



UNIVERSITÀ
DEGLI STUDI
DI PADOVA

UNIVERSITÀ DEGLI STUDI DI PADOVA
DIPARTIMENTO DI INGEGNERIA INDUSTRIALE
CORSO DI LAUREA MAGISTRALE IN INGEGNERIA CHIMICA E DEI PROCESSI INDUSTRIALI

Tesi di Laurea Magistrale in
Ingegneria Chimica e dei Processi Industriali

**ANALYSIS OF POLLUTANT EMISSIONS IN A COMMERCIAL
PELLET STOVE AT DIFFERENT WORKING CONDITIONS**

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Abstract

This Thesis work involves the measurement, statistical analysis and evaluation of parameters related to the behavior at different working conditions of a commercial pellet stove. Specifically, data on temperatures inside the combustion chamber to obtain a thermal map and pollutants' levels in the outlet flue streams like CO_x, NO_x and particulate matter ones have been collected.

Temperature and emission measurements have been carried out to verify if the stove respects the 2022 Ecodesign emission limit values for the pollutants analyzed; moreover, tests aimed to assess the best operating conditions in terms of variables in a commercial pellet stove, in particular the front vent velocity, suction vent velocity and power level.

Other variant tests have been carried out changing the initial conditions to verify how the system reacted to changes in the initial conditions with short pellet, water vapor inlet and a 20 kg initial test.

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Chapter 1

State of the art on stoves emissions measures

In this Chapter, the focus is on the limitation of pollutant emissions from flue gases exiting from biomass combustion plants, in this case pellet stoves for domestic heating, by a specific study on emissions and their relationship with temperature and internal parameters of the stove.

In the first paragraph, a review of the previous work on stoves emissions reduction developed through CO and soot emissions tests inside the laboratories is provided. Some relevant results are highlighted to explain why understanding the internal behavior of the combustion equipment is a crucial step before any secondary emission reduction implementation.

In the second paragraph, literature research concerning recent advances in the field of Ecodesign stoves and their emission reduction potential is described, gathering the most significant articles. The techniques are quite always referred to experimental setup schemes with sensors aimed at measuring variables and assess pollutant concentrations for biomass heating appliances. for this application.

1.1 Soot interaction and real equipment tests

Pollutant emissions from biomass stoves represent a major problem now and in the next years: in fact, in order to face the “greenhouse effect”, environmental impacts at any level should be minimized, if not eliminated, especially regarding factories, automotive and domestic heating emission sources; for this last one, emissions have been growing in importance in recent years, increasing their relative contribution to the total ones; some industries closed and vehicles have gradually evolved in order to respect the more and more demanding requirements from European legislation regarding emissions of gaseous and particulate pollutants. Domestic stoves have therefore switched from secondary to primary emission source, releasing from flue gases pollutants like incomplete combustion products, such as CO and VOCs (volatile organic compounds), and soot precursors, such as ethylene, propylene, and other unsaturated compounds that could form PAH (polycyclic aromatic hydrocarbons), called “soot”.

Tests taken from a previous thesis project inside K-Inn Lab and focused on the study of Mn_2O_3 , regarding soot interaction and deposition on catalytic crosses to simulate the combustion chamber environment are now briefly presented.

The initial mixture fed to an experimental quartz tube reactor is constituted by CO (1%), soot precursors (ethylene and propylene, 0.5% both) and O_2 (15%) diluted in helium (83%). Catalyst had been deposited along a metallic cross-like support by means of an organic varnish painted there.

The cross was then inserted in a layout with a quartz tube used as a reactor for the gas feed, and quartz wool was used to mechanically sustain the cross.

The reaction resulted to be controlled not only by convection but also by diffusion: in fact, reactants were consumed at catalytic interfaces inside the reactor, and this caused a concentration gradient, thus a mass flux aimed at reducing it, but the process was continuous, so it was always present.

Overall, in CO and C₃H₆ cases, replicated tests showed a better conversion of pollutants, while activity in ethylene oxidation was still very low.

Unfortunately, the abatement of CO and hydrocarbons is quite low, phenomenon mainly driven by two factors:

- The operative conditions, due to the basic role of contact time;
- The catalyst deposition technique, which will overcome further improvements.

The next mentioned tests assessed the crosses' catalyst performance in a wood stove.

Three different places inside the wood stove were selected by a primary inspection for crosses arrangement in a real equipment scale: left and right upper ceiling, nearer to the fireplace, and immediately before flue. Results showed quite low global conversions due to mass transfer issues.

Applying Mn₂O₃ spreading deposition to one of two stove prototypes from "Nara" model of *Edilkamin*, the catalyzed one showed damped CO values with respect to the other one. Differential particulate weight was calculated from filters, inferring a slight reduction in soot concentrations and a marked decrease in carbon concentration. The main trouble arose when a third model, with a better deposition technique used, gave surprisingly negative emissions performance values with higher and denser peaks all over the measurement range.

Because the real model was not Nara, but one just similar, a different combustion development was speculated.

To deeply investigate the issues arisen for the previous CO trends, the possible affecting variability in gaseous phase is analyzed. Therefore, the following test dealt with two non-catalyzed stoves, structurally identical from two different production chains, a store and a fair.

The key point is that the reproducibility between two identical pieces of equipment is the basis to correctly assess performances.

Qualitative trends were very different, and this made not reliable the previous measures from comparison tests between catalytic and non-catalytic stoves.

These uncertainties and the asymmetry between CO and soot emissions' results seriously compromised the reproducibility of two stoves in terms of emissions: the catalyst performance therefore could not be evaluated by comparison tests. The problem of repeatability was faced adopting suitable internal procedures, considering the variables affecting more the combustion process:

- cochlea rotation and roughness;
- the feeding system slope;
- door and gaskets seal, responsible for air entering in the combustion chamber;

- shape and length of the feed air duct, a paper tube whose pressure drops determined the air inlet flow;
- internal fluid dynamics.

The most recent tests consider two versions of catalytic and non-catalytic pellet stove, with the same structure but different removable parts. Parameters like flue fan velocity and pellet cochlea rotation velocity were kept constant. Catalytic stove gave paradoxically worst performance than the non-catalytic case and the differences in the average values for soot and total carbon amount were negligible, showing no catalytic impact on emission reduction. The previously faced problems in reproducibility between different stove prototypes are still present and will be one of the main issues to solve, first looking for interesting configuration ideas in literature research.

Despite the effective improvement in terms of varnish recipe and mass transport and contact time issues concerning the catalytic aspect, the deepest and primary problem to face is the reproducibility between the behavior in different pieces of equipment, linked to the internal parameters affecting the combustion process inside the stove combustion chamber.

To face them and improve the precursors and soot abatement, literature research is carried out focusing on the state of the art for stove emissions reduction procedures and arrangements to better understand the strategies to scaleup this process at an industrial scale in the future.

1.2 Literature review

Solid heating fuels are mainly wood and coal, but can also include forestry, agricultural residues and even garbage. Domestic heating with wood and other biomass is still diffused in many countries in Europe and North America. Most of these fuels are burnt in small-scale combustion devices, such as household heating stoves and small boilers for single houses and apartment buildings. Despite the option might appear as ‘green’ and could contribute to climate change mitigation and energy security, different drawbacks are related to this. One of the first issues is that to be perfectly carbon-neutral wood fuel has to be harvested sustainably, but also completely converted into CO₂. Most fuel burning for space heating is incomplete, and some reasons could be: low combustion temperatures, suboptimal air circulation thus oxygen availability, firebox overloading with wood and moist biomass fuel. This results in relatively high pollutant emissions per unit of fuel, in particular CO, PM, NO_x, OGC but also PAH and PCDD. Black carbon (soot) from wood combustion domestic emissions is carcinogenic and could contribute to about 40% of outdoor air pollution (Bond et al., 2013). Short-term exposure to pollutant gases on individuals can be as harmful to health as particles from fossil fuel combustion: the main impacts related are respiratory and cardiovascular mortality and morbidity. In particular, infiltration phenomena could cause high exposure from own appliances and/or those of surrounding homes. Increasing outdoor PM concentration is shown to increase mortality and hospitalizations. The magnitude of the problem depends heavily on geography, the prevalence of solid fuel, and technologies used. Chafe et al. (2014) reported 61000 annual premature deaths in

Europe caused by PM_{2.5} (particles with a diameter lower than 2.5 µm) outdoor pollution in 2010, which was 55% worldwide related to wood and coal combustion for residential heating and the amount of European PM_{2.5} pollution was the 47% worldwide, with 21% in Central Europe only. This makes biomass fuel heating an important public health burden, not only in terms of health but also of healthy life-years lost. In a report from European Commission UNECE from 2014 different recommendations were provided to tackle this issue. First, any renewable energy or policy supporting wood combustion should consider air pollution impacts on global warming and health, promoting the lowest emission or at least the best available combustion technologies. Incentives to replace old heaters with new, retrofit and certified fireplaces were also encouraged to overcome limits like the cost of new technologies and the service life of appliances once installed. In fact, besides incomplete combustion other technological drawbacks could emerge, such as poor ventilation, back drafting and insulation infiltration in the fuel housing: most residential stoves and boilers in 2014 were relatively inefficient compared to the best models available for sale. Accelerated substitution of inefficient fuel burning with alternatives could result in a more efficient biomass combustion with mitigation of residential wood smoke (UNECE, 2014); certifications could come from the American Environmental Protection Agency (EPA). Fuel switching was identified as another promising measure, in particular replacement of coal chunks with coal briquettes and wood logs with pellets. Pellet stoves saw an important growth and installation in residential and commercial sectors in Europe, with a four-time increase in EU production from 2001 to 2009. Because they use processed biomass as fuel and some have also pellet-feeding systems that often run on electricity, they are considered cleaner than many other options: pellet gives a more efficient combustion, which releases fewer organic compounds and more inorganic salts. Pushing also on flat rate incentives as grants for buyers, the ideal scenario would be to have only pellet, gas and EPA-certified stoves (UNECE, 2014). To overcome coal or inefficient biomass, specific legal regulations for heating appliances with tighter limits from primary PM emissions, gas hydrocarbons and CO were considered crucial and were effectively developed with the 2015 Ecodesign Directive for energy efficiency and emissions. The requirements were referred to solid-fuel fireplaces, especially using wood logs, pellets and biomass bricks with the aim of selling more energy-efficient products and reduce the environmental impact of PM, OGC, CO and NO_x emissions. Specifically, from 1/1/2020 eco-friendly design has become compulsory for biomass boilers and from 1/1/2022 rules are extended for all solid fuel heating appliances with nominal heat output less or equal to 50 kW, like roomheater stoves, fireplaces and kitchen ranges (Ecodesign regulation, 2015).

Bindig et al. (2012) studied the behavior of a wood log stove aiming at a reduction of PAH and OGC. High emissions for such stoves during the start and the burnout phases were highlighted. In subsequent burning cycles, maximum concentrations of CO and THC appeared during heating up phase after refilling the stove, 1650 ppm and 1400 ppm respectively. After the 10 minutes high temperature combustion phase, smoldering lasted 15 minutes showing a maximum CO concentration of 3000 ppm, as in Fig 1.1.

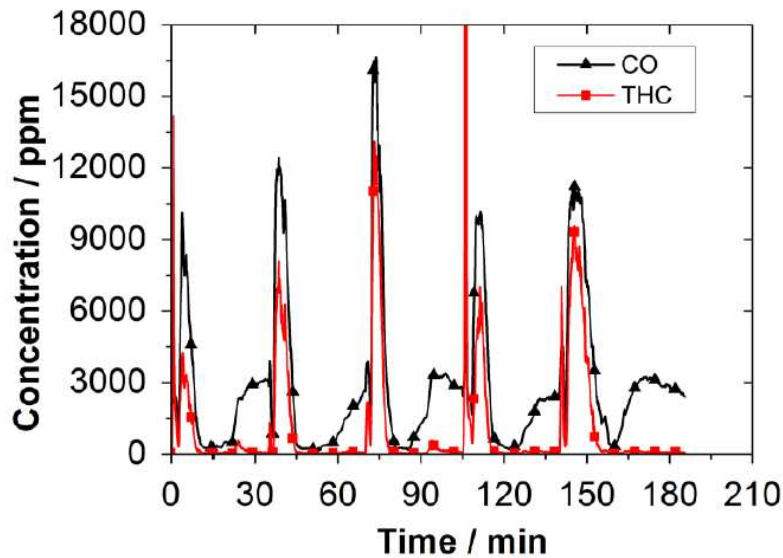


Fig. 1.1: Carbon monoxide (CO) and total hydrocarbon (THC) concentration in the exhaust gas during several burning cycles tests (Bindig, 2012)

To measure CO, CH₄, NO_x, SO₂, OGC and BTX concentrations FTIR spectroscopy sensors were chosen, while an FID was used for total OGC and a PMA100 for O₂. Particulate matter was determined by gravimetric method. Testing two selected catalysts based on noble metals, the highest reduction of 99.5% for CO was observed using a fresh knitted wire catalyst, while using a honeycomb catalyst the emission reduction was 89.1% for total hydrocarbons and 86.3% for aromatics.

Bensaid et al. (2012) analyzed a wood fired stove for domestic use where inside the stove chimney flue gases were monitored and kept hot by a flexible hose pipe to avoid condensation; moisture was measured by a hygrometer. The temperature was also sampled with a K-type thermocouple placed just below the gas sampling point, as shown in Fig. 1.2.



Fig. 1.2: Monitoring system of the temperature and the exhaust gases composition at the stove chimney (Bensaid, 2012)

Thermo-gravimetric analyzer was used to assess the PM composition, while the PM size and number distribution were measured through a SMPS: after two dilution stages achieving a dilution ratio with

air of 60, flue gases reach the SMPS, made up of an electrostatic classifier, an inlet impactor, a DMA and a particle counter. A wide range of diameters could be measured (3-10000 nm) and distributions were recorded as $dN/d\log D_p$.

As in the previous article, O_2 was measured by a paramagnetic sensor and an FID for total hydrocarbons. NDIR was used for NO , CO , CO_2 and SO_2 . It emerged that, at a 10% O_2 concentration and a GHSV of 3500 h^{-1} , a 6% loading of a perovskite catalyst $La_{0.9}Na_{0.1}CrO_3 + 2\%$ Au completely removed all CO and HC from the gaseous flow around $400\text{ }^\circ\text{C}$.

Paulsen et al. (2019) set a dedicated hood and exhaust experimental system to collect and direct a cookstove emissions to several pieces of analytical equipment, as in Fig. 1.3.

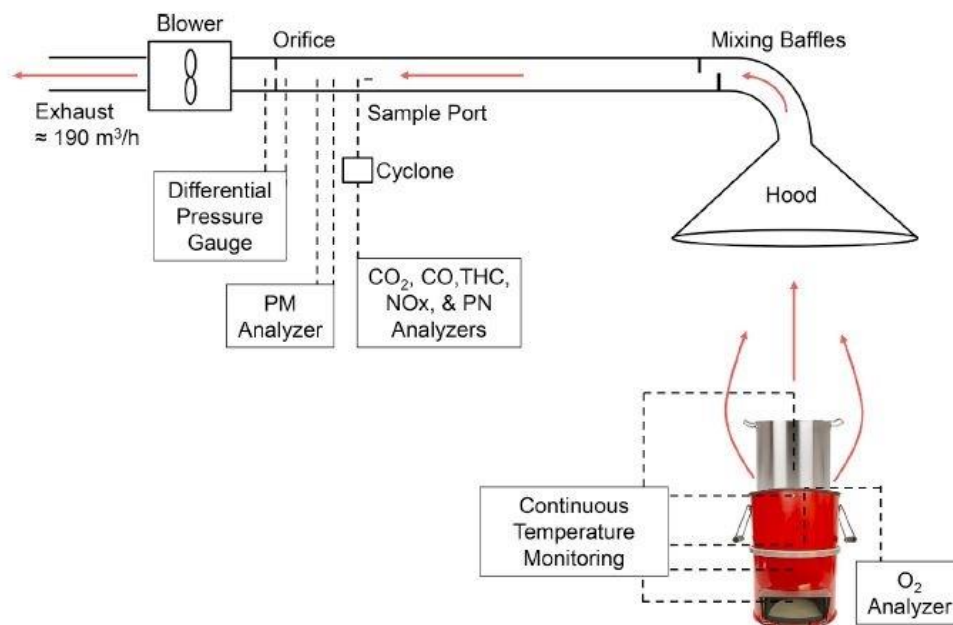


Fig. 1.3: Experimental setup with hood and exhaust system (Paulsen, 2019)

The hood was located above the rocket-style, improved cookstove, a blower maintained the flowrate constant through the duct, exploiting a choked orifice backed by a diaphragm vacuum pump. A set of baffles ensured a well-mixed emission sample and a sample probe led to the analytical equipment. PM concentrations were measured by a PPS analyzer while PN concentration by a Condensation Particle Counter CPC. NO_x concentration was measured through an FID analyzer, different from the one used for THC. The line included also a cyclone, to exclude coarser particles. Using a cordierite monolith to incorporate a potassium titanate catalyst within a cookstove led to a 36% reduction in particulate matter emissions relative to a baseline stove with a blank monolith. Additionally, the catalytic stove reduced particulate matter emissions by 82% and carbon monoxide emissions by 70% compared to a carefully tended, three-stone fire.

Kaivosoja et al. (2012) tackled the issues of sauna stoves, related to insufficient air supply and fast gasification, leading to incomplete combustion and emissions of CO , OGC , PM and PAH .

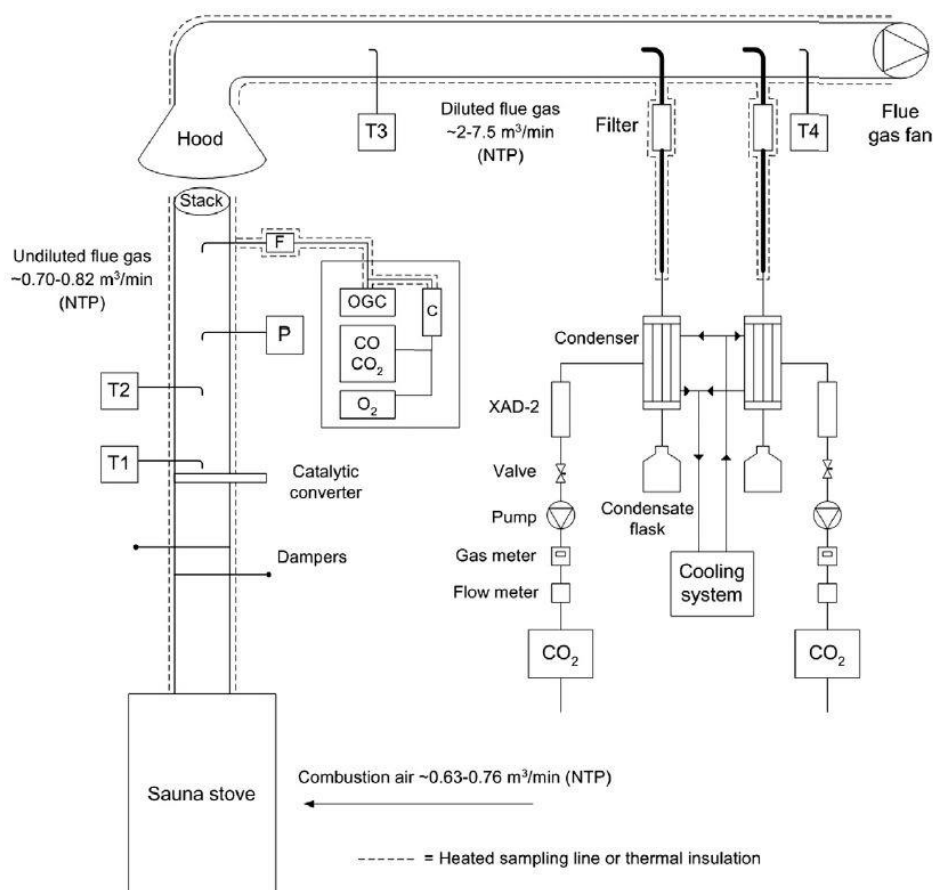


Fig. 1.4: test setup with thermocouples, pressure sensor, filters, pollutant sensors (Kaivosoja, 2012)

As in the scheme in Fig. 1.4, the flue gases crossed a heated stack and were aspirated by a dilution hood and draught was imposed by a set flue fan velocity. In both locations, heated measurement probes are present. In the stack line OGC, CO₂, CO and particulate matter were measured, while in the hood line PCDD/Fs, CPhs and PAHs system consisted in a glass probe, a filter holder, a cup-shaped filter, a condenser, and a condensation flask. A filter to collect the particulate compounds was placed inside the probe but outside the stack. After the particle collection the sample flow was cooled with the condenser. The flue gas stream was pumped through an adsorbent material to collect gases. Emissions are connected to the dilution ratio, calculated from CO₂ concentration of undiluted and diluted flue gas.

Total PAH concentrations were lower (on average 0.8-fold), and chlorophenol and PCDD/F levels were substantially higher (4.3-fold and 8.7-fold, respectively) when a Pd-Pt catalytic converter was used.

The emissions of another sauna wood stove were measured by Hukkanen et al. (2012) collecting samples from start-up to burnout phases within a combustion cycle. In the tests, natural draught was approached again by using a vertical stack with a hood equipped with a flue gas fan, as in Fig. 1.5. In particular, the focused phases are the gasification phase, with volatilization of hydrocarbons and high emissions, and the burnout phase, when the CO emission is typically high.

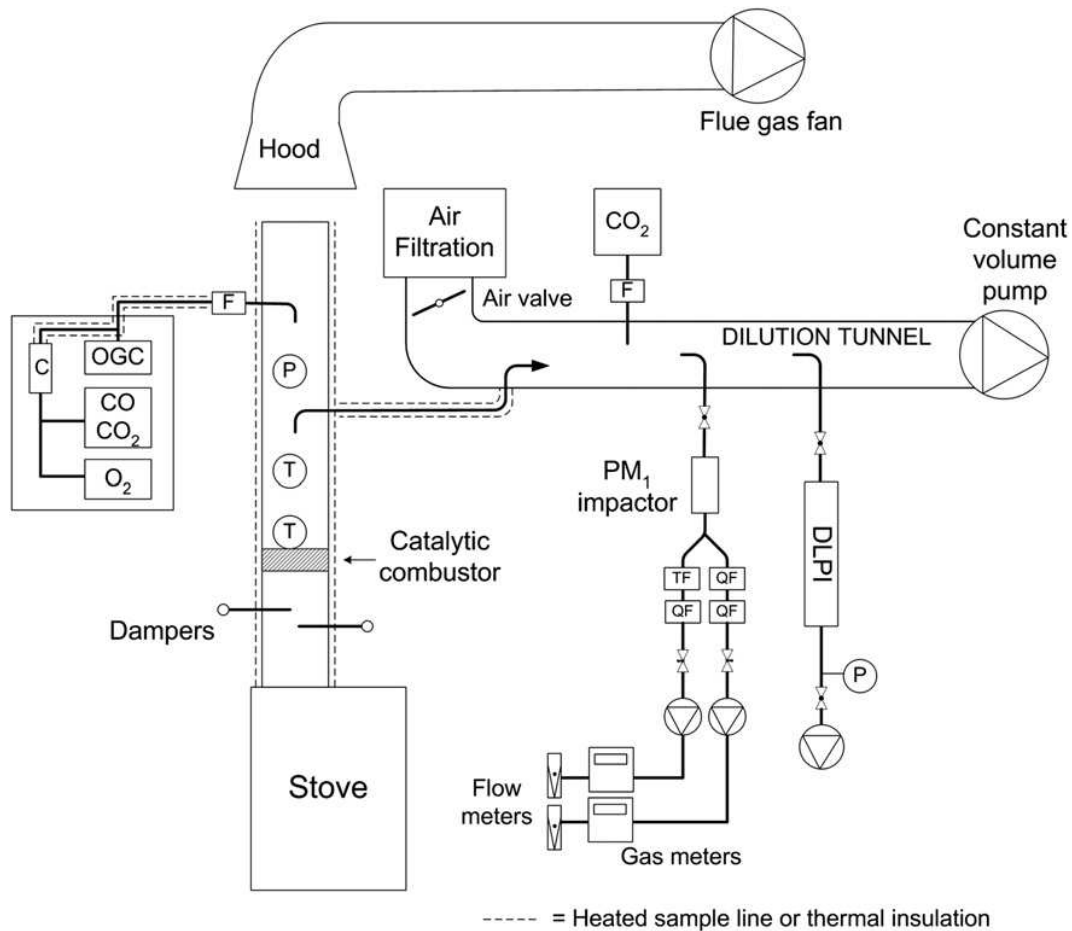


Fig. 1.5: measurement scheme with condenser, low pressure impactor, Teflon and quartz filters (Hukkanen, 2012)

With respect to the previous setup, here a partial flow from the stack crossed a heated steel tube to the dilution tunnel and air was filtered in three stages: a pre-filter for coarse particles, a chemical filter to remove hydrocarbons and a post-filter for finer particles. The particle mass size distribution was measured through a DLPI, separating particles to 13 different size fractions from 30 nm to 10 μm . PM samples for gasification and burnout phases represented average concentrations for the whole combustion cycle and were collected in quartz and Teflon filters after a pre-impactor used to remove coarse particles: elemental and organic carbon fractions from filters were analyzed by a thermo-optical method. CO and OGC concentrations in batch combustion were highest during gasification, and then decreased rapidly with time. CO emissions were also high during burnout phase. In smoldering combustion, particles size increased by condensation of OGC on particle surfaces. With a Pt-Pd metal wire mesh catalyst, reductions of 21% for CO and 14% for OGC were achieved during the whole combustion cycle. During the burn out phase, a reduction as high as 80% was achieved for CO. PM_{10} was reduced by 30% during the whole combustion cycle. During gasification, a 44% reduction of PM_{10} was achieved and the organic and elemental carbon analyzed from PM_{10} had reduced also only during gasification by 56% and 37%, respectively.

More recent publications dealt with the new Ecodesign legislation for solid fuel boilers in force from 1/1/2020 for biomass boilers. Caldera et al. (2016) studied methods to reduce emissions in a pellet boiler, with the advantage that primary measures involve combustion optimization and electronic control devices; in particular, the speed of the primary and secondary air fans and the rotation of the fuel supply cochlea were automatically controlled by the boiler.

PM concentrations were determined by a cascade impactor and after crossing a catalytic filter fine PM was measured by a PPS. The cascade impactor classified airborne particles into four size fractions: up to 10 μm , from 10 to 2.5 μm , from 2.5 to 1.0 μm , and particles smaller than 1 μm . The typical distribution of the particle fractions is in Fig. 1.6.

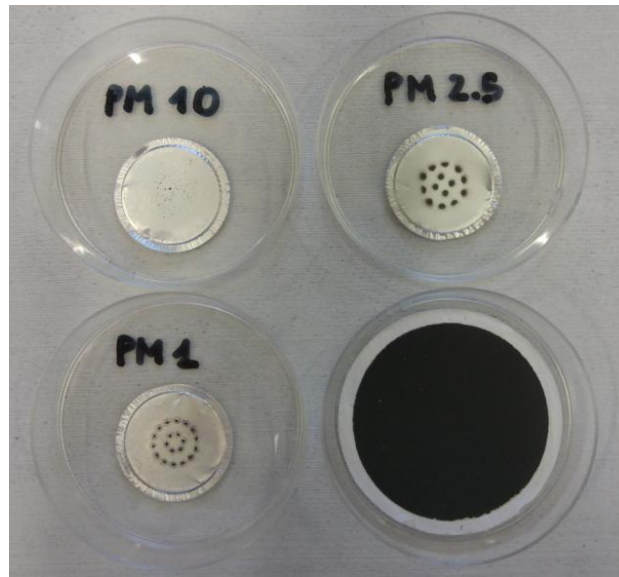


Fig. 1.6: particulate emissions particle fractions (PM_{10} , $PM_{2.5}$, PM_1) upstream the filter (Caldera, 2016)

The PPS is a real-time detector of the concentration of particles with an aerodynamic diameter up to 1 μm , in the range of concentration between 1 and 300 mg/m^3 . The forced draught in the exhaust duct and the pressure loss in the filter were measured by piezoelectric transducers. Tests were conducted using second-grade quality wood pellet and this affected the appliance operation, leading to a lower thermal performance and an increase in CO, PM and TOC. Exploiting wall flow catalytic filters with a SiC matrix with 20% wt of CuFe_2O_4 tests showed a high efficiency in PM reduction, by over 90%. Wohler and Jaeger in 2017 an 8-kW firewood stove from the German company GmbH. Firewood stoves are characterized by natural convection and as expected showed limited combustion quality with respect to automatically controlled systems such as firewood or pellet boilers. In order to meet the more stringent limits set by Ecodesign legislation two types of emission reduction measures are considered: primary measures result in a direct influence on combustion, while secondary ones have a post-combustion role. The measurement section installed above the stove is sketched in Fig. 1.7.

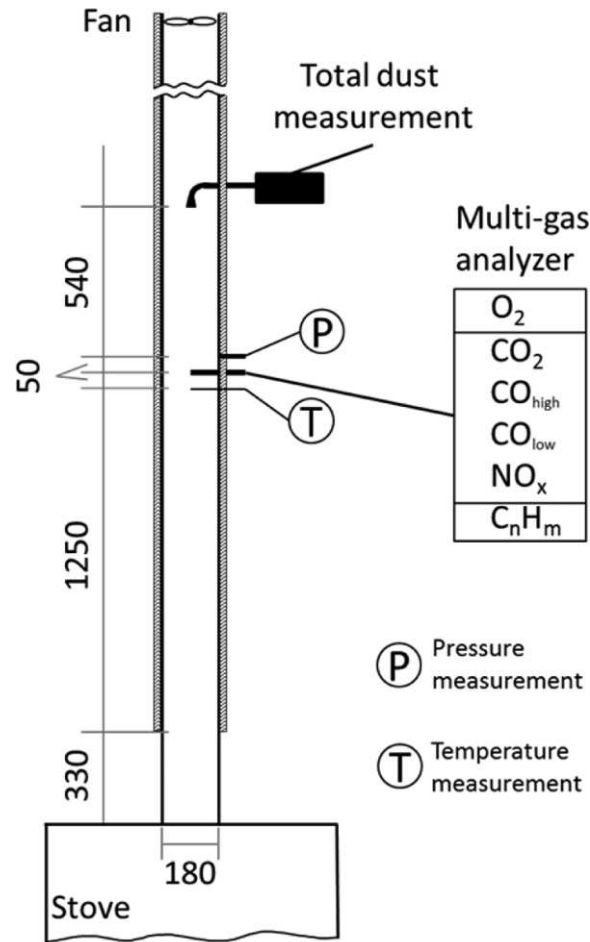


Fig. 1.7: Sketch of test setup (Wohler-Jaeger, 2017)

For gas sampling, the measurement section was equipped with a suction probe and a K-type thermocouple to measure exhaust gases temperature. An NDIR multigas analyzer was used for CO and CO_2 measurement, while O_2 was measured by a PMA and OGC with FID. The tube between the measurement section and the gas analyzers was heated to 180 °C to avoid condensation of hydrocarbons. PM was measured gravimetrically by using out-stack filtration in an undiluted flue gas stream. A filter was heated to 180 °C, and sampling was conducted by using a sampling nozzle. The total sampled mass was determined by weighing the filter with an analytic balance before and after sampling. Three emission control systems have been tested: a foam ceramic element showed no relevant emission reduction rates, while a noble metal catalytic-active coated foam ceramic element reduced the emissions up to 32% for CO, 61% for OGC and up to 41% for PM; finally, a noble metal honeycomb catalyst produced reduction rates equal to 73% for CO, 58% for OGC and 33% for PM. Reichert et al. (2018) faced the approaching of 2022 regulations for firewood operated room heating appliances, in particular the Emission Limit Values for CO (1500 mg/m³), OGC (120 mg/m³) and PM (40 mg/m³), seen as quite challenging to reach. Five commercial firewood stoves were tested in real-life operating conditions, including ignition and pre-heating. The measurement setup is shown in Fig. 1.8.

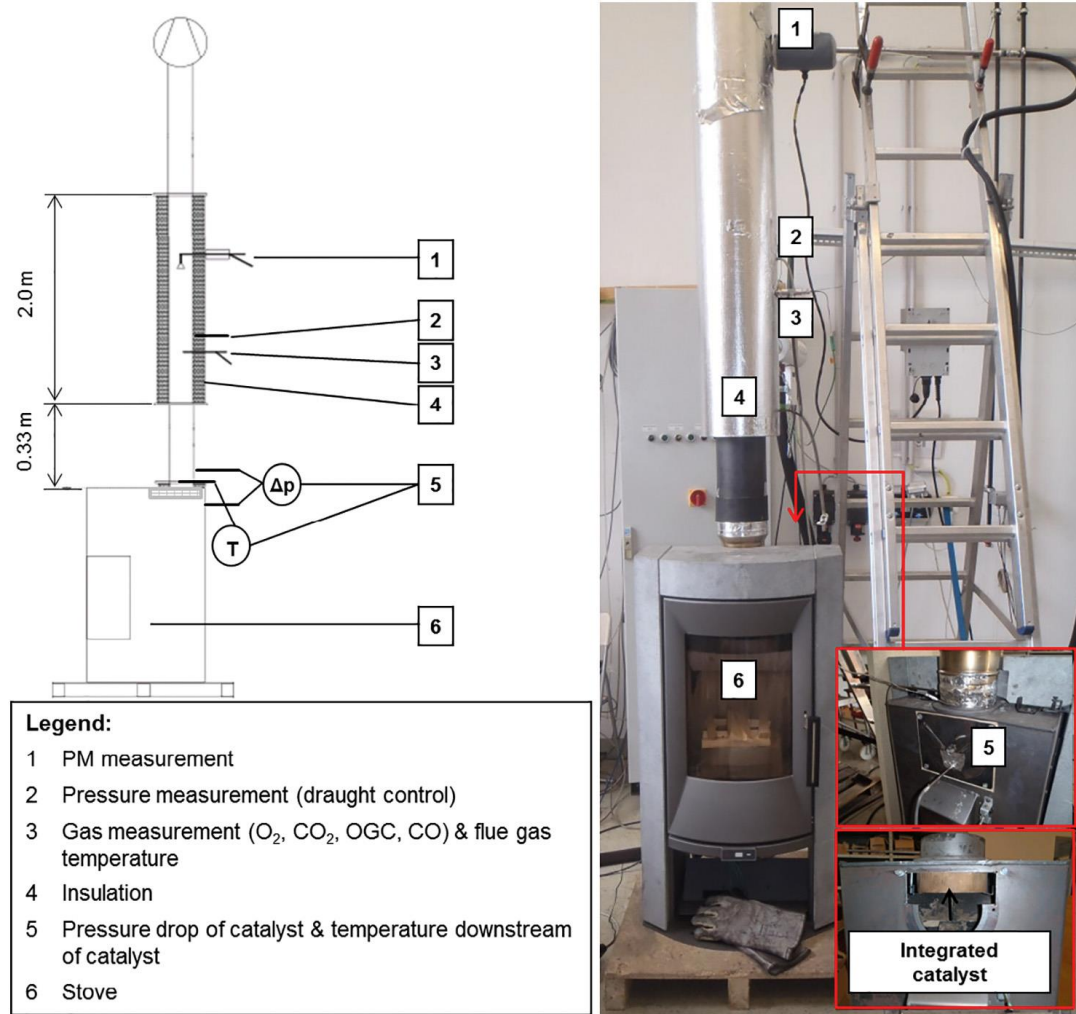


Fig. 1.8: schematic test setup (1) and example picture (2) (Reichert, 2018)

Each tests cycle consisted of five consecutive batches, starting from cold conditions with the ignition batch. The draught in the chimney system was constantly controlled during the whole test cycle. Temperatures, pressure drops and the gaseous composition (concentrations of O_2 , CO_2 , CO, OGC as THC) were measured continuously. The gas analysis was conducted with an NGA 2000 gas analyzer, while OGC were measured by an FID device. PM sampling was conducted gravimetrically by out-stack measurement in each batch, while for retention of particulate matter emissions quartz-plane filter and stuffed quartz wool cartridges were used. PM emissions were determined according to the particle mass on the filter and the sampled partial volume flow of the flue gas.

A Pt and Pd catalyst on a $\gamma-Al_2O_3$ washcoat was tested on metallic and ceramic supports: the CO emission reduction for the ceramic catalyst was 83%, while for the metallic 93%. The net emission reduction of OGC (~30%) and PM (~20%) was similar for both types of catalysts.

Klauser and Schmidl (2018) measured discontinuously TSP, TC, EC, OC and PAHs. After gravimetric determination of TSP concentrations, fractions of the filter samples were used for further analysis of TC, EC, OC, and 19 different PAHs. TC, EC, and OC contents were determined by a thermal-optical method. Nineteen different PAHs were determined by a standardized method for

aerosol samples consisting in coupling gas chromatography with a mass spectrometer. The same noble metal catalyst of the previous article was here examined with metallic and ceramic supports. The ceramic and the metallic catalyst led to distinct reductions of CO (−69%, −88%) and OGC (−27%, −39%). In the test with the metallic catalyst, TSP increased (+17%) and PAHs were clearly reduced (−63%).

One last paper from Matthes et al. (2017) aimed at reaching Ecodesign ELVs for wood-log stoves i.e., 1250 mg/m³ for CO and 40 mg/m³ for PM. Two types of heat exchangers were chosen a novel method to recover exhaust heat thus increasing thermal efficiency (Fig. 1.9).

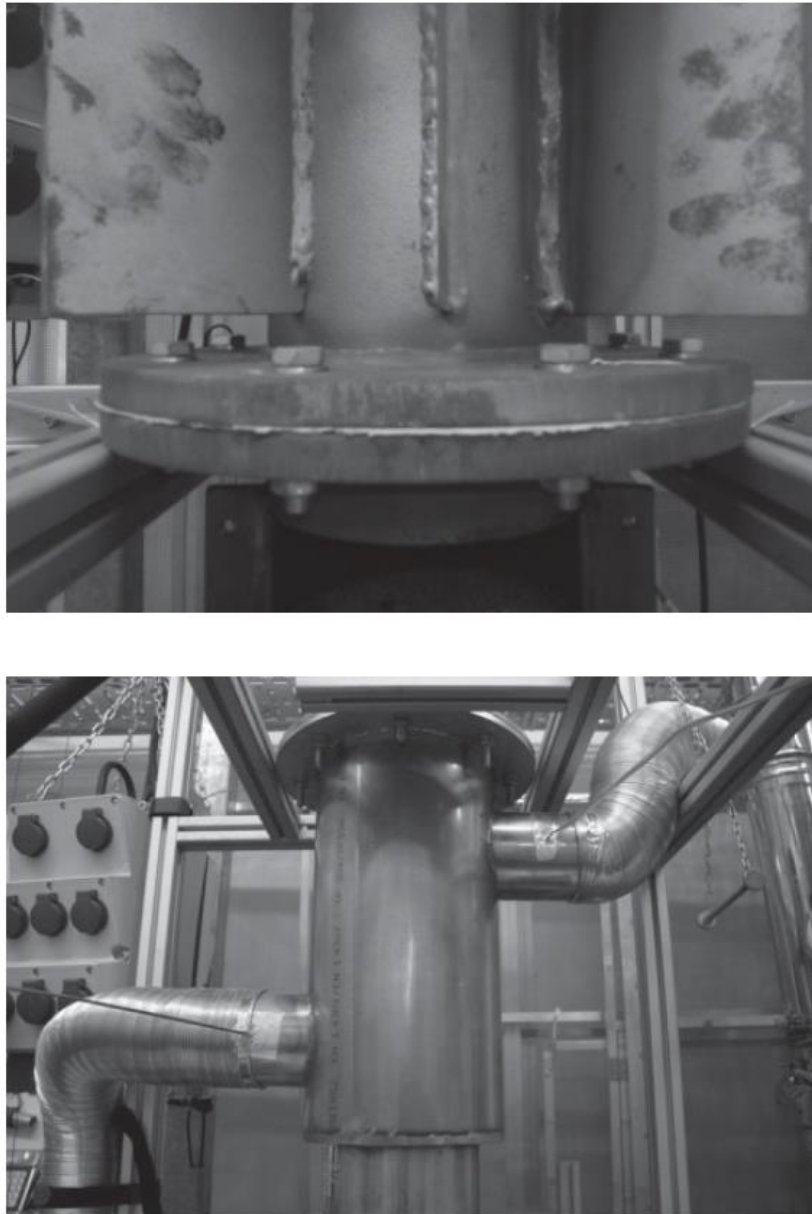


Fig. 1.9: heat exchangers exploited for tests: fin-tube heat exchanger (1) and heat exchanger with passing ambient air (2) (Matthes, 2017)

A fin-tube heat exchanger raised the surface area to increase the heat transfer, while a heat exchange with fan-driven circulating ambient air increased the transfer by a double-walled tube.

Assessing the differences of thermal exhaust gas losses for stoves' operation with or without heat exchangers, efficiency has been proven improved.

The integrated heat exchangers resulted in an efficiency increase between 5 and 19% with a variation dependent on the applied stove and heat exchanger. The reduction of CO, VOCs, and even PM was achieved with commercially available oxidation catalysts. The best results were observed for a metal honeycomb catalyst. The CO concentration was on average below 20 mg/m³ related to standard temperature and pressure and 13 vol% O₂, the VOC concentration below 100 mg/m³, and even PM was reduced below 30 mg/m³.

New Ecodesign emission limit values for pollutant compounds are summarized in Table 1.1. Because this Thesis work will focus on a commercial pellet stove, the section related to pellet appliances has been highlighted.

Table 1.1: recap of emission limit values for solid fuel heating appliances according to type, fuel and pollutant concentrations

Appliance type	Fuel	PM (mg/m ³)	OGC (mg/m ³)	CO (mg/m ³)	NO _x (mg/m ³)
Open fire	Wood	50	120	2000	200
Open fire	Smokeless	50	120	2000	300
Closed appliance	Wood	40	120	1500	200
Closed appliance	Smokeless	40	120	1500	300
Closed appliance	Pellet	20	60	300	200
Cooker	Wood	-	120	1500	200
Cooker	Smokeless	-	120	1500	300

Chapter 2

Equipment and measurement instrumentation

2.1 Edilkamin stove design and pellet

The piece of equipment used for this thesis is an Edilkamin pellet stove taken from a production chain of the series “Lena”. Its structure is one of the simplest among the diffused commercial versions, and in particular details are given for the crucible and the ash collector in the combustion chamber, the inlet air pipe, the igniter in the lighting box, the pellet hopper and auger (Fig.2.1).

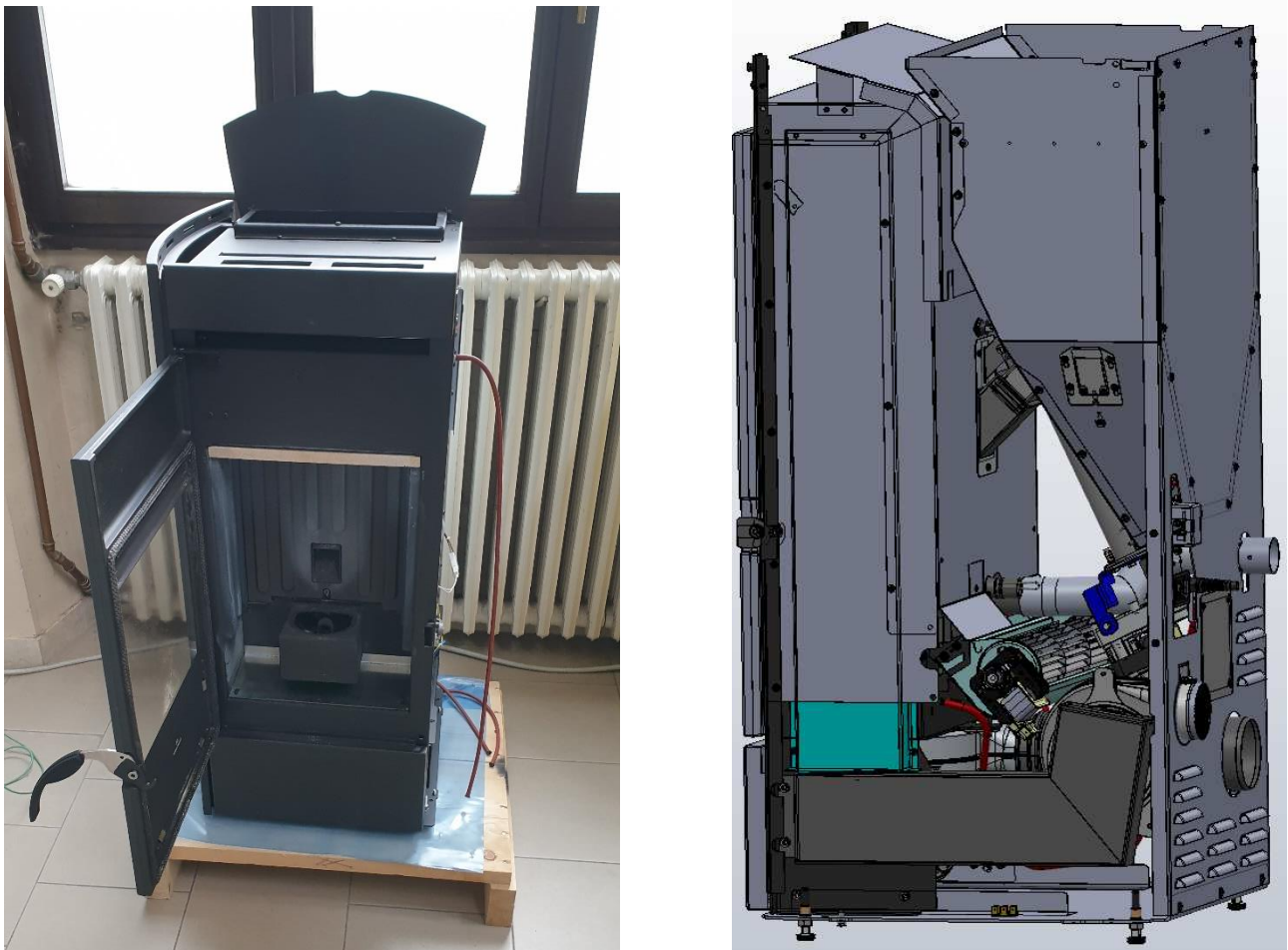


Fig. 2.1: picture of the analyzed pellet stove (1) and technical insights (2)

The oxidizing air enters from a rear inlet pipe and crosses a corrugated pipe, where a pressure drop measurement is taken through a differential sensor. The ΔP value will be proportional to the squared flowrate.

To measure the flowrate, there are four possible instruments:

- A Pitot tube
- A hot wire anemometer
- A known obstruction and a differential pressure measure at the two ends
- A Venturi meter, using the same principle if the obstruction.

The Pitot tube requires specific velocities to be measured, and here they are not adequate. The anemometer is very precise, but in a domestic application dust aspired with air could accumulate more and more and in a year the heating element could be irreversibly compromised. Moreover, if the measured ΔT results higher than a certain value, such as 100°C , the sensor does not work. A rigid metallic pipe has been chosen to ensure a constant obstruction. Because the interesting variable is the flow difference, the installer will provide dimensionless values for the calibration. What matters is the inlet mass flowrate, so the higher the temperature the higher will be the suction flowrate, because the lower will be the concentration.

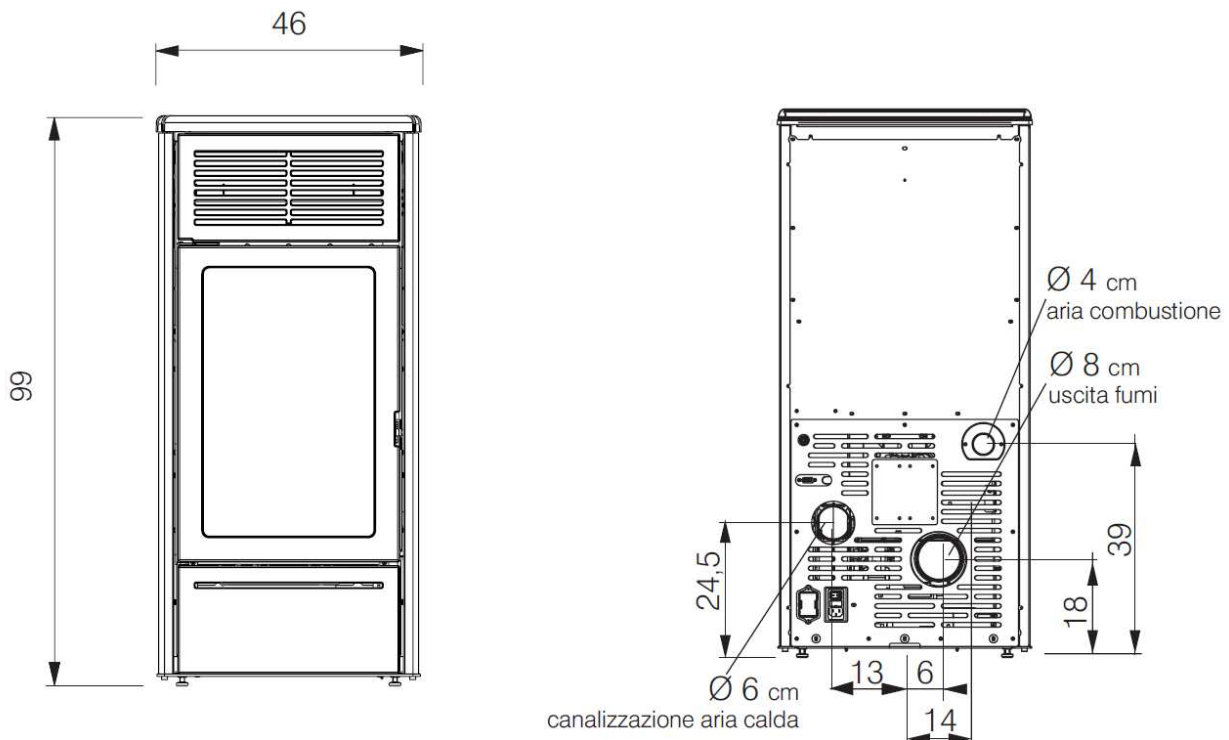


Fig.2.2: measures of the stove from the front side (1) and the rear side (2)

On the other side, pellet is loaded in a 22 kg charging hopper equipped with a removable safety grid, mounted to prevent entrance of bigger-sized objects, and a level sensor. If the sensor does not perceive an overlying weight the stove will keep working for 30 minutes before shutting down. The auger is the charging element, whose aim is to fill in the pellets and load them to the combustion chamber through a rotational motion. It is made up of a vertical Archimedes screw with a Hall-effect sensor with a phase-cut regulation system to control velocity. To avoid blockage from badly arranged pellets, smaller gearmotors are employed slightly increasing the drive torque, thus working at laminar conditions. Moreover, switching to brushless mode allows to have a torque even with slow rotation and to reverse the rotation direction, emptying and starting again the pellet charging.

Through a depression, ambient air is aspirated in the ignition box (Fig. 2.2) inside the combustion chamber where a ceramic heater is placed 1 cm inside with respect to the primary air hole. When the pellet covers the hole for a sufficient zone, despite the absence of a direct contact, the air flux starts increasing its temperature. This is because of an electrical resistance, fed with a 300 W supply and reaching 1300°C , so that the air flowrate entering the hole decreases, the cooling drops and the air has more time to heat up to 640°C , which is the pellet combustion temperature. Now, the combustion reaction can start with the first flame.

In the figure, crucible and ash collector are represented (Fig. 2.3). The combustion chamber has a wide glass door, the crucible is circular, giving a higher glass fouling but with better combustion conditions than a crucible with a long and narrow-shaped septum. In figure, the crucible is shown like a screwed pocket with an inclined septum, which will be even more inclined in commercialization to reduce soot deposition in the glass surface. Because the pellet tank is not insulated, another undesired air inlet flux could add to the primary one, causing issues on emissions and a split shape flame. In fact, more demanding customers require even a specific elegant flame shape during combustion, such as a slow and compact appearance. The ash collector collects the ashes from combustion and could be removed to allow temperature measurement through thermocouples fixed below.

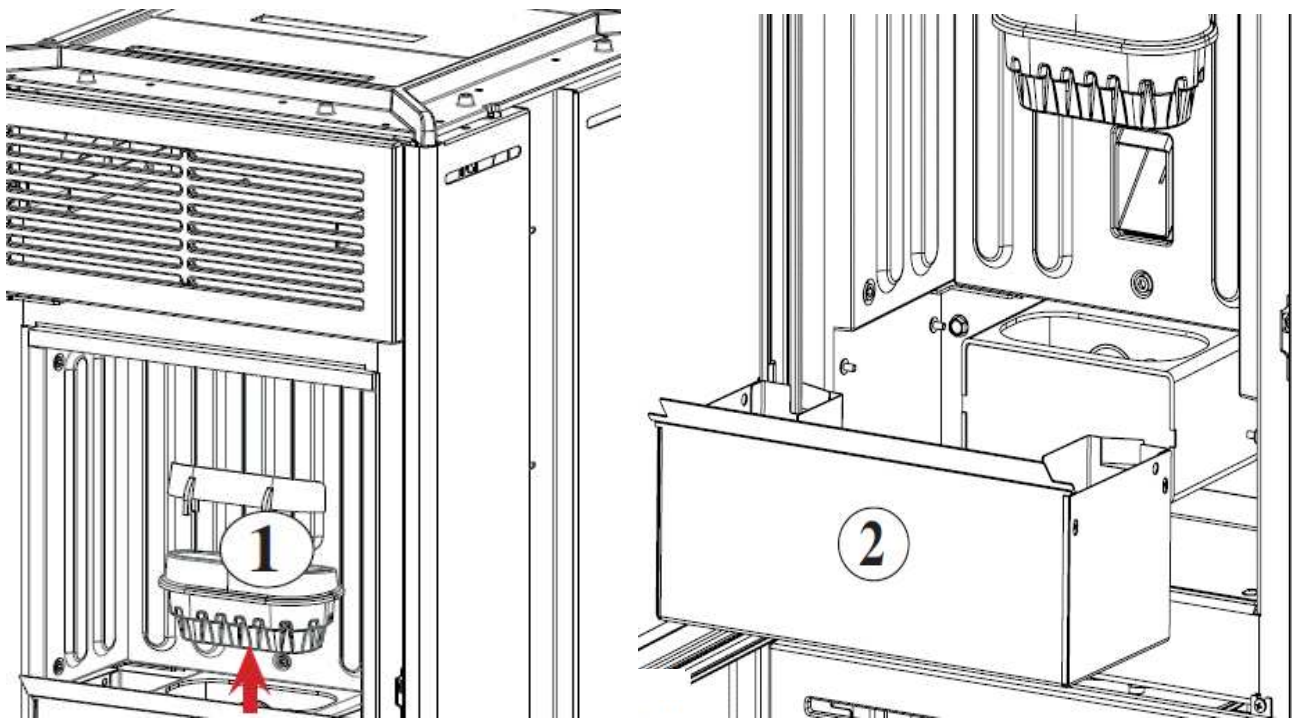


Fig. 2.3: stove crucible (1) and ash collector (2)

During the pellet combustion, flue gases are aspirated from the top through a depression generated by a downstream exhaust fan. They cross an S-shape path through the removable ceramic ceilings (Fig. 2.4), placed to help powder deposition and then they cross the rear side where they exchange heat with the secondary air to be fluxed outside, through cast-iron exchangers. These devices are made up of many waterdrop-shaped elements (Fig. 2.5) to increase the exchange active area and heating up the inlet air for the consumer.

The element profile was studied to have the maximum surface with the minimum pressure drops. The flue gases flow tangentially and countercurrent, heating up the air flux, moved by a secondary air blower. Two slabs are in contact and present the same shape. There are other negative and positive contributions to heat exchange, such as dispersions and radiation.

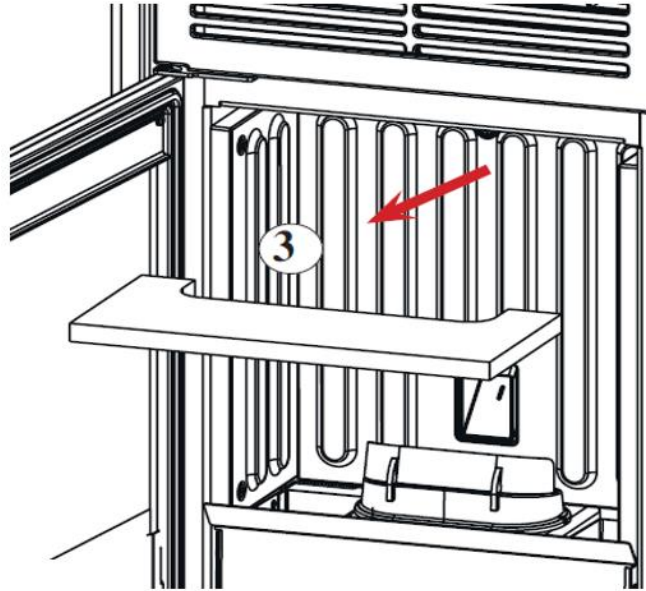
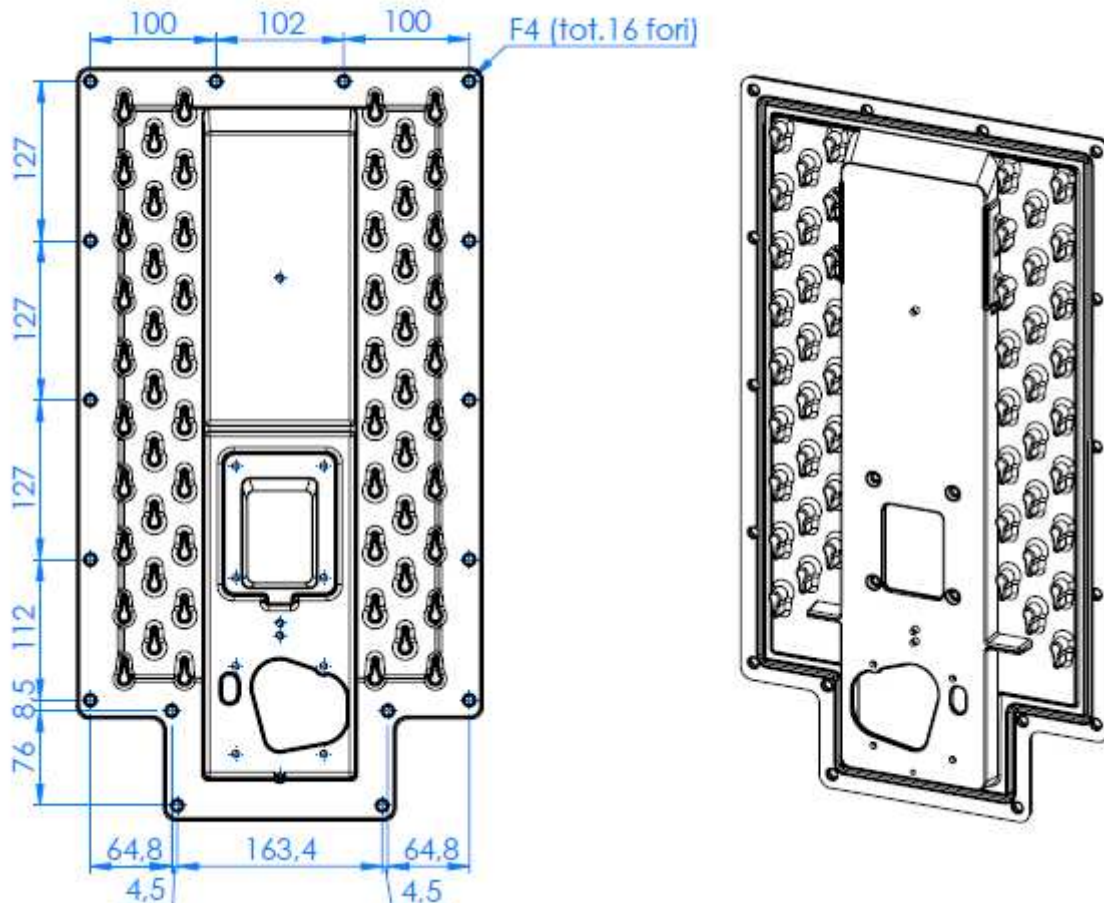


Fig. 2.4 stove ceramic ceiling



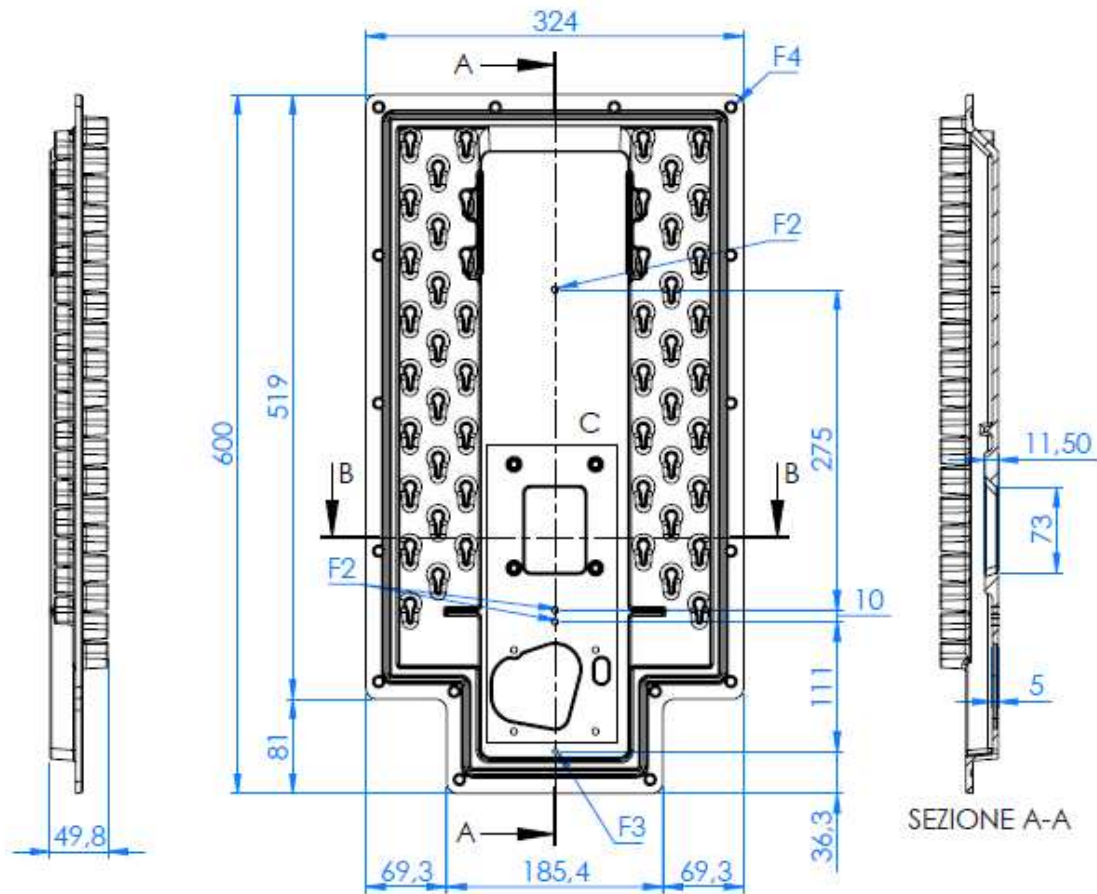


Fig. 2.5 waterdrop-shaped heat exchangers measures: front (1) and rear view (2)

The flue gases enter in an exhaust fan (Fig. 2.6) which depends on flue temperature and pushes the fumes outside the stove through a horizontal rigid tube and then a flexible aluminum pipe (Fig. 2.7). There are three possible temperature probes for each of the zones.

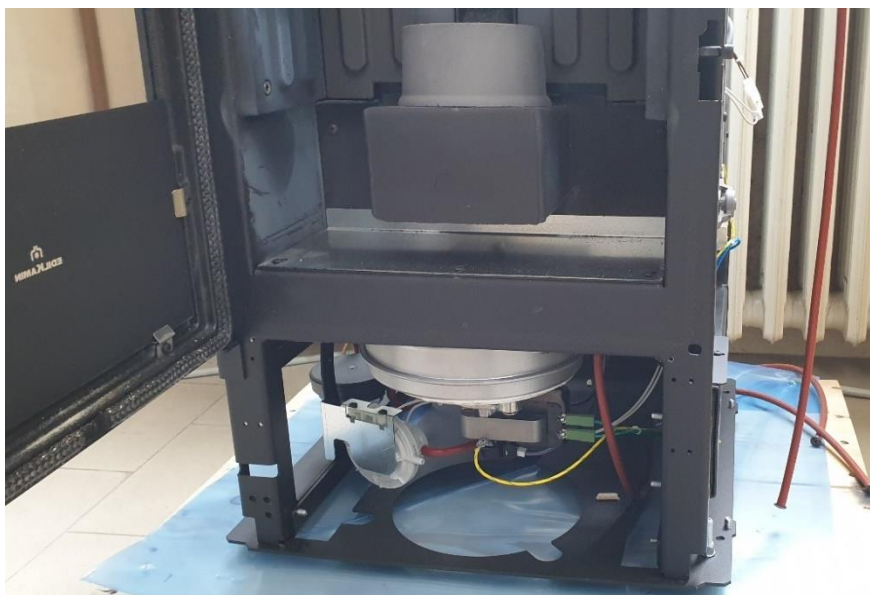


Fig. 2.6: stove exhaust fan detail

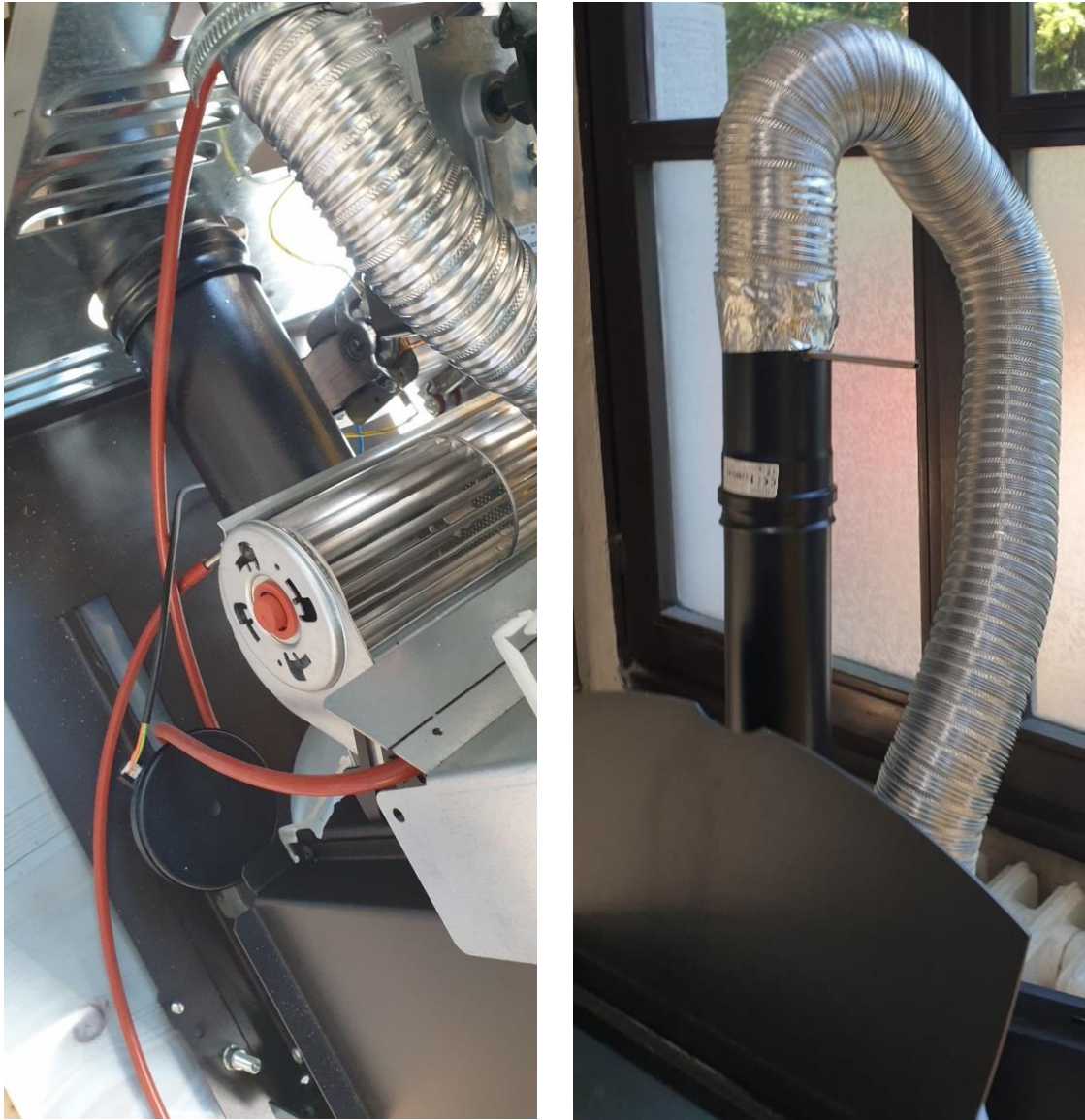


Fig. 2.7: rigid tube (1) and flexible aluminum pipe (2)

The user can manually set five different power levels, and the front vent (V1) and the suction vent (V2) should be adequate to those values, or the set could be done on the ambient temperature and the device needs to modify its power level to give that specific temperature value.

During ignition, temperature increases and if a ΔT of 10°C is not reached in the first 15 minutes and a ΔT of 60°C is not reached in the second 15 minutes, an alarm rings and burnout starts automatically. Beyond a certain flue temperature, the fan starts working automatically, and now that ignition has been overcome through the remote control the power levels are now three, and of course $P=3$ will be the maximum. Decreasing V2, the suction vent, influences the flue temperature decreasing it, acting like a power level reduction.

During the shutdown, pellet loading ends, fan drastically increases velocity, residue pellet is burned, the flue temperature gradually decreases and the functioning ends in about 7 minutes.

ARCOL[®] pellets are used for the experiment; they are fir pellets with ENPlusA1 certification AT303, whose charging and distribution are dealt by an Austrian company, GmbH (*Genol Gesellschaft m.b.H. & Co KG*[®]). Fir dry sawdust is compacted by pressing, without glues or other additives. The diameter is 6 mm, length spans from 10 to 25 mm, heat of combustion is 5.4 kWh/kg, and ashes percentage is below 0.7%.

2.2 Temperatures

To assess the temperature range and variations to specific operating conditions, temperature measurements in the stove are carried out considering K-type thermocouples (Fig. 2.9) to be inserted in the combustion chamber from the lower part of the stove opening.

An arrangement where the thermocouples were inserted through a top hole inside the combustion chamber was discarded because the presence of the lower ceiling for flue gases was a hindrance to correctly locate the sensors. The ash collector needed to be removed to allow the entrance from below. The set of thermocouples are then linked to a data logger (Fig. 2.8) which transmits the information to a program called Picolog, useful also to get electric signals from sensors, visualize the trends and extract the datasets for the subsequent plots.



Figure 2.8: K-type thermocouple (1) and Picolog data logger (2)

2.3 Flue gases concentrations

To measure the concentration of pollutants from the flue gases exiting the stove exhaust duct in the lab, an Alphasense[®] sensors line was installed; each sensor is specific for detecting a toxic gas, in this case carbon monoxide (CO), nitrogen oxide (NO), nitrogen dioxide (NO₂) and carbon dioxide (CO₂). CO, NO and NO₂ sensors are electrochemical sensors, while the CO₂ one is an NDIR, exploiting infrared radiation.

In the first case, the operating principle includes the presence of three parallel electrodes, generating a current directly proportional to the volumetric concentration of the analyzed gas.

The working electrode allows to optimize the gases oxidation reactions (e.g., CO, NO, H₂S...) or reduction (NO, Cl₂), favoring an intimate contact with the liquid electrolyte and the electro catalyst; a three-phase system is obtained. A potentiometric circuit keeps fixed the potential value of this electrode with respect to the reference one. The working electrode is the only one exposed to external air and it risks poisoning if in contact with the "interfering gases" for that sensor; these poisons can in fact inhibit the catalyst by direct adsorption or by reaction and formation of harmful by-products (e.g., NO₂ for H₂S).

The counter electrode compensates for the reaction of the working electrode with an inverse reaction on another component, thus generating an equivalent current in the opposite direction and a total redox-type reaction. Its potential depends on the concentration of the gas, hence on the consumption of the other component to compensate; the potentiometric circuit therefore supplies a current so that this electrode operates at the optimum potential value which can change, differently from the working one.

The reference electrode must maintain a stable potential, as it sets the potential value of the sensitive electrode to ensure its operation in the correct area of the current-voltage curve.

The reference will be the constant current zone because the sensor current can't change as the applied potential varies or due to minimal oscillations of the reference potential; this fact is due to the total control of the diffusive flow of the gas analyzed. At the two ends of this region, the kinetics of the electrochemical reaction will be controlled and therefore the trend will no longer be constant but exponential. In the plateau, the current is directly proportional to the concentration of the toxic gas in the external environment.

An NDIR (Non-Dispersive Infrared) sensor consists of an infrared source, an optical cavity, a dual channel detector and a thermistor. The light starts from the source and interacts with the gas to be analyzed diffused in the cavity before reaching the detector. The gases absorb the radiation at specific wavelengths, the absorption bands; the detector is made up of an active channel and a reference channel: the first is equipped with a filter that allows passage only to the wavelengths of the radiation that correspond to absorption bands; therefore, increasing the mixture gas concentration in the presence of the target gas, the signal will decrease.

2.3.1 Sensors arrangement and calibration

The first step was schematizing and setting the series connection line of the measurement sensors (Fig. 2.9).

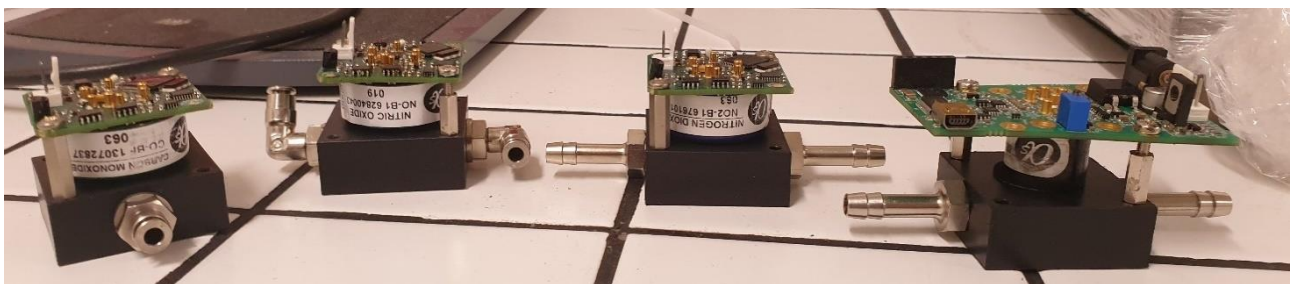


Figure 2.9: available sensors, from left CO, NO, NO₂ and CO₂

Because spacers resulted insufficient, some sensors were fixed with only two spacers at the corners, while the joints of the gas inlet and outlet lines would be later replaced with others equal to the CO sensor ones, with more mechanical stability. The power supply must deliver a potential of 12 V, while the resistance should ensure a moderate potential drop in the circuit to be processed, in this case 125

Ω ; there were no resistances with this exact value and the closest one was 127 Ω , so this resistance was coupled to another in parallel to have a total resistance of 125 Ω .

$$\frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{R_{tot}} \Rightarrow R_2 = \frac{1}{\frac{1}{R_{tot}} - \frac{1}{R_1}} = 7937.5 \Omega$$

8000 Ω was chosen, getting a tolerable error as it is less than 1%.

Each sensor will be connected to a Picolog Recorder channel, which will then be interfaced to the computer to read the potential values: once the calibration has been carried out, concentration values are deducible from potential ones. Each channel will have the corresponding GND, the reference to zero potential or ground. To communicate, the sensor will be able to set on the powered loop a current i , spanning from 4 to 20 mA. If the sensor does not detect, the value will be 4 mA, therefore the potential multiplying by 125 Ω will be 0.5 V, while the maximum will correspond to 20 mA (2.5 V). The GNDs are connected to the same base inside the Picolog.

The circuit diagram is shown in Fig. 2.10. Picolog measures only positive voltages, so the positive pole must be connected to one of the channels, while the same negative of the GND will be linked to the Picolog GND.

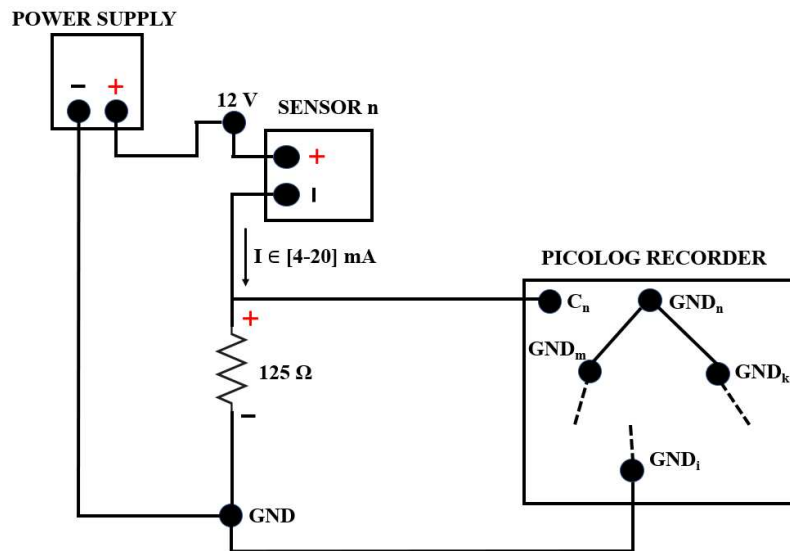


Figure 2.10: sensor connection diagram to the power supply and to the Picolog Recorder

Because CO₂ sensor has a double input with positive and negative poles (red and black) alternated, resulting in two GNDs. For each sensor there will be a channel, so four wires per channel, a wire for GND and the wire of the power supply circuit. The power supply and the "ground" with double wire have been reinforced sending one wire to channel 1 and another to the remaining channels. The power supply should not undergo current control (DC) instead of potential control and stay on the 12 V supplied.

Sensors need to be calibrated before installing the sensors' train under the hood to be interfaced with the PC.

Electrochemical sensors are pre-calibrated for immediate use but need to be recalibrated after a certain period of time due to wear or even at the end of their working life. This procedure requires to

connect the transmitter board to an interface and in turn to a computer with the related Alphasense® software. Calibration follows two subsequent steps, current calibration and voltage calibration.

2.3.1.1 CO sensor calibration:

The sensor is called CO-BF 50, with board identification number 04026 and selected range of measurable concentration [4, 5000] ppm. The sensor is exposed to a certain flow rate of CO and compressed air (inert to CO at ambient temperature) through flow meter lines: according to the manual, the minimum flow rate to be fluxed in presence of CO is 300 mL/min and the maximum 500 mL/min. A flow rate range exists because smaller values give minimal and hard-to-detect variations, while beyond the maximum value there are high pressure drops, therefore the output data can be misleading. Current calibration is performed only to assess if diffusive regime is controlling with the following steps: once the generated current reaches a value equal to or less than $0.25\ \mu\text{A}$, air at 300 mL/min and 0 mL/min of CO are sent to the sensor for 10 minutes to calculate the zero, the first useful parameter; the value obtained is $0.18\ \mu\text{A}$, which will be associated with the minimum value of the output current, 4 mA.

The second parameter is the span and from the range an intermediate value of 2500 ppm concentration is chosen. A total flow rate from the lines equal to 1000 mL/min with 0.25% CO concentration is divided into two flows at 400 mL/min at the sensor and 600 in the hood; the span results $177.01\ \mu\text{A}$ and will correspond to the maximum output value, 20 mA.

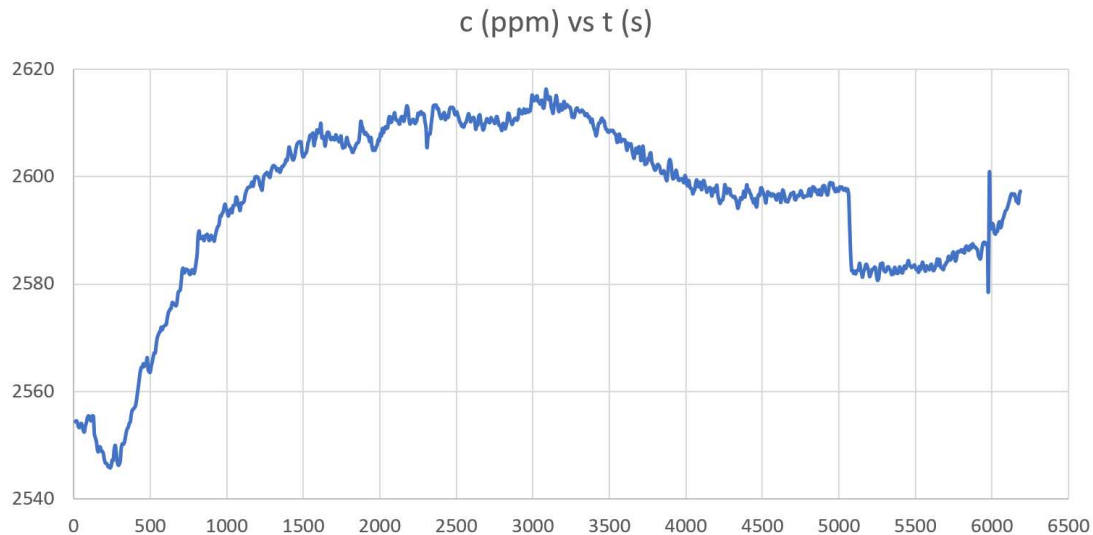


Fig. 2.11: CO concentration trend (ppm) vs time (s) plot

The concentration stabilizes after about 5000 s at about 2595 ppm and then has a sharp drop, reaching values next to 2580 ppm; the concentration-current curve is linear, confirming that diffusive regime is controlling (Figg. 2.11 and 2.12).

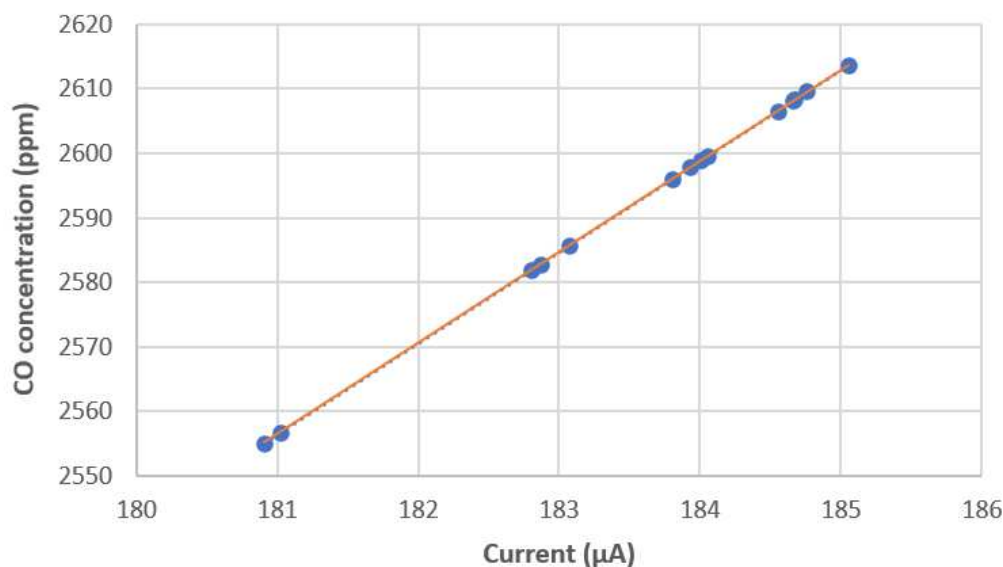


Fig. 2.12: CO concentration (ppm) vs current (μA) plot

The voltage calibration of the sensor can be carried out: zero and span in μA will have the corresponding in 4 and 20 mA, the minimum and maximum of output current; through Picolog these values need a conversion into potentials (V) to derive the potential vs concentration calibration line. The potential range will span from 0.5 to 2.5 V, while the layout will not change from the current calibration procedure, with a flow rate of 400 mL/min reaching the sensor.

A flow rate of 2.5 mL/min (0.25% CO) is initially set, giving a potential value of 0.95 V; however, the flowmeters oscillate for low flow rates, so this value will not be considered in the final concentration-voltage dataset. Fig. 2.14 shows the voltage points of the analysis against time in the blue curve and Table 2.1 sums up their values.

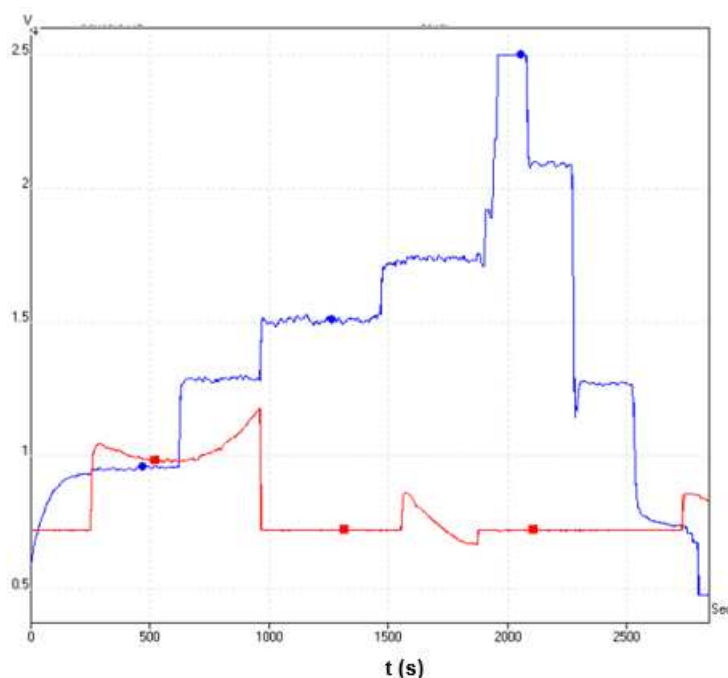


Fig. 2.13: CO sensor voltage calibration: voltage (V) vs time (s) plot in the blue line; red line is referred to another lab test, not linked to calibration

Table 2.1: voltage calibration dataset: %CO, CO and air flowrates and voltage values

% CO	CO flowrate (mL/min)	Air flowrate (mL/min)	Voltage (V)
0	0	1000	0.5
0.4	4	996	1.29
0.5	5	995	1.51
0.6	6	994	1.74
0.3	3	997	1.27
0	0	997	0.7
0	0	0	0.49

At 0.7% CO saturation is reached. With 0% CO and only air fluxed the potential value results 0.7 V, but should not be higher than 0.5 V: this denotes a vulnerability of the CO sensor calibration, which seems to be affected by saturation and therefore gives little sensible potentials at decreasing concentration values. The other potential value measured in those conditions is 1.27 V and corresponds to 0.3% CO; considering an offset of 0.2 V, an adjustment at 1.07 V value is chosen. The final dataset obtained is shown in Table 2.2.

Table 2.2: final voltage calibration dataset for CO sensor

V	% CO
0.5	0
1.07	0.3
1.29	0.4
1.51	0.5
1.74	0.6

The resulted calibration line is represented in Fig. 2.15 and its corresponding equation from fitting is $y = 0.4847x - 0.2323$.

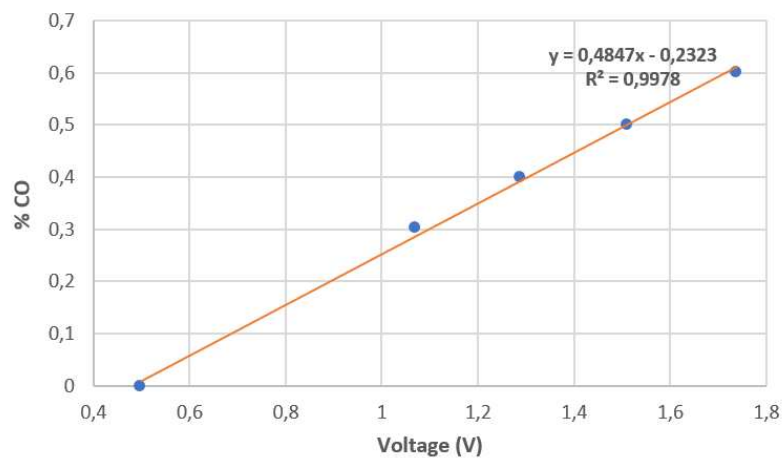


Fig. 2.14: calibration line plot with fitting (%CO vs voltage)

2.3.1.2 NO sensor calibration:

The NO sensor is NO-B1 25, with board ID 04030. NO cannot be taken as pure gas from the gas bottler, but only at 1% mixed with 99% of He. The usual zero is calculated by fluxing only air, while for to calculate the span several conditions are required. First, the sensor is set in the measurement range 0-250 ppm; an intermediate value, 100 ppm of NO, is chosen and will correspond to 0.01% of the total flow rate. Second, the maximum flow rate of the mix must be 170 mL/min. Third, the air flow must not exceed 1300 mL/min.

It is therefore decided a total flow rate of 1200 mL/min, with 12 mL/min of mix (1%) and the rest (1188) of air; the mix will in turn have 1% NO, 0.12 mL/min. The flow rate will be divided into 400 mL/min to the sensor and 800 mL/min to the hood.

Voltage calibration points are listed in Table 2.3.

Table 2.3: voltage calibration dataset for NO sensor

Air (mL/min)	Mix (mL/min)	NO (mL/min)	Voltage (V)	Concentration (ppm)
1188	12	0.12	1.16	100
1176	24	0.24	1.9	200
1188	12	0.12	1.16	100
2000	0	0	0.5	0

The plots with the trends and calibration line are shown in Figg. 2.15 and 2.16.

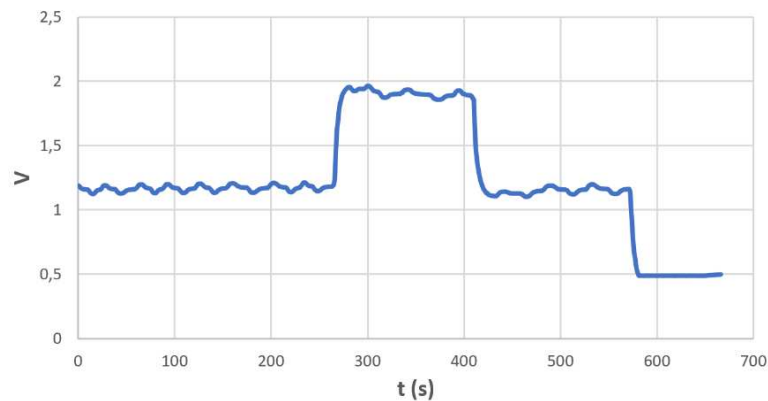


Fig. 2.15: NO concentration trend (ppm) vs time (s) plot

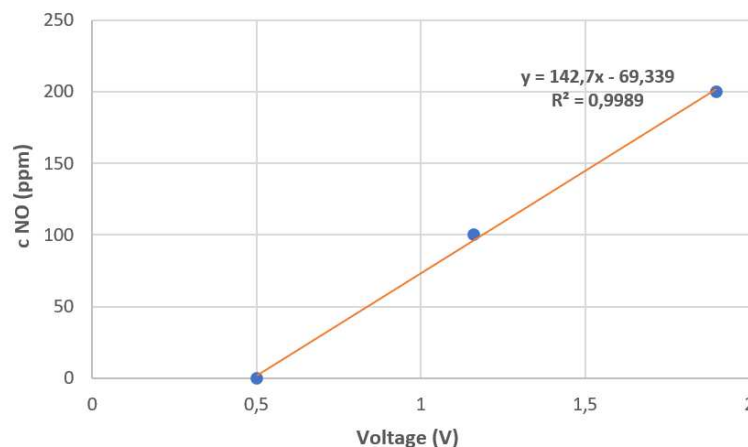


Fig. 2.16: calibration line plot with fitting (ppm NO vs voltage)

The relative equation, in ppm NO, is $y = 142.7x - 69.339$.

2.3.1.3 NO₂ and CO₂ sensors calibration:

The calibration of the NO₂ sensor is waived as it is not considered among the main pollutants to be analyzed in the exiting flue gases.

The CO₂ sensor (Fig. 2.18) is an NDIR, that is, it uses a laser beam emitted by a source, such as a lamp, and its interaction with the gas to return a signal linked to the concentration. It is of the IRC-A1 type and can be chosen from several concentration ranges, recommended according to the specific application: from 0 to 5000 ppm for low concentrations, from 0 to 5% vol for safety, rarer, from 0 to 20% for combustion, while from 0 to 100% for high concentrations, more common at an industrial level.

The relations are expressed by the following equations:

$$x = \left[\frac{\ln \left(1 - \frac{ABS}{SPAN} \right)}{-b} \right]^{\left(\frac{1}{c} \right)}$$

$$ZERO = \frac{ACT_0}{REF_0}$$

$$ABS = 1 - \left(\frac{ACT}{REF \times ZERO} \right)$$

$$SPAN = \frac{ABS_x}{1 - \exp(-bx^c)}$$

ACT is the signal from the active channel and REF from the reference channel, with 0 representing their value when the gas to be analyzed is not present; ABS_x is the absorbance at the calibration concentration value, x the concentration to be selected within the chosen range and b and c are linearization coefficients (Fig. 2.17).

Sensor	Gas	Range (SPAN Conc.)	Linearisation Coefficients		Temp. Comp. Coefficients		
			b	c	β_0	α	β_A
IRC-A1-IAQ	CO ₂	0 to 5000 ppm (4000 ppm)	4.1×10^{-4}	0.897	N/A	0.0009	0.0005
IRC-A1-Safety	CO ₂	0 to 5 % Vol (4 % Vol)	0.520	0.680	0.0021	0.0009	0.0014
IRC-A1-Combustion	CO ₂	0 to 20 % Vol (16 % Vol)	0.491	0.613	0.0024	0.0009	0.0020
IRC-A1-Industrial	CO ₂	0 to 100 % Vol (100 % Vol)	0.698	0.302	n.d	n.d	n.d

Fig. 2.17: linearization coefficient for CO₂ sensors

Initially, the voltage is maintained 3.27 V, when the indications would advise to fix 4 V. To start the current calibration, the sensor is exposed to a flow of air at 0% CO₂ and zero value is found 18904.

Now for span, 50% CO₂ (500000 ppm) is sent on a total flow rate of 300 mL/min, and a very unstable signal is obtained, with an approximate span of 10442 (Fig. 2.18).

The screenshot displays the 'EEPROM Configuration set to 1000000 PPM' window. It is divided into three main sections:

- EEPROM Data (Read Only):** Shows current sensor parameters including Gas Range (20%), Lamp (On/10/50), NDIR coefficients (T Cal: 20, Alpha: 0.0007, Beta: 0.0005, B coeff: -0.00176, C coeff: 1.63292, Offset: 16320, Span: 10314), Temperature (995/32767), and Voltage/DAC values.
- EEPROM Editing Template:** Provides a template for editing the EEPROM data with the same fields as the read-only section, but with values highlighted in yellow for editing.
- NDIR Calibration Calculator:** A panel on the right, outlined in red, used for calculating zero and span. It includes fields for PPM (476464), % CO₂ (47.6), CO₂ Act (244), CO₂ Ref (503), B Coeff (-0.03665), C Coeff (3.12609), NDIR Offset (18904), and NDIR Span (10442). Buttons for 'Start', 'Stop', 'Set Zero', and 'Set Span' are present.

Fig. 2.18: CO₂ sensor current calibration with software for zero and span calculation

In addition to the instability, it saturates for 100% concentration and the entire procedure needs to be repeated. Total flow rate has been changed to 100 mL/min divided equally between air and CO₂, but the instability remains: hence the cause is not the flowrate value but the sensor itself.

Next, the operating range is decreased, passing from [0, 100] % to [0, 20] %, calculating 32 mL/min of CO₂ in a total flow rate of 200 mL/min (16%), while the remaining 168 mL/min will be of air.

The resulting zero is 18357. Testing with a 10% concentration, zero is 18364 and considerable fluctuations in the signal are still present (Fig. 2.19), even for 5% and 20%.

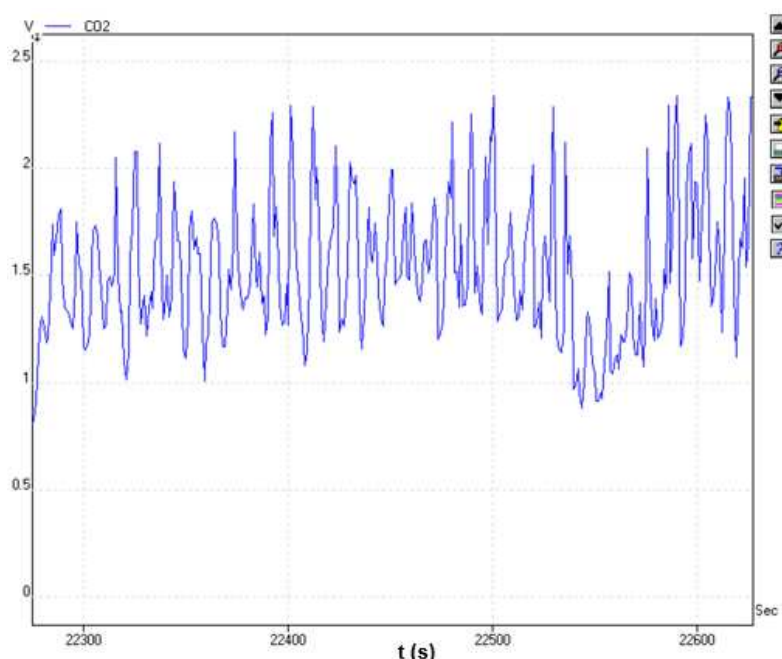


Fig. 2.19: voltage vs time plot, CO₂ sensor oscillations

It is then proposed to increase the voltage of the lamp, the source of the laser beam. The lamp is the most sensitive element of the system, it determines the errors on zero and span and is linked to the sensor working life. It is possible to proceed because the average life is 5 years, while the sensor has only 3 years. From Fig. 2.20, as the voltage of the lamp increases, the noise decreases considerably, but this also brings the drawback of reducing the working life. Mechanically, it corresponds to fix more the screw present in the CO₂ board, reaching 4 V as initially requested. Overcoming 5 V is not possible as the maximum limit is 4.38 V.

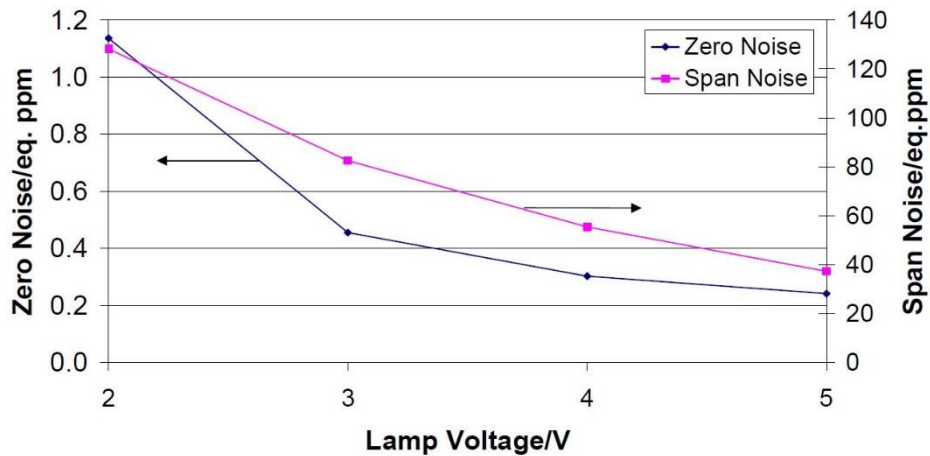


Fig. 2.20: noise plot on the calculation of zero and span, scaled on the concentration and voltage of the lamp

With 10% CO₂ at 4 V voltage, the calculated span is 9002. Now voltage calibration is started, the dataset obtained is in Table 2.4, with saturation at 2.335 V. Data errors are around +/- 30%, sometimes even +/- 50%, it was always tried to visually identify the average value around which the signal oscillated.

Table 2.4: CO₂ calibration dataset

V	% CO ₂
0,465	0
0,548	2
0,88	5
1,57	10
1,88	12
2,25	15

The following plot is obtained, excluding 0% CO₂ value.

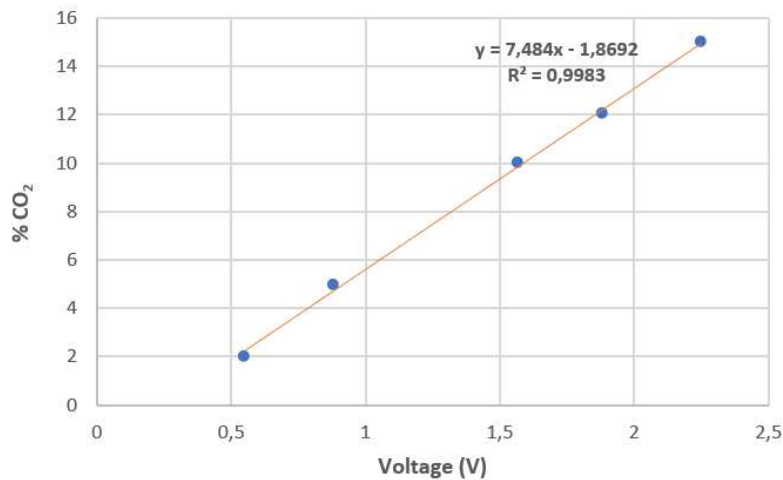


Fig. 2.21: CO₂ calibration line plot with fitting (% CO₂ vs voltage)

The final equation for CO₂ is therefore $y = 7.484x - 1.8692$ (Fig. 2.21).

An O₂ sensor is then purchased, getting a calibration line of $y = 12.038x - 4.7292$, where y is in % O₂ in the mixture. The final aim is the measurement of pollutants "in situ", carrying out several combustion cycles tests in the stove at different conditions.

2.4 Particulate matter concentration

To measure soot powders, an Optical Particle Counter (OPC) is employed (Fig. 2.22); it uses the principle of laser diffraction to measure both the number of particles and their size in real time, dividing them into particle size classes such as PM₁, PM_{2.5} and PM₁₀, i.e., with diameters of 1, 2.5 and 10 μm respectively. PM₁₀ will therefore have at any time a value greater than or at the same limit as the other two, as will PM_{2.5} with respect to PM₁.

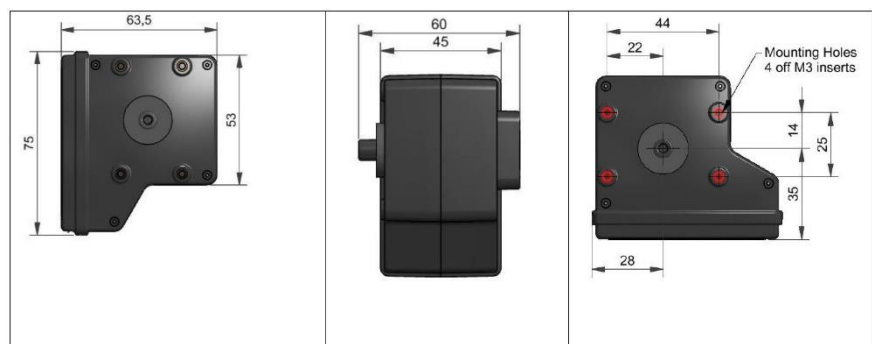


Fig. 2.22: Optical particle Counter (OPC): structure and sizes

The laser passes through the mixture and hits a mirror and then a detector: the number and size are determined from the angle of deviation with two basic hypotheses, namely spherical particles and included in the interval (0.35, 40) μm; the frequency is approximately one sample per second.

The OPC-N3 software allows to plot four different trends, in histograms: particles (#) per second (s) vs size (d), #/ (mL mix) vs d, #/s vs t and $\mu\text{g}/\text{m}^3$ vs t.

The maximum measurable PM_{10} is $1500 \mu\text{g}/\text{m}^3$, while the maximum frequency is 104 particles per second, avoided with the control on the suction fan, with a total flowrate of about 5.5 L/min, a portion of which does not go to the measurement in order not to saturate, the “Sample Flowrate”, in #/mL.

The moving average values of the real values are selected as they are considered reliable.

2.5 Inlet air velocity and flowrates

To understand the variation of the air velocity according to specific combustion conditions, air velocity is sampled through a hot-wire anemometer, placed in the rear inlet air tube. It is cooled by the air flow and, depending on the voltage variation, provides the speed value. The anemometer is positioned at a rear pick-up point (Fig. 2.23). The relationship between this variable and the depression will be further investigated.

Depression is measured with a pressure difference between an intermediate obstruction, which must be kept fixed for the calculation, for which a rigid and not very deformable metal tube was chosen to allow measurements considered valid; if the air is hot, having a lower density and needing to keep the massive flow rate constant, the volumetric flowrate will increase, hence the suction.

The flowrate of gases feeding the sensors has been superimposed by inspiring and splitting a part of the flow in air, through flowmeters regulation by opening at a suitable degree. The typical gas flowrate is 0.5 L/min, chosen not to compromise sensor calibration, avoiding peaks and noise in the measurement.

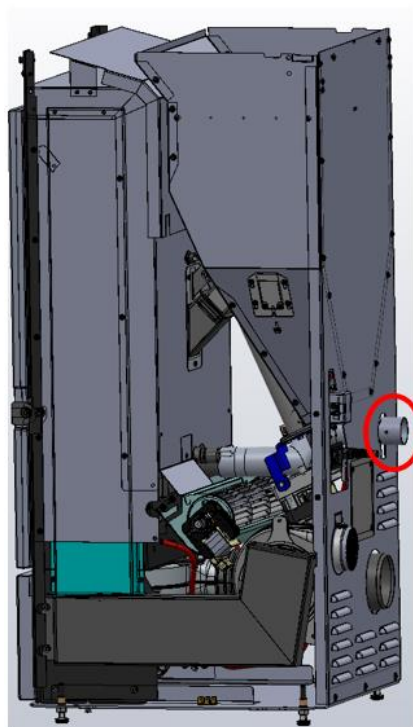


Fig. 2.23: stove air inlet pick-up point

2.6 Edilkamin software parameters

Thanks to “HTool” software, it is possible to monitor in real time the progress of about 600 variables in the same combustion cycle in the stove. Proceeding by exclusion, the most important seem to be "Flue fan velocity", "Cochlea speed", "Air depression" and "Flue temperature", while other possible ones to be considered perhaps for future tests are "Room temperature 1", "Board temperature", "Exchanger" and "Cochlea set".

Chapter 3

Results and discussion

The obtainment and study of the thermal map inside the combustion chamber and the values of pollutants' emissions compositions in the flue gases are both of prominent importance to determine the best operating conditions and parameters for the pellet stove functioning.

In the first case, thermocouples fixed and placed at various spatial locations inside the chamber are aimed at mapping temperatures as close as possible to the walls, both side and rear ones. Each test requires to set two or three thermocouples at different positions and to modify different variables: front fan, suction fan, and power level. Temperatures are analyzed in three steps for every single condition: starting from acquired profiles, histograms with a suitable number of classes to detect an eventual main behavior in statistical distribution have been plotted. Then, compact plots comparing mean and standard deviations for different fan velocities considering the same test thermocouple have been carried out as a final step.

In the second case, CO, NO, NO₂ (just the trends) and CO₂ compositions values have been measured by the sensors and acquired to identify their trends and relative behaviors profiles changing various variables: the main one is power, set and modified in "Manual" mode to identify specific variations mainly in parameters like cochlea rotation speed and fan velocity. Other variants require studying emissions variations at conditions such as short pellets load (2 cm long maximum), humid feed and all-day running (approximately 8 hours).

3.1 Combustion chamber temperatures

In a first test, K-type thermocouples are preferred to the N-type, while platinum ones are much more expensive. K-type ones will be confirmed for all the following tests. During previous cycles in lab thermocouples have been inserted through a front top-left hole above the sealing surface, not to compromise the adherence in closing the glass door.

It is crucial that thermocouples stay suspended, so they can reach a maximum temperature of 800°C inside the combustion chamber. A contact with cast-iron walls would rise the temperature up to 1000°C, threatening the measurements' reliability and the thermo-mechanical stability of the temperature probes, most likely due to their width.

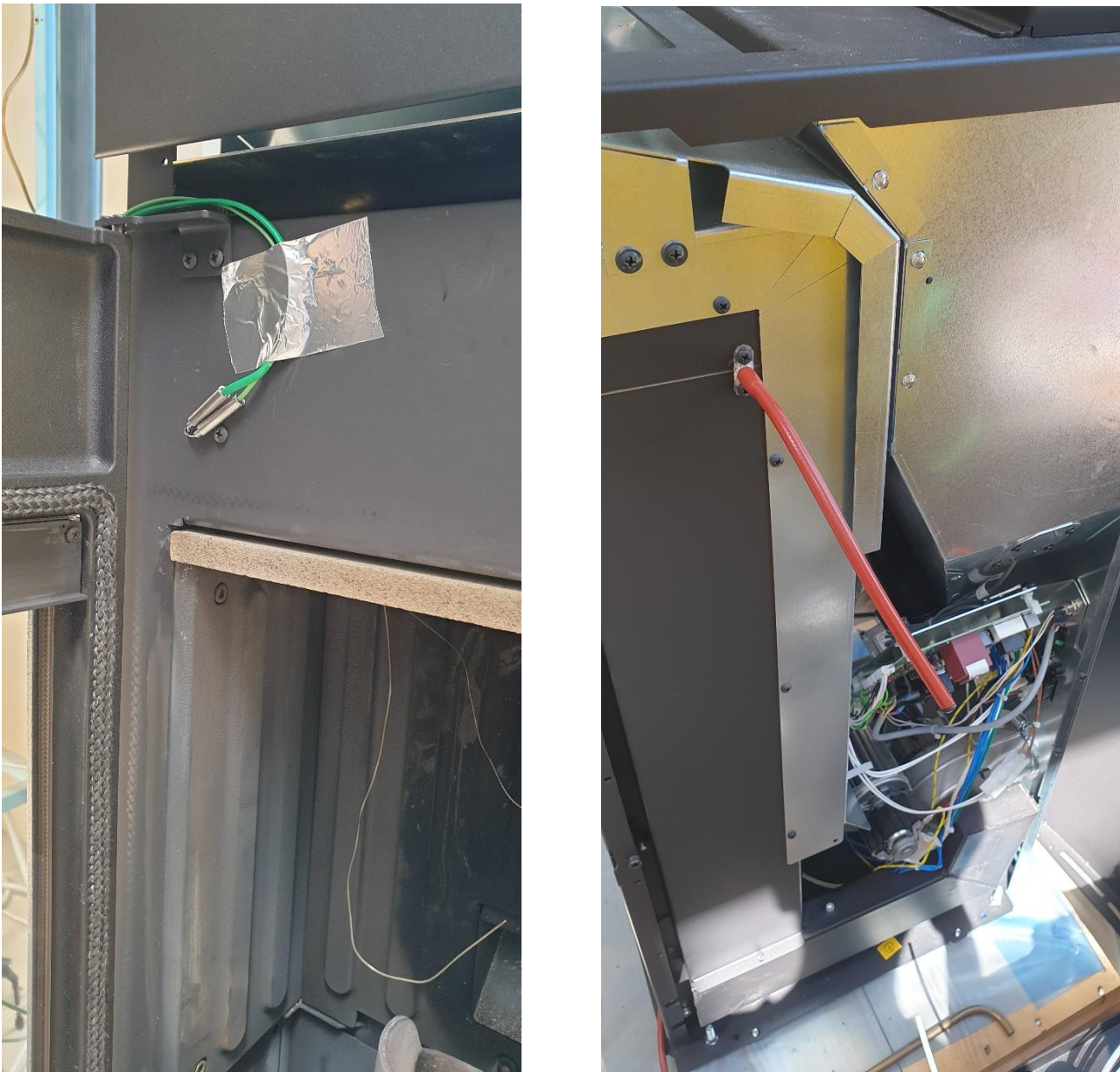


Fig. 3.1: first temperature lab test: two thermocouples inserted through a top-left inside the combustion chamber (1) and example of temperature probe (2)

Temperature probes are temporarily inserted not only inside the chamber but also in other pick-up points by fixing the probes on one side and connecting the data-logger on the other. In particular, the other three zones considered are shown in Fig. 3.2:

- below the chamber (0.25-0.3 m distant), next to the fan box
- in the pipe before the vertical exhaust duct (0.3 m before the pipe elbow)
- inside the vertical aluminum duct. (1.2 m high with respect to the horizontal tube)

The exit flue line, made up of rigid aluminum pipes, is connected with an aluminum scotch to another flexible aluminum duct which conveys the gases to the outside air, to avoid permanence of pollutant

compounds in a closed environment. When the stove will be moved to another lab, the destination will be a fumes hood.

The pellet tank level sensor answers to a pressure input and it does not allow stove ignition if it does not perceive a minimum weight above.

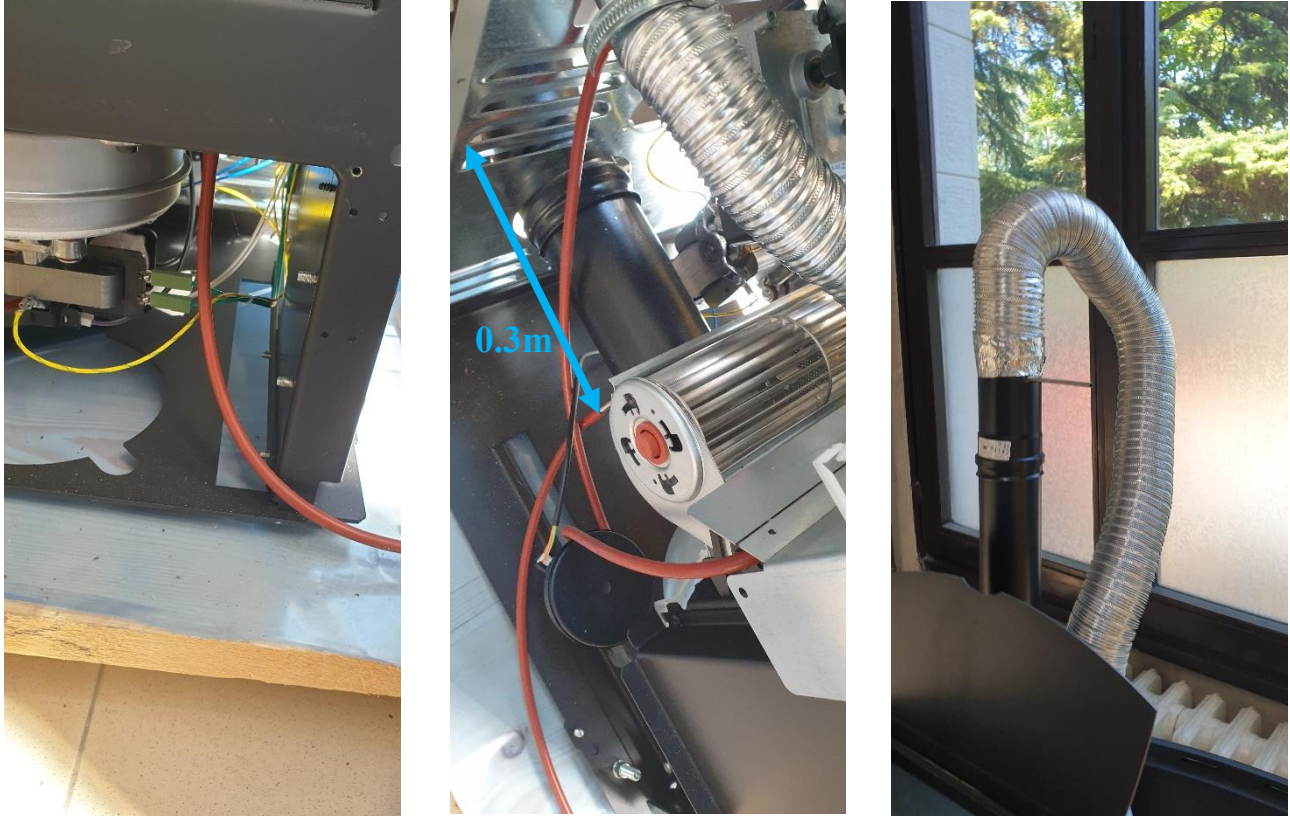


Fig. 3.2: first test, external probe zones for temperature measurement: below the chamber (1), flue line before pipe elbow (2), at the flexible duct inlet (3)

Thermocouples are placed as observed: two of them are inserted in the combustion chamber, one next to the crucible (about 0.1 m from its base), the other one at the flue exit from the chamber, right below the lower ceiling.

The other three measure the temperatures of the flue gases, as in Fig. 3.3.

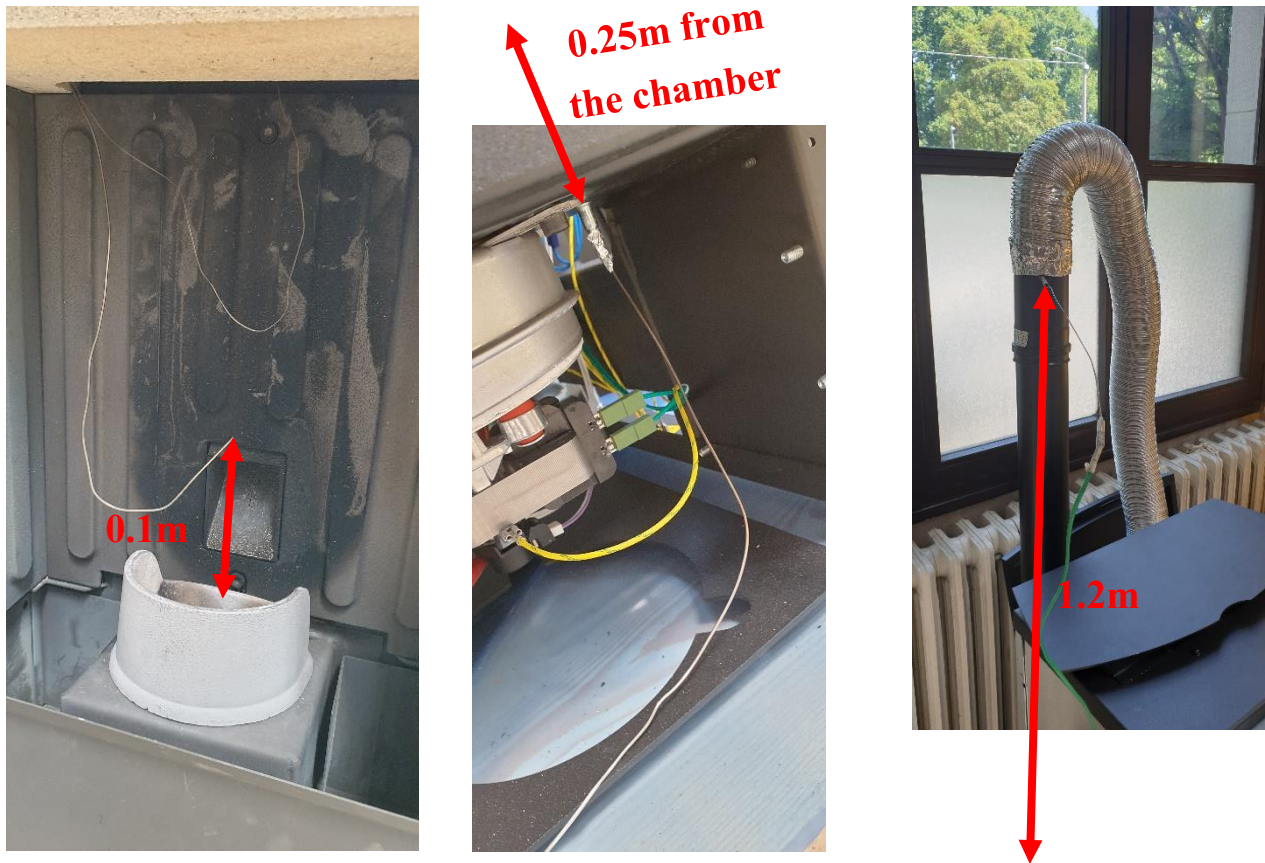


Fig. 3.3: example of thermocouples placed for the first temperature test: next to the crucible inside the combustion chamber (1), next to the fan box and the chamber (2), at the flexible duct inlet (3)

Thermocouple signals are connected to a data logger and an acquisition program named “Picolog”. The main aim of this test is first of all running a whole combustion cycle and determine the times for ignition and burnout phases. Second, front and suction fans’ velocities are also modified at different power levels set by a remote control.

The thermocouple near the crucible is referred as T_1 , while the one next to the lower ceiling is named T_2 . Ignition phase is plotted in Fig. 3.4.

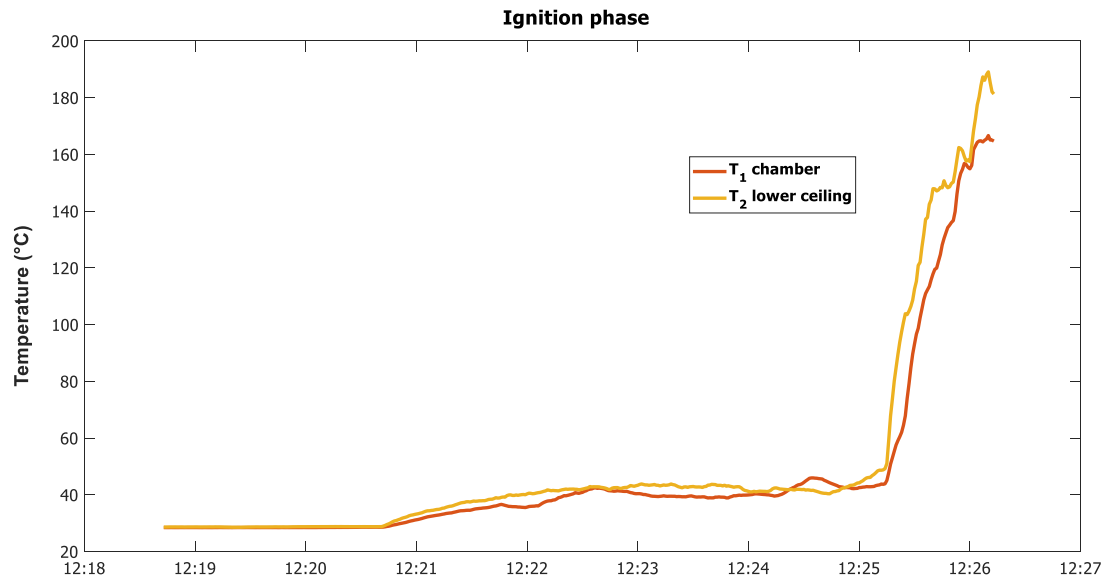


Fig. 3.4: pellet stove ignition phase temperatures measured by two thermocouples inside the combustion chamber

In this plot it is possible to distinguish three phases: in the first one, lasting 2 minutes, temperatures are constant and equal to ambient temperature; in the second one, of about 4.5 min with no fire, it slowly increases to $T_1 = 44^\circ\text{C}$ probably due to the radiation heat transfer from the ignition resistance; the third one sees a steep increase up to $T_1 = 175^\circ\text{C}$ and $T_2 = 190^\circ\text{C}$ in less than 1 min due to the beginning of pellet combustion. T_1 and T_2 are closed to each other in this first phase and T_2 value becomes even greater with a maximum temperature difference of 35°C : this is because in the first minute of combustion temperature gradients inside the chamber have not stabilized yet.

Initially, the front vent (V1) is off to ensure the best conditions for ignition, by holding heat and therefore accelerating the process. Once the flame appears, heat will be dissipated externally to avoid thermal accumulation thus overheating, and V2 vent must be kept at the maximum value, 5.

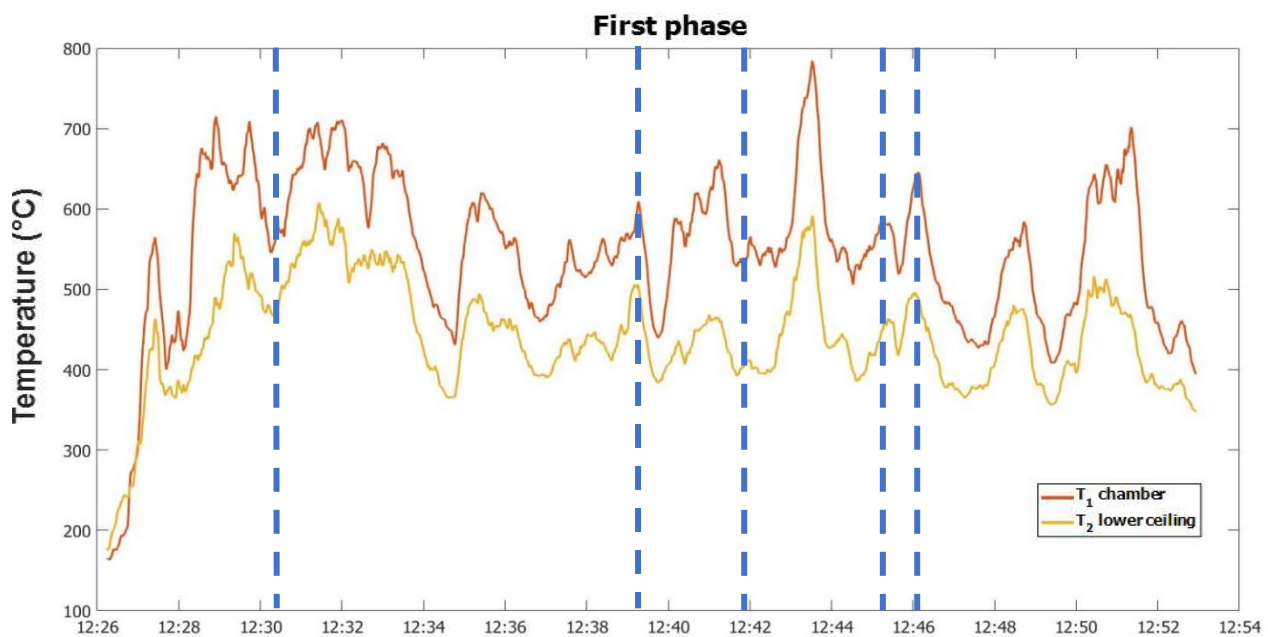


Fig. 3.5: first part of combustion phase at $P=1$, divided by time changes in V1 and V2 values

The first part of the combustion phase begins at a power level equal to 1. As in Fig. 3.5, after the sudden rise, the two temperatures fall at about 400°C , and after a short stabilization (30 seconds), T_1 overcomes T_2 , and will be higher till the burnout. The maximum value reached by T_1 is 710°C , while 570°C for T_2 .

The successive variations in V1 and V2 values are represented in Table 3.1.

Table 3.1: manual variations in V1 and V2 values during the test at $P=1$

Hour	V1 (front)	V2 (suction)
12:30	1	5
12:39	2	5
12:42	3	5
12:45	5	5
12:46	1	1

This test was short just to verify a general trend in temperature profiles. The trends present many peaks and a periodical behavior, never reaching a clear asymptotic range for a given couple of vent velocities. The wider cycles look the $V1=2$ cycles, with also intermediate peaks. The effect on temperatures of vent velocities changes could be steeper or smoother, so the speed of change is not homogeneous; the temperature trends of the two thermocouples are always aligned, so V1 and V2 variations do not impact on temperature gradients inside the chamber.

In the second combustion phase power level is raised at $P = 2$. The thermal profiles are shown in Fig. 3.6. while the transitions timetable in Table 3.2.

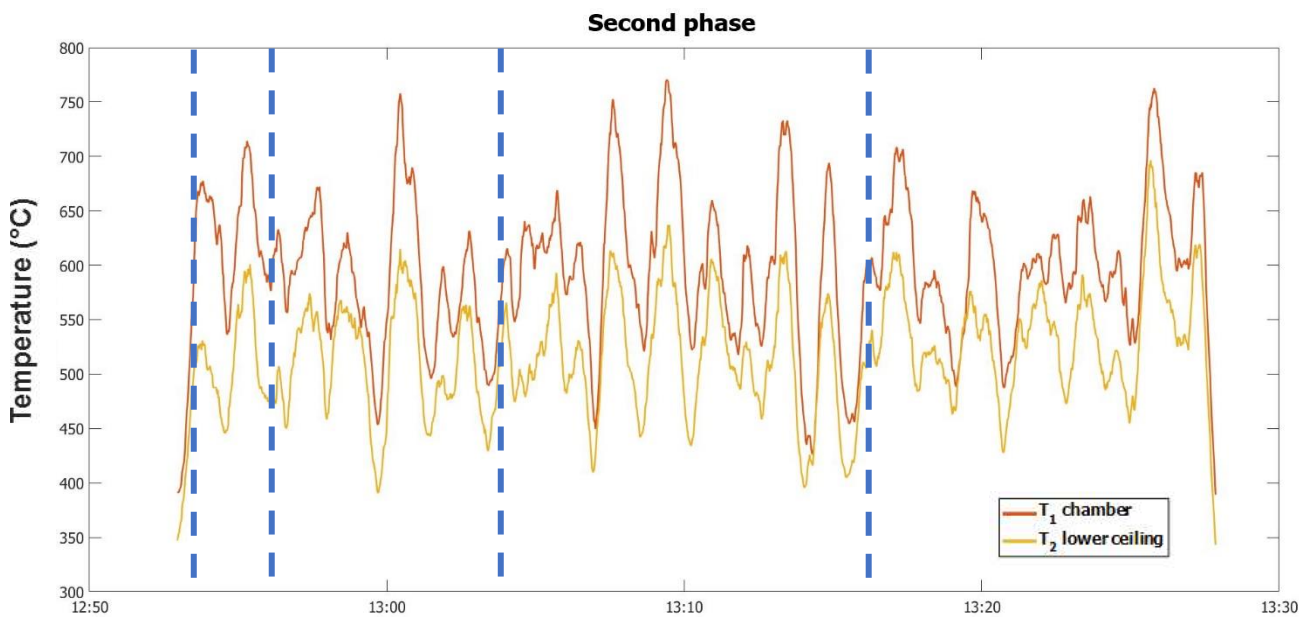


Fig. 3.6: second part of combustion phase at $P=2$, divided by V1 and V2 changes

Table 3.2: manual variations in V1 and V2 values at P=2

<i>Hour</i>	<i>V1 (front)</i>	<i>V2 (suction)</i>
12:54	3	3
12:56	5	3
13:04	3	5
13:16	5	5

At any set couple of vent velocities, despite keeping the same conditions for more than 10 minutes, there's no stabilization and peaks are much sharper due to irregular flames at such high temperatures. In the first phase, the maximum ΔT value is 250°C , while in the second one 160°C , suggesting that a power level increase results in lower temperature gradients in two different zones of the combustion chamber. The burnout phase starts at 13:27 and follows the trend in Fig. 3.7.

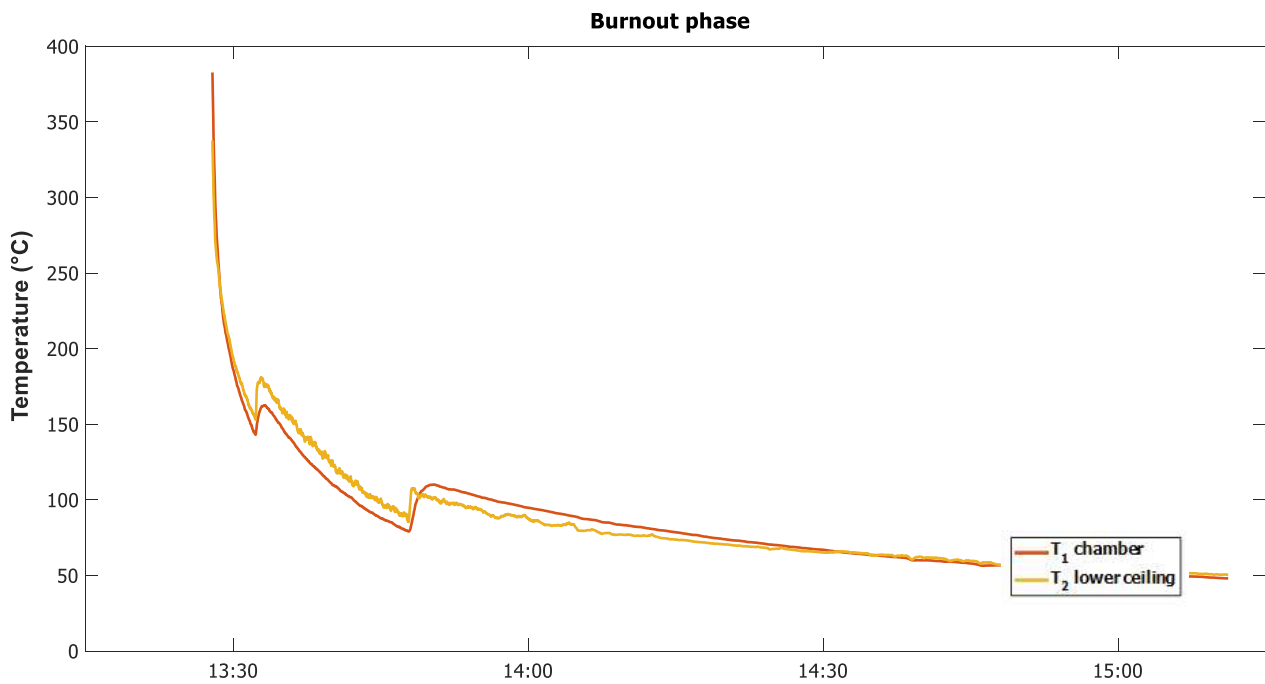


Fig. 3.7: stove burnout phase until turning off

The complete cycle is shown in Fig. 3.8, considering also the temperatures sensed in the flue paths, in the fan entrance and the horizontal and vertical pipes: the maximum is reached for power level equal to 2 and all vents set at 5 with values 205, 155, 130°C respectively.

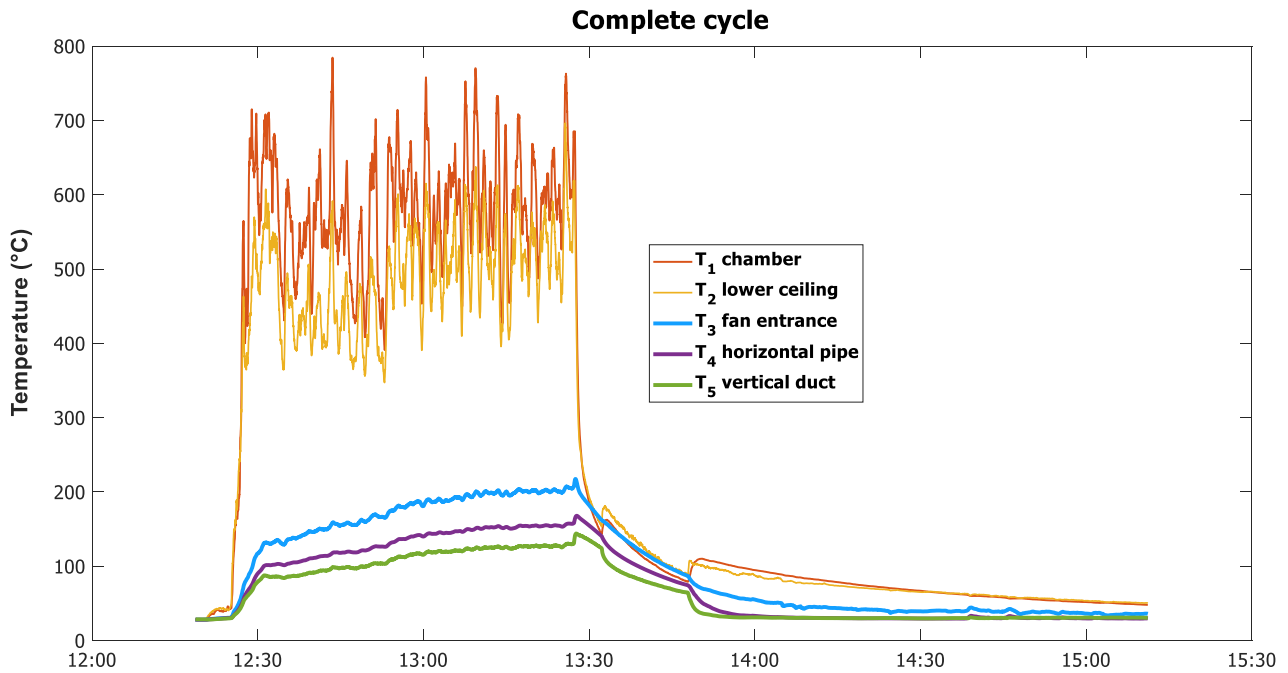


Fig. 3.8: complete cycle with all thermocouples' values till burnout

The next Temperature Tests have different aims: plotting temperature behaviors with longer cycles and phases and changing thermocouple positions to get a wider understanding of temperature gradients inside the chamber. Every test will keep the power level constant for the same cycle and will study variations of one single variable at a given experimental setup with two or three thermocouples.

3.1.1 Temperature Test 1

The entrance of two thermocouples was the same from the top-left hole and did not allow more than two probes to enter because of reciprocal hindrance: for the next tests it was decided an entrance from below the glass door by removing the ash collector to stay more flexible. Thermocouples must respect three constraints:

- reciprocal contact should be avoided because of data cross-contamination;
- walls contact must be avoided not to compromise data reliability;
- thermocouples should be fixed at the set position, ensuring that closing the door or fixing the other probes does not modify it.

The height of the temperature probe inside the chamber is measured considering the distance from the crucible circular profile. In fact, above the profile contact with upgoing flames is possible while below it's less probable due to the front septum hedge. Thermocouples are arranged specifying 3D distances from the circular profile (height), nearest side wall (left or right) and rear wall, as shown in Table 3.3 and Fig. 3.9.

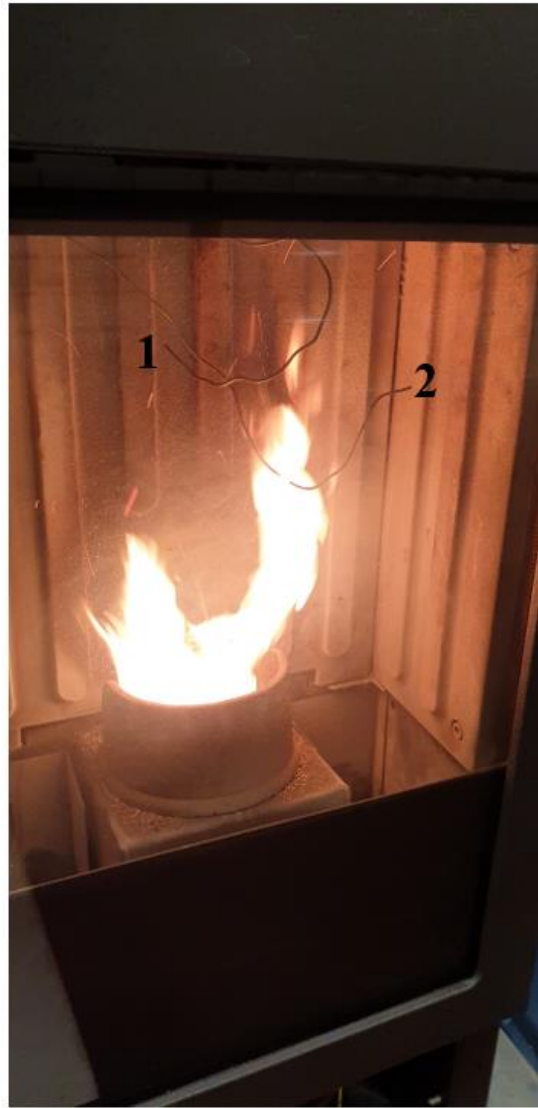


Fig. 3.9: thermocouples inside the combustion chamber for Temperature Test 1

Table 3.3: thermocouples 3D placement inside the combustion chamber in cm for TT_1

TT_1	d from side wall (cm)	d from circular (cm)	d from rear wall (cm)
1, center-top left	16	15	1
2, right	2	12	2

Named V1 the front vent, V2 the suction vent and P the power level, V1 will be changed from 1 to 5, while $(V2, P) = (5, 1)$ are kept constant.

Unfortunately, T_2 resulted in contact with the flames: this caused an additional heat conduction contribution to heat radiation but more importantly caused continuous oscillations and unstable data, seriously compromising the measurement reliability. Therefore, this test was used to understand the statistical method followed also in subsequent tests in acquiring temperature data, but only T_1 trend was kept for the final discussion on Temperature Tests.

Variations of V1 values followed the order shown in Table 3.4.

Table 3.4: $V1$ variations during $TT1$

<i>Hour</i>	<i>V1 (front)</i>	<i>V2 (suction)</i>
15:14	1	5
15:33	2	5
15:50	3	5
16:08	4	5
16:20	5	5

Temperature trends are shown in Fig. 3.10.

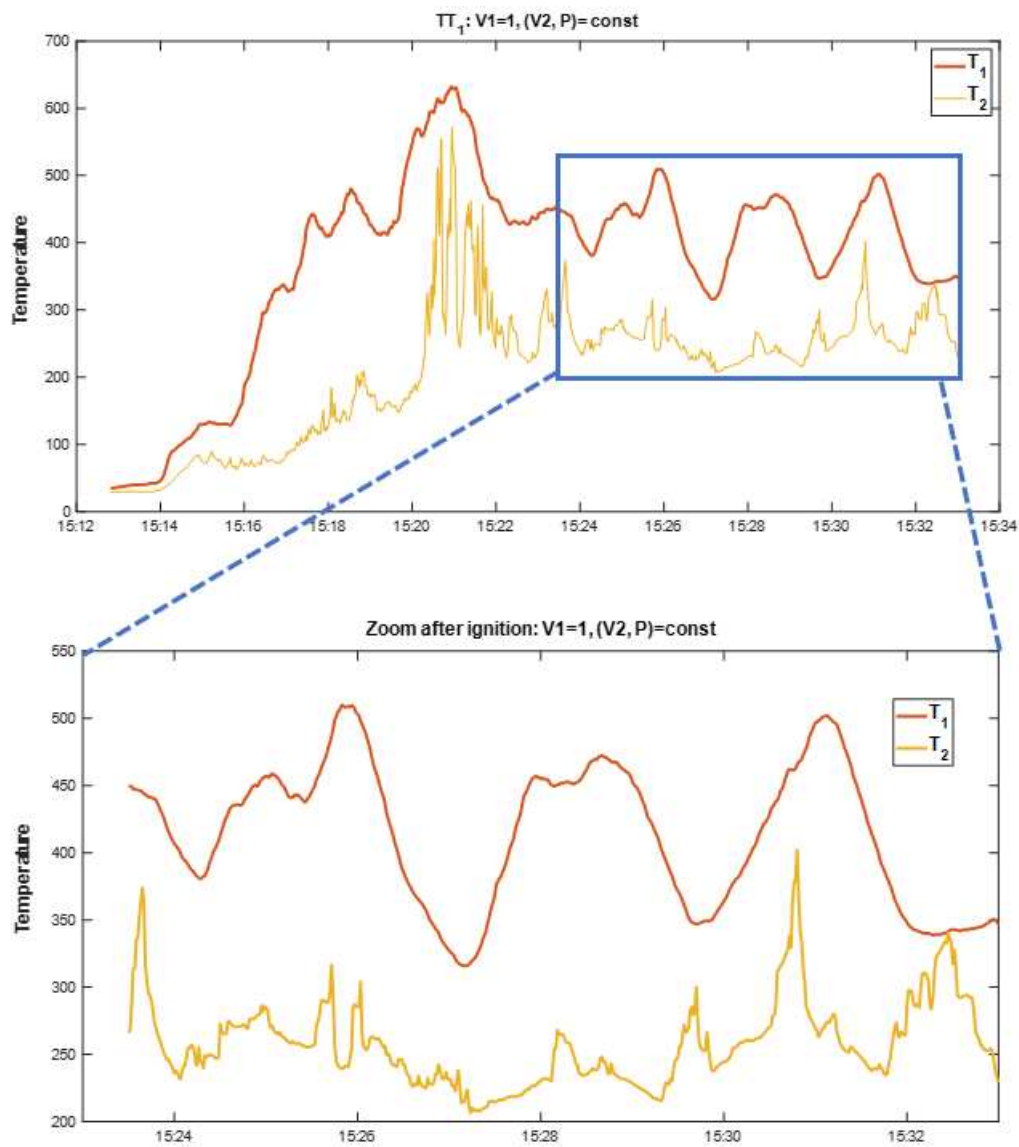


Fig. 3.10: temperatures at $V1=1$ and $(V2, P) = \text{constant}$ (1) and zoom after the ignition phase (2)

After ignition, periods are about three minutes wide for T_1 , while T_2 has sharper peaks and it mainly maintains in the range $[225, 290]$ °C.

Histograms like the ones in Fig. 3.11 are plotted at a specific number of classes to identify a specific statistical behavior and an average value and, if not, at least pick the most frequent range and use it to calculate a mode and a standard deviation from it.

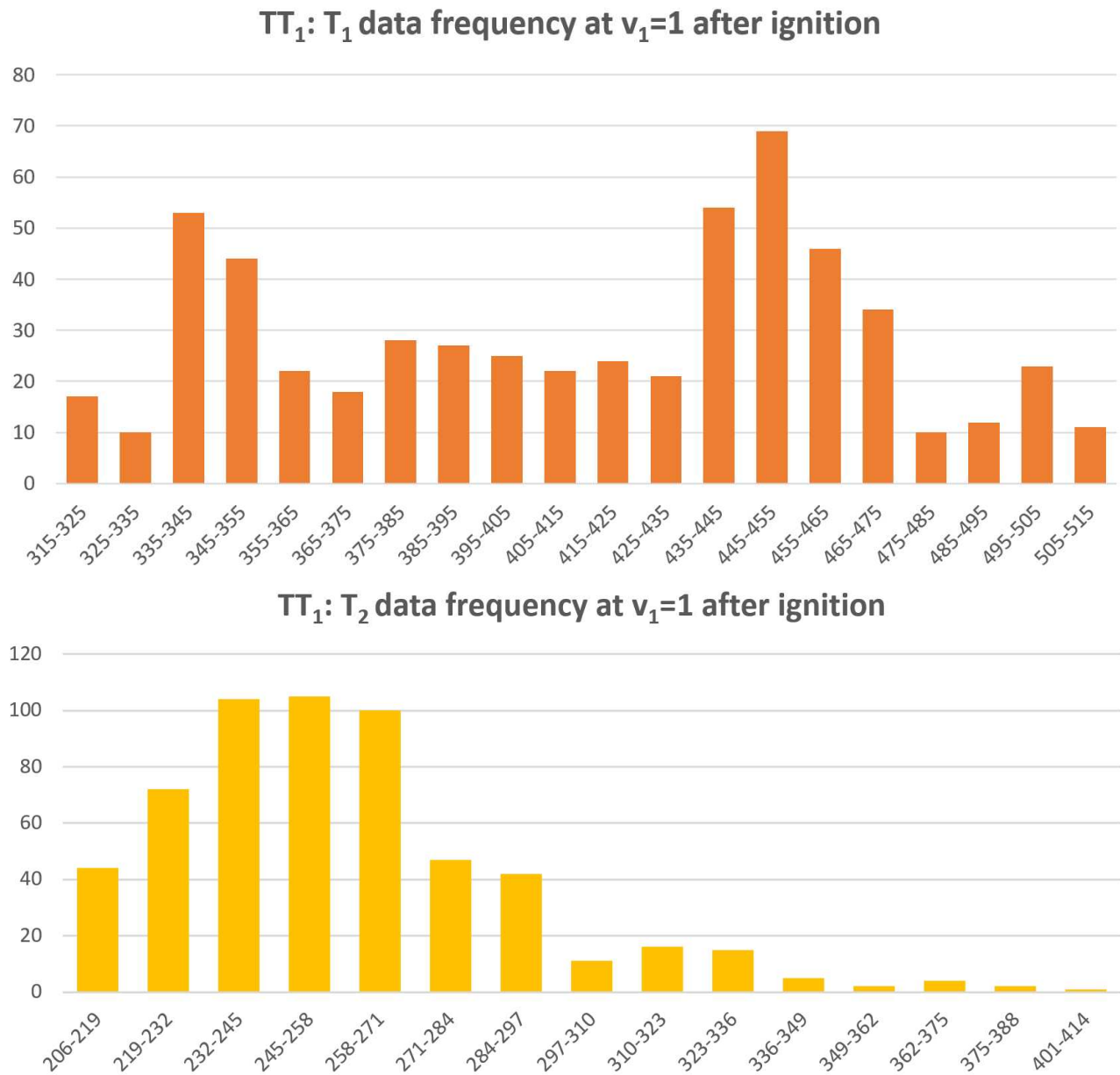


Fig. 3.11: temperature histograms for T_1 and T_2 at $V_1=1$ with different number of range classes

For T_1 the trend is slightly bimodal, the dominant behavior being in the range $[440, 460]$ °C, while for T_2 there is a peak for the range $[250, 265]$ °C.

Temperature plots for $V_1 = 2$ are shown in Fig. 3.11.

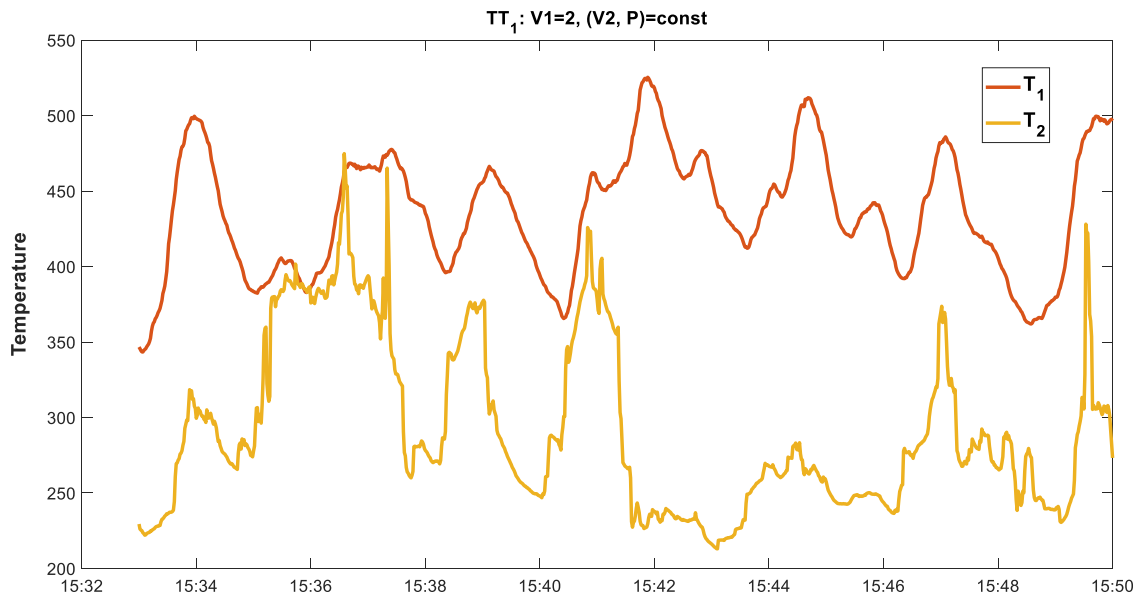


Fig. 3.11: temperatures at $V_1=2$ and $(V_2, P) = \text{constant}$

For $v_1=2$ peaks become a little wider as time progresses, from 2 min to 3 min period, while greater periodic cycles last first 4 min and then 8 min. The instability of T_2 is marked and there is no stable signal or clear behavior.

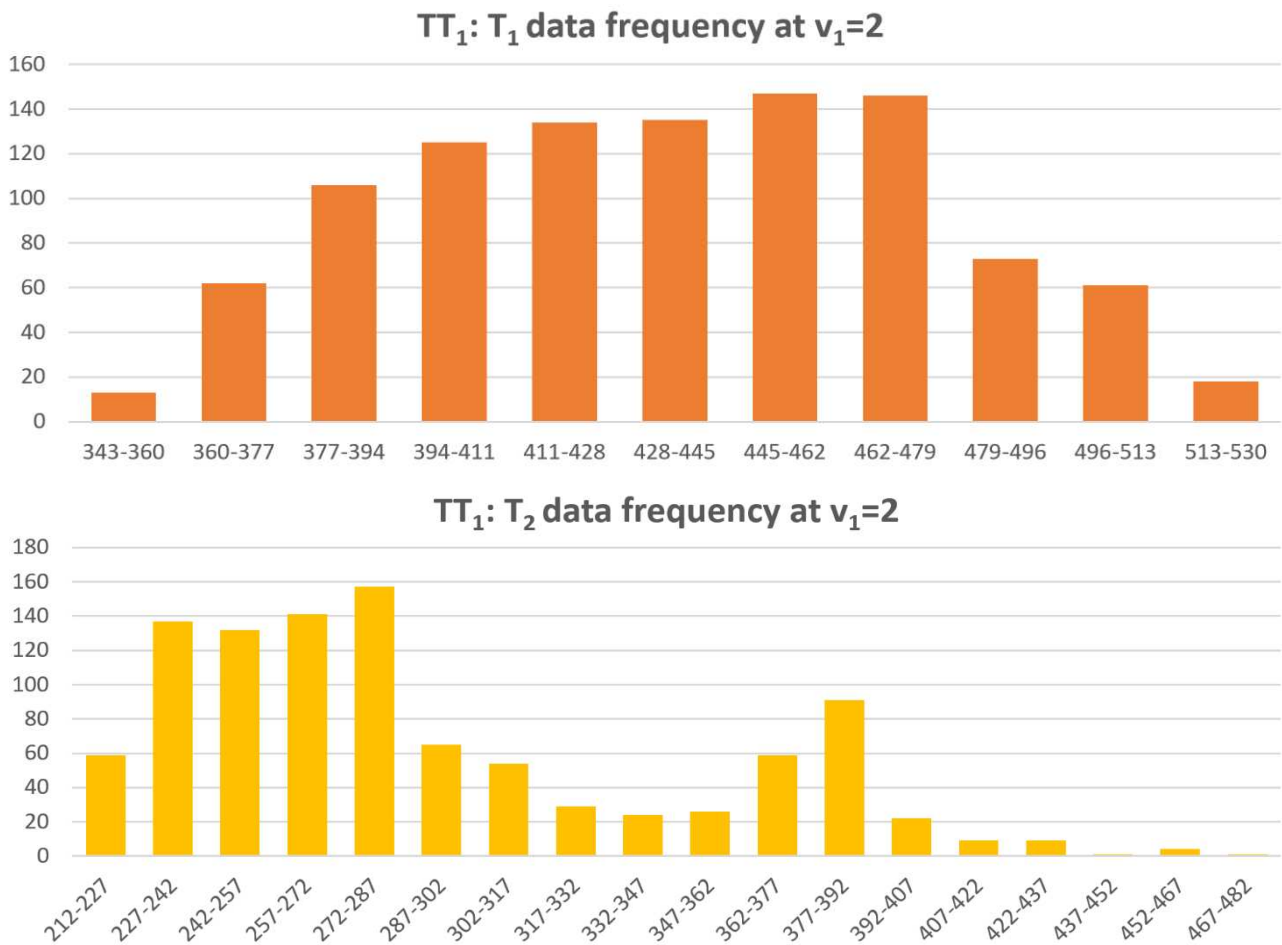


Fig. 3.12: temperature histograms for T_1 and T_2 at $V_1=2$

Histograms in Fig. 3.12 show that for T_1 the most frequent values span from 460 to 470°C and the distribution approaches unimodal trend, while for T_2 [270, 280] and [230, 240] °C have the greater density of frequency.

The same histograms have been plotted also at $V1=3$, $V1=4$ and $V1=5$.

T_1 approaches unimodal distribution only for $V1=2$, while the other T_1 trends are bimodal or irregular. Most frequent values and standard deviations (σ) for each $V1$ value are shown in Fig. 3.13 plots.

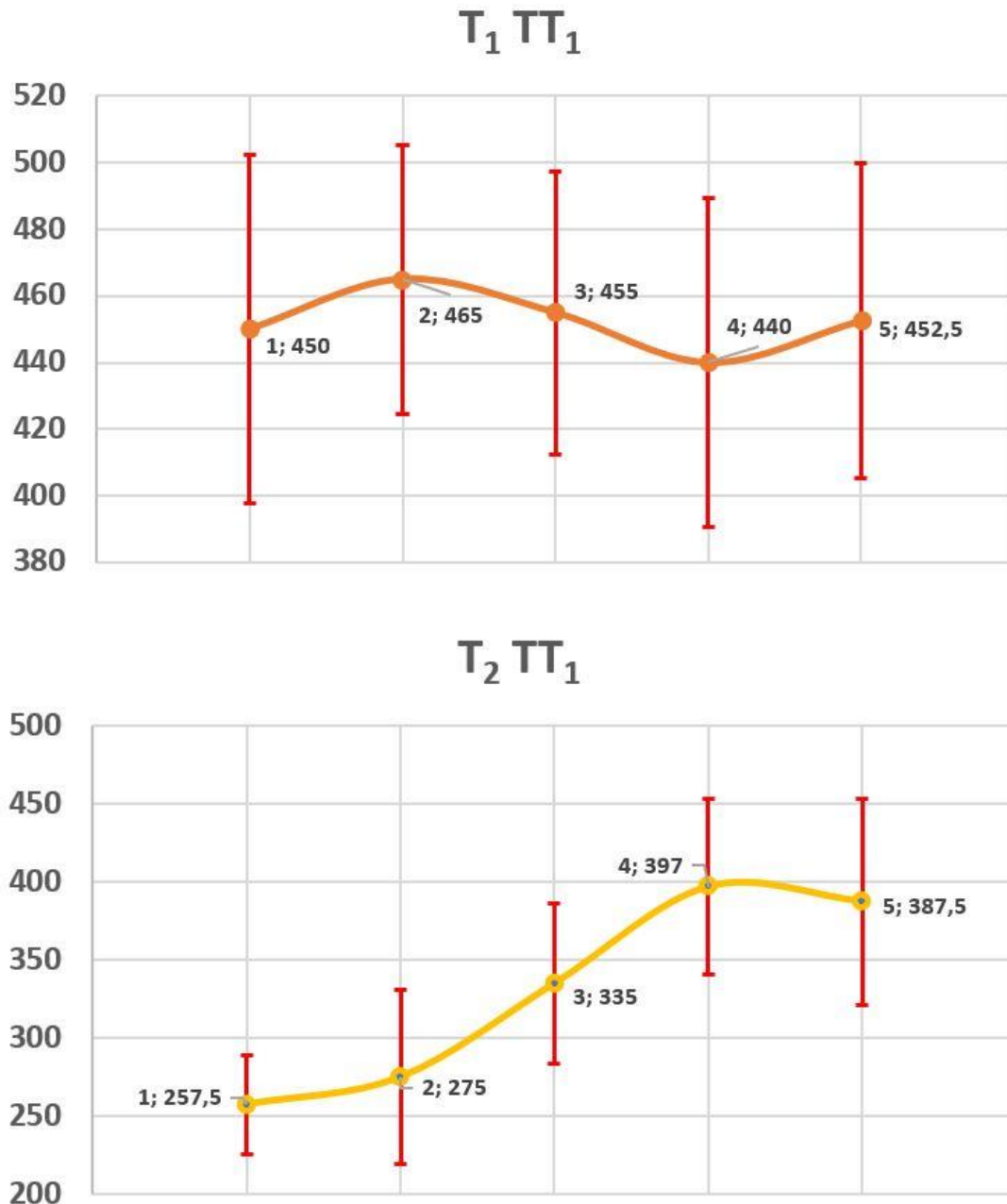


Fig. 3.13: mode and standard deviations for T_1 and T_2 at $V1$ variations

For T_1 temperatures are in the same range [440, 465] °C, but standard deviations are quite high, spanning an error range (2σ) of 100°C. T_2 increase with $V1$ is confirmed, it then stabilizes at $V1=5$. Standard deviations gradually increase during the cycle.

3.1.2 Temperature Test 2

In the second temperature test, the ash collector is removed, and thermocouples are in contact with the tissue of the glass door, ensuring adherence at closing. Three thermocouples are available, each one fixed at the bottom of the stove with aluminum scotch. The locations are specified in Table 3.5 and depicted in Fig. 3.14.

Table 3.5: thermocouples spatial location inside the combustion chamber in cm for TT2

TT_2	d from side wall (cm)	d from circular (cm)	d from rear wall (cm)
1, bottom left	0.5	-0.5	6
2, top right	1.5	20.5	5
3, middle left	5.5	15	3



Fig. 3.14: thermocouples placed for Temperature Test 2

(V2, P) = (5, 1) are kept constant, while V1 is increased throughout the cycle. Burnout starts at 16:12.

Table 3.6: V1 variations during TT2

<i>Hour</i>	<i>V1 (front)</i>	<i>V2 (suction)</i>
14:25	1	5
14:40	2	5
15:15	3	5
15:42	4	5
15:57	5	5

During the cycle, T₂ shows the highest temperature values, followed by T₃ and T₁. In this case, trends are more regular and aligned one each other. Stabilization phase after ignition lasts six minutes, then for V1=1 there are two periodic cycles, one greater five minutes wide and the others shorter two minutes and one minute wide. For V1=2, there are no evident greater phenomena, but just shorter cycles, one-minute wide for the first five minutes and two-minutes wide and sometimes three for the remaining time. V1=3 shows greater oscillations, mainly six minutes wide, one four. Smaller peaks have an average period of two minutes, three just for the last ones. V1=4 has greater peaks five minutes wide, while the smaller ones last two minutes. Greater cycles are again present for V1=5 but the duration is variable from three to five minutes, while smaller peaks have a period from one to two minutes. Cycles' period is summed up in Table 3.7.

Table 3.7: cycles' period in minutes at different V1 values during TT2

<i>TT₂</i>	<i>Cycles' period (minutes)</i>	
<i>V1</i>	<i>greater</i>	<i>smaller</i>
1	5	1-2
2	X	1-2
3	4, 6	2-3
4	5	2
5	3-5	1-2

Statistical plots for the three thermocouples of Temperature Test 2 are shown in Fig. 3.15.

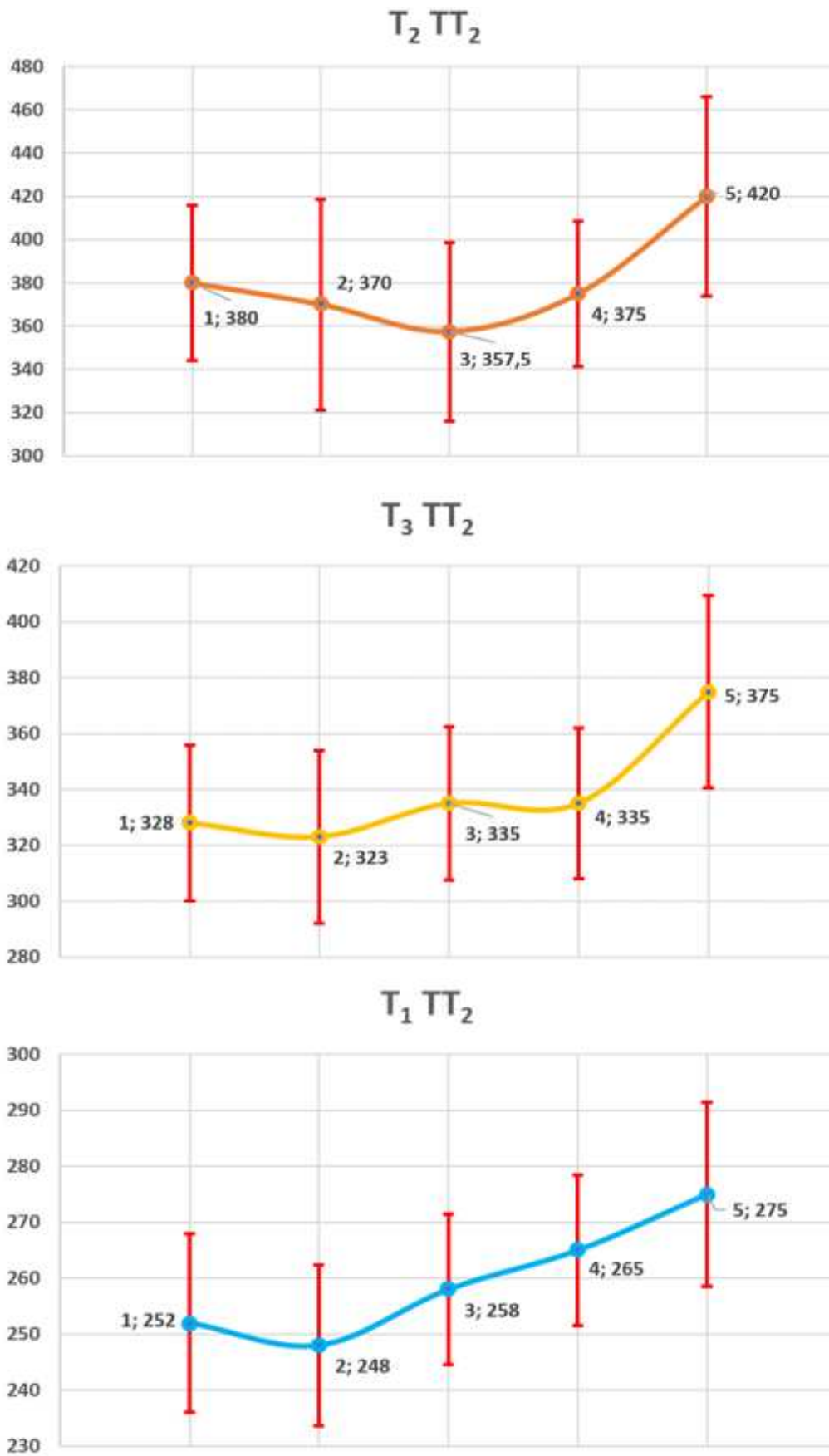


Fig. 3.15: statistical plots for T_1 , T_2 and T_3 from the hottest to the coldest one in Temperature Test 2

For T_2 , temperatures reach a minimum at $V1=3$ and overcome $V1=1$ value only for $V1=5$. Again, standard deviations bound an error range higher than the difference between the greatest and the lowest temperature. T_3 shows similar values for the first four $V1$ conditions and sensibly increases at $V1=5$. T_1 shows standard deviations of 30°C max, lower than T_2 (100°C) and T_3 (70°C): for temperatures lower than 300°C the trends seem more stable. As for T_2 and T_3 , a maximum is reached for $V1=5$.

3.1.3 Temperature Test 3

In a new test, different locations are chosen for thermocouples. In particular, while two of them will be placed upside, near the lower ceiling, another will be inserted near the crucible but below the circular profile, as shown in Fig. 3.16 and summed up in Table 3.8.



Fig. 3.16: thermocouples placed for Temperature Test 3

Table 3.8: thermocouples spatial location in cm for TT3

TT_3	d from side wall (cm)	d from circular (cm)	d from rear wall (cm)
1, bottom right	5	-7.5	7.5
2, top left	2.5	23	6
3, top right	1	19	6

In this experiment, one last transition from $V1=5$ and $V1=1$ is chosen to compare thermal behavior at different cycle heating phases inside the stove at $V1=1$. Again $(V2, P) = (5, 1)$ are kept constant, while $V1$ is increased throughout the cycle and decreased before burnout.

A transitions' timetable is shown in Table 3.9. The test starts at 16:23, ignition at 16:27 and burnout at 18:28.

Table 3.9: V1 transitions timetable for TT3

Hour	V1 (front)	V2 (suction)
16:34	1	5
16:45	2	5
17:10:30	3	5
17:26	4	5
17:50	5	5
18:13	1	5

Temperature profiles are again parallel each other, so thermal oscillations are specular for each temperature. Table 3.10 gathers the data for all temperature peaks at different conditions is represented below.

Table 3.10: greater and smaller cycles' period for TT3 at different V1 values

TT_3	Cycles' period (minutes)	
V1	greater	smaller
1	3	1-2
2	3, 8	2-3
3	3, 5	1-2
4	5, 10	2-3
5	3-4	1-3
1 (6)	5	1-3

$V1$ undergoes an increase in peaks' amplitude as the chamber heats, which results in broader temperature variations. Oscillations for $V1=4$ are again greater than $V1=5$ ones, probably because an excessive increase in turbulence becomes a reductive contribution. Boxplots are shown in Fig. 3.17.

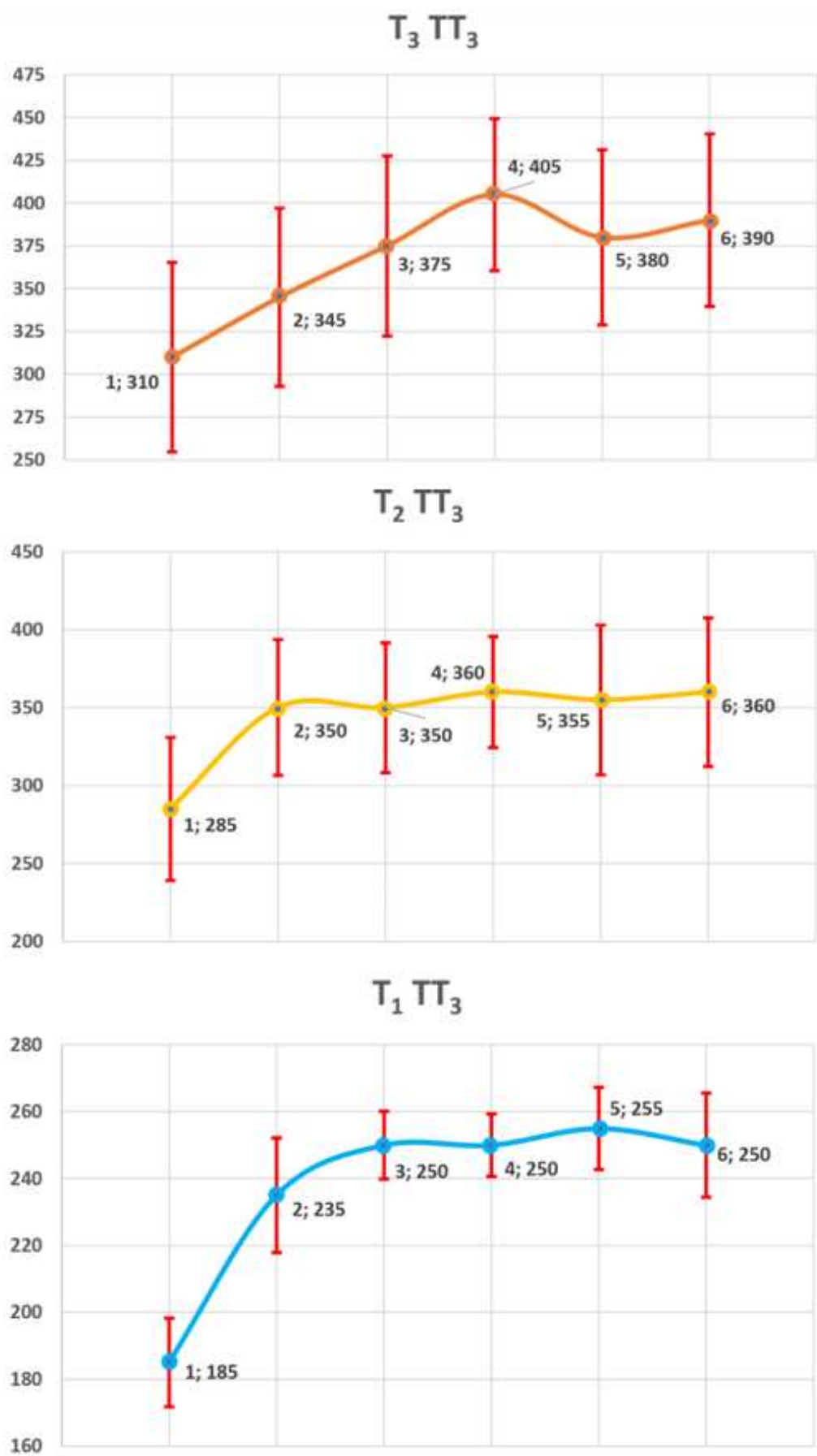


Fig. 3.17: statistical plots for temperatures in TT3

Crucible circular hedge is confirmed as a barrier for heat transfer for T_1 despite the clear proximity to the flames, resulting in temperatures lower than more distant thermocouples.

Standard deviations for T_3 , the hottest measured temperature, define ranges even higher than 100°C ; there's a maximum for $V1=4$, while $V1=1$ undergoes an 80°C increase from cold to heated chamber. As for the hot intermediate temperature (T_2), after the initial $V1=1$ value temperatures are quite aligned at 350°C , despite a relatively wide error band. Even the second $V1=1$ central temperature is closed to the other ones, and this principle applies also to the coldest measured temperature (T_1) in the range $[235, 250]^{\circ}\text{C}$. The cold-heated chamber increase is 75°C for T_2 and 65°C for T_1 , while T_1 standard deviations are relatively much lower. Because $V1=1$ temperature varies significantly, chamber heating was supposed to be another important contribution to temperature values.

3.1.4 Temperature Test 4

Thermocouples are located as in TT_3 , but now power level is increased to 2, keeping $V2=5$ and modifying $V1$ conditions.

$V1$ variations and thermal oscillations are exposed in Table 3.11 and 3.12.

Table 3.11: $V1$ transitions timetable for TT_4

<i>Hour</i>	<i>V1 (front)</i>	<i>V2 (suction)</i>
10:25	1	5
10:37	2	5
10:57	3	5
11:17	4	5
11:37	5	5

Table 3.12: cycles' period for TT_4 changing $V1$ values

TT_4	<i>Cycles' period (minutes)</i>	
V1	<i>greater</i>	<i>smaller</i>
1	4	2
2	4, 7	1-3
3	4	1-2
4	4-5, 10	1-4
5	4	0.5-2

$V1=2$ shows wider greater peaks than $V1=3$ and again $V1=4$ has the broadest thermal oscillations. Smaller cycles increase their range as the chamber heats, while greater ones never fall below 4 minutes. Statistical values for thermocouples at $P=2$ are in Fig. 3.18.

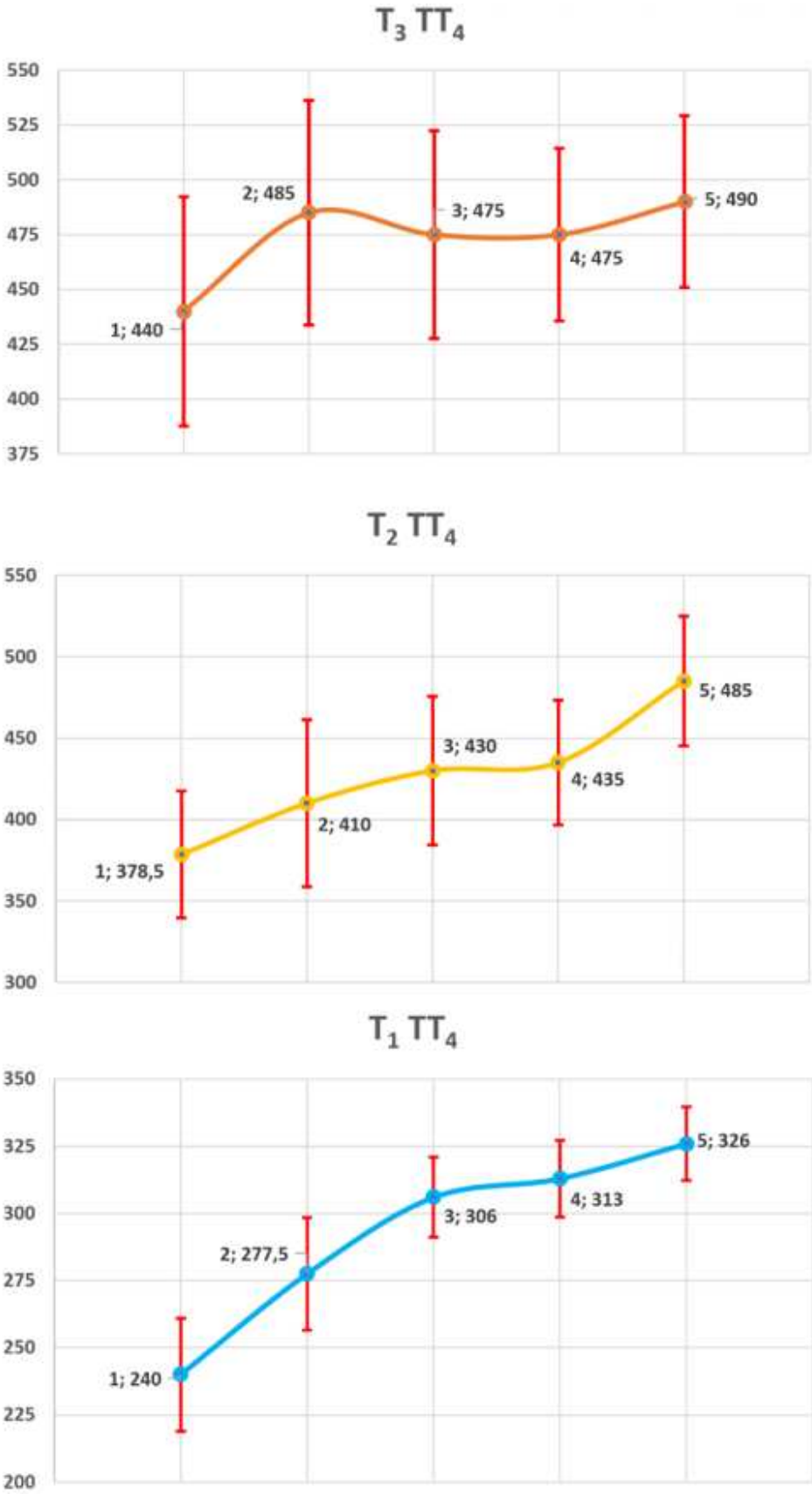


Fig. 3.18: boxplots for temperatures measures at $P=2$ during TT_4

At $P=2$, temperatures generally increase at higher $V1$ set values, but as temperature increases, the growth is slower. Because T_3 and T_2 temperature are the highest and aren't next to the crucible where pellet combustion occurs, there's not much temperature difference at different $V1$ velocities.

Power level seriously impacts on cycle temperatures compared to the previous test, especially looking at the difference on temperatures for the same $V1$ value and probe position, exposed in Table 3.13.

Table 3.13: difference in temperature varying front vent velocities between the same thermocouples at $P=2$ and $P=1$

TT_4 vs TT_3			
V1	ΔT_3 (°C)	ΔT_2 (°C)	ΔT_1 (°C)
1 (cold stove)	130	93	55
2	60	60	43
3	100	80	56
4	70	75	63
5	110	125	76

Considering ΔT_3 and ΔT_2 , the highest differences are for $V1=1$ and $V1=5$. In the first case, probably the high-power level compensates the initial absence of heat radiation mechanism with a more powerful flame. In the second case, the greatest levels of the two variables generates the highest variation, especially for ΔT_2 and ΔT_1 .

3.1.5 Temperature Test 5

During the last combustion cycle, $V2$ is varied instead of $(V1, P) = (1, 1)$, kept constant. The aim is to observe if $V2$ variation impacts on chamber temperatures reveals positive or not.

Thermocouple spatial arrangement is listed in Table 3.14 and shown in Fig. 3.19.

Table 3.14: thermocouples spatial location in cm for TT_3

TT_5	d from side wall (cm)	d from circular (cm)	d from rear wall (cm)
1, top left	2	21	6
2, middle left	0.5	12	4
3, mid-bottom right	0.5	0	3

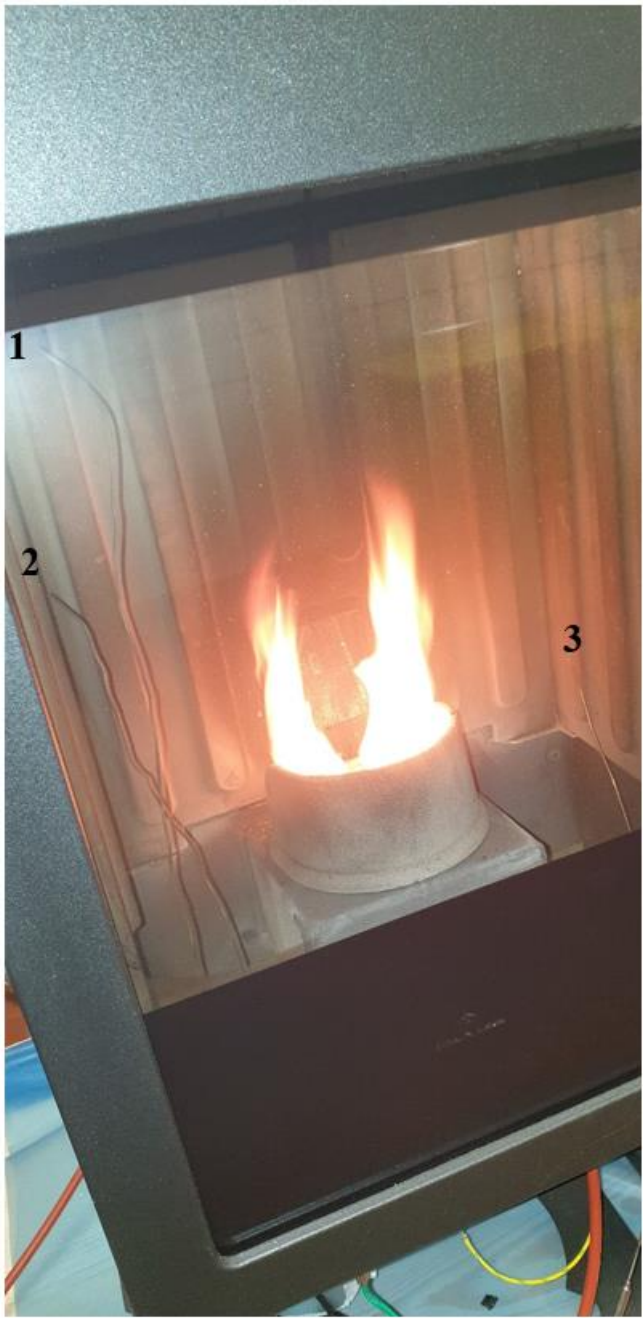


Fig. 3.19: spatial arrangement of thermocouples in TT5

Temperature Test 5 starts at 14:58, ignition at 15:01 and burnout at 16:50. V2 transitions are listed on Table 3.15.

Table 3.15: V2 transitions timetable for TT5

Hour	V1 (front)	V2 (suction)
15:09	1	5
15:30	1	4
15:50	1	3
16:10	1	2
16:30	1	1

Table 3.16 presents thermal peaks' periods for the test.

Table 3.16: thermal fluctuations at different V2 velocities

TT₄	<i>Cycles' period (minutes)</i>	
V2	<i>greater</i>	<i>smaller</i>
5	7	2-3
4	3, 5	2
3	2-3	1-2
2	8	1-4
1	3, 8	1-2

There is not a defined trend for greater nor for smaller oscillations, probably because V2 conditions impacts on thermal distribution instability more than V1.

Statistical boxplots varying V2 are shown in Fig. 3.20.

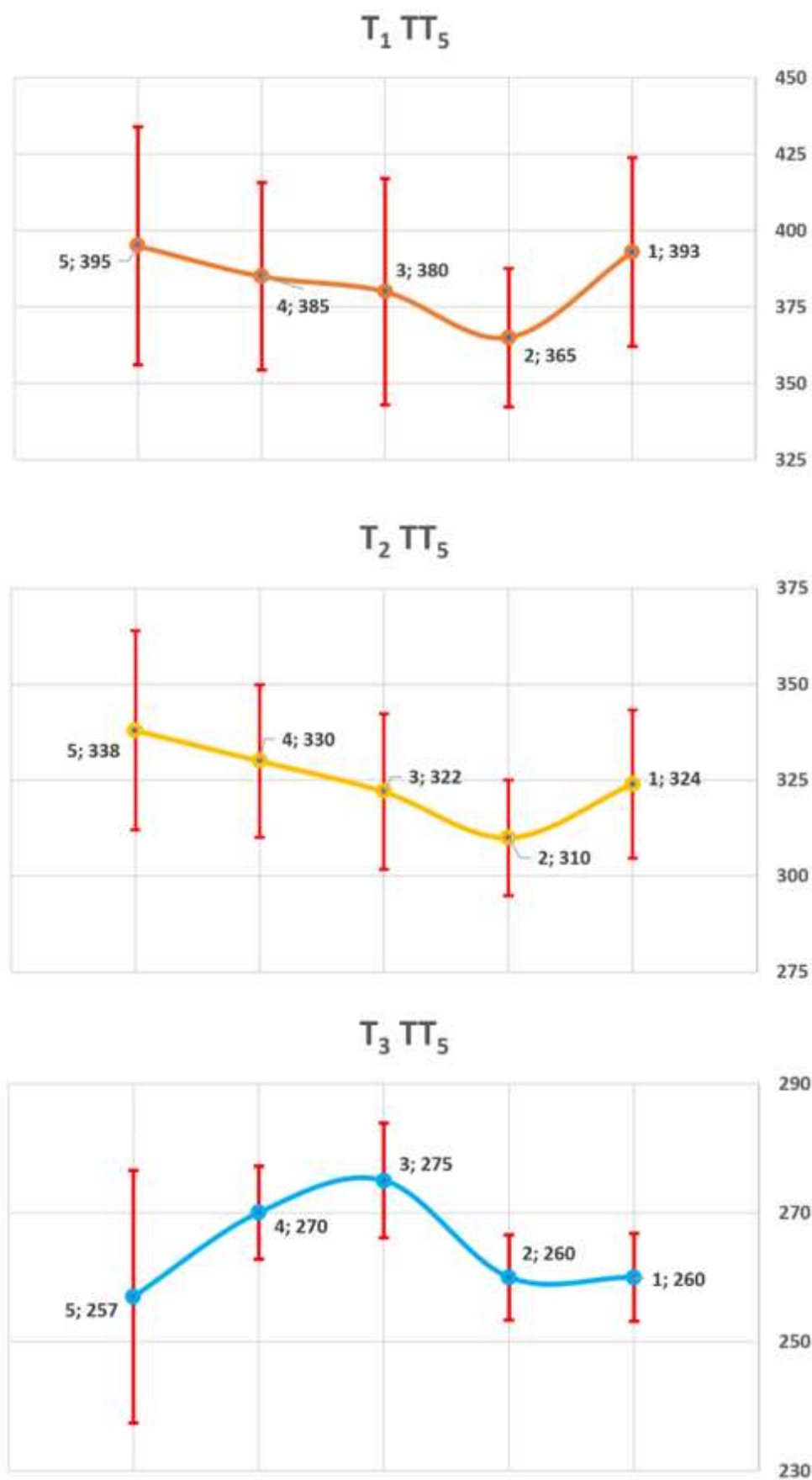


Fig. 3.20: boxplots for temperatures at different V2 velocities

T_3 , the coldest temperature, has a maximum for $V_2=3$, but with an 18°C range of temperatures variations are very slight; moreover, higher temperatures approach more the combustion behavior, so these data are not considered as reference. T_1 , the highest temperature, reach the same maximum values for $V_2=1$ and $V_2=5$; for T_1 and T_2 , the highest temperatures, there is a slight decrease as V_2 decreases despite chamber heating, and this results as a negative effect for combustion conditions.

3.1.6 Scaled error band plot

A temperature dataset has been considered for every temperature test at a given thermocouple and modified vent value. From that, a data frequency histogram with a certain number of classes has been plotted to select a temperature range with the highest distribution frequency. The number of classes has been chosen to highlight a specific statistical trend. From the most frequent range, the extremes have been averaged to obtain a reference temperature (T_r) for that dataset as a central tendency. A standard deviation (σ) has been calculated for the whole dataset to sketch boxplots for every vent value, with T_r as central value and an error band of 2σ ($T_r - \sigma$, $T_r + \sigma$). The scaled percentage error band has been defined as:

$$\% EB = 100 \frac{2\sigma}{T_r}$$

The main aim is to identify possible instability areas plotting the percentage error band against its related temperature in Fig. 3.21. Data for T_2 in TT_1 are not plotted, because they are considered unreliable.

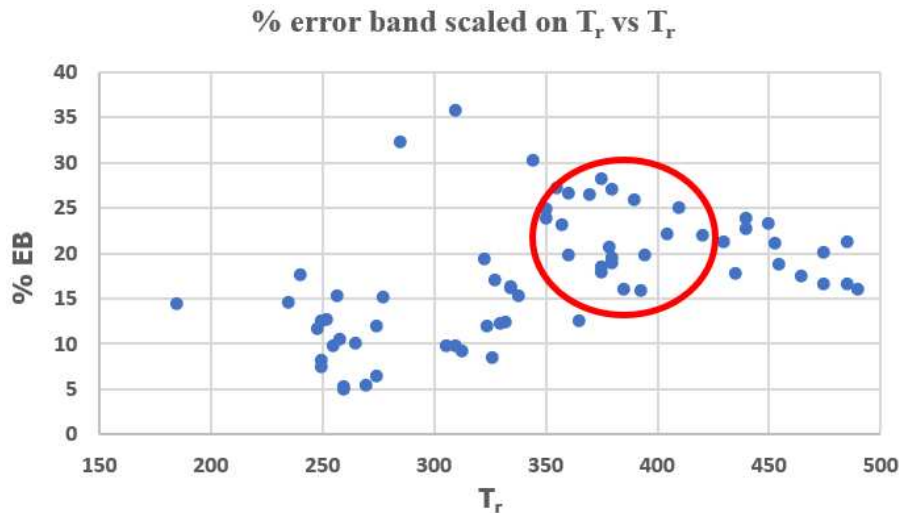


Fig. 3.21: % scaled percentage error band vs T_r scatterplot

In the ranges (340, 420) $^\circ\text{C}$ and (15, 30) % EB there's a denser concentration of values and, despite two points over 30% EB, the error band reaches a maximum in this area; therefore, this could be considered a main instability and accumulation area. Til 420°C the scaled error band increases with temperature, while over 420°C it clearly decreases.

This result shows that the more temperature approaches combustion one the less unstable will be its trend. Therefore, the highest will be the average chamber temperature, the lowest will be temperature gradients, therefore the combustion process will be favored inside a closed environment.

3.1.7 Final remarks on temperature measurements

From the five temperature online tests run in the laboratory with thermocouples inside the combustion chamber of a commercial pellet stove it is possible to draw some conclusions.

As for greater and smaller cycling periods in temperature fluctuation, any V1 velocity could cause greater cycles from 3 to 8 minutes, in some cases even 10 minutes; a power level variation seems affecting temperatures in the same way with a general increase in cycling period, but there's no general behavior at fixed V1 and therefore no better trend suggesting to prefer one V1 velocity to another.

The scaled error plot suggests to reduce instability by increasing the chamber temperature; despite lowest temperatures result in a lowest percentage error band, to better facilitate combustion a higher temperature is preferable and thermocouples measuring highest temperatures are more reliable as a reference. Approaching the flames, temperatures will more and more approach 640°C, the pellet combustion temperature.

Combustion chamber heating during the combustion cycle is an important contribution to temperature increase, as shown in TT3 where two measures at V1=1 have been carried out for the same thermocouple. The new temperature aligns with the others at higher V1 velocities, therefore even here the same thermocouple values are more or less aligned and there's no preferable behavior at different V1 values.

Decreasing the suction vent velocity, V2, results in a negative effect on temperatures in contrast with chamber heating, therefore it is considered a negative contribution to combustion and acts as a power level reduction.

Power level increase has a serious impact on temperatures inside the chamber; $P = 2$ seems a better operating condition with respect to $P = 1$, however this parameter has revealed crucial for temperatures, therefore it will be better assessed during emission measurements to find its best value according to pollutant concentrations.

In summary, despite a 10% temperature rise increasing V1 at temperatures higher than 400°C, chamber heating offsets V1 variations stabilizing high temperatures at a narrower range, so the front vent velocity has only a slight effect on temperature; V1 value for the following emission tests has been chosen to be 1, a conservative value to ensure good combustion conditions. V2 = 5 is chosen as the suction vent velocity for emission tests because it gives the best result in terms of temperature with a better heat dissipation, thus a high temperature.

3.2 Emissions tests

Many tests involving emissions measurements have been carried out to assess the stove performance in terms of pollutant concentration values in order to meet the Ecodesign requirements for pellet stoves. Pollutants are CO, CO₂, NO, NO₂ and particulate matter. O₂ trends are collected mainly to compare them with the other profiles.

Globally, the analyzed variables are:

- temperatures inside the chamber and at the flue exit line through thermocouples connected to Picolog
- pollutants' emissions from Alphasense sensors, whose concentration is determined by conversion of the electric signal through calibration equations
- particulate matter from OPC
- stove parameters through HTool software: flue fan velocity, cochlea rotation speed, inlet pipe depression, flue temperature entering the flue fan
- inlet velocity in the rear tube through a hot wire anemometer.

3.2.1 Air dilution test

The aim of the first test was to verify if a dilution step was necessary before feeding the flue gases to the sensors. The only information needed was if the sensors reached saturation or not at different dilution ratios, therefore it was carried out before calibration. The experimental line is depicted in Fig. 3.22.

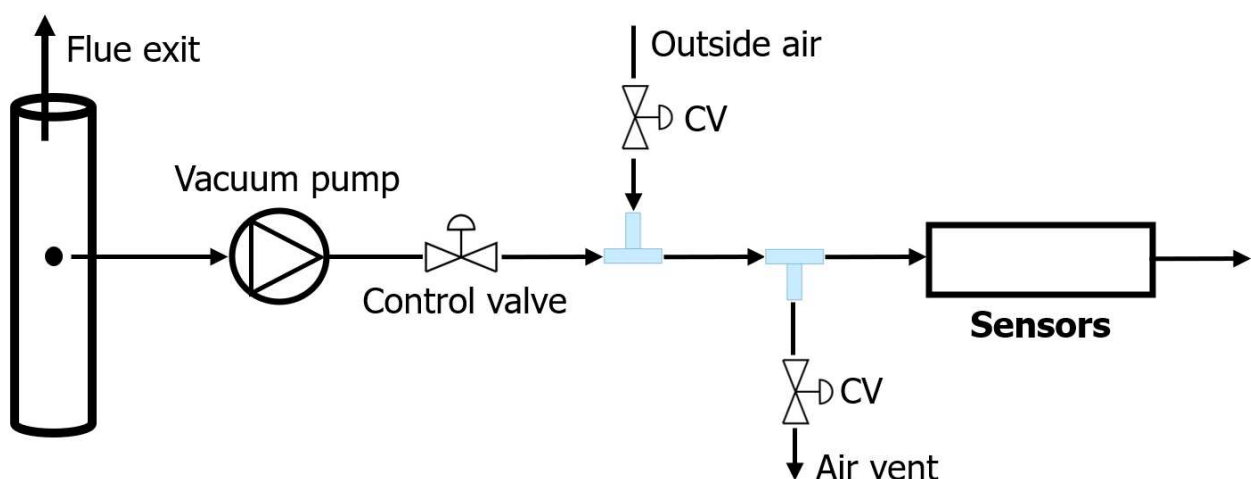


Fig. 3.22: experimental scheme for dilution test

Inside the fumes' hood flue gases are picked up by a little plastic tube working as a probe. The line enters a KNF[®] diaphragm vacuum pump where gases are compressed and sent to a valve which

regulates the flowrate and then to a T-joint where it is mixed with another valve-determined outside air flux, producing an air-pollutants mixture. This step is necessary to assess a given dilution ratio, defined as $DR = 1 + (\dot{V}_{\text{air, dil}}/\dot{V}_{\text{mix}})$ where $\dot{V}_{\text{mix}} = \dot{V}_{\text{air, dil}} + \dot{V}_{\text{gases}}$. Flowrates' values are fixed by a flowmeter fed by a direct current power supply. The mixture is then divided into two streams by means of another T-joint: a part is vented to regulate the most suitable flowrate feeding the sensors. Various DR values have been tested: DR=6, DR=4, DR=2 and DR=1 (no dilution). The maximum values to get sensor saturation is 2.5 V for CO, NO, NO₂ and O₂ and 2.335 V for CO₂. No sensor reaches saturation for DR=1, then dilution is showed to be non-necessary as shown in Fig. 3.23 for pollutants and oxygen sensors.

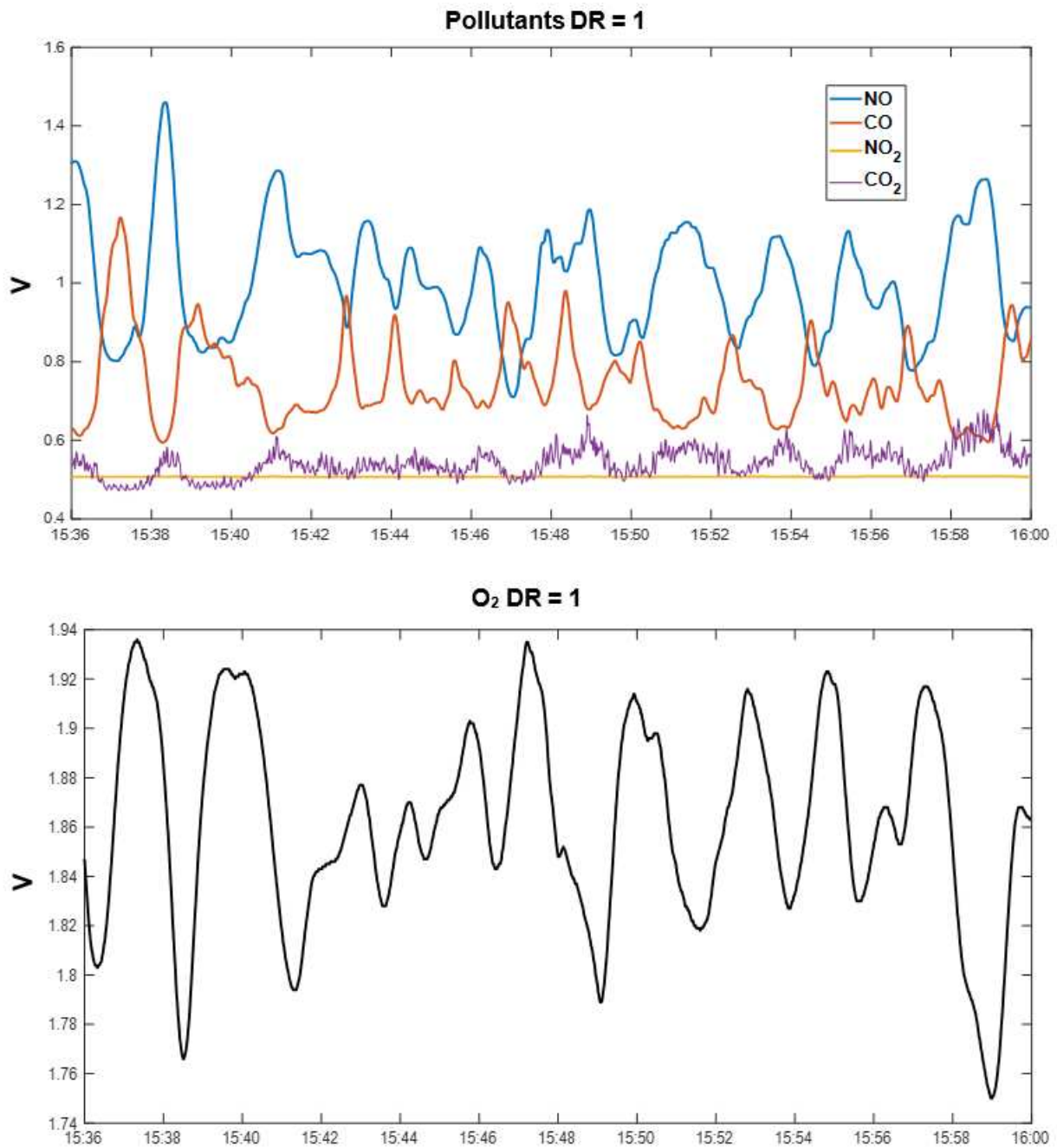


Fig. 3.23: voltage plots for CO, CO₂, NO (1), and O₂ (2) sensors

3.2.2 Experimental setup for emission tests

Fig. 3.24 shows the experimental lines used for emission tests.

A hot flow portable anemometer was used to determine inlet velocity, while outlet velocity and outlet depression were determined by a Pitot tube inserted in the flexible aluminum line entering the lab hood. Temperature is measured inside the chamber with a K-thermocouple placed as in Table 3.17.

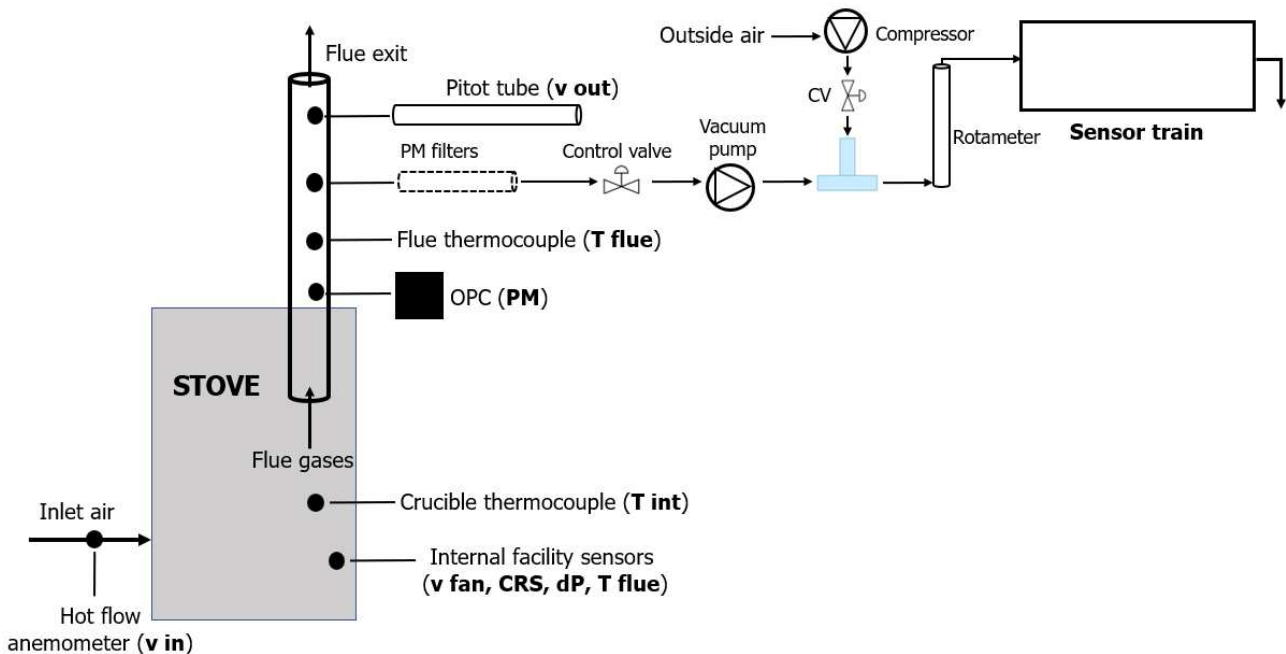


Fig. 3.24: experimental lines for emission tests

Table 3.17: spatial arrangement of chamber thermocouple

<i>Distance from circular</i>	12 cm
<i>Distance from right side wall</i>	3 cm
<i>Distance from rear wall</i>	3.5 cm

Another K-thermocouple probe was placed at the end of the flue line intercepting the exhaust gases. Internal facility sensors measured important parameters through H-Tool software like flue fan velocity, cochlea rotation speed, inlet pipe depression and flue temperature before entering the flue fan. Particulate matter concentrations were determined through an OPC connected with a plastic tube line inserted in the vertical flue pipe. In some tests even filters were used for particulate capture, a quartz wool filter, and a round thin filter inserted in a metallic filter housing. Gases are conveyed to the quartz wool filter when present, then a valve regulates the membrane pump inlet flowrate. The outlet flow is sent to a T-joint where it is mixed with another valve-determined outside air flux, creating an air-pollutants mixture.

The flow then crosses a rotameter, to determine the suitable gas flowrate to the sensor train by the floating movement and stabilization of a spherical element. From the scale, the chosen flowrate was 1.9 L/min of O₂, the flow crosses the sensors placed in series in a box and it exits in the hood. Sensors will determine CO, O₂, NO, NO₂ and CO₂ concentrations through calibration equations. When present, a tube exiting the filter housing line will be linked to a current-fed flowmeter to determine the superimposed filter flowrate. V1 and V2 are set equal to 1 and 5 respectively.

3.2.3 Pollutant relative trends

From the plots, CO and O₂ trends are aligned and opposite to NO, NO₂ and CO₂ ones, as shown in Fig. 3.25 for CO and NO and in Fig. 3.26 for CO₂ and O₂.

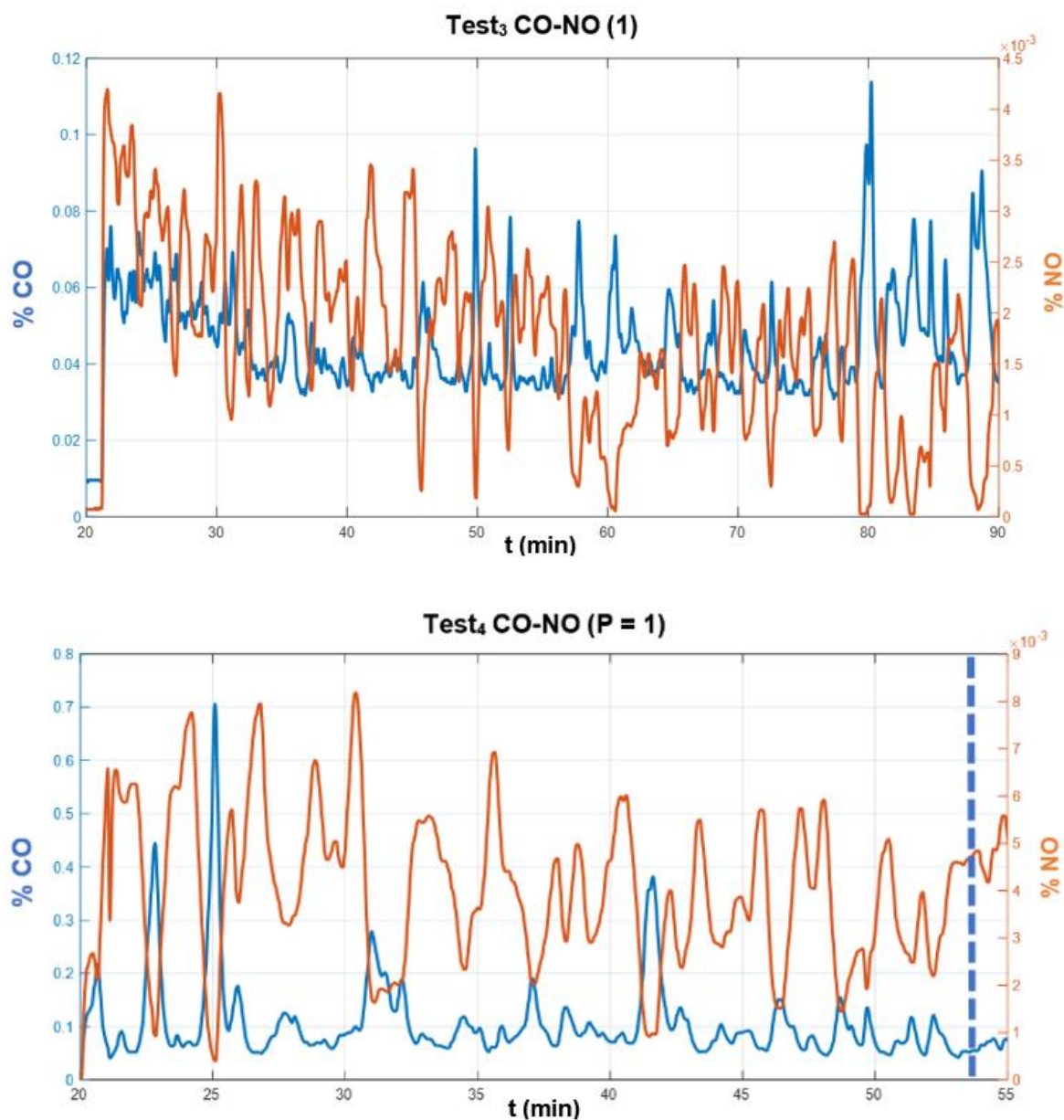


Fig. 3.25: % CO vs % NO trends in different tests

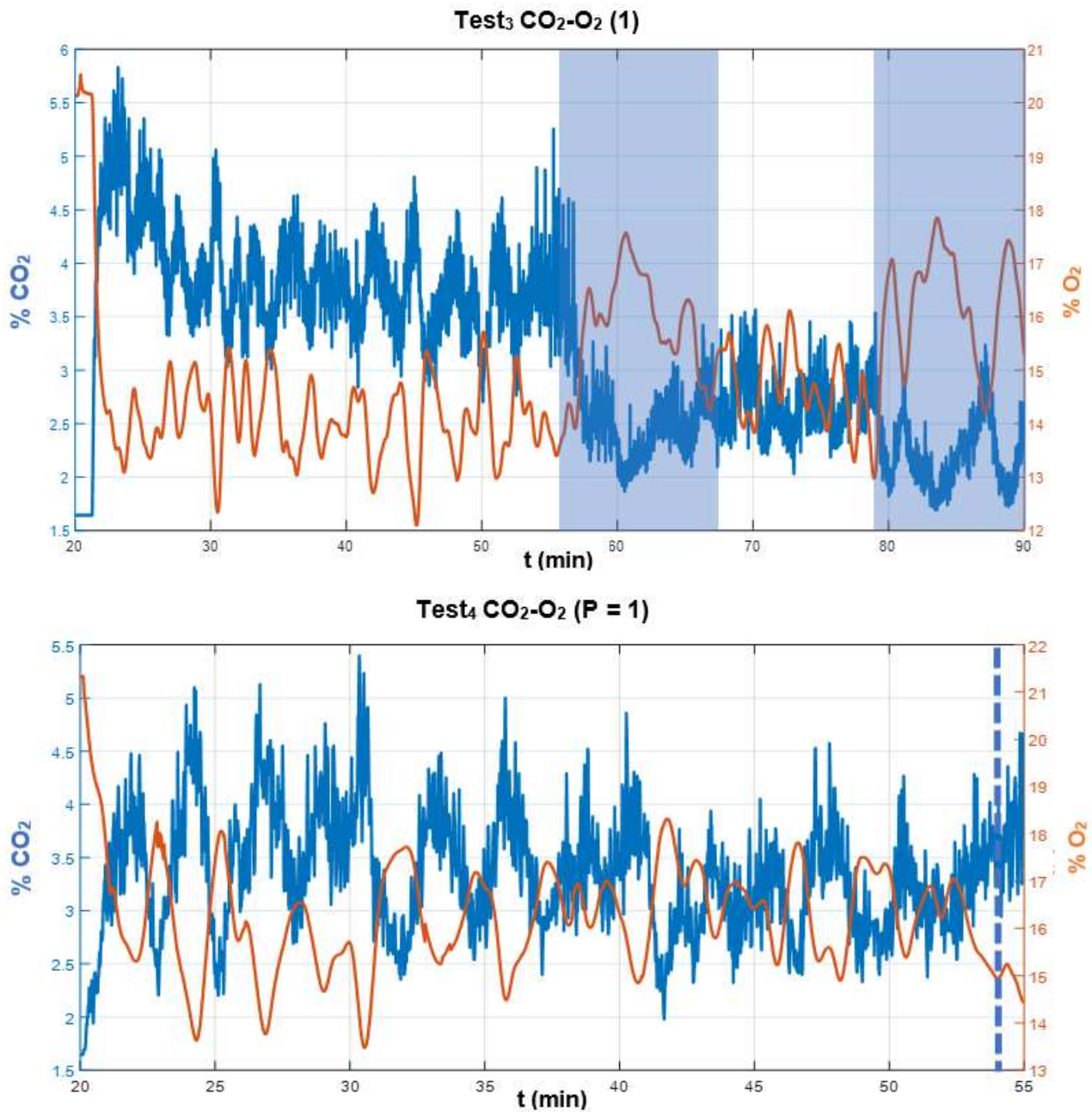
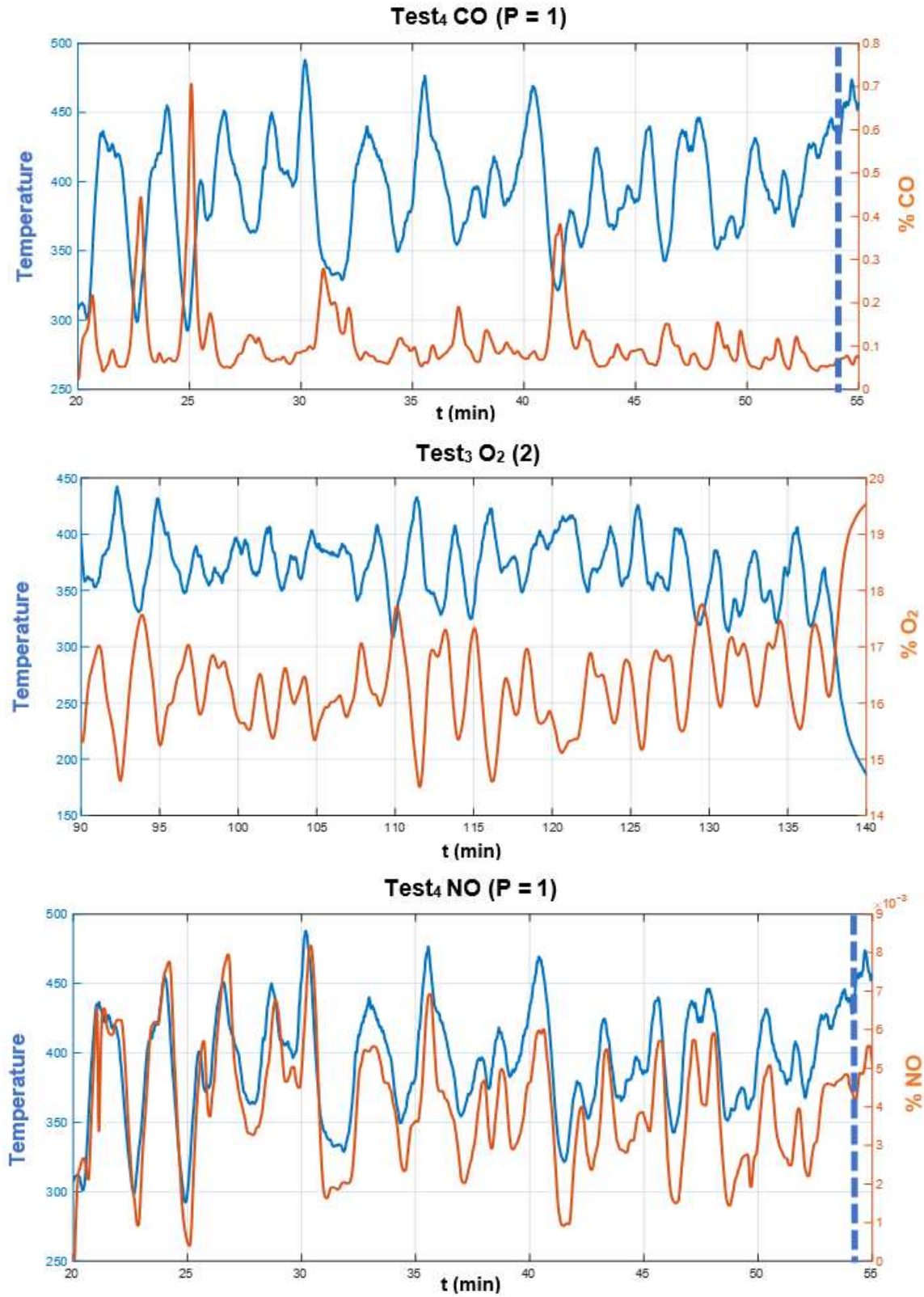


Fig. 3.26: % CO₂ vs % O₂ trends in different tests

NO₂ trends were determined according to the chamber temperature and were aligned to NO and CO₂ ones. This relative behavior between gases is typical of a combustion process; in fact, if concentrations of CO₂, NO and NO₂ increase this is a sign that combustion has improved because carbon and nitrogen from the pellet fuel have been converted adequately. Viceversa, when O₂ concentration increases this is a sign of a worst, more incomplete combustion process because more O₂ remains unconverted and CO increases as an undesired byproduct, while the other desired products decrease in concentration.

3.2.3 Gaseous pollutants trends with chamber temperature

CO and O₂ trends are opposite to chamber temperature, while NO, NO₂ and CO₂ ones are aligned, as exposed in Fig. 3.27.



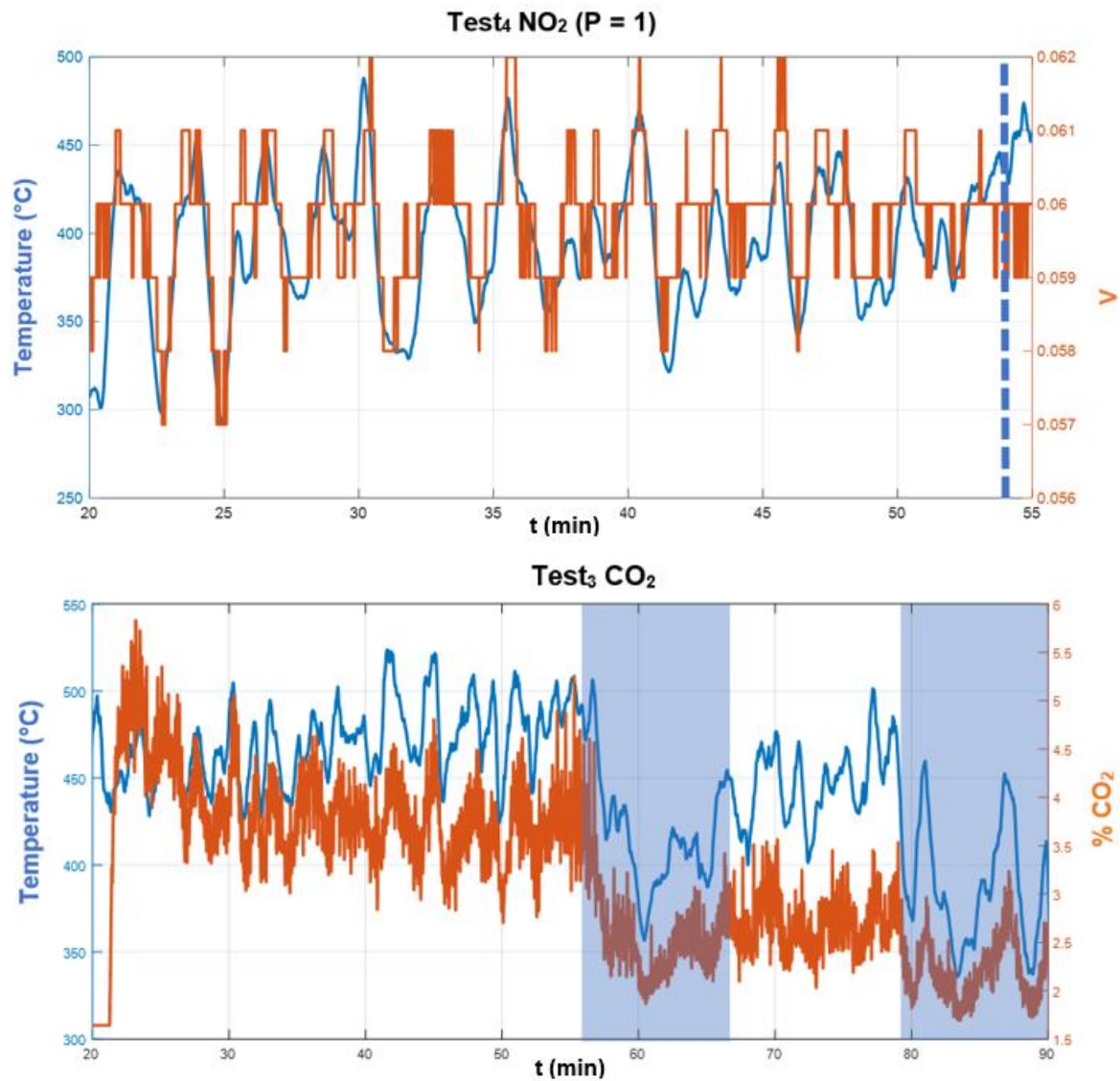


Fig. 3.27: pollutant trends against chamber temperature for different tests: CO (1), O₂ (2), NO (3), NO₂ (4) and CO₂ (5)

Temperatures in the chamber are mainly in the ranges $375 \pm 25^\circ\text{C}$ at $P=1$, $460 \pm 40^\circ\text{C}$ at $P=2$, $510 \pm 40^\circ\text{C}$ at $P=3$.

A higher temperature is signal of a more efficient combustion, therefore NO, NO₂ and CO₂ will increase, vice versa if temperature decreases it means a worst combustion, so CO and O₂ will increase instead.

Therefore, at higher power levels, temperature increases and this will decrease pollutant emissions, resulting in a positive effect on combustion.

3.2.3 Flue temperature and flue fan velocity

Flue temperature determines flue fan velocity, in fact their profiles are in agreement, as shown in Fig. 3.28, where dashed lines show the instant transitions of power level.

Flue temperature entering the fan is 150°C at P=1, 185°C at P=2 and 205°C at P=3. With a higher power level, combustion has improved, thus flue temperature in the exhaust gases.

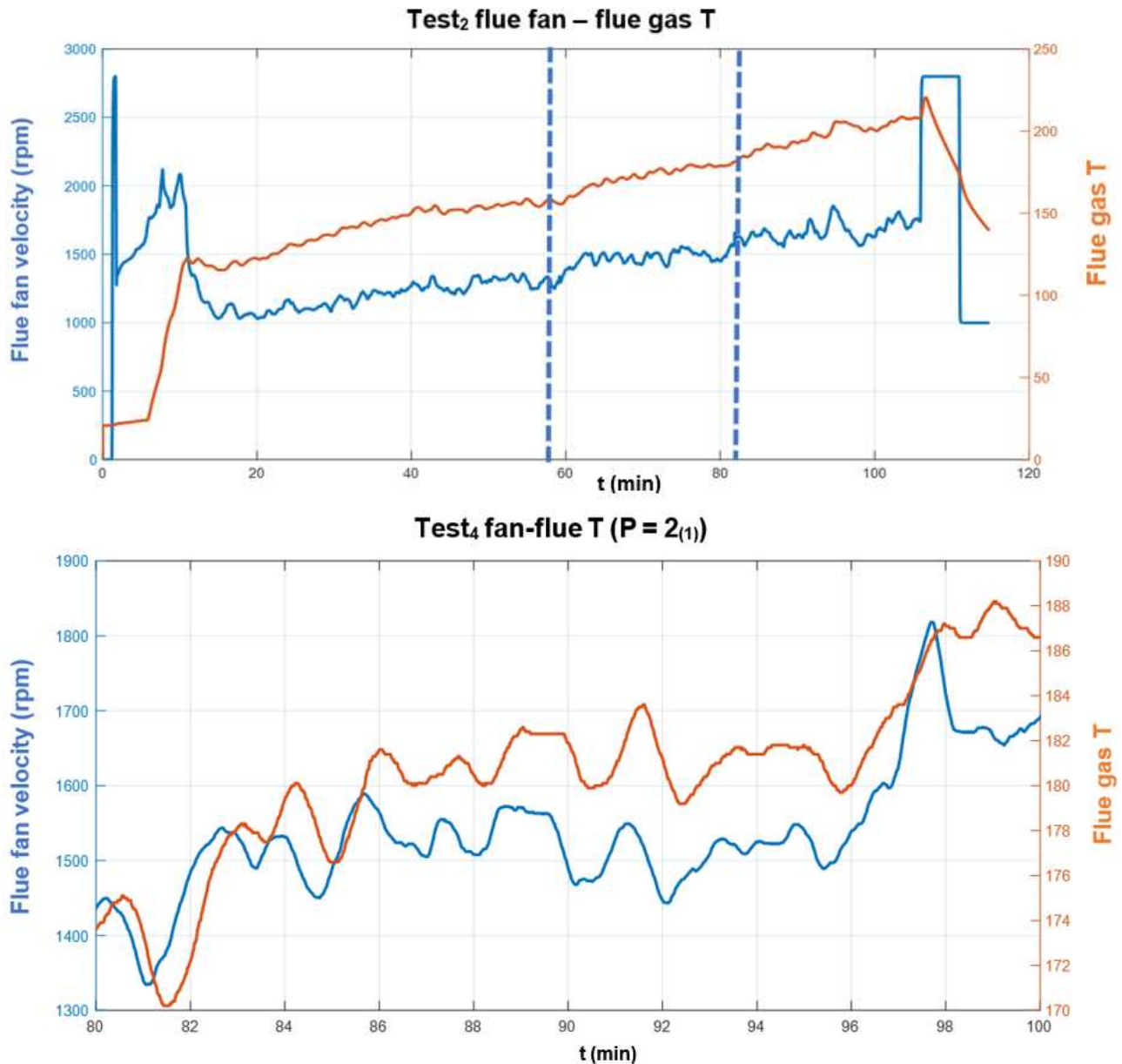


Fig. 3.28: flue fan velocity vs flue temperature entering the fan for different tests

This also affects pollutant concentrations, in fact CO and O₂ trends are opposite to flue fan velocity, while NO, NO₂ and CO₂ ones are aligned, as shown in Fig. 3.29 for O₂ and CO₂ as examples.

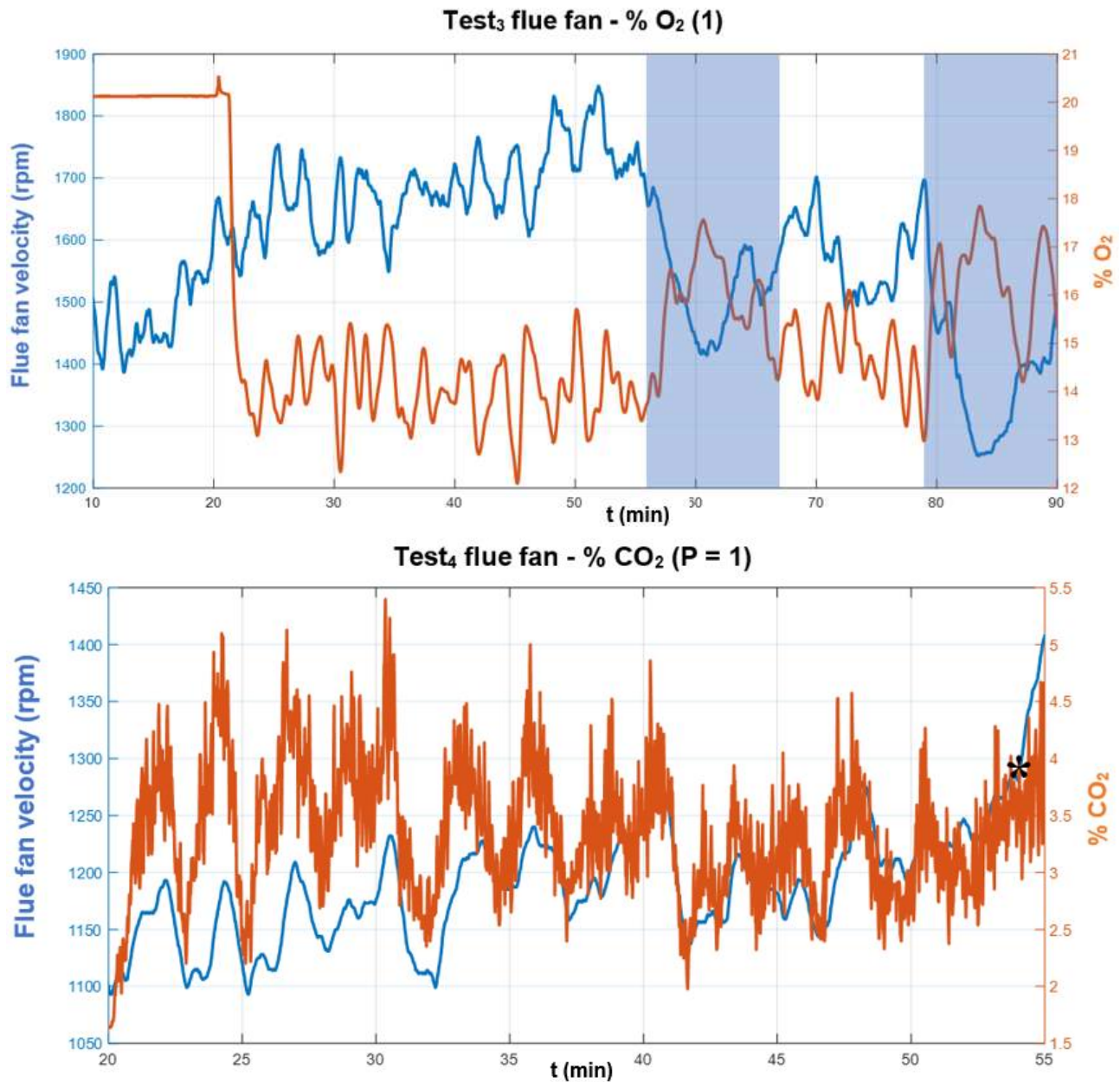


Fig. 3.29: flue fan velocity trends related to % O₂ (1) and % CO₂ (2) for different tests

A better combustion implies a higher combustion temperature, therefore a higher flue gas temperature so flue fan velocity has the same trends against pollutants than chamber temperature.

Ratio between flue temperature and fan velocity is mainly in the range between 0.105 and 0.12 °C/rpm, as in Fig. 3.30.

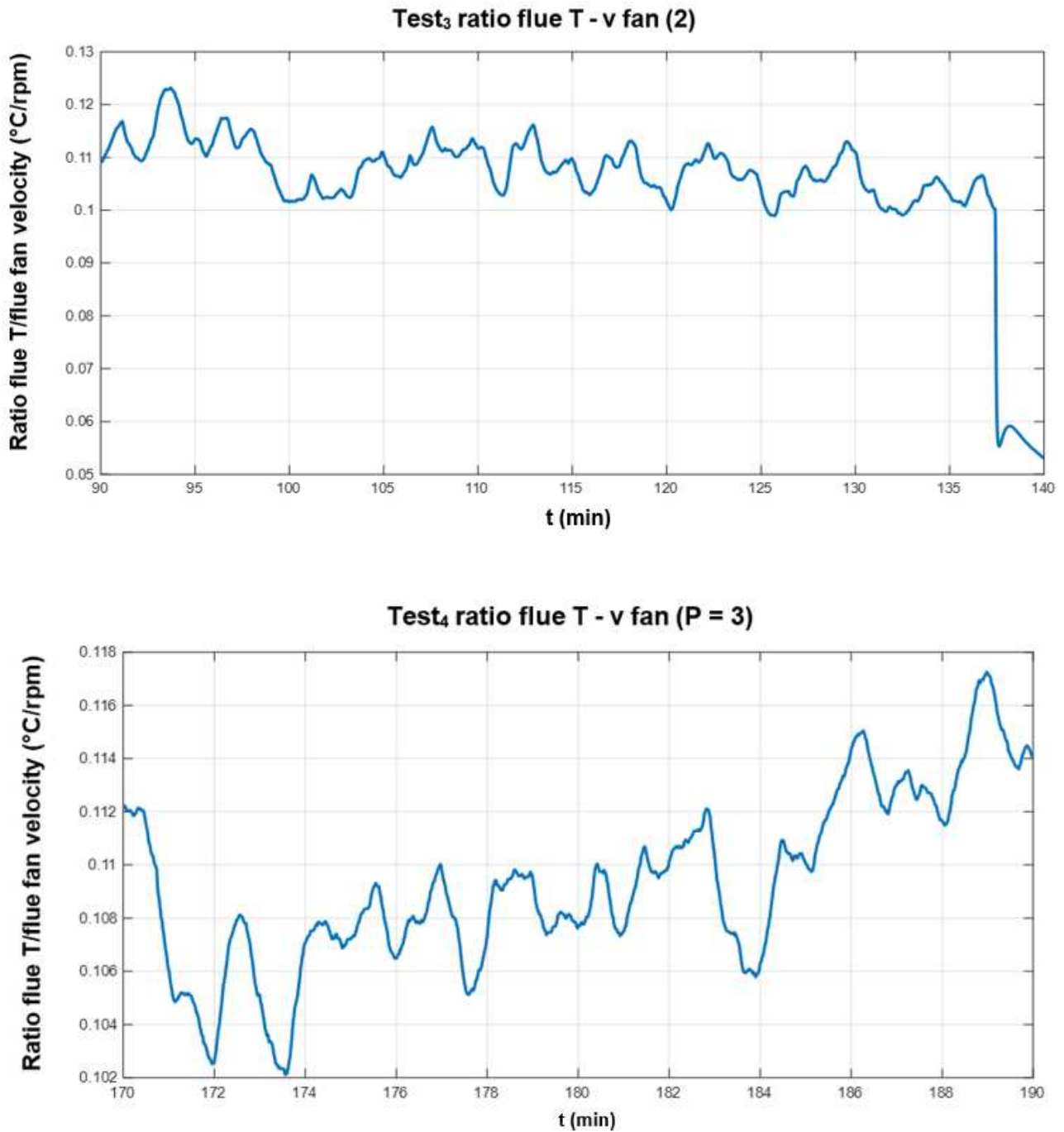


Fig. 3.30 ratio between flue temperature and flue fan velocity for different tests

Flue fan velocity is 1450 ± 50 rpm at P=1, 1650 ± 50 rpm at P=2, 1800 rpm with a 1950 maximum at P=3, with a constant 2800 rpm value during burnout. Some fan plots are shown in Fig. 3.31.

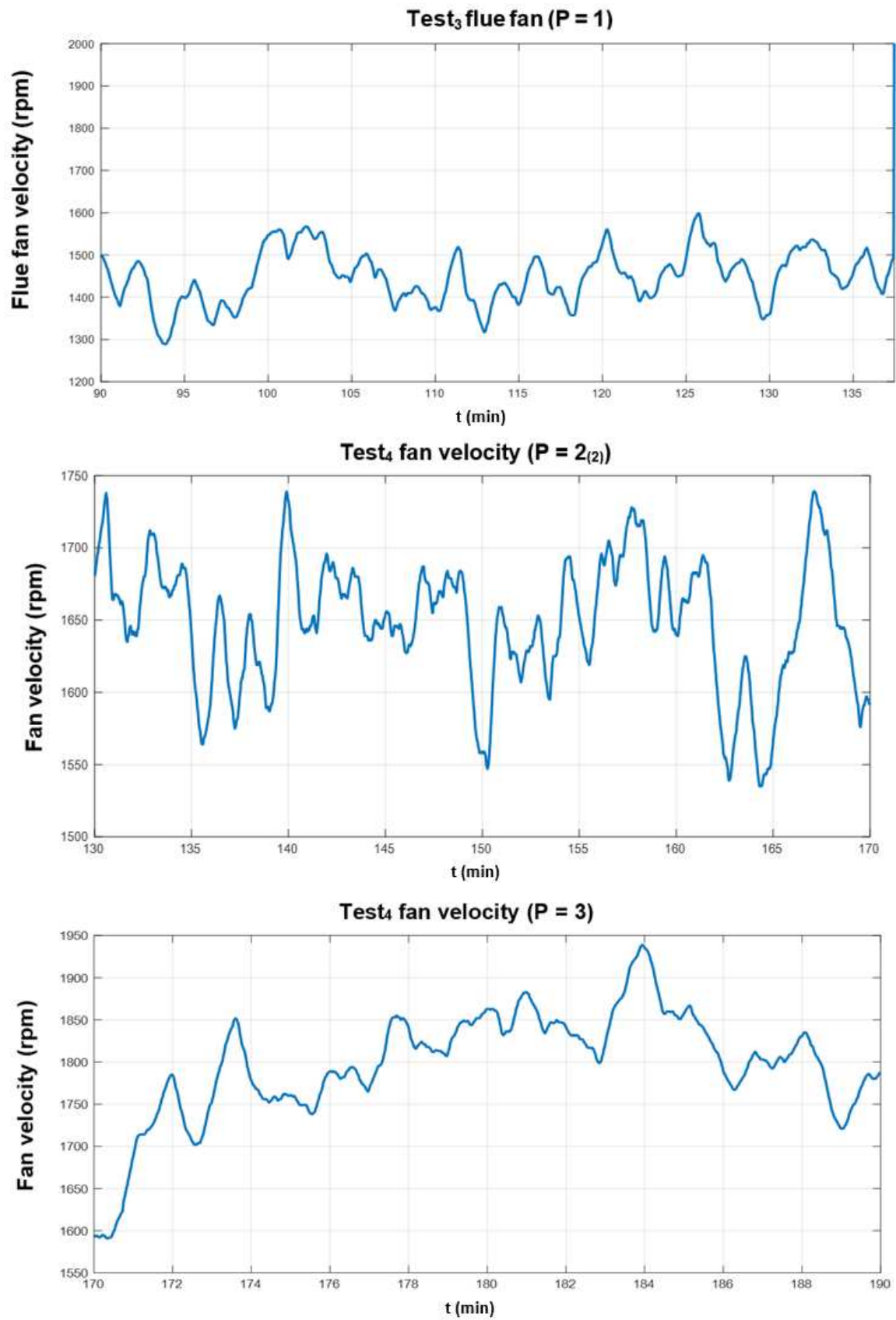


Fig. 3.31: flue fan velocity values at $P=1$ (1), $P=2$ (2) and $P=3$ (3)

To sum up, flue temperature thus flue fan velocity values are effects of combustion conditions and increase for greater power levels, thus higher combustion temperatures.

3.2.3 Cochlea rotation speed and power level

Different tests have been run testing the three different power levels for the pellet stove, increasing or decreasing its value. Power level is shown to be determined by cochlea loading rotation speed, probably in rph: values are 605 for P=1, 800 for P=2 and 990 for P=3, as exposed in Fig. 3.32 for increasing and decreasing power levels. Transitions from lower to higher power levels are instantaneous, while from higher to lower values are in a time range of about 11 minutes, where cochlea rotation minima match with flue fan velocity minima as in Fig. 3.33 for the same tests d decreasing power levels. In fact, if the pellet loading pace decreases, less pellet is combusted per unit of time, the chamber temperature and the flue temperature decrease, and so does the flue fan velocity.

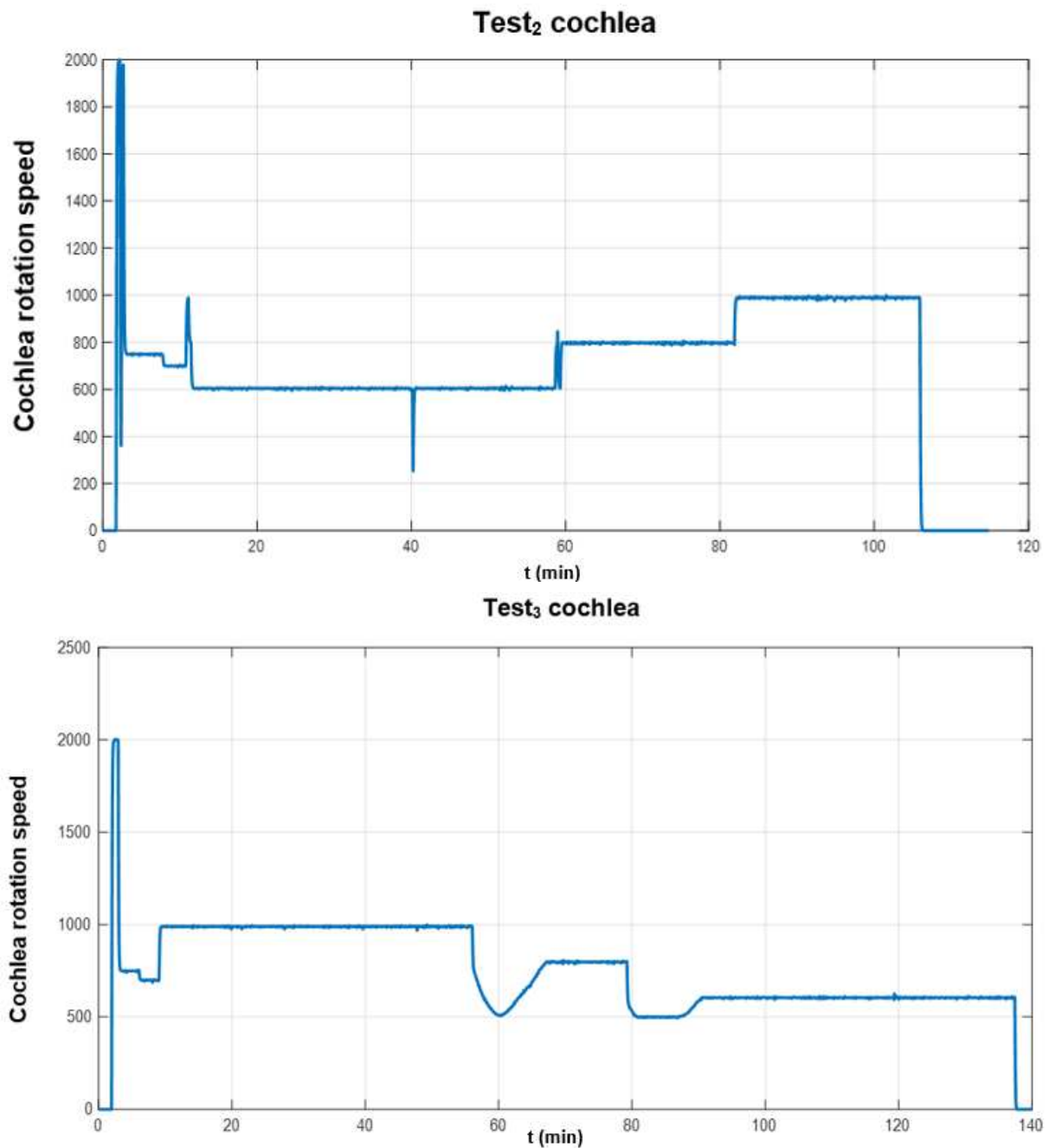


Fig. 3.32: cochlea loading rotation speed at increasing and decreasing power levels

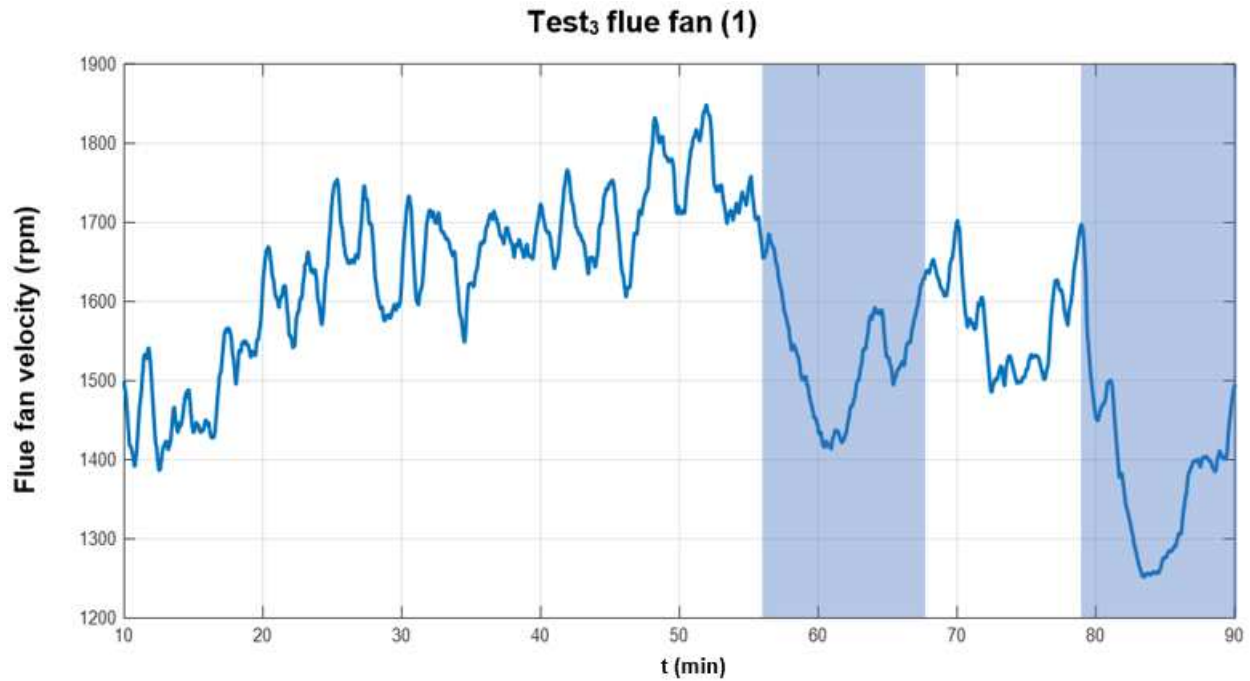


Fig. 3.33: flue fan velocity at decreasing power levels, blue bands are transition time ranges

An increase in cochlea rotation speed is therefore the physical effect due to a remote power level increase and will therefore produce a higher temperature in the combustion chamber.

3.2.3 Ratio CO/CO_2

Ratio CO/CO_2 is 0.04 ± 0.01 at $P=1$ and 0.02 ± 0.005 at $P=2$ and 0.017 ± 0.003 at $P=3$. Fig. 3.34 shows the difference at increasing power levels.

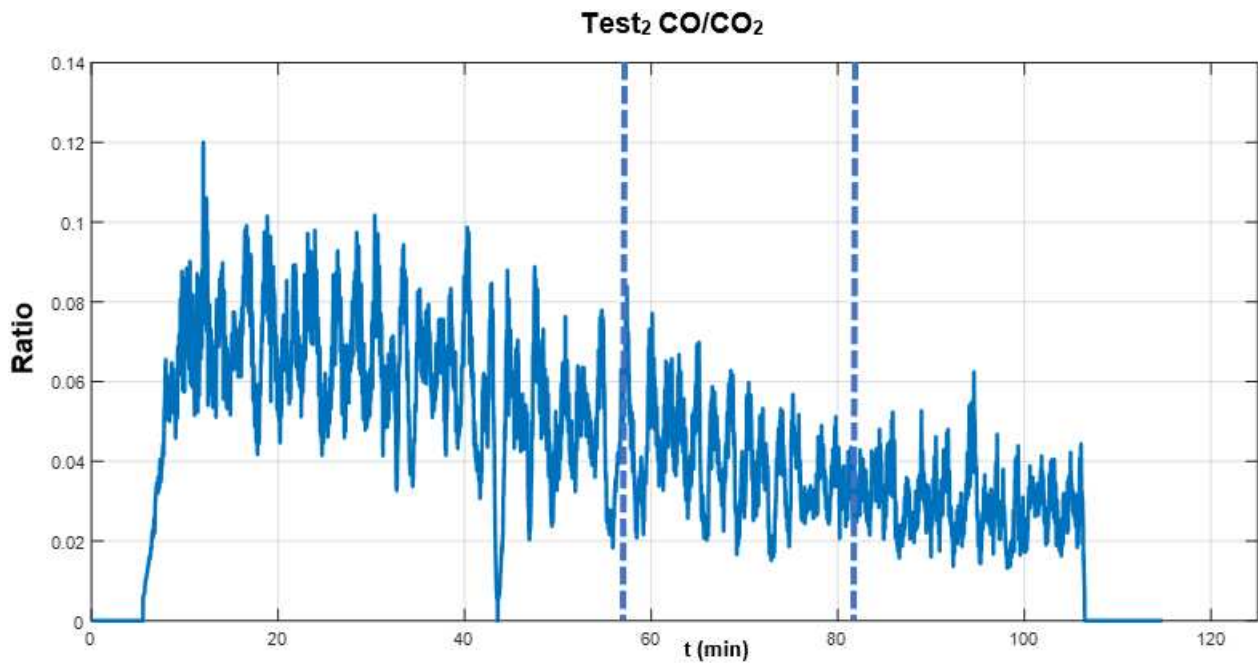


Fig. 3.34: ratio CO/CO_2 over a combustion cycle at increasing power from $P=1$ to $P=2$ and from $P=2$ to $P=3$

CO/CO₂ decreases as power level increases, sign that combustion efficiency improves at higher powers.

3.2.3 Gaseous pollutants concentrations and power level

On average, O₂ is 16±0.5% at P=1, 15±0.5% at P=2, 14±0.5% at P=3, confirming that efficiency increases by oxygen consumption. In Fig. 3.35 a power-depending O₂ trend is shown.

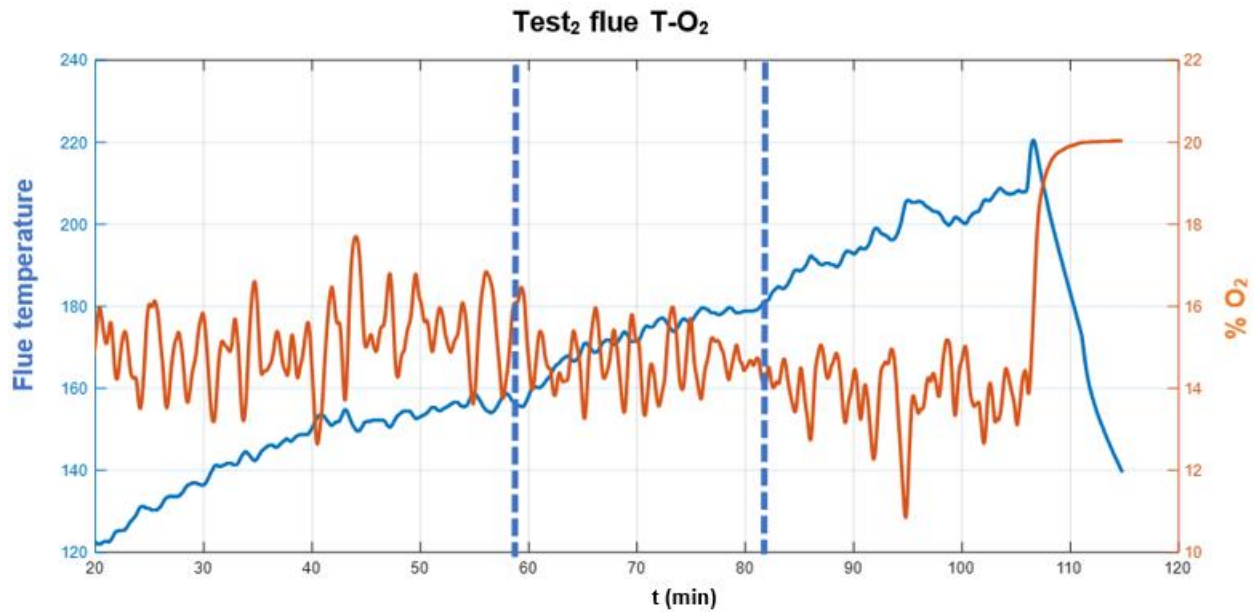
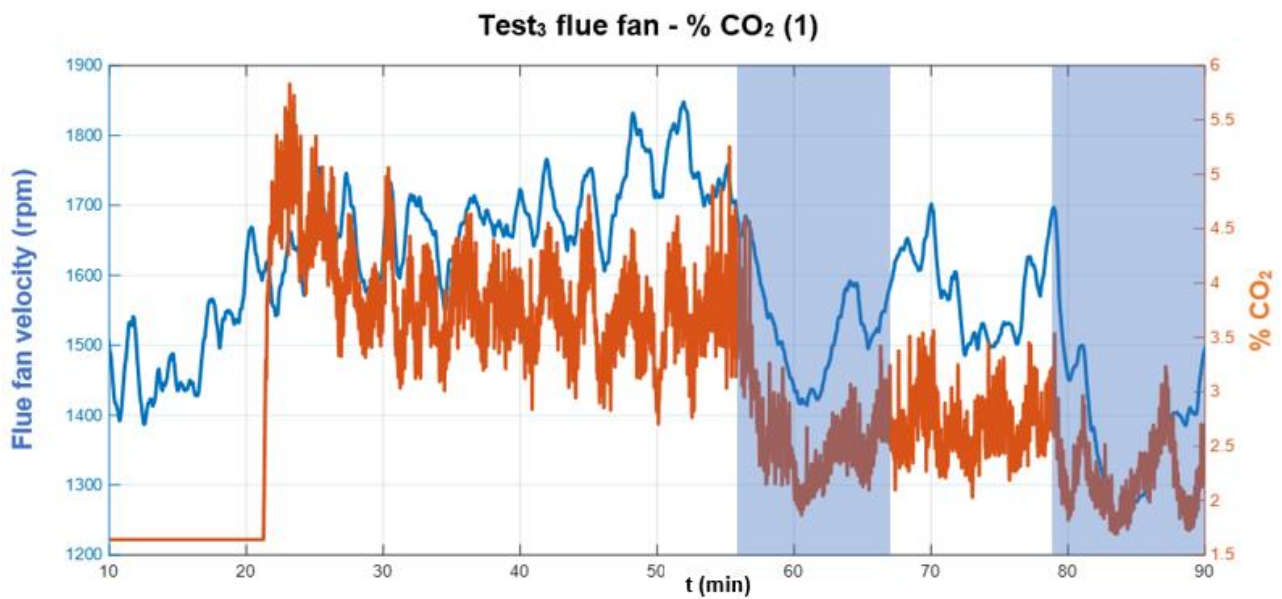


Fig. 3.35: O₂ concentration variation at increasing power levels

Without a particulate residue, at P=1, CO₂ is 2.3±0.1%, at P=2 2.6±0.1%, at P=3 3±0.5%, so it increases with power level due to better combustion conditions. Fig. 3.36 shows the decrease of CO₂ concentration at decreasing power level for the same test.



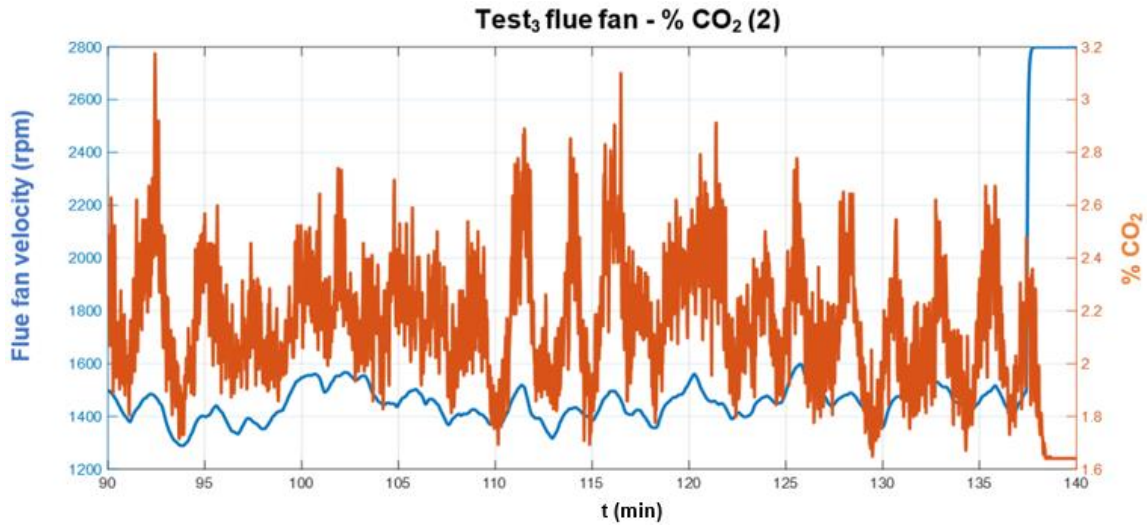


Fig. 3.36: % CO_2 at decreasing power levels: $P=3$ and $P=2$ (1), and $P=1$ (2)

NO emissions measured values slightly decrease with power level decreasing: $2\text{--}2.5 \times 10^{-3} \%$ for $P=3$, $1.5\text{--}2 \times 10^{-3} \%$ for $P=2$ and $0.5\text{--}1.5 \times 10^{-3} \%$ for $P=1$, as shown in Fig. 3.37 for decreasing power levels.

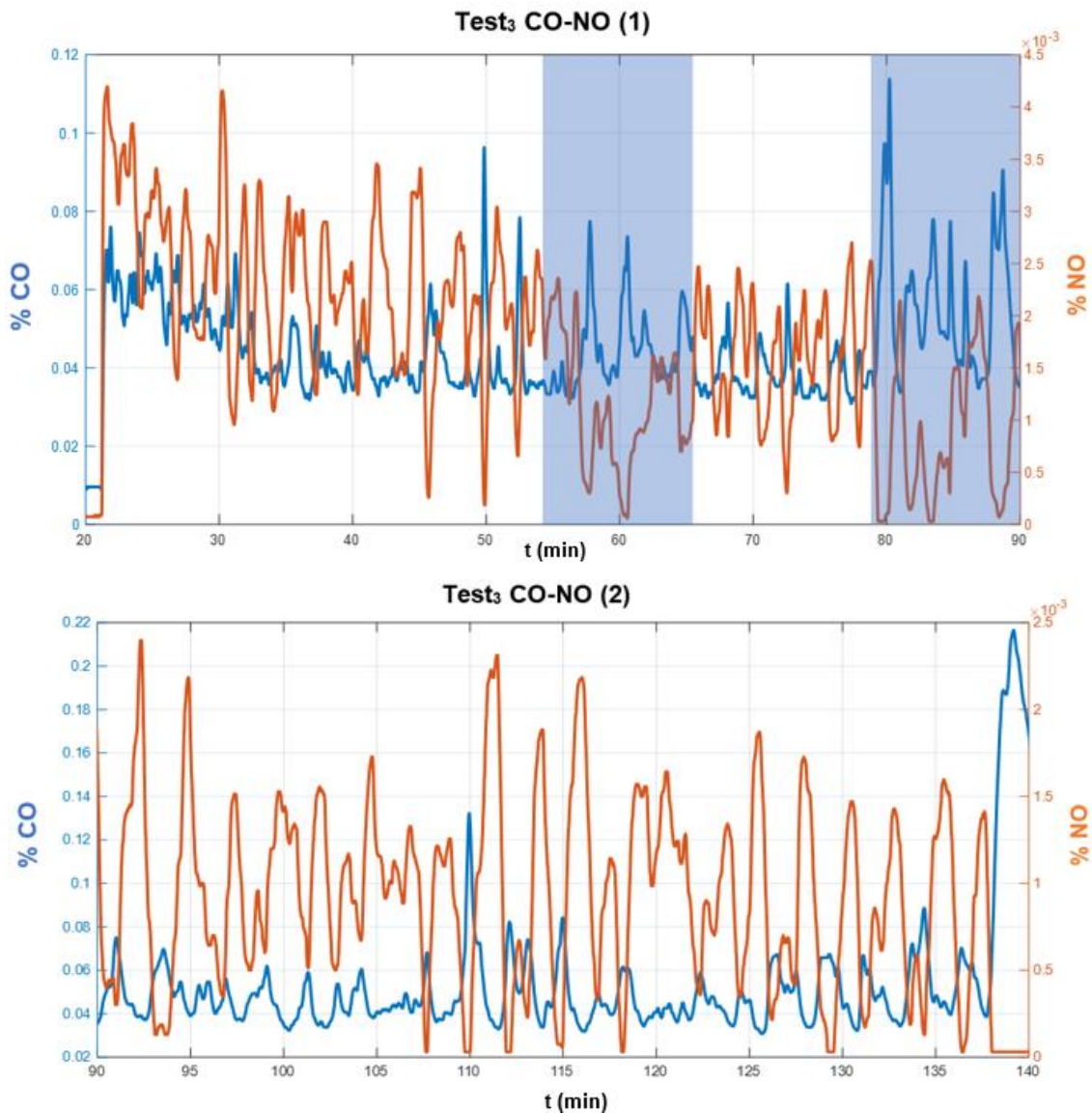


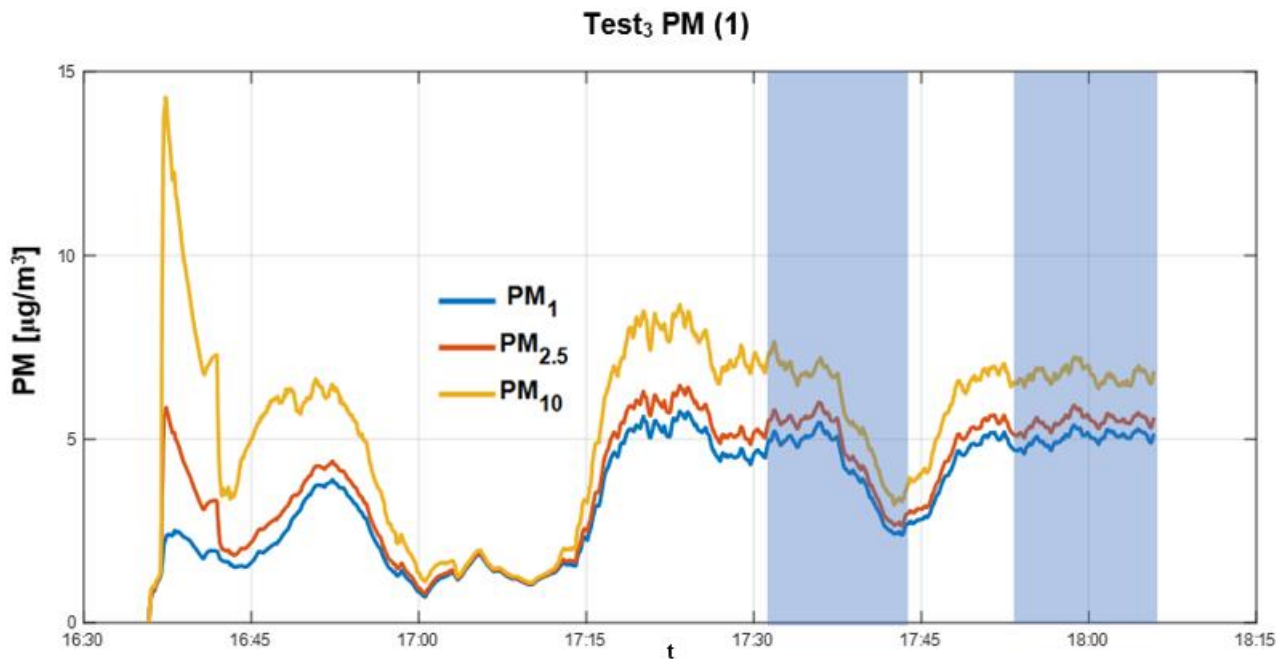
Fig. 3.37: % NO and % CO at decreasing power levels: $P=3$ and $P=2$ (1), and $P=1$ (2)

NO₂ sensor was not calibrated so relative trends with temperature are judged according to potential profiles just to identify a behavior. Anyway, NO₂ concentrations are negligible and the very slight variations of Fig. 3.27 (4) confirm this hypothesis. From Fig. 3.37, CO at P=1 is $0.05 \pm 0.01\%$ at P=2 and P=3 $0.035 \pm 0.005\%$.

In general, lower CO emissions and higher NO and CO₂ emissions are verified at increasing power levels, confirming better combustion conditions, as in the case of chamber temperature.

3.2.3 Particulate matter concentrations

PM₁₀ shows an initial sharp peak during ignition phase: the maximum reached is about $85 \mu\text{g}/\text{m}^3$. then it approaches PM_{2.5}, stabilizing at values lower than $10 \mu\text{g}/\text{m}^3$ (Fig. 3.38(1)). In fact, combustion just started is still an irregular phenomenon and suspended ashes are entrained, and then the constant pellet loading is coupled with a uniform crucible temperature. Heavier particles, with a diameter between 2.5 and $10 \mu\text{m}$, are plotted too. PM₁₀ concentration values and profile largely depends on finer particles and its trend is opposed to flue fan velocity and flue temperature at any power level (Fig. 3.38(2 and 3)). In fact, a higher temperature is symptom of better combustion conditions and so lower concentration of solid particles, suspended and entrained as undesired products.



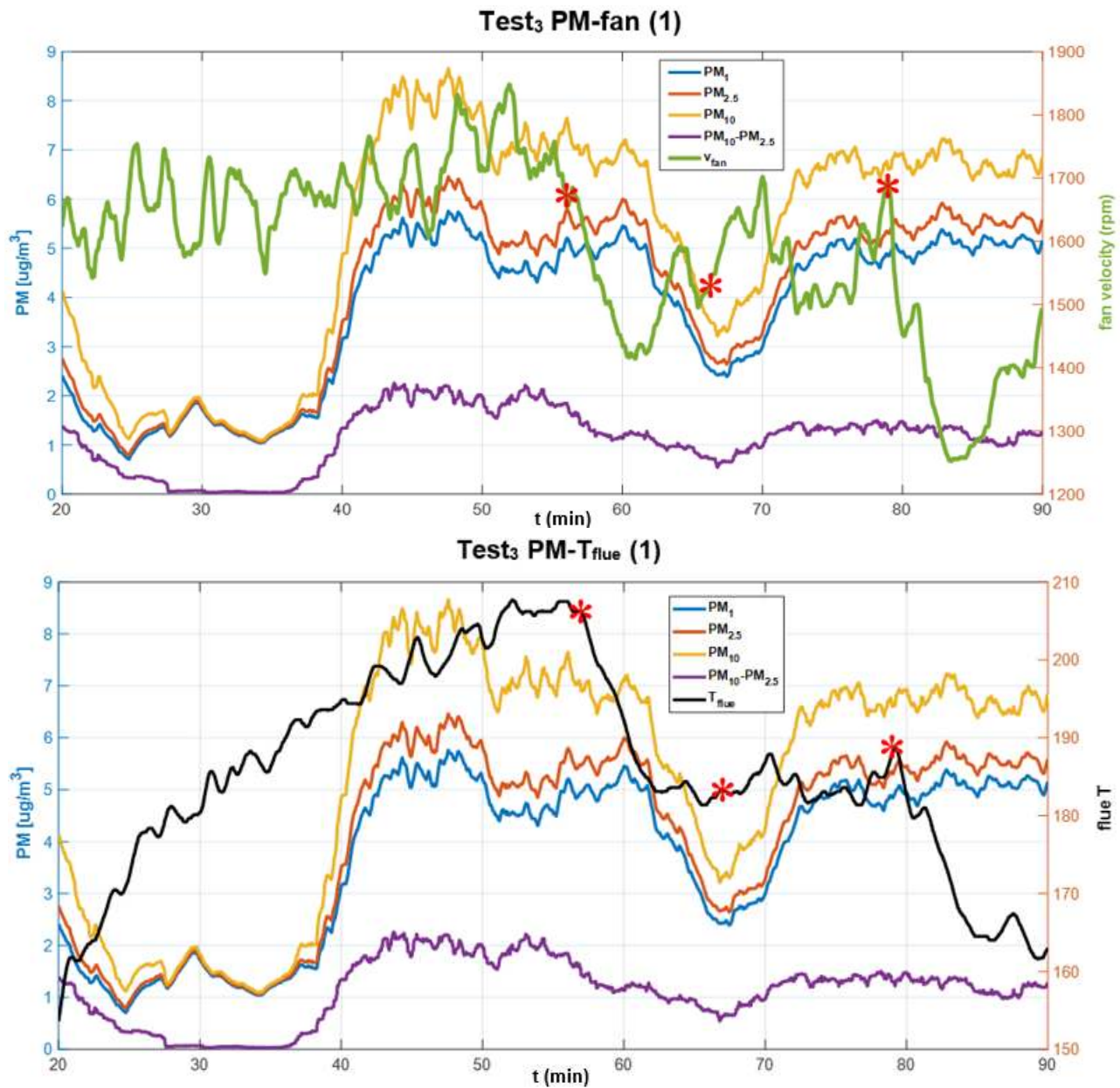


Fig. 3.38: PM_{10} , $\text{PM}_{2.5}$ and PM_1 concentrations at decreasing power levels: ignition and stabilization (1), relative trend with fan velocity (2) and flue temperature entering the fan (3)

Particulate emissions slightly increase with power level, differently from the other flue gases, at $P=3$ and $P=2$ $7.5 \mu\text{g}/\text{m}^3$ for PM_{10} and $6 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ while at $P=1$ 7 for PM_{10} and $5.5 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$; one possible reason is that because fuel loading is more sustained, despite high temperatures combustion side products are formed and this aspect prevails against the previous one. $P=1$ values are shown in Fig. 3.39.

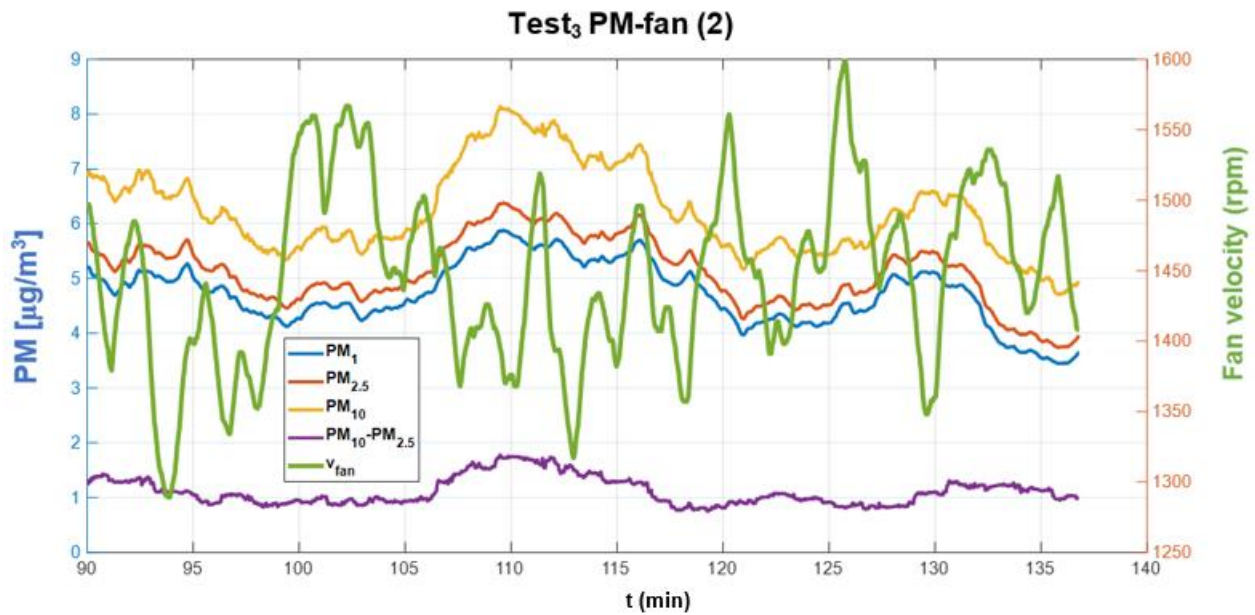


Fig. 3.39: PM concentration profiles at $P=1$

To sum up, at constant power level PM_{10} concentration trend is opposed to flue fan velocity and flue temperature, confirming the positive effect of temperature even for solid particles emissions. However, a slight increase in concentration is verified increasing power level due to more sustained burning conditions.

3.2.3 Effect of particulate residue

One test was carried out at increasing power with ashes still present in the combustion chamber from a previous test. The main evidence from PM profiles is that heavier particles affect PM_{10} profile much more than $PM_{2.5}$, both for trends and numerical values as shown in Fig. 3.40 for $P=1$. The trends have more irregular peaks due to an unexpected additional contribution.

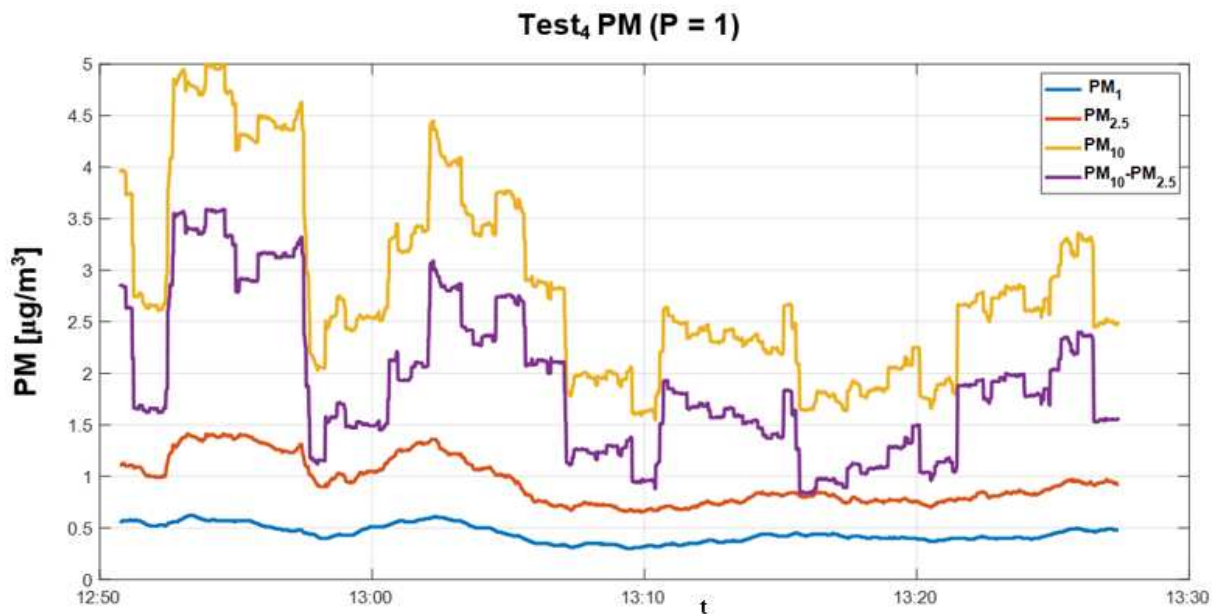


Fig. 3.40: PM profiles at $P=1$ during residue test

At $P=2$, the trends are unexpectedly aligned, as in Fig. 3.41. Because combustion conditions accordingly to the previous tests look the best ones; one possible explanation could be that increasing gas flowrate, fan velocity increases, so even crucible ashes are more entrained with the flue gases.

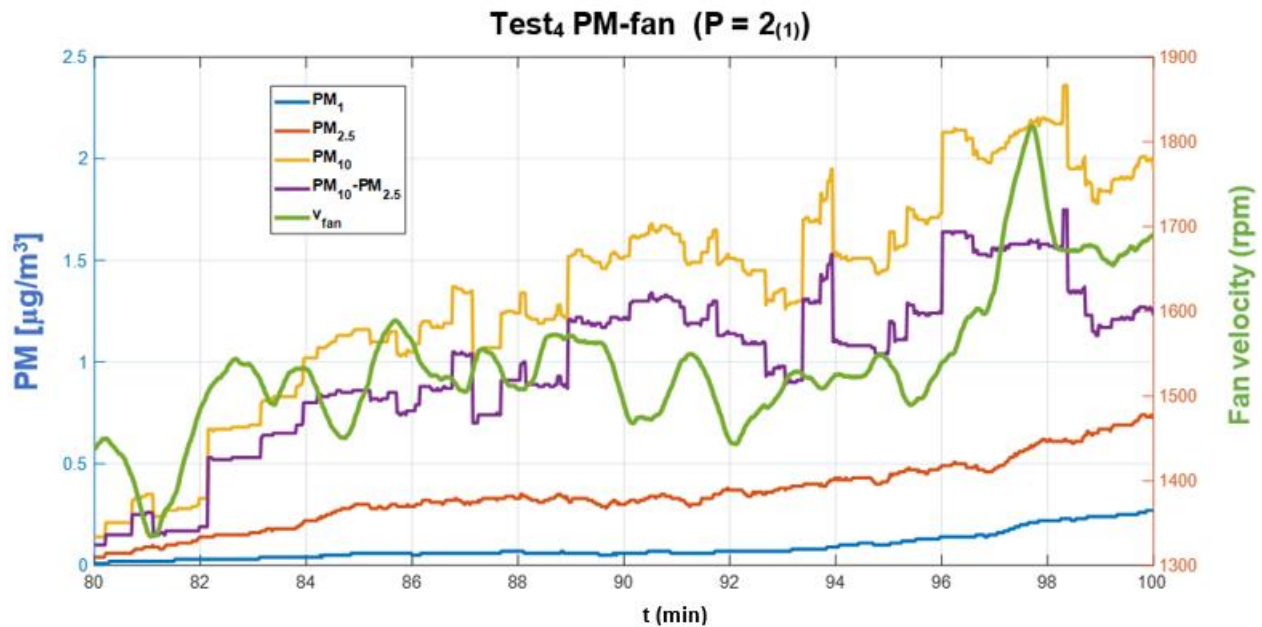


Fig. 3.41: PM and fan velocity profiles at $P=2$ during residue test

Keeping power level constant at $P=2$, ashes contribution becomes more and more negligible with time and relative trends are again opposite and particulate matter is better abated than $P=1$, as exposed in Fig. 3.42. PM_{10} trend again depends on heavier particles ($2.5-10\ \mu\text{m}$), but the long-time exposition shows that sometimes values also depend on finer powders, especially when in figure the violet curve assumes values lower than the red one.

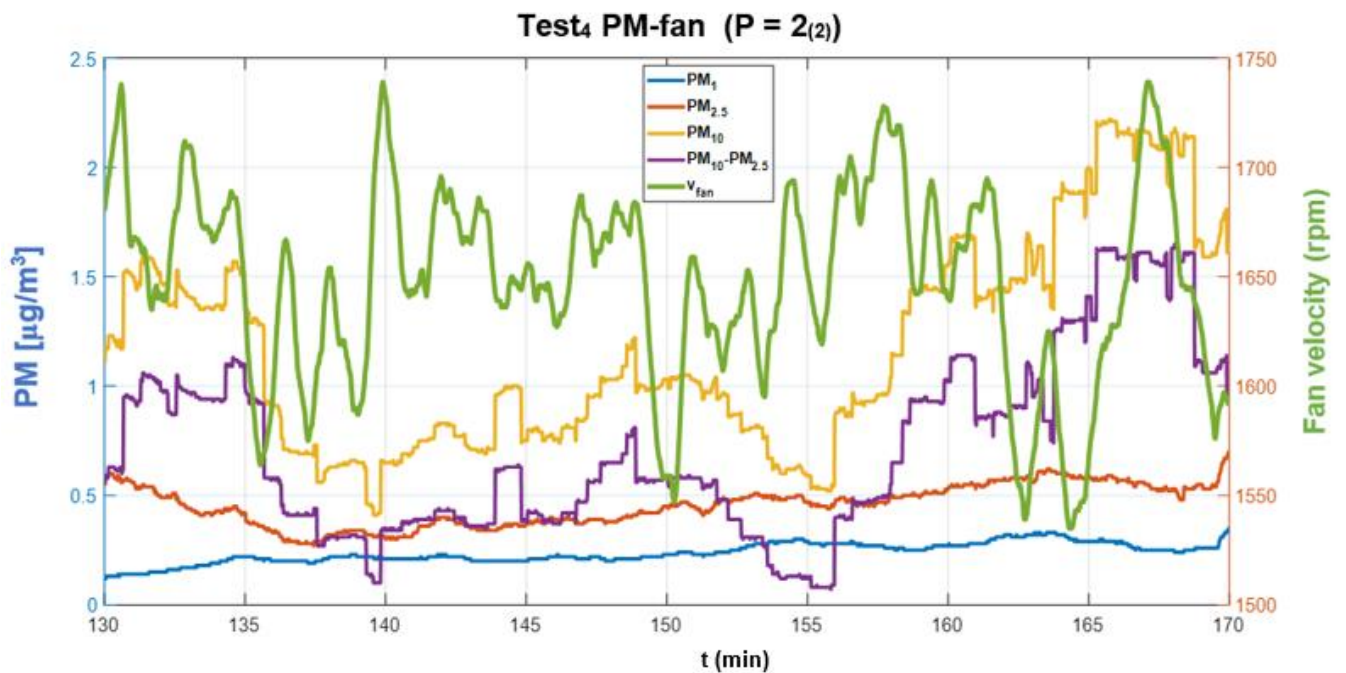


Fig. 3.42: second $P=2$ phase of residue test with PM and fan profiles

At P=3, PM₁₀ has greater values than the other phases. The high loading pace causes in fact a worst pellet combustion. The trend almost completely depends on heavier particles, while values mainly on finer ones, as confirmed from the plot in Fig. 3.43. Trends show a decrease in the entrained particulate residue relative contribution to the total PM₁₀ values.

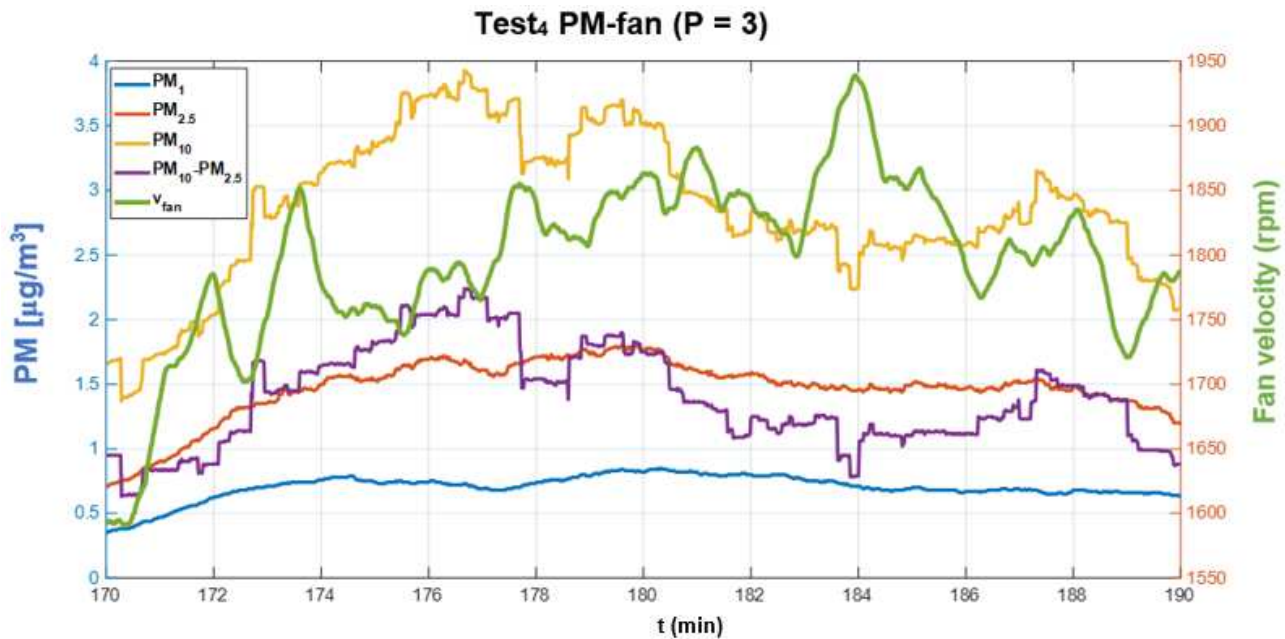


Fig. 3.43: P=3 phase during residue test, PM and fan velocity profiles

With a particulate residue, PM₁₀ trend and values are more affected by heavier particles, despite values halved with respect to previous standard tests. The effect of particulate residue even impacts on pollutants concentrations.

CO₂ levels increase in presence of particulate residue in the crucible mostly due to ashes combustion: At P=1, CO₂ is 2.3±0.1% while 3.5±0.5% with residue, at P=2 2.6±0.1% while 3.5±0.5% with residue, at P=3 3±0.5% while 4±0.5% with residue.

With particulate residue, (4±1) e-3% NO is reached at P=1 and (2.5±0.5) e-3% NO at P=2 and P=3, despite being on a (1, 3) e-3% without particulate residue.

CO at P=1 is 0.05±0.01% while 0.09±0.01% with residue, at P=2 and P=3 0.035±0.005% while 0.06±0.01% with residue.

In general, particulate residue could represent an undesired contribution to solid and gaseous emissions due to worst combustion conditions and ashes entrainment. Heavy powders contribution also becomes dominant respect to finer particles. With a long-time exposition, entrainment becomes more and more negligible because the residue has gradually decreased. To avoid an increase in emissions concentrations, cleaning and maintenance are usually required.

3.2.3 Air depression and velocity measurements

About total depression, the values are constant at 125 Pa for P=1, 128 Pa for P=2 and 130 Pa for P=3, as shown in Fig. 3.44 for increasing power levels from 1 to 3.

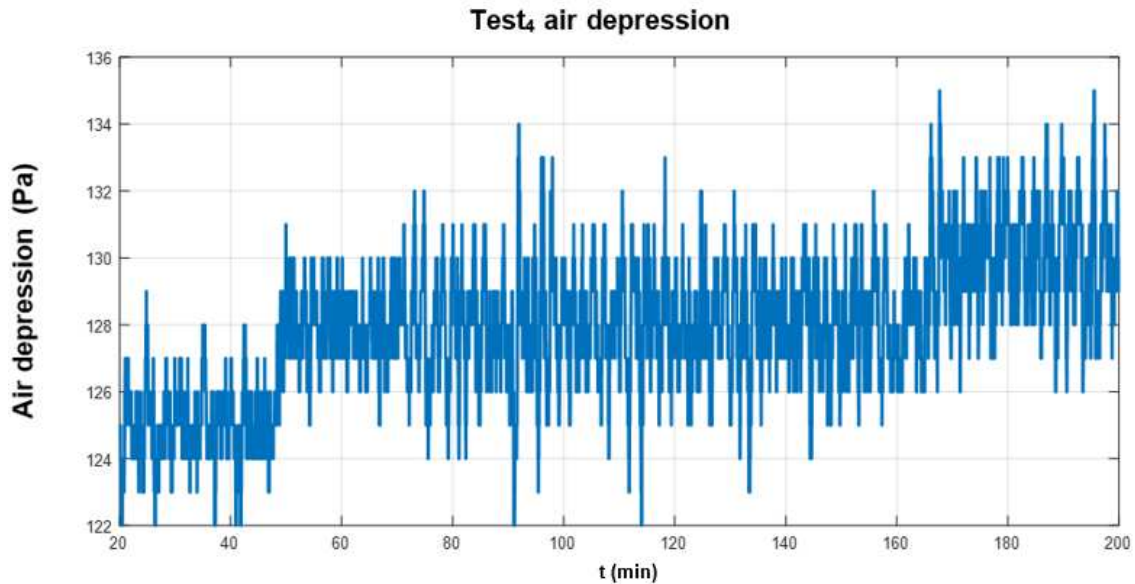


Fig. 3.44: depression plots at increasing power levels

Because the hot wire anemometer damaged, the instrument did not measure adequately. To investigate if and how much inlet velocity depends on the conditions required for combustion. Problems encountered with velocity measurements are tried to be fixed by installing a rigid plastic tube and drilling it to insert a new portable hot wire anemometer to measure air inlet velocity. to calibrate the anemometer by a comparison test, inlet flowrate measurement was carried out with a flowmeter, measuring it in another thinner flexible tube of about 1 cm diameter, linked with the rigid tube through a restriction; the experimental line is depicted in Fig. 3.45.



Fig. 3.45: inlet velocity experimental line: portable anemometer, rigid tube and flowmeter

Anemometer measurements were carried out to link air velocity and depression. Every second, velocity values are collected and knowing the inlet diameter (0.035 m) and times of the two measures were overlapped, calculating the volumetric flowrate for every value of velocity by converting into m^3/h . Plot in Fig. 3.46 was obtained, where flowrate depends on the depression bend placed in the inlet line. The quadratic relationship between depression in Pa and velocity in m/s is expressed by the parabolic tendency curve.

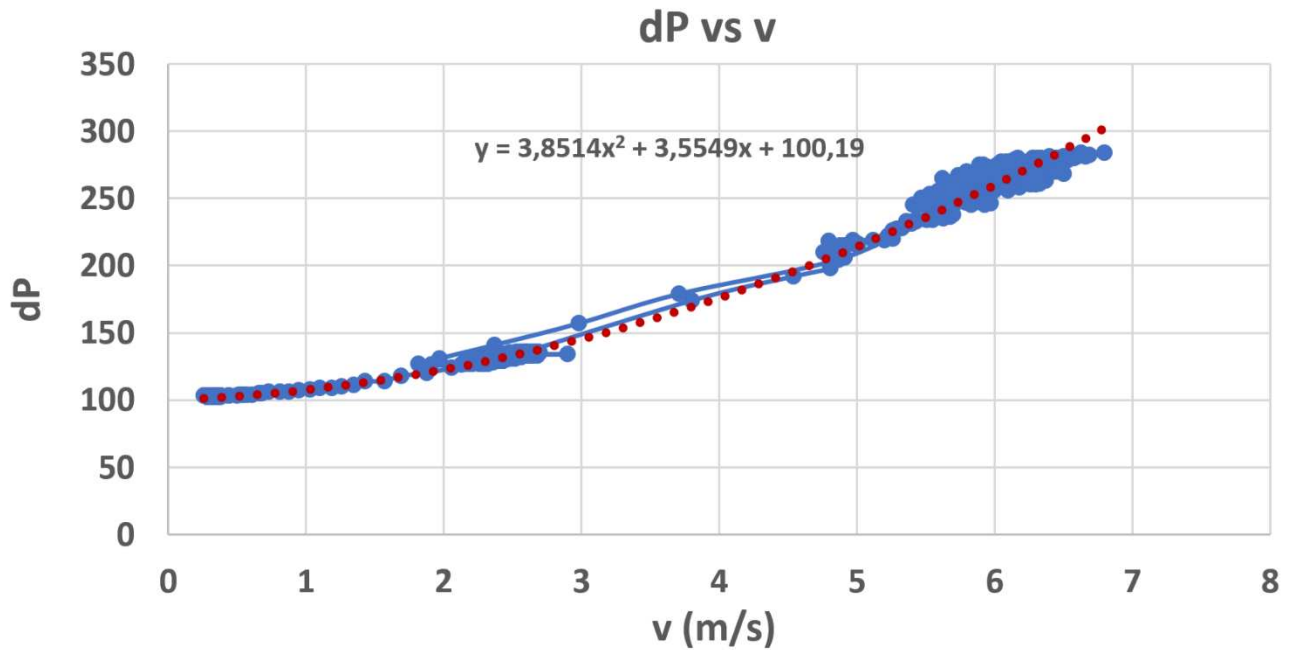


Fig. 3.46: depression vs inlet velocity plot

3.2.3 Comminuted pellets effect

2 kg of pellets have been comminuted to have a maximum length of 1 cm, to evaluate if pellet size will affect combustion conditions and thus emissions. The idea behind is to simulate pellets inaccurately charged in the bag at the end of the production line or bags imprecise arrangement in loading and unloading phases of transportation.



Fig. 3.47: comminuted pellets examples

An empty bag was chosen to contain the small-size pellets. To accurately determine the right amount of 2 kg the tare was weighted over a weight scale giving 41.5 g. A plastic scoop was employed to load pellets 250 g at a time in the stove tank. Its weight was 63.5 g, subtracted to the total weight.

The portable anemometer was used to determine inlet velocity, while outlet velocity and outlet depression were determined by a Pitot tube inserted in the flexible aluminum line entering the hood. Filters were also used for particulate capture, a quartz wool filter, and a round thin filter inserted in a metallic filter housing with a hook as probe.

Filter flowrate was measured after 60 minutes for 30 minutes, after 120 minutes for 30 minutes and after 180 minutes for 30 minutes. Standard pellets were loaded, except for two phases where comminuted pellets were inserted in the tank, i.e., after 120 minutes for 30 minutes and after 180 minutes for 30 minutes.

The stove was set at $P=3$.

A set of measures is shown in Table 3.18. Pellets are inserted 250 g at a time, and comminuted ones entered the tank 5 minutes before the filter flowrate sampling: this is to consider the pellet head already present in the almost empty tank and therefore the delayed combustion of these pellets.

Table 3.18: dataset for comminuted pellets test

<i>Minutes</i>	<i>Inlet velocity (L/min)</i>	<i>Outlet velocity (L/min)</i>	<i>dP out (Pa)</i>	<i>Filter flowrate (L/min)</i>	<i>Pellet loading (g)</i>
09:05 (start)	2.7	2.1	0.4		250
5	2.3	2.3	0.5		250
15	1.5	1.5	0.2		250
20	1.35	1.5	0.2		250
25	1.4	1.5	0.2		0
30	1.36	1.5	0.2		250
40	1.4	1.42	0.2		250
45	1.43	1.5	0.2		0
50	1.4	1.58	0.2		0
55	1.4	1.55	0.2		0
60	1.37	1.55	0.2	5	250
65	1.43	1.53	0.2	5.6	0
70	1.39	1.61	0.3	5.2	0
75	1.38	1.53	0.2	5.5	250
80	1.37	1.48	0.2	5.6	0
85	1.39	1.63	0.3	5.3	250
90	1.52	1.61	0.3	5.2	0
95	1.45	1.53	0.2		0
100	1.4	1.56	0.3		250
105	1.47	1.58	0.3		0
110	1.46	1.65	0.3		0
115	1.41	1.75	0.3		250
120	1.53	1.74	0.3	5	0
125	1.54	1.8	0.3	4.8	250
130	1.58	1.75	0.3	5	0
135	1.46	1.65	0.3	5.2	250
140	1.46	1.67	0.3	5.3	0
145	1.54	1.8	0.3	5.2	250
150	1.39	1.81	0.3	5.3	0
155	1.39	1.75	0.3		250

160	1.54	1.77	0.3		0
165	1.48	1.74	0.3		0
170	1.38	1.87	0.3		0
175	1.57	1.83	0.3		250
180	1.44	1.82	0.3	5	0
185	1.55	1.87	0.4	4.7	250
190	1.59	1.81	0.3	4.9	0
195	1.54	1.9	0.4	4.9	250
200	1.31	1.92	0.4	4.5	0
205	1.58	1.94	0.4	4.7	250
210	1.57	1.86	0.4	5.2	0
215	1.59	1.79	0.3		0
220	2.7	2.8	0.8		0

Filter flowrate slightly decreases during small-size pellets charging, probably because with small size pellets combustion approaches more powder combustion so one pellet burns easily. The particulate plot (Fig. 3.48) shows a little tendency of higher soot emissions with smaller fuel, in the ranges (120, 150) and (180, 210). If the filter captures more particulate, an effect could be the pressure drops increase, so a lower flowrate.

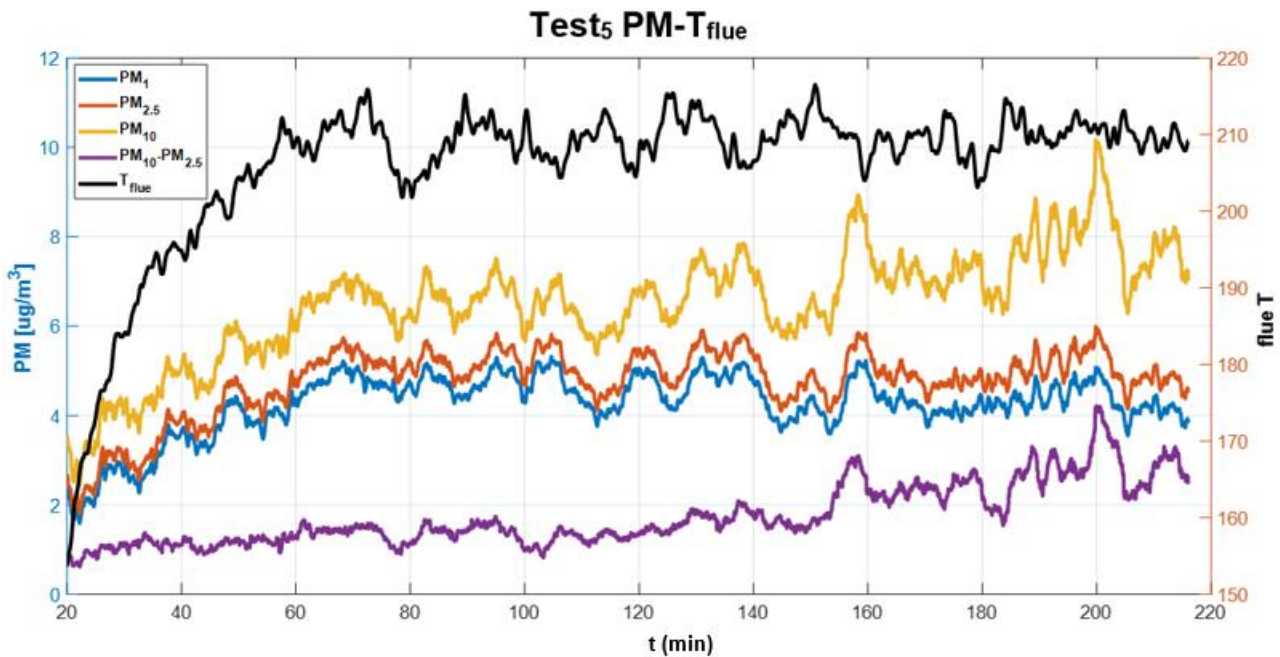


Fig. 3.48: particulate plot for comminuted pellets test

Comminuted pellets caused little higher soot emissions and also gaseous ones, in particular NO, reaching 0.022%. In general, with short pellets combustion efficiency has slightly worsened.

3.2.3 Water vapor effect

A test simulating a humid external environment, where water concentration in the air is higher and the aim is to evaluate the impact of humid inlet air on combustion conditions and in particular particulate concentration.

To inflate steam inside the feed line, two components are necessary. The first one is a nebulizer which changes phase to a water substrate generating a water-steam aerosol in a plastic box. The second one is a simple rigid but flexible tube to send the aerosol in the feed line (Fig. 3.49).



Fig. 3.49: vapor test experimental: nebulizer, plastic box and flexible tube

Steam was inflated after 130 minutes for 30 minutes and after 240 minutes for 30 minutes.

Again, the filter flowrate is slightly lower than 5 L/min, so it seems confirmed the effect of particulate matter. Comminuted pellets and humid air feed therefore have as consequence a slightly higher increase in particulate matter emissions in the flue gases.

3.2.4 20 kg load test

A test with a 20 kg pellets load in the tank was carried out to get information about cochlea velocity behavior for a long cycle. 8 hours were chosen as the lasting time.

The tank cover was sealed with short plastic tubes fixed with aluminum scotch to amortize the closing and avoid supplementary air entry (Fig. 3.50). Supplementary air decreases as pellet head increases, so the aim is to minimize as much as possible this value.



Fig. 3.50: tank cover sealing for 20 kg load tests

Power level was set at 3. The value for cochlea loading rotation velocity typically is 1374 ± 4 rph, the maximum so far: this is probably due to the high weight burden pressing on the screw in order to avoid blockage from badly arranged pellets increasing the drive torque (Fig. 3.51).

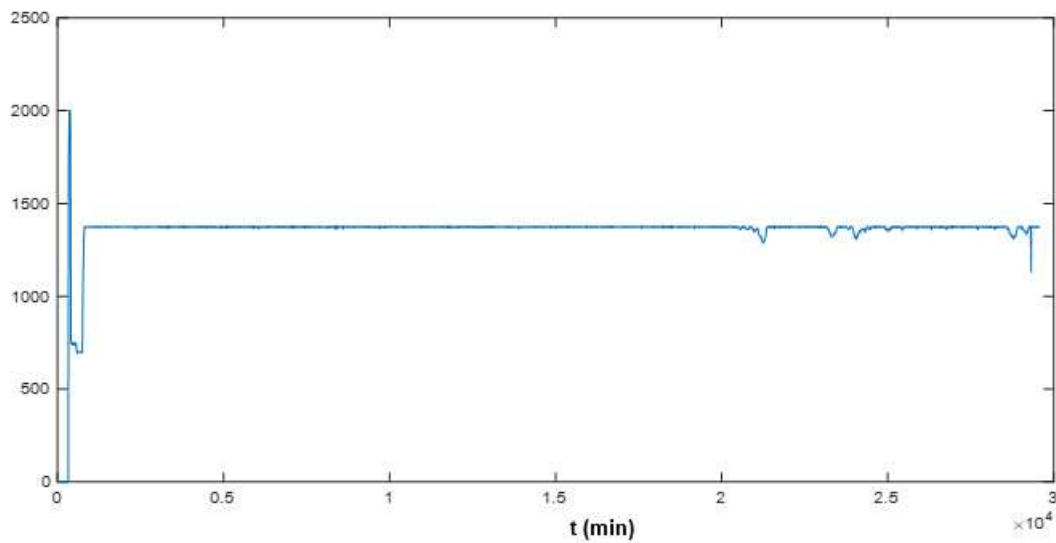


Fig. 3.51: cochlea loading speed for 20 kg test

Fan velocity starts from 1500 rpm and continuously increases and eventually sets at a value of 2300 ± 20 rpm, with even a maximum at 2443 rpm, as in Fig. 3.52. This is because of the gradually increasing chamber heating during the 8 hours test. Emissions show no particular difference with emission parameters measurements.

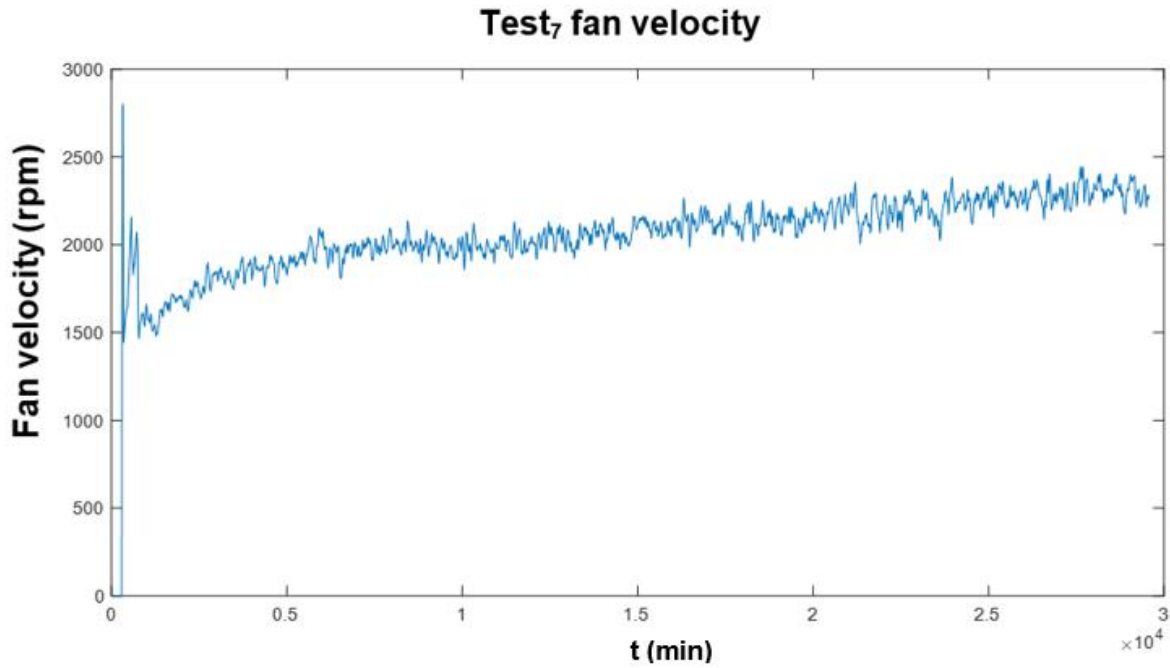


Fig. 3.52: flue fan velocity plot for the 8 hours test

3.2.3 Concentration limits calculations

Ecodesign emission limit values for pellet stoves are 20 mg/m³ for PM, 300 mg/m³ for CO and 200 mg/m³ for NO_x.

During operation, PM₁₀ is constantly below 10 µg/m³ with an 85 µg/m³ maximum during ignition: these values are way below the Ecodesign limit.

CO maximum value is 0.4% for humid air, which compromises combustion. The related concentration value is 19 mg/m³, which is lower than 300 mg/m³. Because at normal conditions its highest value is 0.06%, the CO emissions performance of the stove is excellent.

NO maximum value is 0.022% with short pellet test, while at normal conditions values span from 0.001 to 0.003%. The corresponding concentration is 1.05 mg/m³ and because NO₂ value is lower than NO one, if not negligible, NO_x will be below 200 mg/m³, fulfilling the requirements.

Therefore, the stove widely respects 2022 Ecodesign limits for pellet stoves.

3.2.16 Final remarks on emissions measurements

From the emissions tests carried out to assess pollutants trends and values and to link them with the stove internal parameters, it is possible to draw some conclusions.

A remote power level increase is physically linked to an increase in cochlea rotation speed as an effect to generate a temperature rise inside the combustion chamber. In fact, despite short time transitions at decreasing powers, pellet loading pace assumes constant values for a fixed power level.

A higher internal temperature is sign of better combustion conditions, resulting in NO, NO₂ and CO₂ increase, while a lower temperature gives a worst pellet burning, so CO and O₂ will increase instead, being an undesired byproduct and an unconverted reactant respectively. Therefore, at higher power levels pollutant emissions will decrease, resulting in a positive effect on combustion as confirmed by the performance index CO/CO₂, which decreases at higher powers.

Increasing power level, thus improving combustion efficiency, causes a flue temperature rise and therefore a highest flue fan velocity due to a gas flowrate increase.

At constant power level particulate matter concentration profile is opposed to flue temperature, confirming the positive effect of temperature even for solid particles emissions. However, a slight increase in PM₁₀ concentration is observed with higher power levels due to more sustained combustion conditions.

The effect of ashes inside the crucible of the chamber causes negative effects both for solid and gaseous pollutant emissions, affected by ashes entrainment and worst combustion conditions respectively. While with no residue finer particles determined particulate trends and values, with ashes the heavy powders contribution (2.5 to 10 µm) becomes prominent. Only a long-time exposition will make the entrainment more and more negligible because of the residue slow decrease. To avoid an undesired increase in emissions concentrations, user cleaning is required.

Tests with feed variations with shorter pellets and water vapor in the inlet caused a just worse combustion environment with a slight increase in particulate matter concentrations and gaseous pollutants, with NO maximum for shorter pellets and CO maximum for humid air.

The 20 kg load test showed no particular variations on emissions or trends compared to the previous emission tests.

CO, PM and NO_x concentration are below the 2022 Ecodesign limit values for pellet stoves, therefore it fulfills the requirements.

In summary, despite serious variations on working conditions for different tests the stove performance emissions are aligned with the recent European regulations. As for power level, P = 2 value is more efficient than P = 1 in terms of combustion conditions, therefore on pollutant concentrations. Even though P = 3 ensures better gaseous emissions, PM₁₀ concentrations increase; the suggested power level from these tests is therefore P = 2 as a compromise value.

Conclusions

In this Thesis, temperature and emission measurements have been carried out to assess the best operating conditions in a commercial pellet stove and to verify if the stove respects the 2022 Ecodesign emission limit values for the pollutants analyzed.

Other tests have been carried out changing the initial conditions to verify how the stove reacted to changes in the initial conditions, with shorter pellets, water vapor in the inlet and a 20 kg initial test. From the temperature tests, the most efficient values in terms of combustion conditions for front vent (V1) and suction vent (V2) velocity have been found to be 1 and 5 respectively: these values have been kept for the following emission tests.

A power level $P=2$ is shown to ensure better combustion conditions and gaseous pollutants concentration than $P=1$. $P=3$ certainly reduces gaseous pollutants emission better than $P=2$ but on the other hand increase PM_{10} concentrations; another drawback of $P=3$ from a practical standpoint is fast pellet consumption and a high energy release. Therefore $P=2$ is considered the best value for power level to decrease emissions. The ashes effect shows that user frequent cleaning and maintenance is also important to limit all combustion solid and gaseous emissions. Shorter pellets and humid air tests show a slight but not relevant increase in particulate matter concentrations. 20 kg pellet load test showed regular pollutant and parameter values, with no sensible impact on gaseous pollutants or PM with respect to emission tests. CO , PM and NO_x concentration values are below the 2022 Ecodesign limits for pellet stoves, making the stove fulfilling recent regulations.

List of abbreviations

CO = Carbon Monoxide

VOCs = Volatile Organic Compounds

PAHs = Polycyclic Aromatic Hydrocarbons

O₂ = Oxygen

CO₂ = Carbon Dioxide

PM = Particulate Matter

NO_x = Nitrogen Oxides

NO = Nitrogen Monoxide

NO₂ = Nitrogen Dioxide

OGC = Organic Gaseous Compounds

PCDD = Polychlorinated Dibenzodioxins

UNECE = United Nations Economic Commission for Europe

EPA = Environmental Protection Agency

THC = Total Hydrocarbons

CH₄ = Methane

SO₂ = Sulfur Dioxide

BTX = Aromatic Hydrocarbons (Benzene, Toluene, Xylene)

FTIR sensor = Fourier Transform InfraRed sensor

FID = Flame Ionization Detector

PMA = Paramagnetic Analyzer

SMPS = Scanning Mobility Particle Sizer

DMA = Differential Mobility Analyzer

NDIR sensor = Nondispersive Infrared sensor

PN = Particulate Number

CPC = Condensation Particle Counter

TSP = Total Suspended Particles

TC = Total Carbon

EC = Elemental Carbon

OC = Organic Carbon

ELVs = Ecodesign Limit Values

V1 = Front Vent

V2 = Suction Vent

P = Power Level

OPC = Optical Particle Counter

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