ATMOSPHERIC EMISSIONS FROM GAS FIRED HOME HEATING APPLIANCES

Stefano Cernuschi[1], Stefano Consonni[2], Giovanni Lonati[1], Michele Giugliano[1], Senem Ozgen[1]

[1] DIIAR Environmental Sect., Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano (Italy) stefano.cernuschi@polimi.it, giovanni.lonati@polimi.it, michele.giugliano@polimi.it, senem.ozgen@polimi.it

[2] Dept. of Energetics, Politecnico di Milano, P.za L. da Vinci 32, 20133 Milano (Italy) stefano.consonni@polimi.it

Abstract

Atmospheric emissions from natural gas domestic appliances for combined ambient heating/hot water production were determined experimentally on a laboratory test bench. Measurements were performed on different types of boilers, covering the actual range of configurations available, at full and partial constant heat loads as well as in variable load conditions. Results obtained for pollutants of interest (CO, NO_x, VOC, NMVOC and particulate matter) are reported and analysed in terms of concentrations and emission factors for the different boilers and operating regimes investigated.

Keywords: residential combustion, natural gas, emission factors, conventional pollutants, variable load

1. Introduction

Small residential heating installations make up a significant share of the total air pollutant emissions budget in Italian urban areas, where their spatial concentration and limited flue gas release height might lead to important impacts on air quality. Nevertheless, reliable information on their emission characteristics is generally lacking or very poorly documented, either in data bases generally used for emission inventories (EEA, 2005; US EPA, 2004) or in the available scientific literature, thus making rather difficult the evaluation of their contribution in local inventories and their apportionment to pollutant levels in the atmosphere.

Data shortage is a particular concern for natural gas fuelled appliances of low heat output (< 50 kW_{th}) for combined ambient heating and hot water production, already largely present in single family homes. Most of the reported emission factors in this sector are derived from limited base data, normally referred to operating regimes far from most typical real practice conditions, and they generally do not cover the range of recently commercialized best available technologies. These advanced units, which are equipped to reduce pollutant emissions and simultaneously increase heat generation efficiencies, are predicted to increase significantly their actual market share in the very near future.

With the main purpose of enlarging the data base of emission factors applicable for the source activity sector in the development of pollutant inventories for Italian urban areas, an experimental evaluation was designed to include explicitly all the main factors affecting the emissions regime representative of the source category, in terms of both the different technological configurations of commercially available boilers and of the most typical operating regimes. The investigation was conducted with a standard certification laboratory test rig, where flue gas concentration levels of conventional pollutants from combustion (CO, NO_x, VOC and NMVOC) as well as of particulate matter were measured. The paper reports the main results obtained, in terms of concentrations and emission factors derived and their observed variability with boiler type and exercise conditions.

2. Materials and methods

The study was conducted on three different types of boilers (Table 1), selected through available informations about their actual and prospected distribution among installed units at the national level (AMA, 2003; ATIG, 2004) and considering the different technological options commercially available in the selected heat output range (< 50 kW_{th}). The boilers investigated included:

1. natural draft boiler with conventional atmospheric burner;
2. forced draft condensing boiler with premixed modular air/fuel ratio burner;
3. forced draft boiler with premixed low NO_x burner (“carpet type” flame with water cooling). The unit is included in the highest class of NO_x emissions according to European Regulations (CEN, 1999),

corresponding to the lowest NO_x emission factor (70 mg/kWh);

4. forced draft boiler with conventional atmospheric burner.

The first three boilers were tested in brand new conditions whilst the last unit, already utilized for performance endurance laboratory testing, was evaluated to indicate potential modifications in emissions arising from ageing effects.

Table 1: Main technical characteristics of the boilers investigated

Boiler	$P_n^{(*)}$ (kW)	$E^{(**)}$ (%)	Draft	Burner
1	24,6	91,5	Natural	Conventional
2	24	95,9	Forced + condensing	Premixed + gas/air control
3	24	92,9	Forced	Premixed low NO_x
4	24,2	91,3	Forced	Conventional

(*) Nominal output
(**) Useful efficiency at P_n

Emission measurements were conducted with a standard laboratory test rig for certification procedures (CEN, 1999), during boiler operation at different heat output conditions, selected by considering the most typical operating regimes in real utilization conditions as well as the heat load regulation capabilities of every apparatus. The test included operation at continuous full and minimum heat loads (100% and 30% of nominal heat output, respectively), following the actual requirements of European boiler certification procedures (CEN, 1999) as well as in variable load conditions, with two different operating cycles specifically developed for simulating real exercise regimes of utilization and intended to reproduce repeated start up/shut down cycles (Figure 1) and continuous heat load modulations over time (Figure 2). Test runs in continuous operating mode were conducted for all the boilers, whilst variable load cycles were utilized for the units expected to be representative of the extremes of technical configurations of burners actually available in terms of emissions and heat generation performances (boiler 1 - conventional atmospheric burner and boiler 2 - premixed modular air/fuel burner with flue gas condensation, respectively).

Gas measurements were performed with a multiparametric analyzer, equipped with electrochemical cell detectors for CO and NO_x and additional sensors for flue gas parameters of interest (O_2, temperature, CO_2), and with a VOC analyzer, equipped with a GC/FID detector for speciation of NMVOC and unburned CH_4. Total particulates were sampled with an isokinetic probe and collected on glass fibre filters for gravimetric determination.

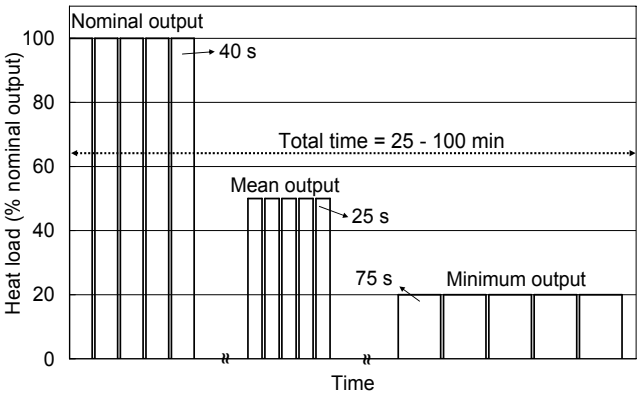

Figure 1. Variable load test cycle in intermittent operating mode (shut down/start up intervals: 5 sec)

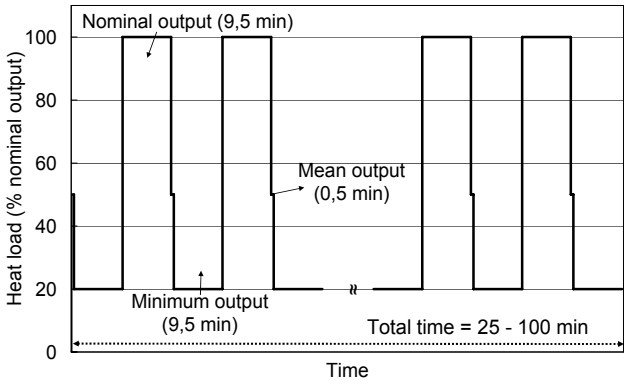

Figure 2. Variable load test cycle in continuous operating mode

3. Results and discussion

Concentrations and emission factors for all the pollutants investigated are illustrated and discussed in the following paragraphs. All the figures are mean values of single data acquired at 1-5 min time intervals during the whole test duration; concentrations are normalized at 3% O_2 in dry flue gas at normal conditions (273°K, 101.3 kPa), whilst emission factors are referred to unit heat released from combustion.

Results obtained for CO during constant full load operation (Figure 3) ranged between 17.5 and 42 g/GJ, corresponding to concentrations in the range 50-120 mg/m^3. The boiler with the premixed low NO_x burner resulted in the lowest emissions, whilst the unit equipped with a similar advanced burner design but with modular air/fuel ratio control showed the highest emission level, even higher than the conventional atmospheric unit (25,3 g/GJ) and the used boiler (29,1 g/GJ). The resulting increase is attributed to the limited excess air maintained by the modular burner design for obtaining maximum thermal efficiencies from flue gas condensation, thus confirming the well known drawbacks related to CO emissions with rich

combustion mixtures. Despite the influence on combustion related to the different designs of the burners investigated, the effect of oxygen on CO formation is further confirmed by the observable reduction in emission factors with increasing oxygen concentration in the flue gas (Figure 4). In accordance with the corresponding decrease in fuel consumption, continuous operation at minimum load results in a generalized reduction of CO emission factors for all the heaters (Figure 3). The only exception is related to the atmospheric boiler, whose operating conditions at minimum loads with extremely lean mixtures (16.2% O_2 in flue gas) and the conventional design of the burner appear to influence negatively the combustion process: in the same operating conditions, some advanced premixed burners (boiler 3) are indeed capable of maintaining very low CO emissions with high excess air levels (Figure 4). The results obtained do not point to any significant influence of aging, with the used apparatus (boiler 4) resulting in emission levels at full load essentially comparable with those measured from the new most similar unit (boiler 1) and with the same decreasing trend in emission factors for load reductions already illustrated, with the lowest absolute value at minimum load operation measured for all the boilers investigated.

Variable load discontinuous regimes give rise, as expected, to higher emission factors (Figure 5), mostly attributable to the technical difficulties in maintaining optimum combustion conditions during shut down/start up episodes: the latter influence is substantially confirmed by the results obtained for boiler 2 during the variable load continuous operation test, where the absence of any interruption in exercising the unit results in CO emission levels comparable with those obtained in continuous operation at constant loads (28.4 g/GJ in variable regime, 42.2 g/GJ and 14.1 g/GJ in continuous full and minimum load regimes, respectively).

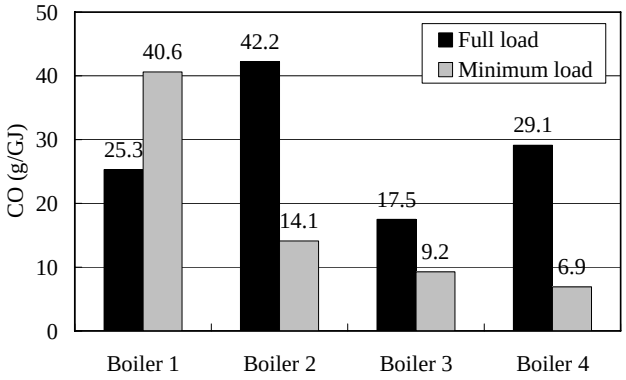

Figure 3. CO emissions at constant heat load

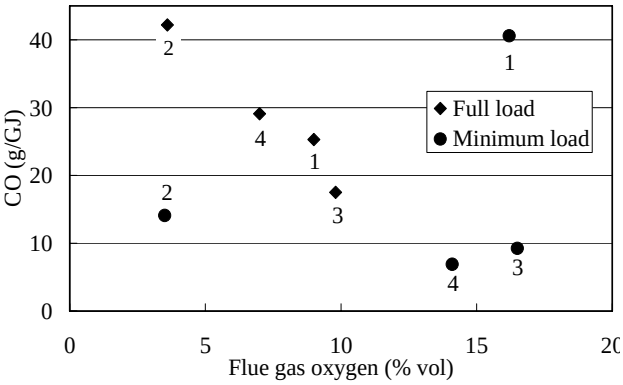

Figure 4. CO emissions variations with flue gas oxygen content. (Boiler numbers for single dot points as in Table 1)

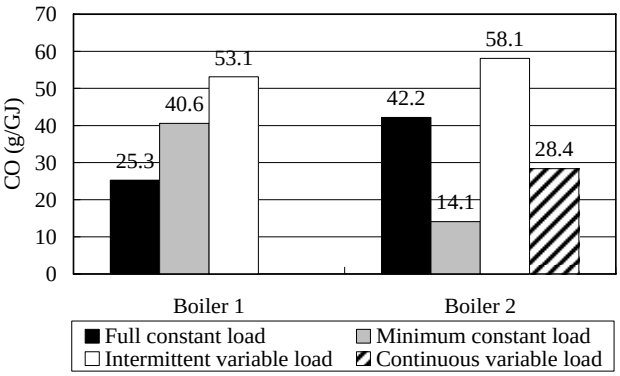

Figure 5. CO emissions at constant and variable heat load

Emissions of NO_x in constant full load tests (Figure 6) ranged between 18 g/GJ and 85 g/GJ, corresponding to concentrations in the range 50-250 mg/m^3. Units equipped with advanced design burners (boilers 2 and 3) achieved significant reductions with respect to conventional atmospheric burners, with the latter resulting in rather higher emissions and with the used boiler characterized by the highest absolute value. Very interesting results were obtained for the premixed modular air/fuel unit, characterized by the lowest absolute emissions (18 g/GJ), even lower than those measured for the low NO_x dedicated burner (29 g/GJ): extreme reductions in excess air appears thus to affect positively NO_x production rather than CO, confirming the well known technical difficulties in achieving optimal simultaneous reductions for both pollutants by regulating only the excess air. Emissions obtained during constant operation at minimum heat loads result in appreciable reductions with respect to full load operation, with the higher values still obtained for the conventional new and aged units. The reductions appear well correlated to the corresponding variations in excess air (Figure 7): the effect of oxygen on emitted NO_x might be further observed with the premixed modular burner

(boiler 2), whose operation with constant air/fuel ratios under variable load conditions result in rather small differences between emission factors measured in either load condition. Variable load emission results (Figure 8) appear essentially comparable to continuous data, with rather small observable increase in emission factors for the conventional apparel (69 g/GJ vs. 53,9 g/GJ - 62,3 g/GJ at constant load) and no appreciable variations for the advanced unit. Tests with shut down/start up episodes, applied to boiler 2, also result in no practical influence.

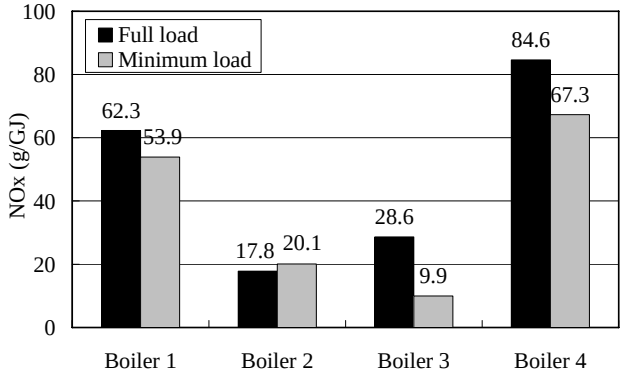

Figure 6. NO_x emissions at constant heat load

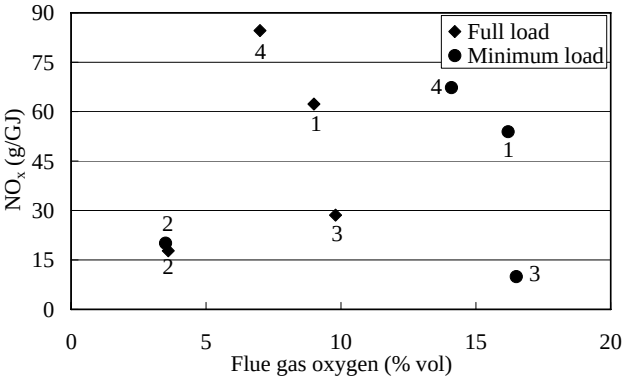

Figure 7. NO_x emissions variations with flue gas oxygen content. (Boiler numbers for single dot points as in Table 1)

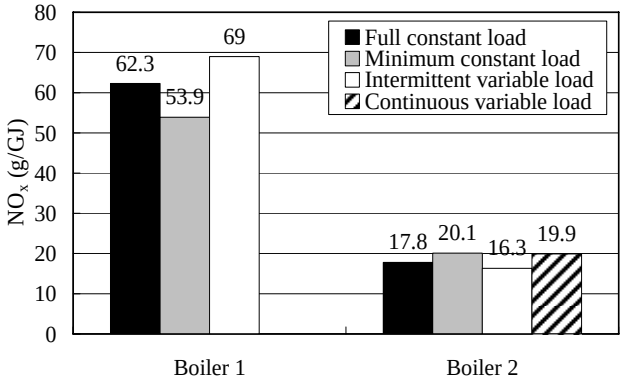

Figure 8. NO_x emissions at constant and variable heat load

Due to technical operating problems, test failure occurred during VOC measurement runs for the atmospheric conventional boiler (boiler 1) and for the variable load continuous regime with the premixed modular boiler (boiler 2). Results available for all the boilers and conditions properly measured are reported in Figures 9 and 10.

Constant full load test conditions (Figure 9) were generally characterized by rather low emissions, with VOC values between 0.3 and 1.8 g_C/GJ (concentrations of 1.2 - 6.2 mg_c/m^3). Operation at minimum load results, with the exception of the premixed modular burner (boiler 2), in appreciably increased emissions, with VOC emission factors as high as nearly 6 g_C/GJ (concentration of 20 mg_c/m^3). VOC emissions performance is more difficult to interpret in general terms, with the observed values and their corresponding load variations strictly related to single boiler characteristics. Higher emissions in either load conditions were recorded for the premixed low NO_x burner (boiler 3), with a substantial increase from full to minimum load conditions: the relatively large prevailing fraction of unburned methane measured in both conditions (over 80% of total VOCs) might indicate technical problems arising from burner design in feeding properly all the fuel to the burner nozzles at decreasing loads.

The unit equipped with premixed modular burner (boiler 2) resulted in the lowest emission levels, essentially independent from load conditions and with almost negligible VOC values in the range 0.2 - 0.3 g_c/GJ; almost all measured VOCs were unburned hydrocarbons (NMVOC) thus indicating, as already observed for CO, emissions arising probably from incomplete combustion. Emission levels from the used conventional unit (boiler 4) were intermediate between the values recorded for the two advanced burners, with higher emissions at lower load conditions and with a prevailing fraction of unburned methane detected only during minimum load tests. Variable load test results, available for the premixed modular unit in intermittent operating mode (Figure 10), resulted rather clearly in higher total VOC emissions with respect to continuous operation at constant loads, with an increase from 0.2-0.3 g_C/GJ to nearly 70 g_c/GJ and with a very significant fraction of unburned methane detected (over 75%). The difference might thus be related to fuel losses arising from the technical difficulties, already claimed also for CO, in maintaining optimum burner feeding conditions during shut down/start up episodes.

The investigation was also extended to particulate matter emissions, normally not considered for natural gas combustion sources and thus very poorly documented, particularly for small heating appliances. Measurements were conducted

at continuous full load operation on the atmospheric conventional unit (boiler 1) and the premixed modular condensing boiler (boiler 3), in order to obtain indications about the emissions performance expected over the whole range of technical configurations investigated. Results obtained (Table 2) show almost negligible emissions, with concentrations typical of background conditions and emission factors essentially independent from boiler configuration, as expected from the nature of the fuel utilised.

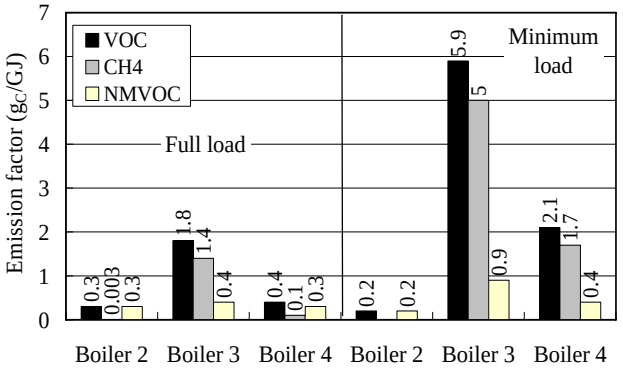

Figure 9. VOCs emissions at constant load

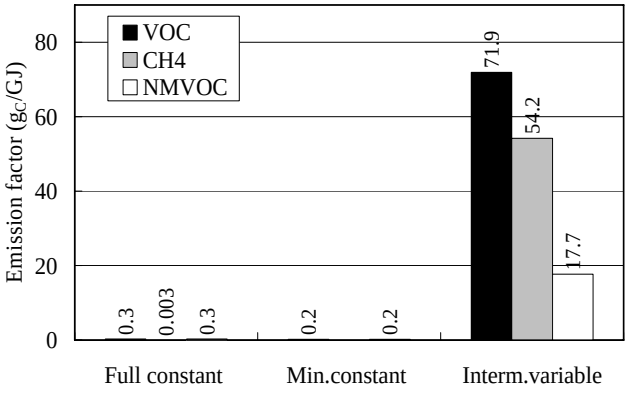

Figure 10. VOCs emissions at constant and intermittent load measured with boiler 2

Table 2: Particulate emissions measured in the study.

Boiler	Concentration ($\mu g/m^3$ @ 3% O_2,dry normal flue gas)	Emission factor (mg/GJ)
1	39	13.4
2	33	11.3

4. Conclusions

Following progressive regulatory restrictions introduced in recent years, the technological options adopted in small gas fired heating appliances have experienced a significant development towards highly sophisticated designs, with particular attention addressed, through proper burner design and control, to the optimization of combustion conditions for reducing pollutant emissions while maintaining higher heat production efficiencies and secure operating conditions. However, proper documentation on emission levels expected from most advanced units is generally lacking, particularly in most typical utilization regimes characterized by variable load and intermittent operating conditions.

The experimental laboratory investigation conducted on several different commercial boilers in a range of continuous and variable load operating conditions result in the following main indications about emissions performance:

- simultaneous emissions minimization and heat recovery optimization appear rather compatible even in advanced boilers with dedicated burner designs (premixed flames with modular air/fuel control). On the other hand, even with most recent options available for emissions reduction (low NO_x premixed burners) air/fuel ratios are far from constant during variable heat load operation;
- very significant reductions in NO_x are achieved through advanced premixed burners, whilst for CO the low air/fuel ratios maintained for optimizing heat efficiencies at variable loads in modular burners appear to increase emissions at full output. On the other hand, the low NO_x premixed burner shows substantial VOC emissions, mostly of unburned methane fuel;
- results available from variable load operating conditions indicate a significant increase in CO and VOC emissions during intermittent operation with shut down/start up episodes;
- ageing of the boiler seems to mainly influence emissions of NO_x and unburned CH_4, with CO and VOC emissions being essentially comparable with those measured with new units in the same operating conditions;
- primary particulate emissions are almost negligible, as expected from the fuel utilised, with levels comparable to typical concentrations measured in background air.

Acknowledgments

The study was conducted within a research contract between Politecnico di Milano and CESI. The authors greatly appreciate the cooperation of Unical during the laboratory tests.

References

AMA (Agenzia Milanese Mobilità Ambiente) 2003. *State of the environment in Milan municipality, chapter 4* (in Italian). Milano (Italy).

ATIG 2004, *Natural gas utilization in Italy: general market situation of commercial heating boilers* (in Italian), ATIG, Italian Technical Gas Association, Milano (Italy).

CEN (European Committee for Standardization) 1999, *Gas fired central heating boilers - Type C boilers of nominal heat input not exceeding 70 kW*, European Standard EN 483:1999.

EEA (European Environmental Agency) 2003, *EMEP/CORINAIR Emission Inventory Guidebook - Third edition, October 2003 update*, EEA, Copenhagen (Denmark). Available online at: http://reports.eea.europa.eu/EMEPCORINAIR4/en/page002.html.

US EPA 2004, *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*, *5th Edition, update 2004*, U.S. EPA Office of Air Quality Planning and Standards, Washington D.C. (USA). Available online at: http://www.epa.gov/ttn/chief.