THE COMBUSTION BEHAVIOUR OF FORDED-DRAUGHT INDUSTRIAL BURNERS WHEN FIRED WITHIN THE EASEE-GAS RANGE OF WOBBE INDEX

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ABSTRACT

In Europe, a common business practice for the cross-border exchange of natural gases has been formulated by EASEE-gas. The proposed range of Wobbe Index for this purpose is 48.96-56.92MJ/Nm^3 (25°C/0°C, 1013.25 hPa). However, it is unclear whether the entire range of end-use equipment can accept the suggested range and still function as desired. Research is currently underway tot assess whether this range of gases can be accepted by domestic appliances. To our knowledge, there has been little systematic investigation of the acceptable range of gas quality for large-scale, forced-draught industrial burners. Although natural gas is predominantly methane with lesser amounts of higher hydrocarbons and inerts, the variation in gas composition can have significant effects on burner performance. The vast majority of forced-draught industrial burners features a flow of air independent of the gas composition, therefore the air factor is (inversely) proportional to the Wobbe Index of the gas.

In this paper we present the results of experiments on a number of generic large-scale industrial burners for boilers and industrial processes in which the Wobbe Index is varied across the EASEE-gas range. The combustion effects focused mainly on flame stability (burner overheating/blow-off and vibrations) and the pollutant emissions, such as CO, NO_x and unburned hydrocarbons over the desired range of turndown ratio.

The experimental results showed that, for the burners studied the measured oxygen concentration was the predominant factor governing burner behaviour; between 0.5 and 7% O_2, all burners showed a stable flame while emitting less than 400 ppmv (dry, air free) CO. Outside this O_2 range, the low-NO_x boiler burners, being the most sensitive, showed decreasing flame stability and increasing CO production. One burner even exhibited blow-off, causing the safety system to shut down burner operation, an undesirable event in practice. In the burners studied, the NO_x emission can increase significantly with increasing Wobbe Index. Even a relatively small increase can cause the burner to exceed the locally enforced NO_x limit. The visible flame length increased with increasing Wobbe Index, due to the concomitant decrease in air factor and increase in thermal input. This can lead to a higher thermal load on furnaces, which may be unacceptable in some cases.

The experimental results indicate that to widen the acceptable range some form of active control is necessary for the burners for boilers. The merits of using a feed-back control system, using oxygen measurement in the flue gas, compared to a feed-forward control using the Wobbe Index of the fuel gas are discussed. In particular, aspects regarding safety in the event of sensor malfunction are seen to be important when choosing a system. In this case, the Wobbe method seems technically preferable.

1. INTRODUCTION

In Europe, the common business practice for the cross-border exchange of natural gases has been formulated by EASEE-gas. The proposed range of Wobbe Index for this purpose is 48.96-56.92MJ/Nm^{3}with the EASEE-gas references (25°C, 0°C. 1013.25hPa). However, it is unclear whether the entire range of end-use equipment can accept the suggested range and still function as desired. Research is currently underway tot assess whether this range of gases can be accepted by domestic appliances. To our knowledge, there has been little systematic investigation of the acceptable range of gas quality for large-scale, forced-draught industrial burners.

Although natural gas is predominantly methane with lesser amounts of higher hydrocarbons and inerts, the variation in gas composition can have significant effects on burner performance. The two main consequences of this variability pertain to the thermal input and the aeration of the burner. As is well known, the thermal input to a burner is directly proportional to the Wobbe Index of the gas. Additionally, the air factor divided by the calorific value is constant to within 0.7% for the major alkanes in natural gas. Taken together with the fact that, without an air-ratio control system, the flow of air is independent of the gas composition, the air factor is (inversely) proportional to the Wobbe Index of the gas as well.

In this paper we present the results of experiments on a number of generic large-scale industrial burners in which the Wobbe Index is varied across the EASEE-gas range. The combustion effects focus mainly on flame stability (burner overheating/blow-off and vibrations) and the pollutant emissions, such as CO, NO_x and unburned hydrocarbons over the desired range of turndown ratio. The experimental results indicate that to widen the acceptable range some form of active control is necessary for the burners for boilers. Further, the merits of using a feed-back control system based on oxygen measurement in the flue gas, compared to a feed-forward control using the Wobbe Index of the fuel gas, are discussed.

2. EXPERIMENTAL METHOD

For this study, one line burner for air heating and four low-NO_x boiler burners were tested in a water-cooled furnace representing an industrial warm-water boiler. Three high temperature process burners were tested in a test furnace representing a kiln for firing ceramic products. In total 8 burners were tested in 2 different furnaces.

The Wobbe Index of the natural gas was varied by adding propane to Groningen gas, a relatively low calorific value natural gas common in the Netherlands. Three different gases, having a Wobbe number of 48.3 MJ/Nm^3 (9% propane), 52.0 MJ/Nm^3 (18% propane) and 57.2 MJ/Nm^3 (29% propane) were blended during the tests, slightly wider than the EASEE-gas range. The compositions were monitored using a micro-gaschromatograph. The observed Wobbe Indices remained within +/- 0.2MJ/Nm^3 of the desired value at all times.

This relatively high propane content can be considered "worst case" for CO production and soot formation, since a distribution gas having a Wobbe Index of 57,2 MJ/Nm3 will ordinarily have a smaller fraction of higher hydrocarbons and more methane. However, the large fraction of higher hydrocarbons can be considered favourable for preventing lift-off as compared to commonly distributed natural gases. Since the excess oxygen is in principle only dependent on the Wobbe Index and not the composition, we do not anticipate significant effects of the propane content on visible flame length a priori.

The burners were tested at three different loads; minimum load (according to the manufacturer 10-20% of maximum load), half-load (50% of maximum load) and maximum load (100%).

The effect of the Wobbe Index of the natural gas used when installing or adjusting the burner (particularly the air/fuel ratio) was considered by setting the desired oxygen fraction (usually 3-5%) in the flue gas at each of the three Wobbe Indices mentioned above. This oxygen fraction in the flue gas is required to guarantee safe and reliable combustion at all times. Once the thermal input and air ratio were set using the given "adjustment" gas, the measurement series were performed using the other Wobbe Index gases. This procedure simulates a “worst case” industrial practice, where this adjustment is done by the service engineer unaware of the Wobbe Index of the supplied gas during burner adjustment. The actual gas quality and its possible variations are not always taken into account during adjustment of the burner.

3. RESULTS AND DISCUSSION

3.1 CO emissions

The experimental results showed that, for the burners studied the measured oxygen concentration was the predominant factor governing burner behaviour; between 0.5 and 7% O_2, all burners showed a stable flame while emitting less than 400 ppmv (dry, air free) CO. Outside this O_2 range, the low-NO_x boiler burners, being the most sensitive, showed decreasing flame stability and increasing CO production, increasing to several thousands ppm (Figure 1).

This figure shows the influence of the Wobbe Index used for adjustment and the Wobbe Index variations at each adjustment with varying thermal load. The results also reflect the effects of the air/gas control system intended to maintain the air ratio during turndown. These various effects are a result of our choice to simulate industrial practice.

One burner even exhibited blow-off, upon which the safety system shut down burner operation, an undesirable event in practice. With the range of Wobbe Index used, the measured oxygen fraction in the flue gas varied between 0 (Wobbe Index gas 57.2MJ/Nm^3, burner adjusted at 48.3MJ/Nm^3) and 9% (Wobbe Index gas 48.3MJ/Nm^3, burner adjusted at 57.2MJ/Nm^3), a wider range than that for safe and reliable operation determined above. Variation within the EASEE-gas range, leading to a variation in oxygen fraction between 0.3 and 8.6% is also outside the range for safe and reliable operation.

Burners adjusted using the "middle" gas (Wobbe Index 52MJ/Nm^3) burners could just perform satisfactorily if the air/fuel controller operated accurately, keeping the O_2 fractions between roughly 1 and 6%,. This range incorporates a margin of safety compared to the 0.5 to 7% range of acceptable boiler burner behaviour mentioned above, to allow for the significant changes observed during turndown (see below). Two burners exhibited hysteresis in the control system during turndown, leading to larger variations in O_2 fraction, with ensuing instabilities and excessive CO formation in some cases. This range is equivalent to a range of Wobbe Index of roughly ± 5%, significantly more narrow than the EASEE-gas proposal.

The line burner and the 3 process burners considered here exhibited a more robust behaviour; in all experiments the flame stability and the emissions were within values deemed acceptable.

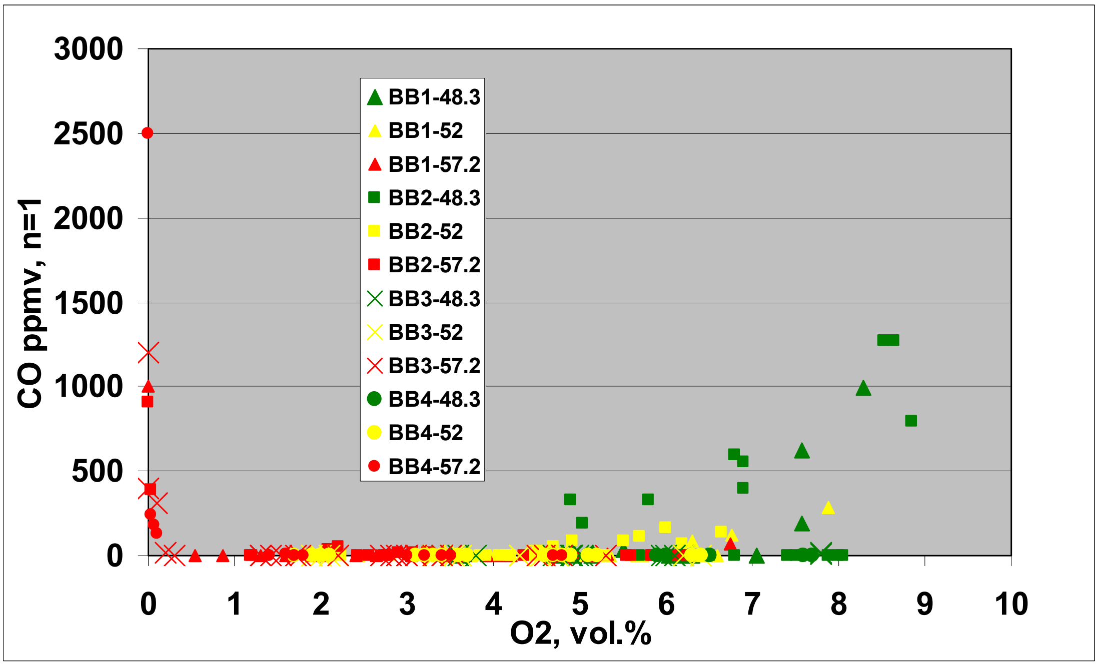

Figure 1 – Boiler burners BB1-4: CO vs O_2 at different Wobbe Indices (48.3, 52 and 57.2) of the natural gas, at different themal loads

In Figure 1 the oxygen concentration varies almost continuously from 0 to 9% and is not grouped in distinct clusters as one would expect with three different fuels and three different "Wobbe adjustments" of the burners. This is mainly caused by hysteresis in the burner control systems with turndown, as described above. Generally, after a few changes in burner load the fuel/air ratio (and thus the oxygen fraction in the flue gas) has changed noticeably.

3.2 NO_x emissions

In the burners studied, the effect of the Wobbe Index of the fuel gas on the NO_x emission of the burner varied significantly as can be seen in Figures 2 and 3. In two of the cases illustrated below the NO_x emissions decreased with increasing Wobbe Index of the fuel (Boiler Burner 4 and Oven Burner 1) . In two cases (Oven Burner 2 and Boiler Burner 3) the NO_x emission approximately doubled with an increasing Wobbe Index of the fuel gas. In the other cases the NO_x increased between 10% and 50%. The dependence of the NO_x emission on the Wobbe Index of the fuel gas varies widely among the burners investigated here. While clear that this variation arises from the details of the combustion process created by each burner design, it is not clear how burner design causes these differences.

In industrial practice, burners often barely meet the locally enforced NO_x limit. In those cases, even a relatively small increase can cause the burner to exceed this local NO_x limit.

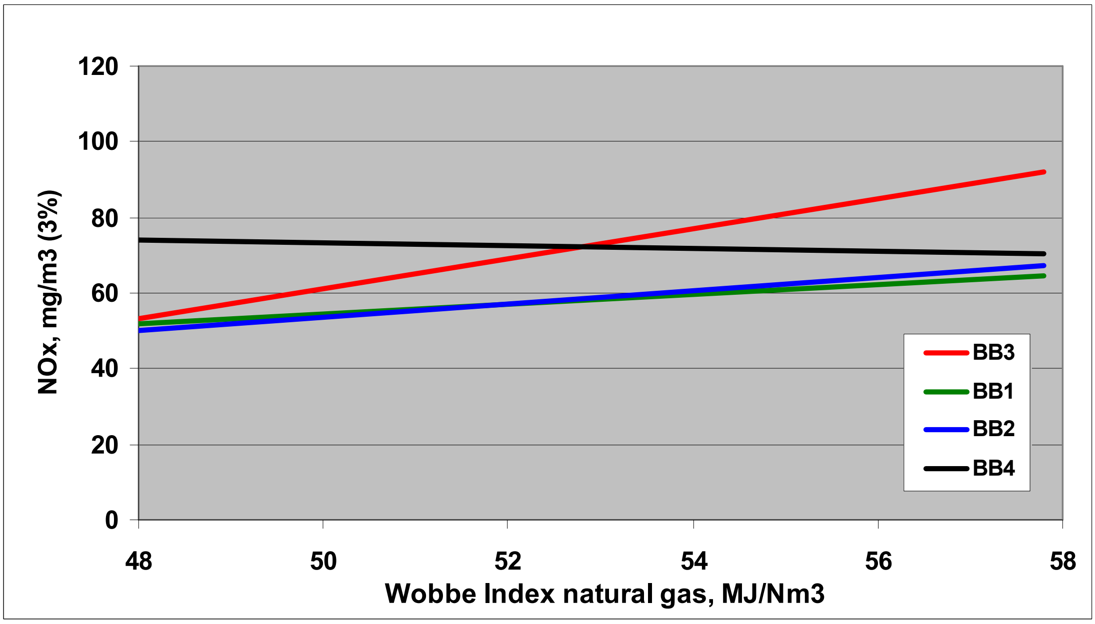

Figure 2 – Boiler burners BB1-4: NO_x vs Wobbe Index of the natural gas

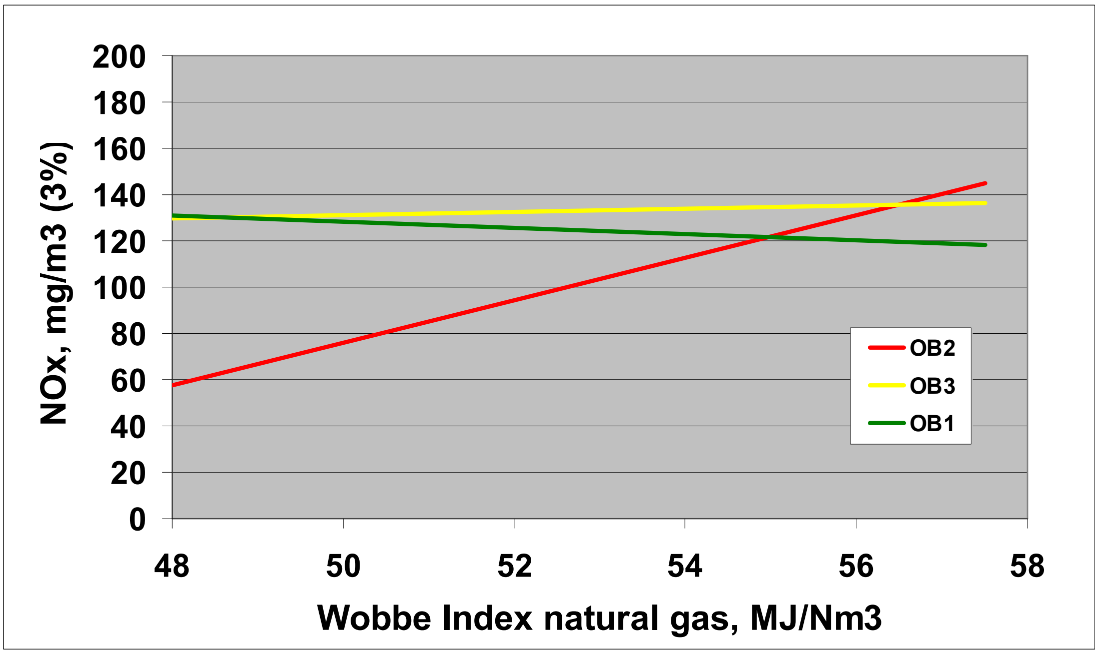

Figure 3 - Oven burners OB1-3: NO_x vs Wobbe Index of the natural gas

3.3 Visible flame length

The visible flame length of the 4 boiler burners investigated was measured. The flames of the 3 oven burners could not be measured due to the visible radiation of the hot (approximately 1000ºC) furnace walls.

Figure 4 shows an increase in visible flame length with increasing Wobbe Index of the fuel gas, mainly due to the decrease in air factor. As discussed above, the air factor is inversely proportional to the Wobbe Index of the fuel gas, in principle independent of the detailed composition of the fuel. The flame length of boiler burners 3 and 4 in particular increased dramatically at flue gas oxygen levels lower than 1%. This can lead to a higher thermal load on furnaces, especially on the rear wall of the first flue, which may be unacceptable in some cases.

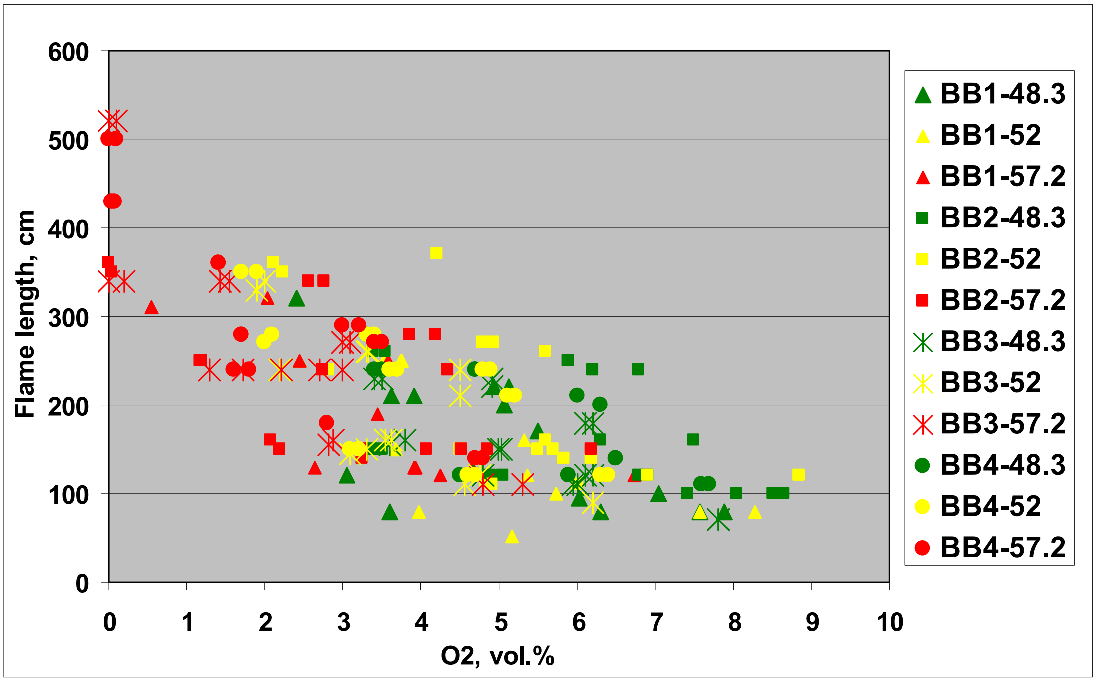

Figure 4 - Boiler burners BB1-4: Flame length vs O_2 at different Wobbe Indices of the natural gas

3.4 Discussion

The experimental results indicate that to widen the acceptable range of performance some form of active control is necessary for the burners for boilers. If the O_2 fraction in the flue gas can be kept at a desired level, regardless of the Wobbe Index of the fuel, the burner will perform satisfactorily at all times.

Oxygen trim is a closed loop control system available as an option on some electronic fuel/air ratio controls. Oxygen trim was employed on industrial installations for the first time in the late seventies, about the same time that Lambda control came into use in cars. But, the oxygen probes on several early systems suffered from short operating lifetimes, giving the oxygen trim a bad reputation. More robust probes are available now. When oxygen trim is included the oxygen levels can be set at their optimum level. If the oxygen level is set at about 2%, allowing for a small margin of safety, it will contribute energy savings of approximately 0,5% for every percent of oxygen fraction reduction at the common boiler flue gas temperature of 150ºC. A reduction of oxygen fraction from the usual 5% to 2% improves the boiler efficiency by 1.5%. For a boiler of about $4M_{th}$ an oxygen trim system will typically be paid back between one and two years, depending on the load duration curve of the boiler.

However, oxygen trim is a feed-back control system; the oxygen is measured after combustion and it takes typically 20-30 seconds after a change in measured oxygen faction before the control systems starts acting. After a sudden change (“step”) in the Wobbe Index of the fuel gas the burner can operate outside its safe limit for a certain period of time, producing considerable CO emissions and/or flame instability, even to the point of blow-off or flame extinction.

A feed-forward control system, using an input signal ("Wobbe signal") reflecting the oxygen required for a safe and reliable combustion, ahead of time, will be able to maintain safe and reliable combustion under all circumstances, including sudden changes in Wobbe Index of the fuel gas. For very large installations, such as power plants and refineries, such feed-forward Wobbe control systems are common practice.

For medium-sized installations, these systems are still too expensive. However, there are a few promising developments towards a more affordable Wobbe sensor. We have performed a numerical simulation, using MATLAB®/Simulink® software, to assess the feasibility of a feed-forward Wobbe control system. Using a typical first-order response time t_{63} of the Wobbe sensor of 6 seconds, as measured in our lab, a delay time of 2 seconds before the fuel gas sample enters the sensor, and a fuel gas valve servo behaviour given by the manufacturer, the results show the feasibility of the system. The relationship between Wobbe Index and flue gas O_2 was modeled using the relations described in Physical Properties of Natural Gases, june 1988, N.V. Nederlandse Gasunie, the Netherlands; the relations are based on simple arguments of stoichiometry.

The results of the simulation are depicted in Figures 5 and 6. At t = 10 seconds the Wobbe Index increases suddenly by about 5MJ/Nm^3. At t = 30 seconds the Wobbe Index decreases suddenly by the same amount (Figure 6). This is a substantially unfavourable situation. The corresponding oxygen fraction in the flue gas, as predicted by the model is shown in Figure 6. At a setting of 2.2% the control system keeps the oxygen fraction in the flue gas between 0.8% and 3.4%, an acceptable range for safe and reliable operation of the burner.

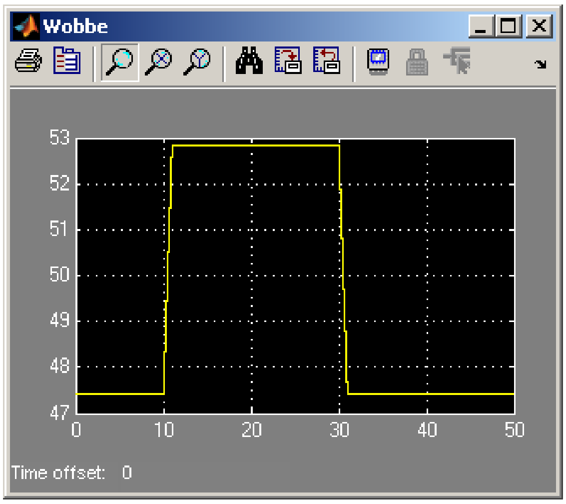

Figure 5 – Wobbe Index vs time

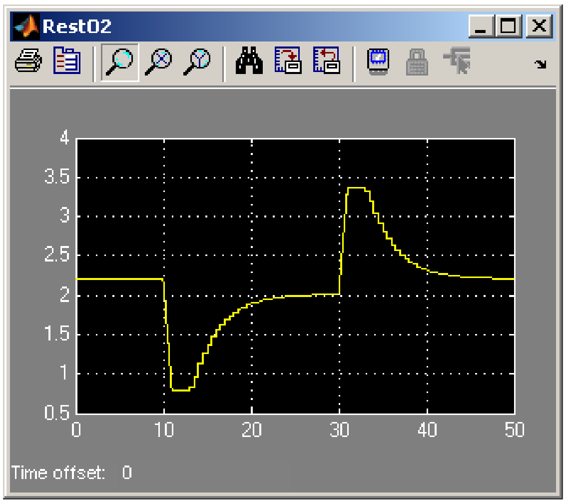

Figure 6 – O_2 vs time

In particular, aspects regarding safety in the event of sensor malfunction are seen to be important when choosing a system. If a sensor, e.g. an oxygen, carbon monoxide or Wobbe sensor fails, a back-up control mode assuming a Wobbe Index of the fuel gas in the centre of the Wobbe range automatically takes over the burner control. This setting must be “known” by the control system. This is impossible with an oxygen trim control not “knowing” the Wobbe Index of the fuel gas. In industrial practice this problem can be addressed by setting the burner at a very high oxygen fraction in the flue gas to fall back on. This oxygen fraction can exceed the upper level (7% for LowNO$_x$ boiler burners) for safe and reliable combustion at the lower Wobbe Indices of the fuel gas in the Wobbe range. Another “solution” is a limitation in the allowable reduction in oxygen fraction by the control system, rendering it less efficient. In this case, the Wobbe method seems technically preferable to the oxygen trim.

4. CONCLUSIONS

1. *For the burners studied the measured oxygen concentration was the predominant factor governing burner behaviour*

Between 0.5 and 7% $O_{2,}$ all burners showed a stable flame while emitting less than 400 ppmv (dry, air free) CO. Outside this O_2 range, the low-NO$_x$ boiler burners being the most sensitive, showed decreasing flame stability and increasing CO production.

2. *The EASEE-gas range) is a wider range than that for safe and reliable operation of LowNO$_x$ boiler burners.*

3. *In the burners studied, the effect of the Wobbe Index of the fuel gas on the NO$_x$ emission of the burner varied significantly.*

In two cases the NO$_x$ decreased with an increasing Wobbe Index of the fuel gas. In two cases the NO$_x$ emission approximately doubled with an increasing Wobbe Index of the fuel gas. In the other cases the NO$_x$ increased between 10% and 30%. In industrial practice burners often barely meet the locally enforced NO$_x$ limit. In those cases, even a relatively small increase can cause the burner to exceed this local NO$_x$ limit.

4. *The visible flame length increases with increasing Wobbe Index of the fuel gas, mainly due to the decrease in air factor.*

This longer visible flame can lead to a higher thermal load on furnaces, especially on the rear wall of the first flue, which may be unacceptable in some cases.

5. *The experimental results indicate that to widen the acceptable range some form of active control is necessary for the burners for boilers.*

If the O_2 fraction in the flue gas can be kept at a desired level, regardless of the Wobbe Index of the fuel gas the burner will perform satisfactorily at all times.

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