

# **MITIGATION OF CO POISONING HAZARD IN MALFUNCTIONING GAS APPLIANCES THROUGH USE OF HYDROGEN BLENDED GAS**

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## **ABSTRACT**

The HyDeploy project [1] has undertaken an extensive research programme to assess safety and performance of the existing UK gas appliances population fueled with natural gas / hydrogen admixtures (hydrogen blended gas). The first stage of this work [2] focused on well maintained and normally functioning appliances. This work demonstrated that unmodified gas appliances can operate safely with hydrogen blended gas (up to 20 vol% hydrogen) and the key hazard areas of carbon monoxide (CO) production, light back and flame out, and the operation of flame failure devices are unaffected.

It is widely recognized that due to aging and variable degrees of maintenance that the combustion performance of a gas appliance will depreciate over time. In extreme cases this can lead to situations where high levels of CO may be released back into the dwelling resulting in CO poisoning to the occupants. To obtain a universal appreciation of the effect of hydrogen addition on the safety and performance of all gas appliances operation under sub optimal conditions is required, and therefore it is important that the operation of malfunctioning appliances fuelled with hydrogen blended gas is assessed.

A review of failure modes identified six key scenarios where the composition of the fuel gas may lead to changes in safety performance - these primarily related to the resulting composition of the flue gas but also included delayed ignition. Gas appliance faults that will increase the CO production were tested through a series of experiments to simulate fault conditions and assess the effect of hydrogen blended gas. The fault modes examined included linting, flame chilling, incorrect appliance set up and modification of gas valve operation. The programme utilized six different appliances tested with three methane-hydrogen fuel blends (containing 0, 20 and 28.4 vol% hydrogen).

In all cases the switch to hydrogen blended gas reduced CO production. The change in CO production when using hydrogen blended gas is a consequence of a decrease in the theoretical air requirement to achieve complete combustion. In some cases, the amount of CO produced was identical to the non-fault baseline performance on methane, thereby fully mitigating the consequence of the malfunction. In the case of very high CO production a 90% reduction was recorded when using 20 vol% hydrogen blended gas. In situations such as non-optimal boiler set up the addition of hydrogen to the gas supply would prevent the production of high levels of CO.

The findings here, together with the results from HyDeploy 1 [2] indicate that the safety and performance of unmodified existing UK gas appliances are not detrimentally affected when using hydrogen blended gas. Furthermore the addition of hydrogen to the fuel gas has been shown to reduce CO production under fault conditions, therefore the introduction of hydrogen into the gas network may serve to mitigate the hazard posed by existing faulty appliances that are producing elevated levels of CO.

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## 1.0 INTRODUCTION

HyDeploy is a demonstration project funded by OFGEM, Cadent and Northern Gas Networks to establish the feasibility of supplementing natural gas in the UK distribution network with up to 20 vol% hydrogen. As part of the background research undertaken by HyDeploy an assessment of the operation and performance of the existing and unmodified UK gas appliance population has been performed. An initial programme of work [2] generated a wide range of safety and performance data on the use of domestic and commercial gas appliances with hydrogen blended gas. This work demonstrated that unmodified gas appliances can operate safely with hydrogen blended gas (up to 20 vol% hydrogen) and the key hazard areas of CO production, light back and flame out, and the operation of flame failure devices are unaffected. However, that study was limited to assessing safety and performance of well-maintained appliances that conformed to British and European standards for the relevant appliance type, and therefore excluded appliances that had developed fault conditions.

The UK appliance population has been built up over many years. During that period, appliances have been installed “as new” against the safety and design standards in force at the time of installation. During the intervening period between installation and final disposal of an appliance the safety and performance characteristics of the appliance may change (typically reduce) compared to the “as new” installation condition. Furthermore a reduction in safety and performance may be particularly evident where routine maintenance or servicing is not undertaken. The DIDR report [3] identified that 36% of all reported cases of CO incidents (both fatal and non-fatal) have a root cause in a lack of correct servicing and shows a strong link to CO production. In-situ assessment of appliance operational condition was undertaken by Croxford [4] on approximately 600 London properties and by Scotia Gas Networks [5] on 900 properties in Oban. These two studies indicate that between 6 to 11% of the UK appliance population may be in an unsafe operating condition. Therefore appliances in a suboptimal condition that may be operating outside the assumed safety and performance criteria would form a significant proportion of the appliance population if a national roll out of hydrogen blended gas was to occur.

Previous studies relating to the use of blended gas have demonstrated that fuelling correctly-operated, maintained and serviced appliances with blended gas will lead to a reduction in the production of CO in the flue gas. As CO poisoning is the main hazard resulting in fatalities from gas use [3], this reduction has the potential to reduce the risk of fatality where flue gases interact with members of the public. For the purpose of demonstrating that the introduction of a hydrogen blend into the gas grid does not lead to deterioration in safety, it is important to consider the effect that changing the gas composition may have on appliances in a compromised state. To address this knowledge gap an additional programme of appliance assessment work has been undertaken to extend the initial findings from HyDeploy to all UK gas appliances, regardless of age or condition.

The work presented in this paper focuses specifically on the production of CO by faulty appliances and how the addition of hydrogen to the gas supply can lead to a reduction in CO production. The first stage of this work was to assess and identify the nature of gas appliance faults that maybe affected by the composition of the fuel. This was coupled with an understanding of the mechanisms of CO production to devise an experimental programme to that would allow the consequence of appliance fault conditions to be quantified. Operation of appliances in simulated fault conditions was undertaken with up to four natural and hydrogen blended gas.

## 2.0 CO PRODUCTION IN GAS APPLAINCES

A review of appliance fault modes has identified the mechanisms were by the fuel composition has a bearing on the CO poisoning hazard. In most scenarios occurrence of a single fault mode will not result in a hazardous situation and combination of two or more events are required. The key areas where excessive exposure to CO can occur are as a result of incomplete gas combustion coupled with the products of combustion not being safely removed and/or oxygen depletion in room where appliance is situated (e.g. through leakage of combustion gases). Mechanisms where these types of

fault can occur can be attributed to six root causes. These are summarised in Table 1 along with practical examples of how the fault can occur and the effect that it has on the operation of the appliance.

Table 1. Gas Specific Appliance Fault Modes.

Fault	Example	Effect
Poor Maintenance	Linting of air inlets	Reduction in aeration Flame chilling
Incorrect set-up	Coal placement in space heater Air-fuel ratio set on low Wobbe Number fuel	Insufficient air to achieve complete combustion
Malfunction	Safety device failure	Flue gas spillage build-up
Maloperation	Varied – drying clothes, inappropriate space heating, interfering with flame	Changes to aeration Incomplete combustion Diverting flue gas into living space Flame Chilling
Ad hoc repairs	Inadequate repair Wrong components	Poor combustion Flue gas spillage
Flue Installation	Poor placement Poor draught	Poor aeration Poor combustion Flue gas spillage

A common feature in the fault modes is the effect on the aeration and how this can affect the composition of the flue gas. Production of CO is dependent on the combustion chemistry of the gas at or beyond the burner surface. Relevant factors include reduction of available oxygen for combustion or chilling of the flame against cooler surfaces before full combustion occurs. This can be generalised as, any process that affects the stoichiometric gas / air ratio. By understanding how production of CO is affected by blended gas relative to natural gas over a wide range of gas / air ratios, it should be possible to summarise the effects of all unsafe operating conditions.

The combustion mechanism of methane with air has been extensively examined and widely reported in literature (e.g. [6]). On a macro scale a single combustion reaction can be written to describe the complete/clean combustion of methane (see Equation 1). The addition of hydrogen to the methane introduces a second, high-level combustion reaction (Equation 2).



Underlying these simple reactions are many complex reaction pathways forming intermediate free radical species, with nearly 300 reactions and 50 different species having been identified (Turns, 2006). The interaction of the combustion system with the physical geometry of the burner can affect how the intermediate reactions occur, and can lead to partial incomplete combustion (even when there is an excess of oxygen) resulting in the formation of CO. A simplified approach to describing the formation of CO during combustion of methane is given by Equation 3 with subsequent conversion of CO to carbon dioxide via the reaction described by Equation 4.



A primary route to forming CO is by limiting the supply of air (oxygen) to levels below that required for the complete stoichiometric combustion reaction. Other relevant mechanisms that can lead to incomplete combustion include cooling of flames by contact with cold surfaces (as would occur in a water heater or a burner during start up).

A normally operating gas appliance will be designed to operate efficiency, burn cleanly and therefore naturally minimise the production of CO. This is typically achieved by operating the appliance with excess air passing through the burner. A number of relationships are commonly used to describe the relative quantities of air and fuel, these include the air-fuel ratio (AFR) and the stoichiometric ratio ( $\lambda$ ). The AFR ratio can be described as:

$$AFR = \frac{Q_{air}}{Q_{fuel}} \quad (5)$$

Where  $Q_{air}$  and  $Q_{fuel}$  are the volumetric flow rates of air and fuel, respectively. Where the quantity of air supplied provides the exact amount of oxygen to achieve stoichiometric combustion the air-fuel ratio may be given the subscript 'st' (to indicate that it is the stoichiometric quantity), or commonly this is also termed the theoretical air requirement (TAR):

$$AFR_{st} = \frac{Q_{air,st}}{Q_{fuel}} = TAR \quad (6)$$

The stoichiometric ratio ( $\lambda$ ) is the ratio of supplied air relative to the stoichiometric amount required for complete combustion for the given fuel mixture:

$$\lambda = \frac{Q_{air}}{Q_{air,st}} = \frac{AFR}{TAR} \quad (7)$$

On a volumetric basis Equations 1 and 2 have different oxygen requirements to achieve complete combustion. For a hydrogen blended natural gas the composition of the fuel will dictate the oxygen (and hence the air) requirement to achieve complete combustion, and therefore TAR will change with the fuel composition. An import parameter when assessing the performance of gas appliances is the Wobbe Number (WN) of the fuel, which is defined as.

$$WN = \frac{C_v}{\sqrt{RD}} \quad (8)$$

Where WN is the Wobbe Number (MJ/m<sup>3</sup>),  $C_v$  is the calorific value of the fuel (MJ/m<sup>3</sup>) and RD is the density of the fuel relative to air. Wobbe Number describes the energy delivery potential of the fuel for a given burner design, and is used to define the interchangeability of fuels in gas appliances. The fuel mixtures used in this study along with the corresponding composition, Wobbe Number, relative density and TAR are given in given in Table 2.

Table 2. Appliance Test Gases.

Test Gas		Composition (vol%)			Wobbe Number (MJ/m <sup>3</sup> )	Relative Density	TAR
		CH <sub>4</sub>	H <sub>2</sub>	N <sub>2</sub>			
G20	UK Reference gas	100	0	0	50.7	0.554	9.55
20 vol% blend	Hydrogen enriched reference gas	80	20	0	48.2	0.457	8.12
28.4 vol% blend	Hydrogen enriched reference gas at lower GS(M)R <sup>1</sup> limit	71.6	28.4	0	47.2	0.417	7.52
G23	Low Wobbe Number limit gas	92.5	0	7.5	45.6	0.585	8.84

### 3.0 EXPERIMENTAL

The objective of the study was to assess the combustion performance of gas appliances under fault conditions identified in Table 1, from which six fault or abnormal operating conditions were identified:

1. Poor maintenance (linting / air inlet blockage).
2. Flame chilling.
3. Incorrect set-up of a space heater.
4. Incorrect set-up of a gas boiler.
5. Gas mixing – the venturi effect.
6. Poor combustion performance.

Fault condition one to three and six have been simulated directly through experimental test work, while the outcome for four and five have been inferred by modifying the aeration set point in an appliance gas valve.

The appliances used in the test work were all compliant with the relevant British Standard for the appliance type and available for purchase at the time of the test programme (due to the nature of the testing undertaken specific details of the make and model are not given). Unless otherwise stated the appliance was operated in accordance with the manufactures instruction. Gas supply pressures ranged from 15 to 22 mbar with the default operation being at 20 mbar, which is the nominal pressure of the UK local distribution network. The test gases, summarised in Table 2, were G20, 20 vol% and 28.4 vol% hydrogen blended gases, and G23. A methane/hydrogen fuel mixture containing 28.4 vol% hydrogen equates to the low non-emergency limit of the Wobbe Number range specified in GS(M)R, namely 47.2 MJ/m<sup>3</sup>. G23, which is the low Wobbe Number limit gas, was included in some tests to assess the effect of lowering the Wobbe Number without the addition of hydrogen. Additionally two commissioning set gases were used that corresponded to the high and low ends of the GS(M)R emergency range. The Wobbe Number of the high and low set gases were 52.85 MJ/m<sup>3</sup> and 46.50 MJ/m<sup>3</sup> respectively and comprised methane plus either propane or nitrogen.

Flue gas composition was determined using commercially available electronic combustion gas analysers that are compliant with BS EN 50379. A Kane 451 plus (Kane International Ltd) was used to assess the first four operating conditions where the levels of CO produced were low to moderate, and did not exceed the instrument's limit of 3,000 ppm. The high CO testing undertaken for conditions five and six used a Multylser STx (Systronix GmbH) that was capable of recording up to 40,000 ppm CO.

## 4.0 RESULTS

### 4.1 Poor Maintenance – Linting

A typical artefact of poor maintenance of an appliance is linting, where the air inlet is fouled and the air flow to the gas valve is restricted. This was simulated in an instantaneous water heater by gradually blocking the air intake locations. The appliance was operated with G20 and linting applied until a marked step change in the CO concentration in the combustion products occurred (the highest level that could be achieved was  $\approx 50$  ppm CO). The fuel gas was then changed and the appliance tested under the same linted condition for each of the blended gases and over ranges of gas pressure and flow rate. The results are summarised in Figure 1. For a gas pressure of 15 mbar and low flow rate, an unexpected increase of ca. 12 ppm CO was measured when the concentration of hydrogen in the fuel gas was increased. Operating with the nominal UK supply pressure (20 mbar) there was negligible change in CO generation for both high and low flow rates when using 20 vol% blended gas. Nevertheless, for the high rate at 22 mbar, a reduction of CO production was observed when the

hydrogen concentration was increased in the inlet gas. In all of the test cases further addition of hydrogen to 28.4 vol% resulted in a reduction in CO production. Overall the simulated linting had minimal effect on the combustion performance of the appliance, and no effect was observed on the flame stability. As expected the addition of hydrogen did reduce the concentration of CO in the flue gas, with the effect more evident at the higher hydrogen concentration of 28.4 vol%.

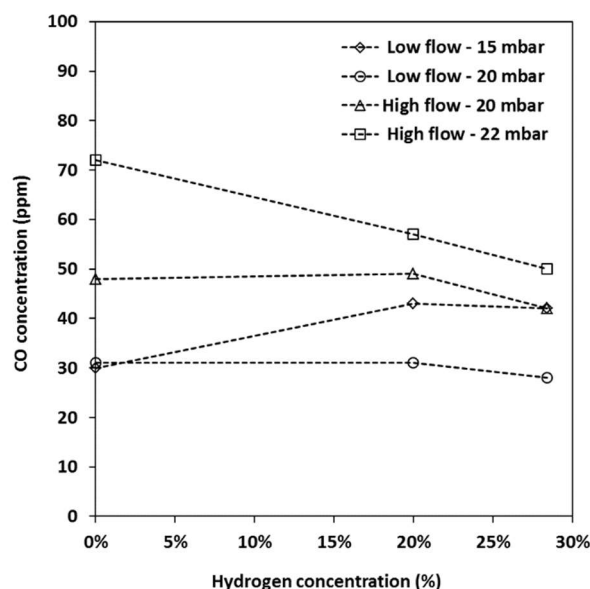


Figure 1. CO concentration in the combustion gases for a linted Water Heater.

## 4.2 Flame Chilling

The flame chilling may occur in a number of situations, and commonly occurs during the start-up of appliances where the flame contacts with cold heat transfer surfaces. Flame chilling may also occur where there is fouling of heat exchangers, or a change in the location of the flame due to flame lift off or damage to the burner. These situations may arise as a result of poor maintenance or maloperation of the appliance. The effect was simulated by heating iced water in a pan on a gas cooker hob. Two control tests were performed with; hot water just coming to the boil, and water that has reached a rolling boil. To mimic different degrees of flame impingement two levels of separation between the burner and the saucepan were used, representing operation as close as possible to the burner and then at the normal support level.

The concentration of CO in the flue gas for experiments with G20, 20 vol% blended gas and 28.4 vol% blended gas are shown in Figure 2. For G20, the CO production was considerably higher for the chilled flame tests in comparison to the control tests. In these tests the height of the pan above the burner only made marginal difference; similarly in the hot pan tests the extent of the boiling regime had little effect. In all cases the reduction in Wobbe Number through addition of hydrogen led to a reduction in the CO concentration. In the flame chilling tests with the pan at a normal height the CO production was reduced to levels comparable with the hot pan surface. However, in those tests with the pan at the lower height the reduction in CO production was not as substantial. In this situation the reduced separation between pan and burner will restrict the flow of secondary air to the burner which will promote incomplete combustion and CO production.

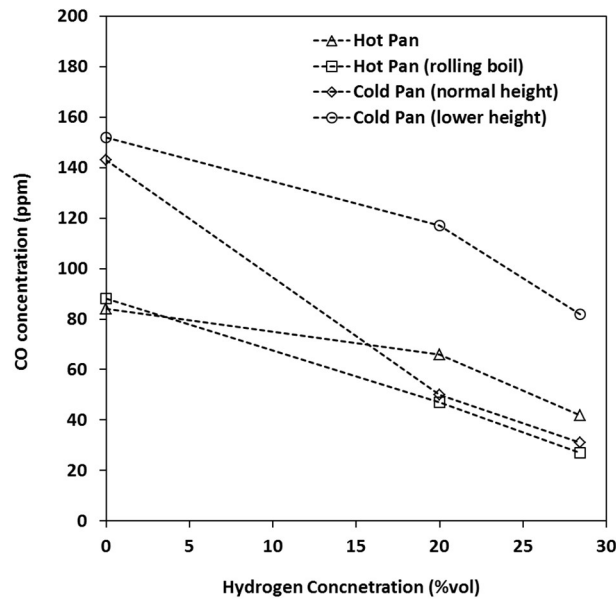


Figure 2 The effect of blended gas on CO production from chilled flames

#### 4.3 Incorrect Appliance Set Up – Space Heater

The set up and placement of coals and ceramics in space heaters are defined in the installation manual and would be completed by a Gas Safe engineer during commissioning. The manufacturer specifies a particular arrangement to ensure good combustion efficiency and to minimise CO and NO<sub>x</sub> emissions. However, it is not uncommon for the coals to be disrupted or deteriorate over time. Testing was undertaken with a Decorative Fuel Effect Fire (space heater) operating at 18 and 22 mbar inlet pressure, and at high and low flow rates for each of the three gases (with G20, 20 vol% blended gas and 28.4 vol% blended gas), and each of the three arrangements of coals. The three coal arrangements examined were: coals installed as instructed; empty coals tray, and incorrect placement of coals where the upper layer was displaced to fill the gaps between the lower layers of coals.

When the coals were placed as instructed, negligible concentrations of CO were measured for low flow rate conditions. However, when high rates were tested, a very low concentration of CO was recorded (4 ppm) and a very slight decrease (to 1 ppm) was detected when the concentration of hydrogen in the fuel gas increased. Operating the fire with an empty tray did not produce any significant modification of the combustion gas composition. Figure 3 shows the effect of incorrect placement of the coals on CO production. When the coals were incorrectly placed there was an increase in CO production for all the combinations of pressure and flow rate examined (values increasing from 0 - 4 ppm CO with correct placement to between 30 - 50 ppm CO when incorrectly placed). The addition of hydrogen from 0 to 20 vol% produced a decrease of CO in the combustion gases. However, for the lower flow rate and with an increase of hydrogen in the fuel gas from 20 to 28.4 vol%, a slight increase of CO concentration was observed. The incorrect placement of coals is likely to have hindered the flow of secondary air into the flame and therefore reduced the aeration relative to the base case with correct coal placement. The addition of hydrogen to the fuel will have mitigated the reduction in aeration due to the reduced TAR of blended gases compared to G20.

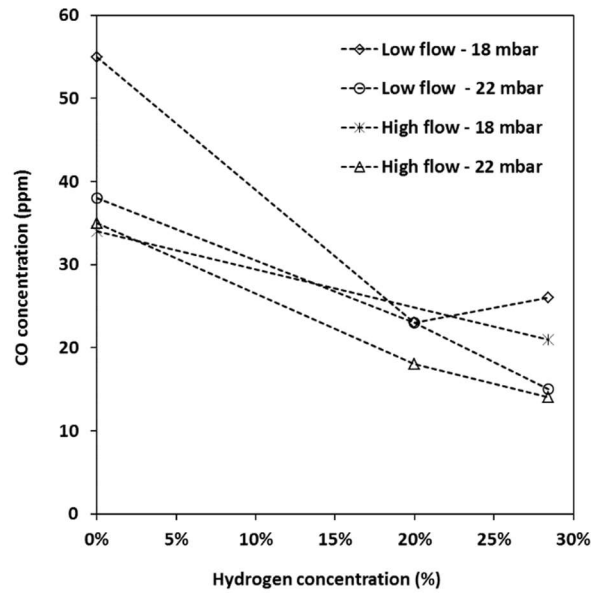


Figure 3. CO concentration in the combustion gases for a decorative fire with incorrect placement of coals.

#### 4.4 High CO Production

An overview of different failure modes that can be influenced by the fuel composition was given in Table 1 from which the abnormal operating conditions four and five were defined. The consequence of these two faults will lead to a variation in the air-fuel ratio which has a direct bearing on the level of CO production by the burner. In terms of simulating these conditions via experimentation, each of the failure modes can be viewed as a process which adjusts the optimised combustion condition that minimises the formation of CO. Due to the robust nature of gas appliances to cope with a foreseeable range of aeration conditions it was envisaged that in many typical fault conditions only a minimal changes in CO production would occur. This was demonstrated in the linted appliance test where application of the simulated fault led to marginal increases in CO levels which were ultimately still within the range of normal combustion performance.

Unfortunately, whilst infrequent, highly developed fault conditions can occur which give rise to high levels of CO production resulting in circumstances that are hazardous to life. This type of fault condition was simulated by using a fully premixed gas boiler with an adjustable air-fuel ratio valve. The valve contained a screw-turn throttle that progressively adjusts the gas flow rate (and hence AFR). This methodology allowed a universal understanding of how the introduction of hydrogen affects maloperating appliances, as all fault modes could be empirically simulated through direct manipulation of the air-fuel ratio. The appliance was commissioned by adjusting the throttle to achieve optimum combustion conditions on G20. Thereafter the combustion performance was characterised by measuring the flue gas concentrations (CO and CO<sub>2</sub>) in response to valve adjustment via the screw turn throttle. It was not possible to quantify the effect of the throttle on the actual air-fuel ratio flow rate; therefore the results are presented qualitatively in terms of increasing throttle screw turns as a proxy for a reduction in AFR. An overview of the results for the boiler is operating with different fuel gas composition is given in Figure 4, where the CO concentration in the flue gas is related to the number of throttle turns.



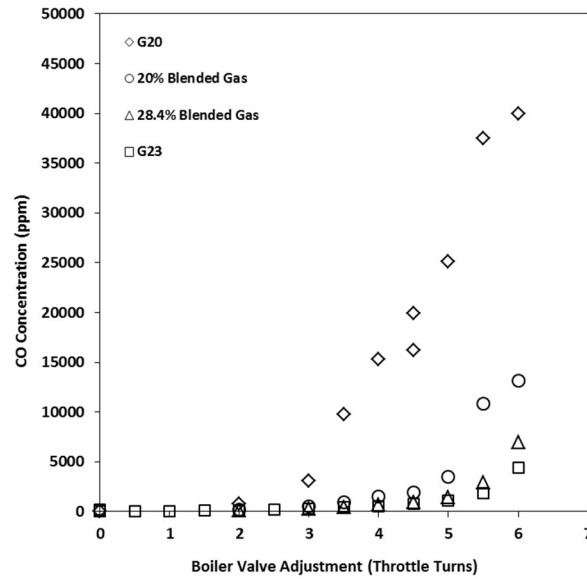


Figure 4. Effect of forced reduction in air fuel ratio on the flue gas CO concentration for a fully premixed gas boiler.

Through the data sets it is possible to assess the effect of two processes on the level of CO production by a burner. Firstly, by considering the effect of changes in aeration for a given fuel type it is seen in all cases that reducing AFR (increasing throttle turns) led to an increase in CO production. This arises due to moving the combustion system (initially optimised to have a lean mixture) towards  $\lambda = 1$ . Inspection of Figure 4 suggests that for G20 a critical value of the  $\lambda$  occurs around 2 throttle turns. After this point further reduction in the aeration leads to rapid increases in the amount of CO produced due to there being insufficient oxygen to achieve complete (or near complete) combustion.

Secondly the effect of changing the fuel type can be assessed. In Figure 4 the highest levels of CO were found when operating with G20, then 20 vol% blended gas, 28.4 vol% blended gas and finally G23 gave the lowest values. By changing the AFR it was possible to cause very high levels of CO when operating with G20. The highest concentration achieved was 39,970 ppm CO. Switching to hydrogen blended gas or G23 led to substantial reductions in the amount of CO produced by the appliance, with over 90% reductions occurring. In the mid-range of valve adjustments (3.5 throttle turns) the level of CO production with G20 was 9730 ppm while it was 892, 463 and 406 ppm CO for 20 vol% blended gas, 28.4 vol% blended gas and G23 respectively. Thus the production of very high levels of CO by a faulty appliance can be mitigated by switching to a fuel with a lower TAR.

Changing the fuel composition couples two physical process which have an effect level of aeration: the effect of fuel density on the flowrate and, the theoretical air requirement for complete combustion. In the case of the hydrogen blended fuels examined here the composition change reduces the density of the fuel (relative to G20), while G23 is slightly more dense than G20. Domestic gas appliances operate with gas injectors that have with a fixed supply pressure (e.g. 20 mbar). Consideration of the fluid dynamics (e.g. Bernoulli or Darcy Weisbach equations) shows that the flow rate is inversely proportional to the square root of gas density. In domestic and some commercial appliances the air supplied through the gas valve is effectively independent of changes in the fuel flowrate [9]. Therefore, in the case of blended fuels there will be an increase in the fuel flowrate, and consequently a reduction in AFR. Compared to G20 the AFR is approximately 10% and 14.5% lower for 20 vol% and 28.4 vol% blended gas respectively. For G23 the density increase will cause a reduction in fuel flowrate and thus an increase in AFR. For both the hydrogen blended fuels and G23 the theoretical air requirement (TAR) to achieve stoichiometric combustion is reduced compared to G20. For each fuel less of the supplied oxygen is required for combustion and the level of aeration increases. For blend gas TAR is approximately 15% and 21.3% lower for 20 vol% and 28.4 vol% blended gas respectively.

Therefore, despite the decrease in AFR for the blended gases the net effect on aeration of the competing processes is to increase the stoichiometric ratio ( $\lambda$ ) relative to G20, with the effect being more pronounced with increasing hydrogen concentration. For G23 both processes promote aeration and  $\lambda$  also increases relative to G20.

Where there is a faulty appliance operating on G20 then switching to a lower Wobbe Number fuel, such as a hydrogen blended gas, will mitigate the hazard and reduce the amount of CO produced. The data presented in Figure 4 shows that quite extreme levels of CO production can occur. In some cases where the fault has marginally degraded the combustion performance with G20, and pushed the system to a lower stoichiometric ratio, then switching to a blended gas mixture will increase stoichiometric ratio and may bring the level of CO production back within safe operating parameters.

#### 4.5 Appliance Set Up – Gas Boiler

High efficiency gas boilers contain a gas air ratio valve that can be adjusted to obtain optimum combustion performance; however this practice is now restricted due to setup errors and the potential for high CO levels. Currently valves are pre-set during factory assembly and subsequent in situ adjustment during commissioning does not occur. However, prior to 2010 it was common place for the gas valve to be adjusted during commissioning and optimised on the line gas present in the network at that time. The consequence of changing the commissioning set point gas will be to modify the baseline air-fuel ratio that the appliance will then operate with for all network distributed gas compositions. For a normally functioning appliance the best combustion performance occurs with fuel compositions (expressed in terms of the Wobbe Number) are in the region of the commissioning set gas Wobbe Number. When the Wobbe Number of the line gas is markedly different from the set gas then higher levels of CO production can occur. The scenario of greatest concern would be when a low Wobbe Number set gas has been used and the line gas has a high Wobbe Number – in this case the greatest positive difference in TAR would occur.

The effect of commissioning a high efficiency fully premixed boiler on a set gas with either G20, a high Wobbe Number natural gas or a low Wobbe Number natural gas, and then operating the appliance on a range of blended gases has been examined. The performance of the appliance was optimised via flue gas analysis following the industry standard procedure (e.g. Gas Safe Technical Bulletin 143 [8]) to ensure that the CO<sub>2</sub> measurement was within the range specified by the manufacturer, and the CO/CO<sub>2</sub> ratio was below 0.004. Figure 5 shows the effect of the commissioning set gas and the concentration of hydrogen in the fuel on the CO concentration in the flue gas. In all three set gas cases a reduction in CO concentration occurs as a result of increasing the hydrogen concentration. As described above this is due to hydrogen blended gases having a lower TAR that leads on to an increase in  $\lambda$ . Irrespective of the set gas used the level of CO produced was below the baseline level of an appliance commissioned and operating with G20.

It is insightful to compare the operation of the boiler under the three different commissioning set gases operating on the same fuel composition, and this can be achieved by using the flue gas measurements to back calculate  $\lambda$ . The resulting  $\lambda$  values for the boiler operating with G20 as the fuel were calculated to be 1.22, 1.27 and 1.36 for the low Wobbe Number, G20 and high Wobbe Number set gases respectively. Therefore, compared to commissioning an appliance on G20 the use of the low Wobbe Number set gas results in a reduced baseline AFR. This is due to the lower TAR of the low Wobbe Number set gas compared to G20. Similarly when a fuel with a higher TAR is used, as with the high Wobbe Number set gas, then an increase in AFR is required to account for the higher air requirement for clean combustion. The consequence of these changes in the baseline AFR are seen in Figure 5 where the highest CO concentrations occurred when the boiler was commissioned with the low Wobbe Number set gas (as mentioned earlier this is the worst case scenario due to the greatest positive difference in TAR). In this case the  $\lambda$  value is reduced during commissioning compared to the base case with G20. Subsequent operation with a higher Wobbe Number fuel (such as G20) that has a higher TAR leads to a further reduction in  $\lambda$  and a tendency towards higher CO production. However,

as seen in the experimental results (Figure 5) the addition of hydrogen mitigated this effect and lower levels of CO were produced.

A potential area of concern when using blended gas is when the boiler is commissioned with a high Wobbe Number set (which leads to a high baseline  $\lambda$  value). Subsequent operation of the boiler with blended gas (that has a lower Wobbe Number and TAR) will further increase  $\lambda$ . Increasing  $\lambda$  should promote a reduction in CO formation, however if  $\lambda$  is increased too far then an increase in CO formation can occur due to reduced flame temperature. In the results presented in Figure 5 this affect is not seen and increasing the hydrogen concentration leads to a reduction in CO production. However, additional tests were undertaken with other fuel compositions, a noteworthy case was when the low operating with G23 (which has a lower Wobbe Number than the blended gases). When this fuel was used in conjunction with the boiler commissioned on the high Wobbe Number set gas, the resulting CO concentration in the flue gas was 210 ppm, which was the highest value recorded for the boiler commissioned on the high Wobbe Number set gas, however in this case the CO/CO<sub>2</sub> ratio was still within in the 0.004 safety tolerance. This demonstrates the effect described above where further increases in  $\lambda$  may ultimately lead to increased CO production.

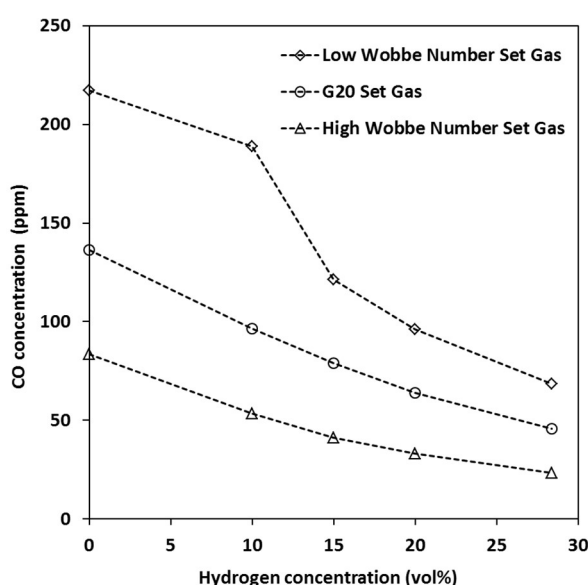


Figure 5. Effect of set gas used to commission the adjustable fully premixed boiler on CO concentration in flue gas for a range of blended gas concentrations from 0 to 28.4 vol% hydrogen

## 5.0 CONCLUSIONS

The effect of blended gas on the consequence of gas appliances operating in a fault mode condition has been examined. Fault modes that are related to gas quality have been identified and simulated through a series of experiments examining how the production of CO is affected by the addition of hydrogen to the fuel. It was found that when operating with pure methane (0 vol% hydrogen) a fault mode would typically lead to an increase in CO production by the appliance. The underlying mechanism for the increase is a reduction in burner aeration leading to incomplete combustion and formation of CO. In the laboratory tests the increases in CO were quite small and would lie within the range of acceptable operation. However, higher rates of CO production can occur and this was simulated by modifying the gas valve setting on combination boilers. In the latter very high CO production levels were recorded ( $\approx 40,000$  ppm).

In all fault modes assessed the switch to blended gas reduced CO production with up to a 90% reduction in CO production being recorded when using 20 vol% blended gas. The change in CO production when using hydrogen blended gas is a consequence of a decrease in the theoretical air

requirement to achieve complete combustion. In some cases, the amount of CO produced by the blended gas was identical to the non-fault baseline performance on G20. In situations such as non-optimal boiler set up the addition of hydrogen to the gas supply would prevent the production of high levels of CO. Overall it has been found that the introduction of hydrogen into the gas network may serve to mitigate the hazard posed by existing faulty appliances that are producing elevated levels of CO.

## 6.0 ACKNOWLEDGEMENTS

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