TRANSIENT CONDITIONS EMISSIONS FROM LOW-POWER GAS HEATING SYSTEMS

G. Grazzini, C. Balocco, M. Sarti
Dipartimento di Energetica, S. Stecco, Via di S. Marta 3, Firenze, Italy

ABSTRACT
This paper presents the results of direct measurements of CO, CO_2 and NO_x emissions from four different boilers with low-emission gas burners and a traditional one (Bunsen flame). Here is stressed the efficiency of lean premixed low-NO_x natural gas burners for domestic applications. This kind of burner has been developed through the stabilisation and operating conditions control of an inverted flame in a conventional low powered domestic burner. Experimental tests have taken place in R&D laboratories of "WORGAS Bruciatori s.r.l.", Italy. Results are applied to evaluate emissions from an heated flat in winter.

INTRODUCTION

European Union has in Kyoto protocol committed itself to an 8% reduction of greenhouse gas emissions from 1990 levels by the year 2010. The formal introduction of emission standards in the European Community and the gradual tightening of voluntary limits within certain of these countries, have focused considerable attention on the development of burners that emit very low levels of nitrogen oxides (NO_x) and carbon monoxide (CO). Germany led the way with the introduction of the "Blue Angel" labelling scheme, which stipulated an NO_x emission limit of 100 ppm for naturally aerated or atmospheric burners, and 57 ppm for fan-powered fully premixed burners [1]. It has been demonstrated that minor modifications to existing burners design of suited for domestic heating appliances can reduce NO_x and CO emissions by up to 50%. This has been achieved by transforming the traditional conical shaped flame to one of a V-shaped flame, stabilised along the centre of a burner blade [1]. The lifted flame allows secondary air to mix with the unburned gas/air mixture before the flame front, effectively enhancing the flame's stoichiometry. The leaner flame allows the fuel to burn out more quickly, reducing flame height and residence time, resulting in a lower contribution of prompt NO. A multitude of lifted flames covering the plan area of a combustion chamber allows an uniform and rapid dilution of products, thus minimising the mean temperature of produced gases and in turn reducing thermal NO_x contributions. This paper summarises results of tests made at R&D laboratories of WORGAS bruciatori s.r.l. where have been investigated four different domestic gas-fired heating boilers with four different gas burners. Starting from these measurements the amount of emissions during a winter day in Florence to heat a flat of 100 m^2 and how emissions depend from the boiler and from the regulation system of gas-burners were evaluated. Raising the awareness of the occupants and owners of buildings is one of the key issues in both reducing unnecessary energy use and also in boosting the market penetration of energy saving technologies. The idea is to ensure that when occupants and owners are replacing or installing energy equipments they have the necessary information to make an appropriate choice [2]. It is important to find ways to encourage replacement of old and inefficient equipment, particularly boilers.

For example in Netherlands energy consumption of households has been recognised as a major environmental problem since the 1980s; to improve energy efficiency of heating installations very efficient condensing boilers have been introduced, so they are now the most common heating appliances in Netherlands [3].

BUNSEN FLAME AND V-SHAPED FLAME

Lean premixed combustion is characterised, especially at high values of excess air, by stability problems with respect to conventional diffusive combustion. In fact, the excessive cooling of the flame, caused by the high value of excess air, can give rise to high carbon monoxide and unburned hydrocarbons emissions or, in more critical conditions, to flame extinction. The lean air-methane mixture outflows from an arrangement of rectangular twin slots and forms, for certain operating conditions, an inverted flame (V-shaped flame or, as it is usually termed, butterfly wing-shaped flame) attached over the burner and extremely stable, owing to fluid dynamic effects, in a wide range of operating conditions. V-flame, contrary to

Bunsenflame, is characterised by an extended bladed combustion front with low average temperatures and low NO_x, CO and HC emissions [4]. In fact we obtain istantaneous combustion of the gas-air mixture with very small and short flames, of violet colour (different from the yellow Bunsen flame), that are stable and quiet.

Flame is stabilised in the low velocity fuel-rich zone of the tapered slot. When the flame brush extends along the burner blade, the air-to-fuel ratio increases because of greater proportion of secondary air is entrained along its length. This occurs to the extent that a super-stoichiometric mixture is achievable at the outer extremities of the flame brush.

The primary aeration of the flame and overall excess air level of the boiler are important in establishing the optimum lift characteristics, without producing high levels of CO through quenching of the flame. Flame temperature (low and uniform all over the front flame) and the recycle of the combusted gases between the two wings bring to the very low emission of NO_x CO and HC.

Benefits of NO_x reduction on the tapered slot plan area burner are more important at higher port loading where conventional burners generally emit the highest concentration of NO_x.

The traditional Bunsen-flame is instead characterized by long soft flame with long combustion time promoting the increase of NO_x , is fully aerated only on the flame front (second aeration), with incomplete combustion and CO formation.

BURNERS REGULATION

To analyse emissions produced by gas boilers it is important to distinguish between one-stage gas burners and modulating gas burners. The first typology can only have two positions: on or off; fuel flow rate is constant and depends from fuel pressure and nozzle parameters. To reduce alternative on and off, there is a temperature difference between a turning off and the following turning on (for example, if the turning off of the boiler is at 90°C, the following turning on is at 85°C). Modulating burners have the possibility to modulate the gas flow rate, proportionally to the heat demand, in the range 100%-20% of nominal power. This study underlines the importance of modulating burners in gas-fired appliances for domestic use that ensure both the heating function and the domestic hot water function, for energy saving and emissions reduction.

LOW- NO_x BURNERS

In order to achieve very low levels of NO_x (<50 ppm DAF (Dry and Air Free basis), an increasing number of burner manufacturers are turning to fully aerated (premixed) burners designed to operate at a primary aeration exceeding that of the stoichiometric air requirement. These super-stoichiometric burners exhibit well-defined flame fronts that stabilise close to the burner surface. Fan powered premixed burners operate at primary aeration between 120% and 130% to ensure good combustion, low NO_x and high thermal efficiencies. In order to modulate down to half of nominal rate and below, air/gas ratio control is required; the simplest of which attempts to maintain a constant aeration across the range of heat inputs.

Naturally aerated premixed burners, that are designed to operate lean of the stoichiometric point, suffer from similar problems during gas modulation.

Fan powered premixed burners have certain advantages over the traditional partially aerated burners. The resultant flames tend to be more intense, and hence shorter, and this characteristic enables them to be fired sideways or downwards without affecting the combustion quality or causing undue damage to the flame-strip or other burner parts.

Premixed burners can usually be operated with a lower excess air level than necessary for correct operation of a partially aerated burner at the corresponding heat input rate. This can result in higher thermal efficiencies during boiler operation.

These burners are ideal for applications in boilers and water heaters of the condensing type in which the temperature of the combustion products is reduced to obtain condensation of water vapour on heat exchanger. Premixed burners generally produce lower emissions of NO_x. Typically NO_x emissions might be in the region of 10 to 40 ppm compared to levels in excess of 100 ppm from partially aerated burners.

DESCRIPTION OF EXPERIMENTS

Four cases have been studied at WORGAS research laboratory to investigate transient conditions behaviour of several kind of heating boilers and of different gas-burners regulations:

A. a wall mounted boiler with room sealed, a nominal power of 26,5 kW and a modulating low-NO_x burner with drawing up fan;
B. a base boiler, 35 kW, with open chamber equipped with a low-NO_x burner with on-off regulation;
C. a condensing boiler, 24 kW, in room sealed version, with totally premixed modulating low-NO_x burner;
D. a wall mounted boiler, 26 kW, with traditional burner (Bunsen flame) with on-off regulation.

A cycle of tests with alternative phases of on and off has been made. Cycle at nominal load is composed by a set of 30 minutes tests (40 for case D), followed by increasing time breaks when the boiler is switched off. Breaks of 5, 10, 30, 120 minutes have been chosen to study transient working conditions of boilers, starting from different combustion chamber temperatures. For boilers equipped with modulating burners, a reduced cycle of tests at intermediate load (63% and 38% of nominal load) for 5 and 120 minutes stop has been made. Data have been taken manually, reading CO_2, CO and NO_x emissions on analysers. To analyse transient working conditions, readings have been made more frequently in the first 5 minutes of test, at half a minute-intervals; then, from the 5^{th} to the 20^{th} minute, every 3 minutes; finally, from the 20^{th} to the 30^{th} minute of test, emission values have been read every 5 minutes, being by then the boiler fully operating. For case D the test duration has been increased (40 minutes) to let the boiler reach fully operating conditions. Italian legislation does not require emission measurements in transient conditions, so this kind of measurements has not been made before: no one of several contacted manufacture's company have done them.

These following measurements have been made thermal efficiency evaluation: gas temperature (T_{gas}), air temperature (T_{amb}), inlet water temperature T_{in} and outlet T_{out}, temperature of exhaust gas (T_f), gas pressure (P_{gas}) and air pressure (P_{amb}). Combustion features have been monitored by a series of sensors and thermocouples. Emission's measurements have been made with a NDIR (Non Dispersive Infra Red) analyser *Rosemount Analytical Inc.- model 880* for CO and CO_2 and a chemio-luminescence analyser for NO_x *Rosemount Analytical Inc.- model 955*. As concerns the instrument's precision, reading's variations ≥ 5 ppm (corresponding to 1,39 mg/MJ for CO and 2,45 mg/MJ for NO_x) are considered significant. CO and NO_x concentrations have been converted to reference conditions (Nm^3, at 0°C, 1013,25 mbar; Sm^3, at 15°C, 1013,25 mbar, dry gas) by:

$$CO = (CO)_M \times \frac{(CO_2)_N}{(CO_2)_M} \qquad (1)$$

$$NO_x = (NO_x)_M \times \frac{(CO_2)_N}{(CO_2)_M} \qquad (2)$$

For the network gas utilised during tests, identified as G20 (LCV=34.02 MJ/Sm^3) $(CO_2)_N$ is equal to 11,74 according to Italian Standard UNI EN 297. From CO and NO_x in ppm we obtain the value in mg/MJ with a conversion factor equal to 0,3 and 0,49 respectively for CO and NO_x .

RESULTS

Results of all the four cases are presented in this paper, whereas figures represent in particular cases A and D because they are the two that can be directly compared (the nominal power is nearly the same).

Case A has a particular control system applied to the burner, the WORGAS Total Control (WTC); it's a close combustion control system that, combined with the V-shaped gas-burner, gives low NO_x emissions over the entire modulating range (100%-20%). The WTC control works on the burner's temperature: when the fixed value (150-200°C) is exceeded, there is a higher air flux in order to cool the combustion chamber and reduce the formation of NO_x (due to the thermal mechanism). As figures 1 and 2 show, with WTC control system both polluting emissions, CO and NO_x, decrease during the test.

This is very important for NO_x because this is the typical performance for this control system; in all other studied cases NO_x always increase. The initial conditions of the combustion chamber considerably influence the result as the difference between tests with a cool initial condition (30 minutes, 120 and cool test) and others show (fig. 1 and 2). It can be seen that, for both pollutants, the first 5 minutes read values are higher when the combustion chamber is cool (higher time break between turning off and the following turning on of the boiler). This is due to the delay at the control start in the cool case. The modulating gas-burner with V-shaped flame and the WTC combustion control system give NO_x emissions close to 15 mg/MJ. When emissions are considered as function of the load (fig. 3) a control action delay in case of cool initial conditions can be noticed again; a time break of five (5) minutes and one of two (2) hours have been made between following tests and for both pollutants values are higher in the second case.

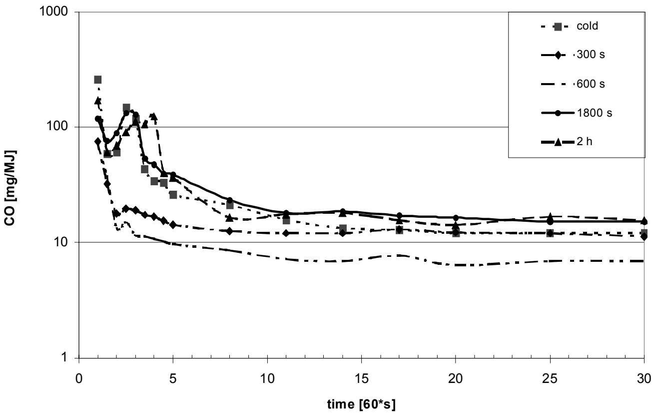

Fig.1 WTC control boiler (boiler A) - CO emissions

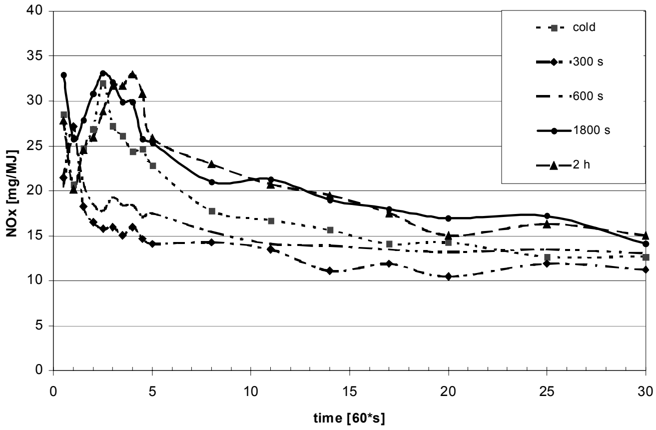

Fig. 2 WTC control boiler (boiler A) - NO_x emissions

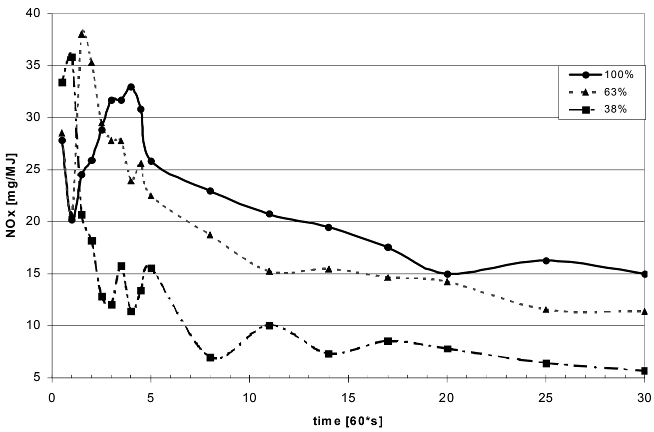

Fig. 3 NO_x emissions as function of load for case A after 2 hours break - control action's delay can be observed

Instability of V-shaped flame at low loads and its difficult management can be observed as a sinuous trend of emissions in 38% load case. In certain conditions a flame extinction can occur.

Figure 4 shows the entire cycle of test at the nominal load for the same boiler; it can be noticed that the time duration for tests is reasonable because the variance of steady condition mean value is low.

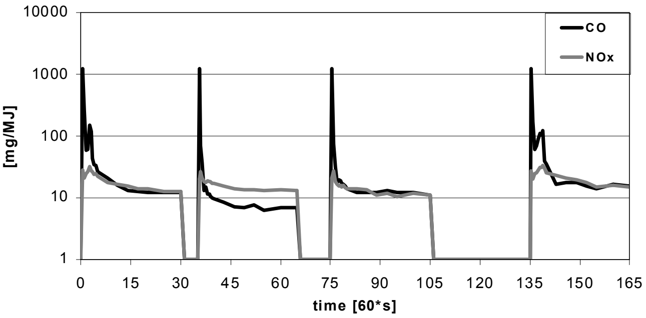

Fig. 4 Entire test cycle at nominal load for case A

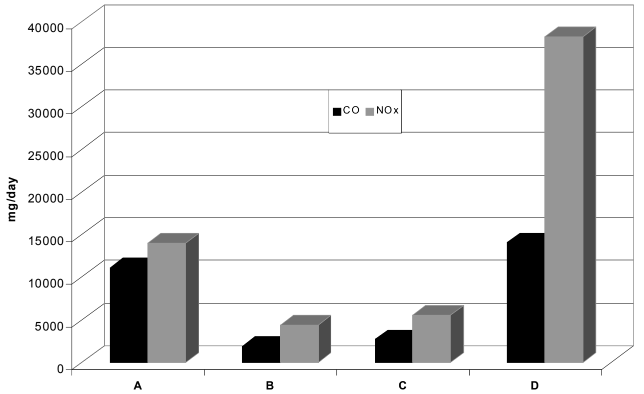

Fig. 5 Daily emissions – investigated cases for 10 kW peak loss

Case B analyses a base cast iron boiler equipped with an atmospheric and on-off regulated burner with a V-shaped flame. Differently to WTC case, here both polluting emissions increase during the test: NO_x because the temperature in combustion chamber increases, CO because short residence time produces unburned hydrocarbons emissions. In case C measurement of emissions for a condensing boiler with a totally premixed modulating radiant low-NO_x burner have been made; this burner is studied by WORGAS in partnership with other laboratories within the LIFEBURN European project. In this case the combustion is very stable: CO goes soon in steady condition and even at minimum load there is a stable working. NO_x emissions are stable too. Case D with a traditional flame burner (Bunsen-yellow flame), has an on-off regulation. The boiler is a wall mounted one, room sealed. Tests length has been extended till 40 minutes because this burner needs more then half an hour to reach steady condition.

Tests have been made only at nominal load, due to the burner's regulation. Emission's values are higher than those of low-NO_x burners with V-shaped flame and both pollutants increase during the test. In steady condition case D is the only one that goes above the law limit (UNI EN 297) equal to 72 mg/MJ (=260 mg/kWh) for NO_x; for CO the law limit is equal to 297 mg/MJ (=1070 mg/kWh), but in this case every boiler gives lower value.

EXPERIMENTAL RESULTS PRACTICAL APPLICATION

Using measurements the amount of emissions during a winter day in Florence from a heated flat of 100 m^2 were evaluated. Heat losses are calculated referring to UNI EN 832, appendix L, and UNI EN ISO 13789. It has been observed the connection between emissions and boiler and the regulation system of gas-burners . Heating demand has been divided from demand for domestic hot water production. In this case it has been supposed that the tap is always completely open for a 5 minutes duration. Under this hypothesis, demand corresponding to hot water delivery is equal to power furnished to water, that is:

$$P_w = m_w \cdot c_w \cdot \Delta T \qquad (3)$$

where ΔT is the temperature rise furnished to water.

Considering a water flow of 0,2 kg/s and a temperature rise of 30 °C, the power is about 25 kW that is more or less the power of the analysed boilers. So there is always peak demand for domestic hot water delivery. For heating need a winter day has been considered, chosen in the standard year, obtained averaging over 20 years of observations [5]. According to UNI EN 832 heat losses are represented by:

$$L = H \cdot [(T_i - T_e)] \qquad (4)$$

Ministerial Decree N° 412/93 fixes the value of highest temperature inside flats (T_i) equal to 20°C (with a tolerance of ± 2°C). When solar and internal contributions are disregarded, heat demand can be considered proportional to the difference between internal and external temperature (T_e). The power demanded for heating is inversely proportional to external temperature as the following formula shows:

$$P[\%] = [(20-Te)/20]*100 \qquad (5)$$

If an on-off regulation is considered it is necessary to estimate the duration of boiler's working and turning off, that is function of the temperature difference, of the heat capacity of building and of the power of the boiler. In this paper an heat capacity value C = 10 (MJ/K) and a temperature variation of 4 K are considered. The duration of boiler's working has been calculated as:

$$\tau_{on} = C * \Delta T / (P - L) \qquad (6)$$

and that of turning off as:

$$\tau_{off} = C * \Delta T / L \qquad (7)$$

When a modulating burner is considered, the boiler works continually and it stops only when the power demand is lower than 20% of nominal power; otherwise the boiler modulates in the entire range (100%-20%). It has been estimated the amount of emissions for the four investigated boilers during the heating period, from 6 a.m. to 11 p.m. by:

$$E_{tot} = \Sigma (E \cdot P \cdot \tau_{on}) \qquad (8)$$

where E is the emission's value, P is the power of the installation and τ_{on} is the time duration of the emission's value. The four case experimentally studied are applied to flat demand considering a heating peak load of 10 kW. Case A and D greatly differ for NO_x and CO produced in a day as it is shown in fig.5. For boiler D with traditional burner the times of working during the all day are only seven, but the high value of NO_x in each working period brings to a great amount at the end of the day.

For the considered losses (10 kW), for a temperature difference of 20 °C, boiler A has a continuous working period in which it modulates from 20% to 100% of nominal load; boiler D has an intermittent working period with more and longer working periods.

CONCLUSIONS

Four different domestic gas-fired heating boilers equipped with four different burners have been analysed in this paper; results of low- NO_x burners with V-shaped flame compared with traditional yellow flame burners were reported and the influence of burners regulation on their working was discussed.

Analysing heating and sanitary hot water demand during a winter day for a flat in Florence has come out how different is the extent (magnitude) of the demanded power and the different law that they follow. In fact heating demand is inversely proportional to external temperature but the demand for domestic hot water production is a peak and instantaneous one. This is the reason why (continua sotto) During winter season there are only few days where heating systems work at nominal load in Florence, because often low power plants are oversized to produce sanitary hot water and so have low efficiency. In a winter day installations work at reduced load in central hours of the day and burners should follow the demand. This depends on the regulation of the burner: in case D there is an on-off burner and an intermittent working so at every starting there is a great amount of emissions. In case A, being the heating demand lower than that for hot water production, the burner can work from 41% down to 20% of nominal rate. From the municipal gas society it is known that there are thereabouts 160.000 heating boilers for single flat in Florence and most of them have on-off regulated burners with traditional flame. It is easy to consider the amount of emissions produced by these installations that can be avoided introducing condensing boilers and low-NO_x burners with modulating regulation.

NOMENCLATURE

C	heat capacity	MJ/K
c	specific heat	J/kg K
E	emissions	mg/MJ
E_{tot}	daily emissions	mg/day
H	heat loss coefficient	W/K
L	heat loss	W
m	mass flow	kg/s
P	boiler's power	W
Q	heat	J
T	temperature	K
τ	time	s
U	total heat transfer coefficient	W/m^2K

Subscripts

e	external
i	internal
M	measured
N	theoretic (DAF emissions)
w	water

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