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The Effect of Flue Gas Recirculation on CO, PM and NO_x Emissions in Pellet Stove Combustion

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Abstract: Pellet stoves are popular appliances because they are an affordable technology and because the fuel is easy to store and to use. The increasing concern for environmental issues, however, requires a continuous effort to reduce pollutant levels in the atmosphere. This experimental work focuses on flue gas recirculation (FGR) as a possible way to improve combustion and decrease the emissions of carbon monoxide CO, particulate matter PM, and nitrogen oxides NO_x in order to fulfill European and Italian emission requirements, for NO_x in particular. A pellet stove has been tested in several experimental sessions with and without FGR. Pollutant emissions have been measured and analyzed in terms of statistical summaries and instantaneous trends. With FGR, the average CO and PM emissions were found to be 80% and 45% lower than the corresponding emissions without FGR. Results for PM are significant since FGR reduces emissions well below the most restrictive limits enforced in Italy. The analysis of instantaneous emissions in relation to excess air indicated that FGR can considerably reduce emissions, especially at the extremities of the oxygen O_2 content range. Optimal ranges of excess air, in terms of O_2 in flue gas, were identified for both the tested configurations, in which CO and PM emissions are minimized. The optimal range is 8–9% without FGR, and it decreases to 5–7% with FGR. Finally, a reduction in NO_x emissions by about 11% has been observed in the configuration with FGR. Although this reduction seems modest as compared to CO and PM, it is important in that it lowers the emission level to the most severe limit in Italian regulations and indicates an improved FGR system as the solution for further reduction.

Keywords: pellet stove; pollutant emission; burner design; flue gas recirculation; biomass

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1. Introduction

In Italy, pellet stoves and boilers are popular residential heating appliances for several reasons, including state and regional incentives for renewable energy heating systems. Moreover, the cost of wood pellets is attractive as compared to other traditional fuels such as liquid petroleum gas and heating oil, which are common options in areas not serviced by natural gas. Finally, wood pellets are easy to store and use. On the other hand, the combustion of wood is a source of unhealthy emissions; this is particularly important in Northern Italy, where geography and average meteorological conditions hinder the dispersion of pollutants into the atmosphere. Products of combustion can be subdivided into classes according to several criteria. For example, one can distinguish between gaseous and solid emissions, or between emissions from complete or incomplete combustion. Considerable attention is generally paid to carbon monoxide (CO) emission; indeed, it is a sign of incomplete combustion and can be considered a tracer of other pollutants such as hydrocarbons or soot (that is, the organic portion of the total suspended particles). In addition to CO emission, an important parameter related to air pollution is particulate matter (PM), which identifies any particles released from the chimney. In recent years, nitrogen oxides (NO_x) emissions from wood-burning appliances have been receiving growing attention, too. In combustion, three types of NO_x with different formation mechanisms are known: thermal NO_x, prompt NO_x and fuel NO_x [1]. NO_x is the sum of nitric oxide NO and nitrogen dioxide NO_2, but NO is the only one present in a significant amount in pellet stove flue gas [1]. It is well known that the principal mechanism of formation of NO_x in biomass combustion systems is the fuel-NO mechanism, by which NO forms from the oxidation of the nitrogen in the fuel; on the other hand, the contributions of thermal NO_x and prompt-NO_x mechanisms are negligible for the relatively low temperatures reached in biomass combustion.

The insalubrity of carbon-based solid fuel combustion and its potential danger to health are extensively addressed in the literature. The scientific community in the field is looking for new methods for the reduction of these emissions, focusing on the causes of their generation to develop primary and secondary reduction measures. In this respect, fuel composition is a key aspect to consider. For instance, inorganic materials in the fuel are sources of emissions of solid particles, whereas the volatility of the elements contained in the fuel determines the amount of total suspended particles in the flue gases as found by Wiinikka et al. [2] and Fuller et al. [3]. Sommersacher et al. [4] described how the amount of the volatile elements potassium, sodium, zinc, lead, chlorine and sulfur in the biomass can be used to predict the concentration of total suspended particles emitted during the combustion. Exploiting the fact that the main process of generation of inorganic suspended particles is the vaporization of inorganic compounds, some researchers have correlated fuel bed temperature with the vaporization of inorganic compounds and, therefore, with the generation of fly ashes (see, for example, the experimental works by Wiinikka and Gebart [5] and Obernberger et al. [6]). Indeed, as fuel bed temperature increases, larger quantities of inorganic compounds vaporize and, in turn, larger quantities of inorganic fly ashes are released. In best quality pellet A1 according to the ISO 17225-2:2021 standard, the ash content is low; the ash deposits are mainly composed of low melting temperature compounds such as K_2SO_4, KCl, Na_2SO_4 and $CaCl_2$ and they tend to increase with CO content in the flue gases as fuel bed temperature increases [7,8].

In addition to fuel properties, burner pot geometry, burning power, air inlet positions, air staging, and excess air also influence emissions and performances of solid fuel combustion. As concerns burner pot geometry, differences in dimensions, air inlet positions, air inlet ratios and depth can lead to important variations in CO and PM emissions [9]. For each stove, there is a specific range of burning power that optimizes combustion, as demonstrated by several studies—see, for example, the works by Morán et al. [10], Colom-Díaz et al. [11] and Fernandes et al. [12], in which the same appliance was tested at different burning powers and an optimum interval was identified for the minimization of CO emission and fly ashes. Air inlet positions also influence emissions: Bunner et al. [13] and Khodaei et al. [14] focused on air supply strategies to reduce fly ashes generation. They found that the best experimental solution consists in reducing primary air, which directly invests the fuel, up to under-stoichiometric values, and increasing the amount of secondary air that invests the flame. Indeed, a lower amount of primary air reduces the temperature and velocity of combustion air in the fuel bed, as found by Caposciutti et al. [15]. Measurements by Jancauskas and Buinevicius [16] demonstrated that the temperature in the primary combustion zone decreases with flue gas recirculation, just above the fuel bed. In the work by Archan et al. [17], the use of flue gas recirculation was found to diminish the average temperature due to the lower oxygen partial pressure and higher inert gas content, avoiding the formation of slag on the grate. As a result of temperature reduction, the entrainment of solid particles and the vaporization of inorganic compounds are also reduced. Instead, secondary air reacts with all products of incomplete combustion generated in the primary zone, such as CO, total hydrocarbons (THCs), volatile organic compounds (VOCs) and soot, completing all reactions and reducing products of incomplete combustion and fly ashes. Excess air, indicated by the oxygen (O_2) content in the flue gases, strongly influences emissions, as shown, for example, by Petrocelli et al. [18], Sher et al. [19] and Moron and Rybak [20]. In particular, an optimum excess air level in the flue gases exists that minimizes CO emissions, and its value changes depending on the design of the stove. Other studies have focused on flue gas temperature and the resulting temperature at chimney-roof penetration [21,22]. In some special conditions, such as during soot fires in the chimney, flue gas temperatures can reach peaks of 1200 °C, causing a strong reduction in efficiency and problems of safety [23,24].

In parallel with academic studies, international, national and local regulations on wood burning appliance emissions are becoming more and more severe. An example is the Ecodesign Directive, implemented by Commission Regulation (EU) 2015/1185 [25], whose requirements for domestic biomass appliances came into force on 1 January 2022 (Table 1). In some regions of Northern Italy, emission limits are even more stringent. From 1 January 2020, in Lombardy only the installation of “4 stars” and “5 stars” biomass-burning appliances is permitted, according to the classification of the Italian Ministerial Decree (DM) 186/2017 [26] taking into account emissions (CO, NO_x, PM and THCs) and efficiency. New limits on installation, replacement and incentives are constantly being introduced on a national and local basis. The NO_x reduction has become more important in recent years after the introduction in Italy of the above-mentioned DM 186/2017, in which the top class, i.e., “5 stars”, requires that for pellet stoves the NO_x must not exceed 100 mg/Nm^3 (13%O_2) (Table 1). Comparing this value with the figures reported in the literature, it is clear that respecting such limits remains a challenge, even with the best available technologies [27]. Many recent works analyzed primary measures for NO_x reduction. Air staging and flue gas recirculation are some of the possible solutions, which proved to be effective also in the reduction of other pollutants (see, for instance, the recent papers by Archan and co-workers [27,28]).

Table 1. Current emission limits for pellet stoves (Ecodesign Europe and Italian Ministerial Decree (DM) 186/2017).

	CO	PM	NO_x	THC
		[mg/Nm^3 (13%O_2)]		
Ecodesign EU	300	20	200	60
“4 stars” DM 186/2017	250	20	160	35
“5 stars” DM 186/2017	250	15	100	10

The recirculation of flue gas (FGR) is a technique of combustion optimization based on mixing combustion air with a fraction of flue gases to reduce the amount of O_2 in the combustive agents below 21% of O_2. This entails a reduction of the fuel bed temperature and, consequently, a reduction of emissions. Early examples of FGR applications can be found in Liuzzo et al. [29] and in Duan et al. [30], where it was tested in a waste incineration appliance and in a pilot-scale vortexing fluidized-bed combustor fed with peanut shell, respectively. This technology has been tested with several fuels such as coal, waste, pellet, diesel and methane: Sung et al. [31] applied it to a circulating fluidized bed facility with pellets used as an auxiliary fuel, Tu et al. [32] to a grate firing boiler, and Shi et al. [33] to small methane-air premixed-flame burner.

Considering studies on wood pellet or biomass-fired, fixed-bed combustors–the only possible configuration in domestic pellet stoves—in the early work by Morán et al. [10], a reduction in NO_x emissions was observed in wood pellets combustion with a strong FGR. In the tests carried out by Jancauskas and Buinevicius [16] on an experimental small-scale model (20 kW) of an industrial biofuel boiler fired by sunflower seed hulls, increasing the FGR ratio in the primary air reduced NO_x by about 20%. Good results in terms of NO_x emissions—below the threshold of 100 mg/Nm^3 (13%O_2)—have been reported by Archan et al. [27] for a 200 kW multi-fuel biomass boiler and by Chen et al. [34] for a 500 kW biomass boiler. A case with power size comparable to that of pellet stoves is the study by Zandeckis et al. [35], who recorded a 11% reduction of NO_x (down to 126 mg/Nm^3 (13%O_2)) in a 15 kW pellet boiler upon the introduction of FGR. However, the authors also detected an increment of CO emissions, entailing the existence of a trade-off between the two pollutants.

In this article, the results of an experimental analysison a pellet stove tested with and without FGR are presented. The stove has a burning power of 7–9 kW. The work aims to experimentally demonstrate that the introduction of this relatively simple technology can considerably reduce the emission of pollutants in the atmosphere, making these products more environmentally friendly. The experimental investigation has been performed in the framework of a collaboration between the University of Brescia and AICO S.p.A., a pellet stove manufacturer, and it is a part of a project for the reduction of CO, PM and NO_x emissions. The stove model used during the tests is indeed the result of an optimization process on the burner pot and the positions of air inlets presented in other publications of the authors [9,36]. This process led to a substantial reduction in CO, an appreciable reduction in PM, and a minor reduction in NO_x. However, this NO_x reduction was not sufficient to meet the requirements for the "5 stars" Italian quality label in Table 1. Therefore, FGR was tested in this study to verify whether it could be a viable solution for low-power size wood pellet stoves to reduce NO_x below the 100 mg/Nm^3 (13%O_2) limit.

The rest of the paper is organized as follows: Section 2 introduces the pellet stove under investigation. The experimental set-up and the test procedure are described in Section 3. Section 4 presents the results of the study, followed by a discussion. Conclusions are drawn in Section 5.

2. Materials

The pellet stove used for the experimental tests was a "Ravelli Natural 7" model manufactured by AICO S.p.A., whose burning power range was 7 to 9 kW. This appliance was classified as airtight, i.e., when subjected to an overpressure of 50 Pa its leakage was less than 1.75 m^3/h under normal conditions (temperature 0 °C, pressure 101.3 kPa). In this appliance, the fuel was fed into the combustion chamber through a screw/auger conveyor system, whose ON/OFF operation regulated the fuel flow. The flow rate of combustion air was adjusted by the speed of the flue gas extraction fan at the outlet of the stove. In its standard configuration, the stove was equipped with the "type A" burner pot described by Polonini et al. [9] and patented by AICO S.p.A. [37]. In the tests carried out for the present study, the stove has been equipped with a deeper burner pot, identified as "type B" [9] and illustrated in Figure 1. The use of this model of burner pot was previously found to be associated with lower CO and PM emissions if compared with traditional, less deep components [9].

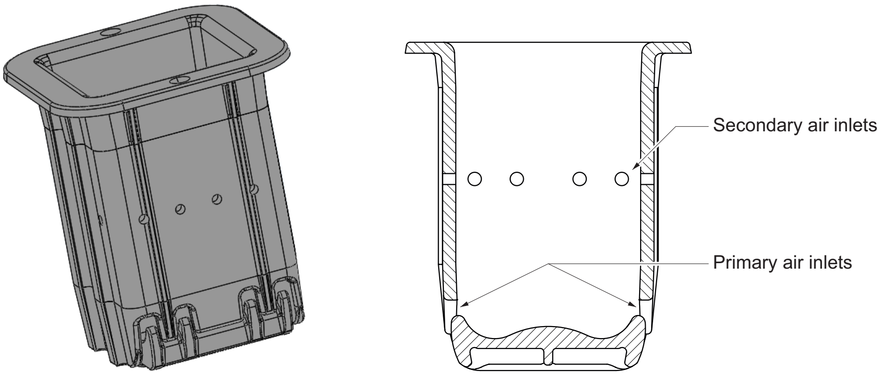

Figure 1. Burner pot mounted on the stove under investigation (denoted as "type B" in the work by Polonini et al. [9]).

Two configurations of the pellet stove have been tested: without and with FGR, both shown in Figure 2. In the tests with FGR, the standard stove model was modified as shown in Figure 2 (right).

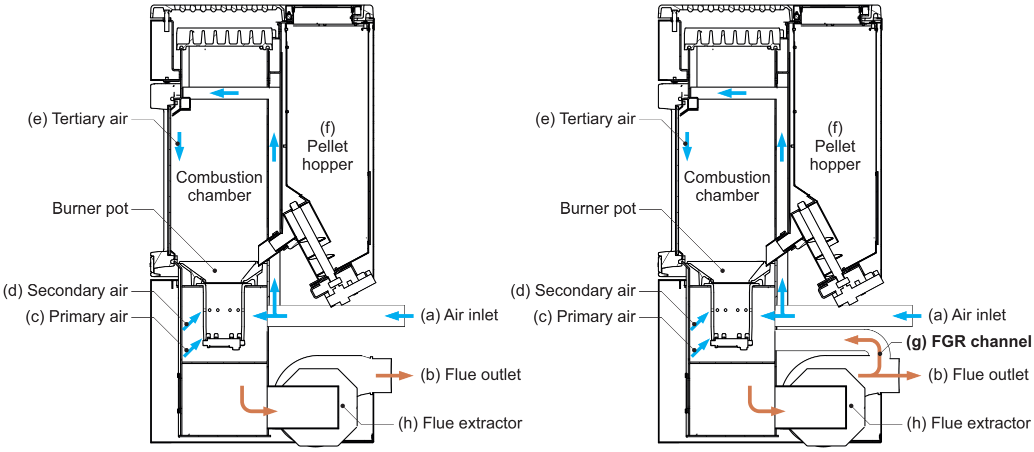

Figure 2. Scheme of the pellet stove without FGR system (**left**) and scheme of the pellet stove with FGR system (**right**).

The stove was airtight. Therefore, with reference to Figure 2, there were only one main inlet for combustion air (a) and one flue gases outlet (b). The air inflow was subdivided inside the stove into primary (c), secondary (d) and tertiary air flows (e). To prevent significant leakage between the inside and the outside of the stove, the pellet hopper (f) was isolated from the external environment. Primary and secondary inlets were separated by the burner pot geometry (Figure 3). The tertiary inlet was separated from the others by a fork of the inlet duct, thus tertiary air entered the combustion chamber flame zone from the top.

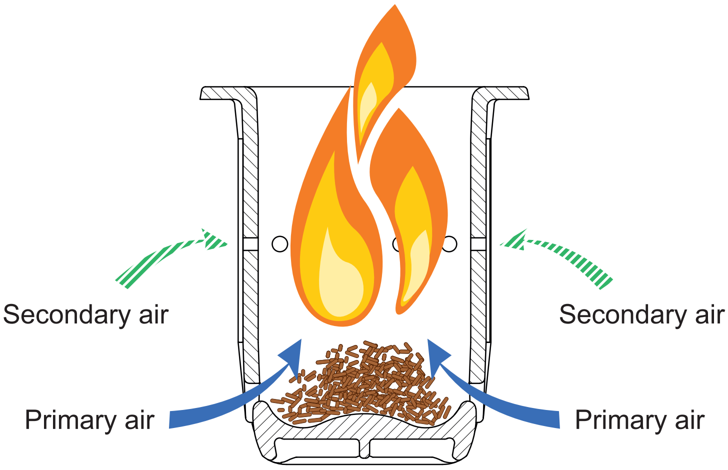

Figure 3. Primary (blue) and secondary (green striped) inflows.

A flue gas extractor fan regulated the excess air ratio, and during the tests it was set to maintain CO emissions as low as possible.

FGR is a technique that deviates a part of flue gases into the inlet air channel to generate a mixture of air and flue gases. As shown in Figure 2 (right), a pipe in the tested stove, FGR channel (g), connected the flue gas outlet (b), downstream of the flue gas extractor (h), with the space around the burner pot, below the combustion chamber. The recirculating flue gas flow rate was not regulated, but resulted from the pressure difference between the outlet pipe and the chamber, due to the flue gas extractor. In the first attempts to introduce FGR in this stove, the flue gas outlet was directly connected to the air inlet pipe: mixing between the two gas streams started in the air inlet pipe, ahead of the chamber. Tests on this configuration were not satisfactory since no significant reduction of NO_x was recorded. Then the configuration presented here was adopted. It was characterized by mixing developing in the chamber around the burner pot; therefore, the combustion mixture fed reactions through primary and secondary inlets only, while ambient fresh air fed the flame through the tertiary inlet.

As concerns fuel, the same ENPLUS A1 quality of pellets has been used in all tests. Mass fractions and lower heating value are specified in Table 2.

Table 2. Characteristics of the pellet used in the experiments (wb = wet basis).

	Mass Fraction wb (% m/m)	**Determination Method**
Carbon (C)	48.12	ISO 16948:2015
Hydrogen (H)	5.70	ISO 16948:2015
Nitrogen (N)	0.11	ISO 16948:2015
Moisture content (W)	6.00	ISO 18134-1:2015
Ash	0.18	ISO 18122:2015
Oxygen (O)	39.80	By difference
Lower Heating Value (LHV)	17,371 kJ/kg	ISO 18125:2017

3. Testing Procedure and Experimental Setup

The tests on the stove in either configuration required 5 days of experiments. All the tests performed during a single day of testing and in the same combustion conditions will be denoted here as a "test session".

A regular day of testing started in the morning with the setting of operation parameters and stove ignition: the burner pot, in particular, was emptied of all the residuals from the previous day. In a range from 60 to 90 min from the ignition, the combustion reached quasi-steady condition which was detected upon monitoring flue gas temperature. At this point, several tests were performed: each test lasted 30 min and up to six tests were performed during a single test session. The operation parameters were kept fixed throughout a test session. At the end of the day, the pellet feeding was switched off and the combustion air flow rate was increased to quickly burn away the pellets left in the burner pot (extinguishing stage). This process lasted approximately 15 min.

For the measurement of burning rate $\dot{m}_p$, the whole stove was put on a platform scale according to the indications of the EN 16510-1:2018 standard (see also prEN 16510-2-6). The average burning rate was evaluated by dividing the stove weight decrement during the entire day of testing by its duration. Here, the duration is defined as the time interval from the beginning of the first test to the end of the last one.

Flue gases measurements and PM sampling were done in the measurement section, just downstream of the stove outlet. The flue gas draft was regulated by a mechanical aspiration system and was maintained constant at 8–10 Pa for all the combustion period. A scheme of the set-up is shown in Figure 4.

During each test, O_2, CO, PM and NO were measured simultaneously and continuously. A gas analyzer ABB EL3020 equipped with electrochemical oxygen sensor was used to measure the concentration of O_2 in dry gas in the form of volume percentage with an accuracy of $\pm 0.2\%$. An ABB Uras26 infrared photometer mounted on the same analyzer was used to measure CO and NO fractions in parts-per-million, with an accuracy of ± 2 ppm. Instantaneous PM emissions (PM_{inst}) were measured with a TESTO 380 probe, with ± 0.1 mg/Nm^3 measurement resolution. For all these measures, the sampling time was 5 s, and the average over the 30 min test (360 samples) was calculated for each gas and for PM_{inst}.

As well as measuring the instantaneous amount of particles during the test (PM_{inst}), the total amount of particles in a 30 min test (PM_{grav}) was measured by the filter-gravimetric method described in the CEN/TS 15883:2009 standard (see also prEN 16510-2-6). The particles were collected by a filter and weighed, then the total particle mass was divided by the amount of aspirated gas (measured by a Dr. Födisch GMD 12 gravimetric measuring device). The quartz fiber filter adopted in the tests had a retention efficiency of 99.998% of the particulate with 0.3 µm diameter, while the analytical balance used to weigh the particles deposited on the filter was a Mettler-Toledo ME104, with ±0.08 mg measurement accuracy. According to the CEN/TS 15883:2009 standard (see also prEN 16510-2-6), the pump was set to extract flue gases at a constant flow rate of 10 L/min (accuracy ±2%).

A time lag between two consecutive tests was necessary to replace the filter and for the instrument self-adjustment. During these operations, the combustion conditions were kept fixed. Although the EN 14785:2006 and prEN 16510-2-6 standards prescribe to average O_2, CO, CO_2, and NO over three hours, here, the average values have been calculated over the 30 min in which the PM is collected by the filter.

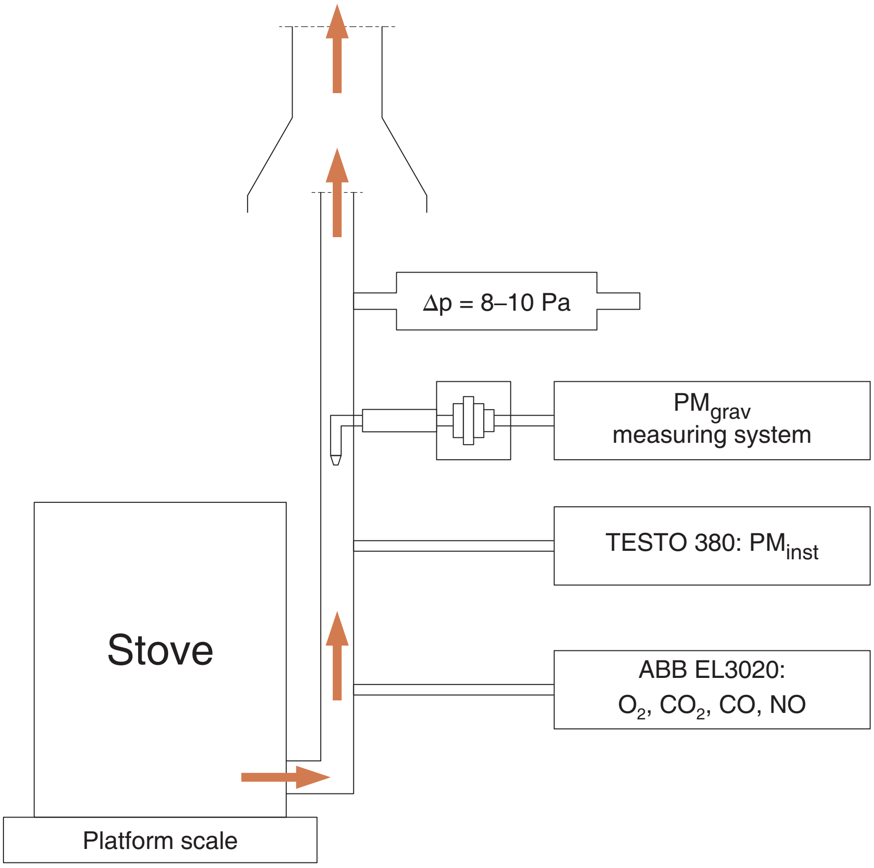

Figure 4. Scheme of the measuring system for gases and particulate matter.

4. Results and Discussion

The experimental results for the stove without FGR and with FGR are summarized in Tables 3 and 4, respectively. Data were collected in 13 tests without FGR and in 11 tests with FGR. In test codes αn-d-s, α is equal to S for tests without FGR and to R for tests with FGR, n is the test progressive numbering, d and s stand for the testing day and test session, respectively.

Table 3. Test data and results for stove without FGR (direct mesurements presented with standard deviation).

Test Code	**Burning Rate** **kg/h**	O_2 %	CO_2 %	**Exhaust Gas Temperature** **°C**	**Efficiency** **%**	**Burning Power** **kW**	**Nominal Power** **kW**	**Excess Air** **-**	**CO** **ppm**	**NO** **ppm**	**CO** **mg/Nm^3 (13%O_2)**	**PM$_{grav}$** **mg/Nm^3 (13%O_2)**	**PM$_{inst}$** **mg/Nm^3 (13%O_2)**	**NO$_x$** **mg/Nm^3 (13%O_2)**
S01-1-1	1.60	8.6 ± 1.0	12.1 ± 1.1	182.2 ± 0.9	90.2	7.71	6.96	1.7	28 ± 13	84 ± 6	23	8.1	15.2	111
S02-1-1	1.60	7.9 ± 1.3	13.0 ± 1.4	183.9 ± 1.0	90.8	7.71	7.00	1.61	34 ± 40	87 ± 6	26	12.2	19.3	109
S03-1-2	1.60	9.6 ± 1.2	11.3 ± 1.3	205.4 ± 2.0	88.0	7.71	6.79	1.86	28 ± 19	82 ± 8	24	10.6	15.5	118
S04-1-2	1.60	6.6 ± 1.5	14.4 ± 1.6	188.9 ± 1.2	91.3	7.71	7.04	1.47	93 ± 153	94 ± 6	65	11.7	NA	107
S05-1-3	1.60	7.2 ± 1.3	13.8 ± 1.4	206.4 ± 0.7	90.1	7.71	6.95	1.54	32 ± 39	96 ± 6	23	11.7	18.4	114
S06-2-4	1.73	8.0 ± 1.2	12.8 ± 1.3	223.2 ± 1.0	88.6	8.34	7.39	1.62	34 ± 21	91 ± 7	26	12.4	18.0	114
S07-2-4	1.73	7.7 ± 1.4	13.3 ± 1.5	224.2 ± 0.5	89.1	8.34	7.43	1.6	44 ± 36	93 ± 8	33	12.6	NA	115
S08-2-4	1.73	8.3 ± 1.6	12.8 ± 1.6	214.3 ± 2.3	89.0	8.34	7.42	1.69	42 ± 38	90 ± 9	34	13.7	18.5	116
S09-2-4	1.73	7.6 ± 1.5	13.5 ± 1.6	214.2 ± 0.8	89.5	8.34	7.46	1.59	53 ± 78	93 ± 7	40	14.2	21.1	114
S10-2-4	1.73	8.1 ± 1.8	12.9 ± 1.8	212.5 ± 0.6	89.0	8.34	7.43	1.67	68 ± 92	89 ± 10	53	16.0	19.3	114
S11-2-4	1.73	7.7 ± 1.6	13.3 ± 1.7	216.3 ± 0.7	89.2	8.34	7.44	1.61	57 ± 71	91 ± 8	43	16.4	20.7	113
S12-3-5	1.85	7.9 ± 1.5	12.8 ± 1.6	218.5 ± 1.8	88.8	8.91	7.91	1.62	36 ± 75	90 ± 9	27	8.7	14.1	113
S13-3-5	1.85	8.4 ± 1.3	12.6 ± 1.4	222.5 ± 0.9	88.5	8.91	7.89	1.69	18 ± 11	89 ± 8	14	11.7	16.5	116

Table 4. Test data and results for stove with FGR (direct mesurements presented with standard deviation).

Test Code	**Burning Rate** **kg/h**	**O_2** **%**	**CO_2** **%**	**Exhaust Gas Temperature** **°C**	**Efficiency** **%**	**Burning Power** **kW**	**Nominal Power** **kW**	**Excess Air** **-**	**CO** **ppm**	**NO** **ppm**	**CO** **mg/Nm^3 (13%O_2)**	**PM$_{grav}$** **mg/Nm^3 (13%O_2)**	**PM$_{inst}$** **mg/Nm^3 (13%O_2)**	**NO$_x$** **mg/Nm^3 (13%O_2)**
R01-4-6	1.75	7.2 ± 1.3	14.0 ± 1.3	216.2 ± 1.6	89.9	8.45	7.60	1.54	7 ± 6	91 ± 6	5	5.8	6.7	108
R02-4-6	1.75	5.6 ± 1.2	15.8 ± 1.2	215.7 ± 0.8	91.2	8.45	7.70	1.37	15 ± 23	92 ± 2	9	6.6	8.2	97
R03-4-6	1.75	5.8 ± 1.3	15.7 ± 1.4	215.1 ± 0.6	91.2	8.45	7.70	1.39	13 ± 19	90 ± 2	9	6.7	8.2	96
R04-4-6	1.75	6.1 ± 1.2	15.4 ± 1.3	210.3 ± 1.1	91.2	8.45	7.70	1.42	13 ± 27	88 ± 3	9	5.9	8.8	97
R05-4-6	1.75	5.5 ± 1.2	15.9 ± 1.2	209.0 ± 0.9	91.5	8.45	7.73	1.37	14 ± 20	87 ± 2	9	6.0	7.6	92
R06-5-7	1.69	7.3 ± 1.2	14.1 ± 1.2	217.9 ± 0.6	89.9	8.16	7.34	1.54	8 ± 6	91 ± 6	6	6.4	7.2	108
R07-5-7	1.69	6.5 ± 1.2	14.9 ± 1.3	218.9 ± 0.8	90.4	8.16	7.38	1.46	8 ± 9	92 ± 4	6	8.6	8.4	103
R08-5-7	1.69	6.2 ± 1.2	15.1 ± 1.3	217.6 ± 0.8	90.7	8.16	7.40	1.44	9 ± 12	92 ± 4	6	6.8	8.7	103
R09-5-7	1.69	6.5 ± 1.1	14.9 ± 1.1	214.8 ± 1.0	90.7	8.16	7.41	1.46	6 ± 4	89 ± 4	4	6.0	6.6	101
R10-5-7	1.69	6.0 ± 1.5	15.5 ± 1.6	216.6 ± 1.0	90.9	8.16	7.42	1.42	13 ± 19	88 ± 3	9	5.7	7.2	96
R11-5-7	1.69	6.0 ± 1.0	15.5 ± 1.1	213.5 ± 0.9	91.1	8.16	7.43	1.41	7 ± 7	88 ± 3	5	4.8	7.5	96

To allow for a proper comparison of results, the average CO, PM_{grav}, PM_{inst}, and NO values collected during a test are normalized to the same concentration of 13% of O_2. The CO fraction is multiplied by its density of 1.25 kg/Nm^3, and NO fraction is multiplied by the density of NO_2 of 2.05 kg/Nm^3 according to the EN 16510-1:2018 standard (in this work, NO multiplied by the density of NO_2 is defined as NO_x). Therefore, CO, PM_{grav} and PM_{inst}, and NO_x results are presented in milligrams per normal cubic meter at 13% of O_2. Indicating the average values with a bar over the symbol, the formulas used for unit normalization are:

$$\mathrm{CO}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}(13\%\mathrm{O}_2)\right] = \overline{\mathrm{CO}}\ [\mathrm{ppm}] \times \rho_{\mathrm{CO}}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \times \frac{21-13}{21-\overline{\mathrm{O}_2}[\%]} \tag{1}$$

$$\mathrm{NO_x}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}(13\%\mathrm{O}_2)\right] = \overline{\mathrm{NO}}\ [\mathrm{ppm}] \times \rho_{\mathrm{NO2}}\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \times \frac{21-13}{21-\overline{\mathrm{O}_2}[\%]} \tag{2}$$

$$\mathrm{PM_{grav}}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}(13\%\mathrm{O}_2)\right] = \frac{m_2-m_1}{fg_{\mathrm{asp}}}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}\right] \times \frac{21-13}{21-\overline{\mathrm{O}_2}[\%]} \tag{3}$$

where m_1 is the mass of the filter before the measurement, m_2 is the mass of the filter after the measurement, and fg_{asp} is the amount of aspirated gas during the measurement period. Similarly,

$$\mathrm{PM_{inst}}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}(13\%\mathrm{O}_2)\right] = \overline{\mathrm{PM_{inst}}}\left[\frac{\mathrm{mg}}{\mathrm{Nm}^3}\right] \times \frac{21-13}{21-\overline{\mathrm{O}_2}[\%]}. \tag{4}$$

The burning power, that is, the chemical power available to the stove, is calculated with the equation

$$P[\mathrm{kW}] = \mathrm{LHV}\left[\frac{\mathrm{kJ}}{\mathrm{kg}}\right] \times \frac{\dot{m}_{\mathrm{p}}}{3600}\left[\frac{\mathrm{kg}}{\mathrm{s}}\right] \tag{5}$$

where P is the burning power, LHV is the lower heating value in Table 2 and $\dot{m}_p$ is the burning rate. The nominal power is obtained by multiplying the burning power P by the thermal efficiency.

Finally, the thermal efficiency is calculated as prescribed in Sec. A.6.2.1 of EN 16510-1:2018 standard.

Tests in testing day no. 1 were grouped in three different sessions. The speed of the flue gas extraction fan was changed twice and was different for each of the three sessions. After each speed change, data collection was started only after reaching quasi-steady conditions as shown by the standard deviation of exhaust gas temperature during each test.

4.1. *Effect of Recirculation on CO, PM and NO_x Emission Mean Values*

In Table 5, the mean values of O_2 content and emissions are summarized for the configurations without and with FGR, along with standard deviations. They are obtained by averaging the values reported in the corresponding columns of Tables 3 and 4.

The experimental measurements illustrated in Table 5 and Figure 5 demonstrate that the application of FGR technology reduces the total amount of emissions.

Table 5. Average result of emissions for each test ("Avg.": average; "Std. dev.": standard deviation).

		Without Recirculation (13 Tests)		**With Recirculation (11 Tests)**	
	Unit	**Avg.**	**Std. Dev.**	**Avg.**	**Std. Dev.**
O_2	%	8.0	0.7	6.2	0.6
CO	mg/Nm^3 (13%O_2)	33	14	7	2
PM_{grav}	mg/Nm^3 (13%O_2)	12.3	2.4	6.3	0.9
PM_{inst}	mg/Nm^3 (13%O_2)	17.9	2.3	7.7	0.8
NO_x	mg/Nm^3 (13%O_2)	113	3	100	5

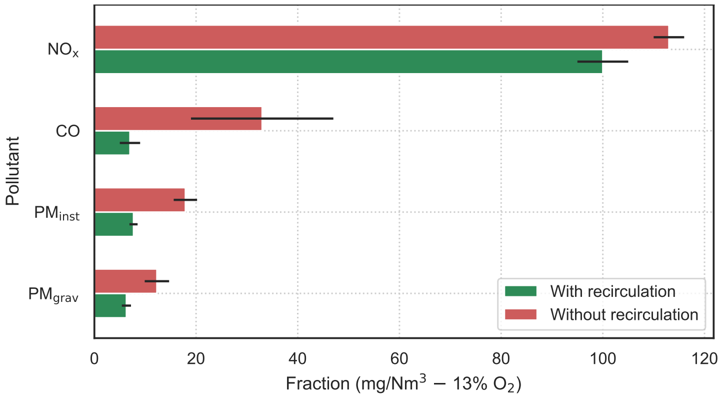

Figure 5. Variations of emissions with the introduction of FGR (error bars: standard deviation).

In particular, CO emissions decreased by almost 80% and PM emissions by over 45%. Furthermore, an 11 % reduction in NO_x was observed.

4.2. Effect of Recirculation on CO, PM and NO_x Distribution vs. O_2 Content

In this paragraph, the relations between emissions (CO, PM and NO_x) and excess air, defined as the O_2 content in the flue gases, are analyzed. It is worth remarking that excess air in the flue gases does not depend only on the flue gas extractor velocity, but also on the instantaneous burning rate and instantaneous temperatures of the fire that continuously vary during the combustion. Moreover, the pellet mass falling in the pot also varies at each release from the conveyor system, depending on the number and total length of the grains released [36]: hence, a wide O_2 variability can be expected even at fixed operation settings. To have a clear understanding of the trends despite data scattering, the instantaneous values of emissions have been synthesized in average values over narrow intervals of O_2. It is worth specifying that all the 8640 data records collected in the 24 tests were used to draw Figures 6–8. A brief description of the procedure that was followed to obtain the average CO, PM and NO_x distribution vs. O_2 content can be found in Appendix A.

It is well known that CO emissions are influenced by excess air, specified by O_2 content in the flue gases; indeed, there is a specific percentage of O_2 that minimize CO emissions, as pointed out in several studies [38,39]. The experimental evidence in Figure 6 shows that this percentage varies depending on the presence or the absence of a recirculation system: in the case without FGR, the lowest CO emissions were found at O_2 content between 8 and 9%, and their value was around 20 mg/Nm^3 (13%O_2). On the other hand, when the FGR system was active, CO emissions attained very low values, below 5 mg/Nm^3 (13%O_2), for a wider O_2 content interval, between 5 and 7%.

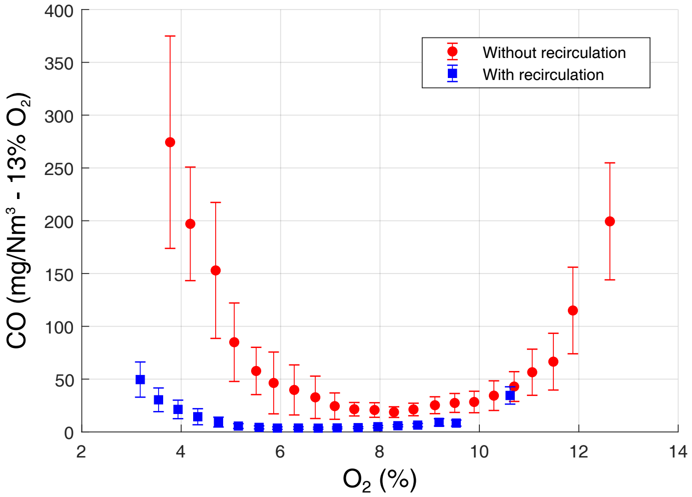

Figure 6. CO versus O_2 content with and without FGR technology.

Furthermore, with FGR, CO emissions did not exceed 50 mg/Nm^3 (13%O_2) over the entire range of excess air, whereas values well above 100 mg/Nm^3 (13%O_2) could be observed without FGR at low and high O_2 content values.

With regard to PM emissions, in Figure 7, PM_{inst} measurements carried out with the TESTO 380 probe are plotted as a function of O_2 content in the flue gases. As in the case of CO emissions, PM emissions were particularly low for a specific interval of O_2, which varied depending on the presence or absence of the recirculation technology: the "optimal" O_2 range was 5–7% in presence of FGR, and 8–9% without this technology. The minimum values of emissions in the two cases were about 6 and 11 mg/Nm^3 (13%O_2), respectively, with the largest recirculation-driven improvement being obtained at low values of excess air.

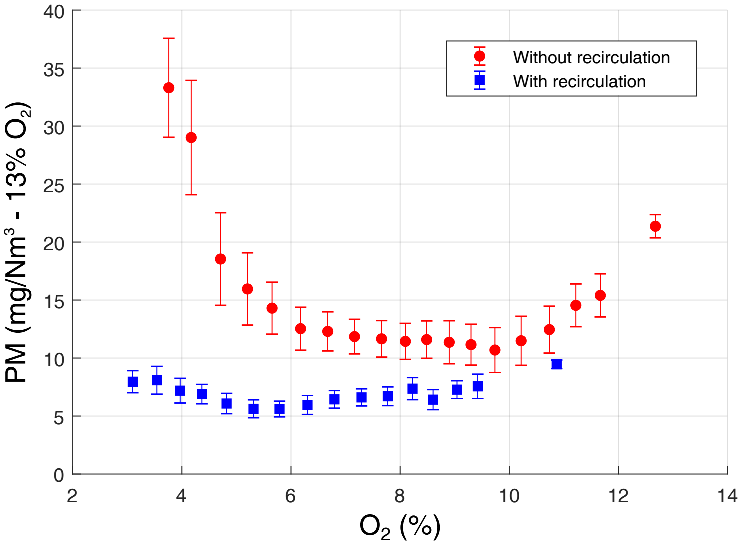

Figure 7. PM versus O_2 with and without FGR technology.

As concerns the emissions of NO_x, which are an unwanted product of combustion, non-correlated with CO emissions, it can be observed that their distribution vs. O_2 content had indeed a behavior different from those of CO or PM, as it tended to increase up to a maximum value and then plateau (Figure 8). In addition, in this case there was a reduction of emissions associated with FGR, although slight. In particular, for percentages of O_2 below 6%, NO_x emissions were lower than 100 mg/Nm^3 (13%O_2), while, without FGR, NO_x emissions were lower than 100 mg/Nm^3 (13%O_2) only for very small O_2 percentages.

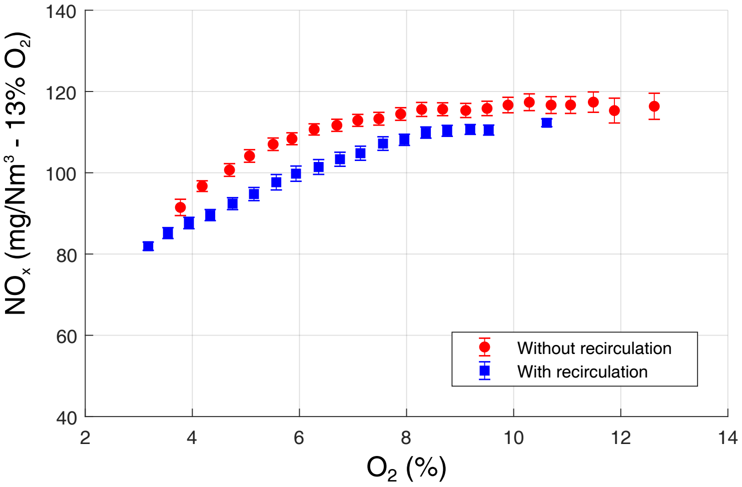

Figure 8. NO_x versus O_2 in cases with and without FGR technology.

From the results plotted in Figures 6–8, it can be concluded that FGR does not influence the shape of the distribution of CO, PM, and NO_x emissions vs. O_2 content. However, FGR shifts the distributions leftwards, i.e., towards lower values of O_2 and, at the same time, it decreases emissions at all O_2 values.

4.3. Final Remarks

The implementation of an FGR system in the stove has reduced pollutant emissions. The reduction is apparent considering both CO, PM, and NO_x average values over several tests (Figure 5) and their distribution vs. O_2 content in flue gases (Figures 6–8). The evaluation of the reduction significance will be based on the comparison with current emission limits enforced by Italian and European regulations, as summarized in Table 1.

With regard to CO, Tschamber et al. [40] and Labbé et al. [41] have shown that the average CO emissions from wood pellet combustion can strongly change depending on the adopted stove model; in these articles, CO emissions varied from 50 to 850 mg/Nm^3 (13%O_2). This interval extends well above the current limit of allowed emission which is 250 mg/Nm^3 (13%O_2) (Table 1). As mentioned in the introduction, the stove model used in this study was optimized to reduce CO and PM emissions. The CO emission levels of the optimized AICO's burner pot are well below the 250 mg/Nm^3 (13%O_2) limit: it can be observed that the average CO value in Table 5 without FGR is 34 mg/Nm^3 (13%O_2). Upon introduction of the FGR, CO emissions decreased by 80% to values around 7 mg/Nm^3 (13%O_2): although the reduction is substantial, the implementation of an FGR system is not worth the cost since CO emissions are very low even without it.

With regard to PM, the emission values reported by Johansson et al. [42,43] and Schmidl et al. [44] range between 12 and 80 mg/Nm^3 (13%O_2), while, in the optimized stove model without recirculation presented in this article, the average PM emissions are around 12.3 mg/Nm^3 (13%O_2) (measured using the filter-gravimetric method as required by the CEN/TS 15883:2009 and prEN 16510-26 standards). This value is below the strictest limit required by "5 stars" label (15 mg/Nm^3 (13%O_2), see Table 1); however, it is close to the limit. With FGR, the average emissions are reduced by a factor of 2, achieving 6.3 mg/Nm^3 (13%O_2). Therefore, the adoption of an FGR system can guarantee a safe fulfillment of the requirement.

Nowadays, the most severe of the limits in Table 1 for the current pellet stove technology is the 100 mg/Nm^3 (13%O_2) on NO_x emissions. As mentioned in Section 1, among studies on fixed-bed combustors fired by biomass, only Archan et al. [27] and Chen et al. [34] report NO_x emissions below 100 mg/Nm^3 (13%O_2) upon use of FGR and air staging–in particular, between 85 and 90 mg/Nm^3 (13%O_2). These values were obtained for 200 and 500 kW biomass boilers. The only study known to the authors characterized by a power rate comparable to that of pellet stoves is reported by Zandeckis et al. [35]: here, the introduction of an FGR system in a 15 kW pellet boiler led to a reduction in NO_x, but from 142 to 126 mg/Nm^3 (13%O_2), i.e., still above the 100 mg/Nm^3 (13%O_2) limit.

In this work, the adoption of FGR in a 7–9 kW pellet stove has reduced NO_x emission by slightly more than 10%. Compared to CO and PM reductions, it may not seem significant; however, it is quite an important result in that the emissions were reduced from 113 to 100 mg/Nm^3 (13%O_2)—that is, they were lowered at or just below the threshold for the "5 stars" requirement of 100 mg/Nm^3 (13%O_2). The implementation of an FGR system coupled with an optimized burner pot seems a feasible solution to develop an environmentally friendly pellet stove.

As an ending remark, in the studies by Archan et al. [27] and Chen et al. [34], the NO_x emission reduction was improved upon control of the flue gas flow rate mixed with the combustion air flow. On the other hand, in the present study, mixing was not regulated and was governed by the pressure difference between the flue gases outlet pipe and the combustion chamber. In this respect, this study has to be considered preliminary. In future developments, a measurement campaign should be set up to investigate the optimal amount of recirculated gas that minimizes emissions without compromising combustion, and to further reduce NO_x emissions to safely fulfill the 100 mg/Nm^3 (13%O_2) limit.

5. Conclusions

The study presented in this article shows the potential for emission reduction in wood pellet stoves associated with the introduction of FGR technology. A 7–9 kW stove was modified to mix part of flue gas flow with primary and secondary air flow. The performances associated to stove configurations without and with FGR were compared in terms of CO, PM, and NO_x emissions.

The experimental evidence has indicated that the emissions of all pollutants decrease with FGR. In particular, average CO, PM and NO_x emissions were reduced by 80%, 45%, and 11%, respectively, following the introduction of the recirculation system. Although CO reduction was the largest, it cannot be considered as important as PM and NO_x reductions, since CO emission levels were well below the threshold imposed by Italian and European directives even without FGR. The implementation of an FGR system played a significant role with respect to the strictest limit currently enforced in Italy on PM and NO_x emissions: PM emissions were lowered to about half of 15 mg/Nm^3 (13%O_2), whereas NO_x emissions were reduced down to the threshold of 100 mg/Nm^3 (13%O_2). Therefore, FGR appears as a viable option to further abate the NO_x emission level.

As far as the authors are aware, data collected and presented in this paper are the first ones that show that FGR may be effective in reducing NO_x also in a low power rate appliance such as a pellet stove. However, to confirm these results and to ensure emission levels consistently below the 100 mg/Nm^3 (13%O_2) limit, further studies are needed to investigate how the amount of recirculated gas influences emissions.

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Abbreviations

The following abbreviations are used in this manuscript:

FGR	Flue gas recirculation
LHV	Lower heating value
PM	Particulate matter
THC	Total hydrocarbon
VOC	Volatile organic compound

Appendix A

To plot the distributions of CO, PM_{inst} and NO_x versus O_2 content presented in Section 4, data were processed in the following way. Data considered here are all the recorded measurements during the tests, that is, 4680 (= 13 × 360) records and 3960 (= 11 × 360) records for tests without and with FGR, respectively. A list of all symbols used is reported in Table A1.

Table A1. List of symbols.

Symbol	Description
X	Emission data of pollutant X collected in all the tests
O_2	O_2 data collected in all the tests
X_{sub}	Emission data of pollutant X for each sub-interval
$O_{2,sub}$	O_2 data for each sub-interval
$n_{data,sub}$	Number of data points for each pollutant and each sub-interval
$O_{2,min}$	Minimum of O_2
$O_{2,max}$	Maximum of O_2
$O_{2,range}$	Range of O_2
$\overline{X_{sub}}$	Mean of the emissions of pollutant X recorded for each sub-interval
$\overline{O_{2,sub}}$	Mean of O_2 for each sub-interval
$\sigma_{X,sub}$	Standard deviation of the emissions of pollutant X recorded for each sub-interval

As the first step, the maximum and minimum values of O_2 among all O_2 data were identified:

$$O_{2,min} = \min\{O_2\} \tag{A1}$$

$$O_{2,max} = \max\{O_2\} \tag{A2}$$

then the whole O_2 range was calculated as the difference between $O_{2,max}$ and $O_{2,min}$:

$$O_{2,range} = O_{2,max} - O_{2,min} \tag{A3}$$

The whole O_2 range was subdivided into 25 subintervals. For each subinterval, the mean of X and O_2 were calculated as:

$$\overline{X_{sub}} = \frac{\Sigma[X_{sub}]}{n_{data,sub}} \tag{A4}$$

$$\overline{O_{2,sub}} = \frac{\Sigma[O_{2,sub}]}{n_{data,sub}} \tag{A5}$$

Finally, for each sub-interval, the standard deviation of X was calculated:

$$\sigma_{X_{sub}} = \sqrt{\frac{\Sigma_i (X_i - \overline{X_{sub}})^2}{n_{data,sub}}} \tag{A6}$$

An example of this procedure applied to a generic set of O_2 and CO data is shown in Figure A1.

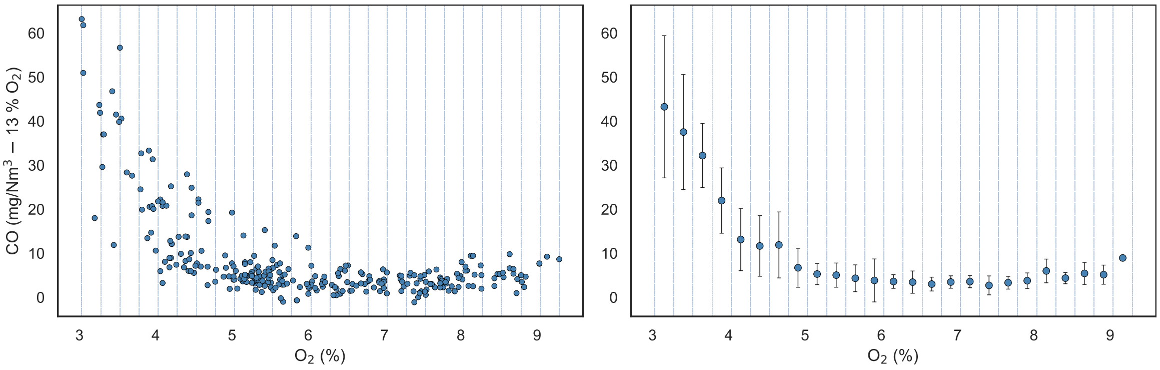

Figure A1. Example of data post-processing to obtain average CO emissions value versus O_2 content. Left: original data; right: mean and standard deviation for each O_2 band.

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