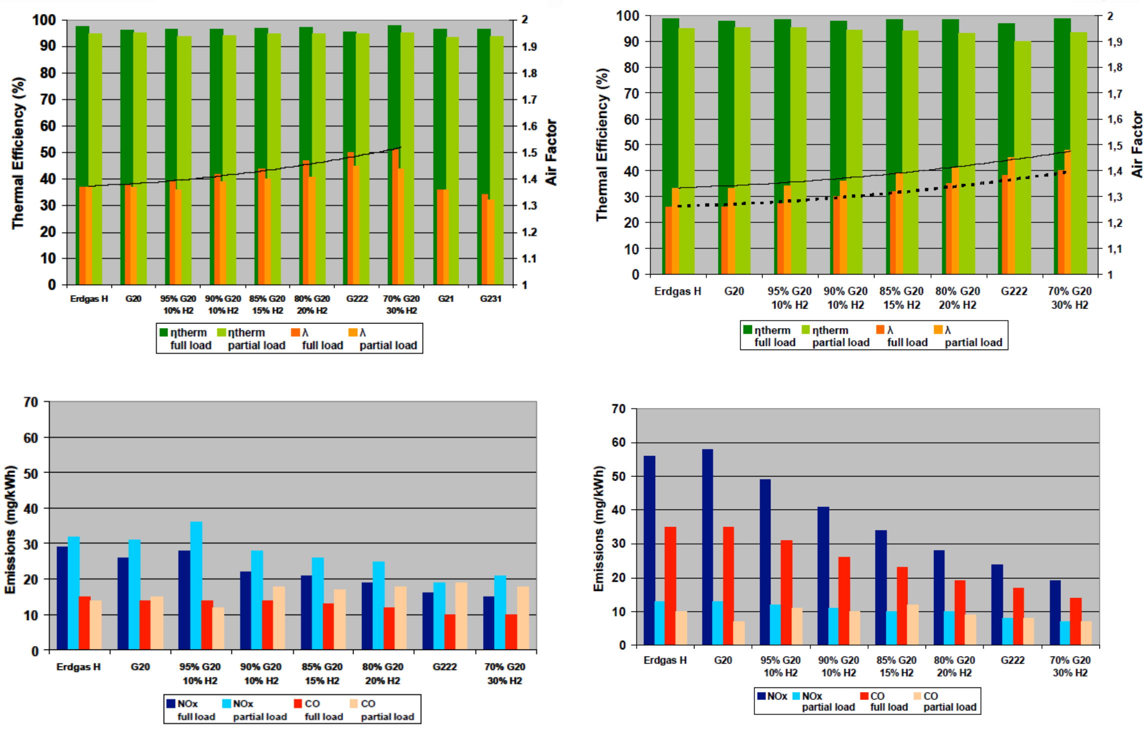

Figure 3 E.ON Ruhrgas test results for a gas boiler with SCOT combustion control (left) and without combustion control (right) when hydrogen is added to natural gas

1.2 Flame and combustion detection

Flames and combustion can be detected in several ways. Among these are:

- Temperature detection. An example is a thermocouple connected to the gas valve. In case of flame failure the gas valve will close when the temperature is not high enough.
- Flue gas analysis. The content of for example O_2 or CO_2 can be measured and used for combustion air flow control.
- Flame ionisation. Hydrocarbon combustion can be detected through the presence of ions in the combustion zone. The ion concentration is dependent on for example air ratio and position in the flame.
- Flame radiation. Radiation in the IR or UV wavelengths. The signal depends on fuel and flame temperature.

The combustion control system used in natural gas fired residential boilers either use flue gas analysis or flame ionisation.

1.2.1 Flame ionisation

The working principle of flame ionisation detectors is to detect the ions formed during hydrocarbon combustion. Flame ionisation is suitable for hydrocarbon combustion.

1.2.2 UV and IR detectors

UV and IR detectors use the flame radiation to detect combustion. Depending on fuel the radiation is emitted at different wavelengths. Hydrogen combustion is detected using this mechanism. In several other burners, especially large burners, radiation in the UV and IR spectra is also used to detect the combustion. UV and IR detection is not suitable in small burners and in burners with low flame temperatures. Both factors reduce the useful radiation flux emitted from the flame.

2 Products on the European market

Some of the major European boiler manufacturers have combustion control system in condensing boilers with premixed burners. In this chapter these systems will be briefly described. The purpose of the combustion control is to keep the air ratio at a point where safe and efficient operation will be secured.

Combustion control also means that the pneumatic connection between gas valve and air fan is removed. The gas valve and air fan are controlled separately using a signal describing the combustion process. It is also mentioned among the system descriptions that combustion control in residential appliances allows a lower power input to the air fan. The reason is that the pneumatic connection between gas valve and the air fan is no longer necessary and the electricity consumption can be reduced.

2.1 Weishaupt SCOT system

Weishaupt has used the SCOT (Safety Combustion Technology) developed by Elster Kromschröder for several years. The system design is shown in Figure 4. It uses flame ionisation as input. The flame ionisation electrode is used both for flame monitoring and for combustion control.

The flame ionisation signal is used to control the gas valve and the fan speed. This is shown in the upper left graph in Figure 4. The ionisation current from the flame is used to control the gas valve opening and the air fan speed separately. The upper right graph shows graphically the operation of valves and air fan during burner operation. The lower left graph shows schematically how the ionisation's current reflects the combustion air factor λ. The ionisation current has a maximum at stoichiometric combustion (λ=1.0). The control system tunes the burner to the set point based on a measured ionisation current.

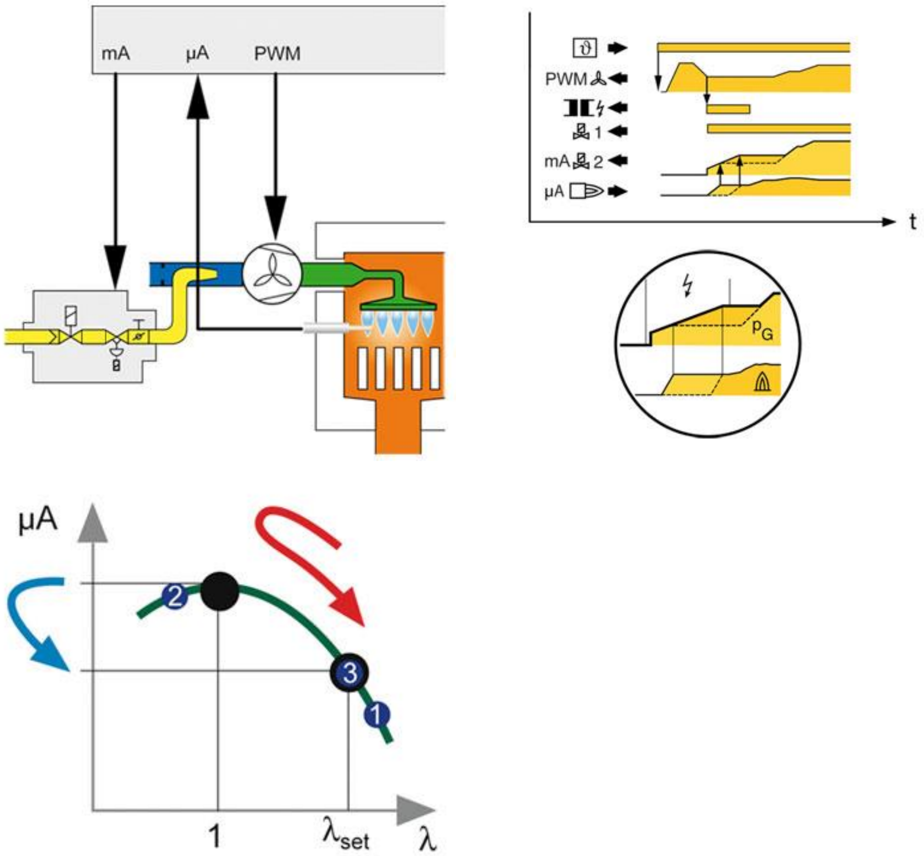

Figure 4 SCOT combustion control system used in Weishaupt boilers as described by Elster Kromschröder

The basis for the technology is presented in two conference papers /3, 4/. Figure 5 shows the difference in burner operation without (upper graph) and with (lower graph) combustion control. The burner is fed with natural gas H (W_s = 14.8 kWh/m^3) and switches over to natural gas L (W_s = 14.8 kWh/m^3), and back. The air factor is 1.2 with natural gas H and becomes 1.4 with natural gas L. The shift from natural gas H to natural gas L clearly shows significant differences in emissions when no combustion control is used (upper graph). CO emissions increase sharply and NO_x emissions are reduced. The CO emissions indicate combustion problems. When the combustion control is used the change between the gas qualities are not observed in the CO and NO_x emissions.

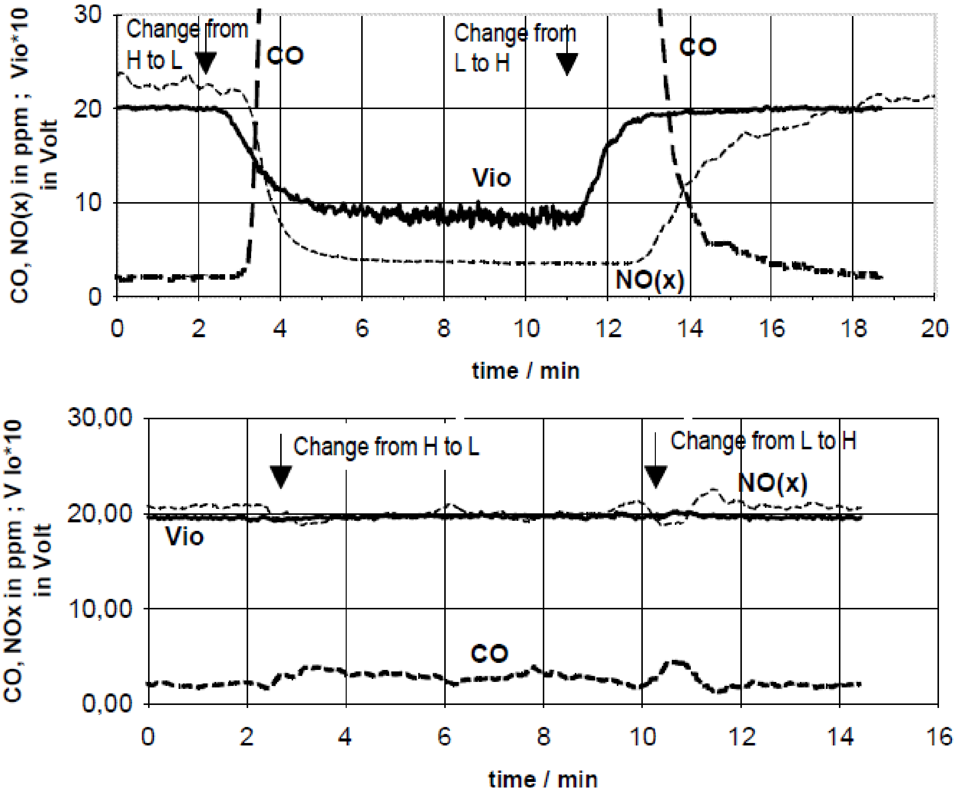

Figure 5 Example of operation without and with SCOT combustion control /3/

2.2 Vaillant

Vaillant has chosen flue gas analysis for combustion control. A CO sensor is used. Vaillant claims that the advantages are /5/:

- The sensor does not have to give an exact emission value
- The optimal excess air ratio may vary between different burner designs. The optimal point may also vary during the burner life time.
- A combustion control system based on a CO sensor can always adjust to a point with safe operation and low emissions.

The CO emissions from low to high air ratios are shown in Figure 6. The graph also shows an optimal operating range, in this case around $\lambda = 1.25$. The combustion control system uses the steep CO gradient to find the proper burner adjustment. Vaillant also claims that the combustion control corrects for wear and other small problems that can disturb the burner operation and performance.

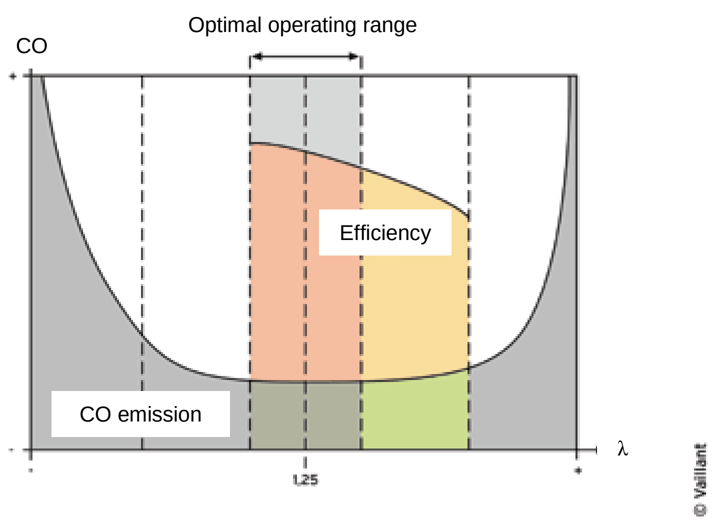

Figure 6 CO emissions and optimal operating range in premixed gas burners (Source: Vaillant)

Figure 7 shows the CO sensor that is located in the flue gas flow.

Figure 7 Vaillant CO sensor for combustion control, 1.6×2.1×1 mm

2.3 Viessmann Lambda Pro

Viessmann has chosen the flame ionisation as input signal to the combustion control system. The design is shown in Figure 8 and is called Lambda Pro. Viessmann describes the operation as follows when a gas is substituted by a gas with lower Wobbe number. Viessmann has an animation[2] on the Swiss' website describing the Lambda Pro operation when natural gas E[3] is substi-

[2] http://www.viessmann.ch/de/flash/animation_lambda_pro.html
[3] Reference gas G20, 100 % CH_4, Wi = 49.60, Ws = 54.76 MJ/m^3

tuted by natural gas LL[4]. The air factor is 1.3 for operation with natural gas E, and a change to natural gas LL with lower Wobbe number increases the air factor. The ionisation current is reduced due to a lower flame temperature. The control system corrects the air factor through increased gas flow to the previous flame temperature and ionisation current. The description shows that Viessmann uses the ionisation current in the same way as Weishaupt to keep the burner tuning constant.

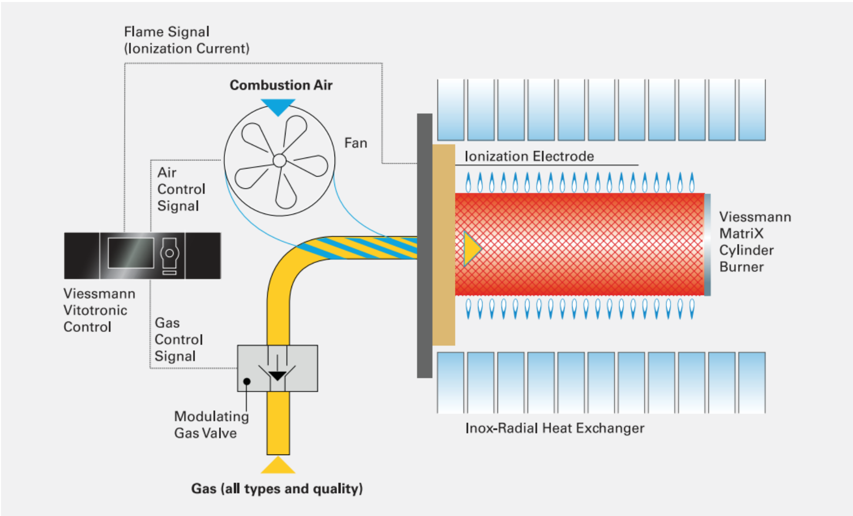

Figure 8   Viessmann Lambda pro combustion control system layout

The signal is used in the control box that controls the gas and combustion air flow. It is basically the same design as used by Weishaupt. Viessmann claims that the system can handle gases with a Wobbe number between 10.0 and 16.1 kWh/m^3 (36.0 – 58.0 MJ/m^3)[5].

2.4 Other manufacturers

Brötje presented a combustion control at the ISH fair in April 2013[6]. Brötje boilers are sold in Denmark under the Baxi brand. Brötje claims that the boiler adjusts automatically to any natural gas. Other Brötje appliances are recommended for LPG. Baxi is marketing boilers in the UK with combus-

[4] Reference gas G25, 86 % CH_4 and 4 % N_2, Wi = 37.38 MJ/m^3, Ws = 41.52 MJ/m^3
[55] Viessmann pamphlet for Canada, http://www.viessmann.ca/content/dam/internet-ca/pdfs/wall-mount/lambda_pro_b2ha_flyer.pdf
[6] Brötje combustion control, https://www.broetje.de/cps/rde/xbcr/broetje_de/DOCUMENTS/Presse/DRANmabr0613_Info_Vorankuendigung_ISH.pdf

tion control called Think[7]. Baxi claims that the boiler automatically adapts to the gas quality, including LPG and natural gas without any hardware changes. Neither Brötje nor Baxi describe the sensor technology used in the combustion control systems.

The Italian company SIT has developed a combustion control called GAMMASIT[8]. It uses the ionisation electrode as sensor and it is then basically the same method as used by Weishaupt (SCOT) and Viessmann (Lambda Pro).

2.5 Studies on methane-hydrogen combustion

There are many studies made on the combustion of methane-hydrogen or natural gas-hydrogen mixtures. The main combustion situations are for example turbulent diffusion flames and emissions of hydrogen enriched natural gas in combustion engines. These studies do not give direct information related to combustion control in premixed gas burners.

2.5.1 Studies on hydrogen addition and flame ionisation

Only one study was found that is related to the ion concentration in methane-hydrogen flames /6, 7/. It can be directly used to suggest an explanation of the E.ON Ruhrgas test results. The German study focussed on flame detection in hydrogen-natural gas combustion in burners with a porous surface. The application was reformers in fuel cells. Calculations (and experiments) were made on premixed laminar flames, which is the same combustion situation as in the E.ON Ruhrgas tests.

The software CHEMKIN[9] was used to calculate the $H3O^+$ ion concentration in the combustion zone. The ion concentration is a measure of the signal strength. An example of calculated results is shown in Figure 9. Four gas compositions were used, pure methane (BM), methane and 72.7 % H_2 (BR), methane and 47.0 % H_2 (B1), and methane and 30.8 % H_2 (B2), Three air factors were used, λ = 1.2, 1.6 and 2.0.

[7] Baxi Think combustion management, http://www.baxi.co.uk/axis-new-think-combustion-management-system-explained.htm
[8] GAMMASIT, http://www.sitgroup.it/content/view/567/218/lang,en/
[9] CHEMKIN is useful for one-dimensional combustion calculations in premixed flames.

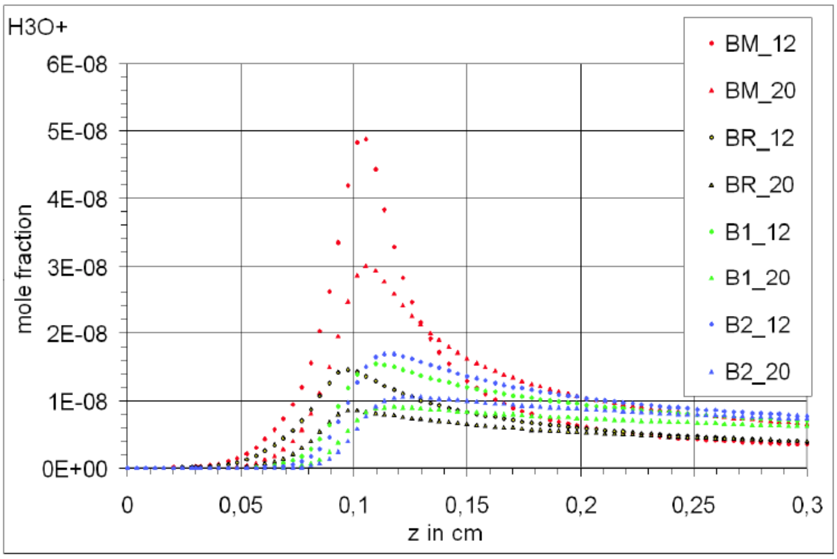

Figure 9 Calculated H3O^{+} ion concentration as function of distance from the burner surface for different gas compositions

The figure clearly shows that the ion concentration is reduced when hydrogen is added to methane. However, the hydrogen content in the gas compositions are significantly higher than in the E.ON Ruhrgas tests, and consequently the calculated results shall be treated with some care.

A conclusion from this graph is that the flame ionisation signal is weaker, and the curve has a peak not as sharp as with pure natural gas or methane. This may explain that the SCOT system did not respond as anticipated when hydrogen is added to the fuel.

No experimental evidence of any sensitivity to hydrogen addition is known for the CO sensor used by Vaillant in their combustion control. The technology seems to be fuel independent.

3 Conclusions

Two combustion control technologies are used for premixed burners in condensing boilers, flame ionisation and flue gas analysis. Observations of combustion controls that were not working properly when hydrogen is added, initiated this study.

Flame ionisation is used by Weishaupt and Viessmann and uses the existing flame ionisation electrode to detect the combustion and adjust gas and air flow in case of changes in the gas quality. Flame ionisation is used for combustion of hydrocarbons and may be a weakness when hydrogen is added to natural gas. The concentration of ions for a hydrocarbon-hydrogen mixture is lower than for the hydrocarbon fuel alone and may disturb the system. Another source is the location of the electrode. The flame position may change the ionisation signal. Both sources are suggested as explanation of the malfunction of combustion control observed in E.ON Ruhrgas tests.

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It seems that flue gas analysis using a CO detector is not as sensitive to moderate hydrogen addition to natural gas as the flame ionisation technology. However, no tests were available to verify this.

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