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Performance characterization of an inertial separator for condensed vapours

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Table of Contents

Abstract.....	4
1 Inertial separator of condensable substances.....	5
1.1 Cyclone	8
1.1.1 Governing forces and flow field	8
1.1.2 Pressure drops and energy consumption	8
1.1.3 Purpose and typical application of cyclones	9
1.1.4 Cyclone operation with hot pyrolysis fumes	9
1.1.5 Global collection efficiency	9
1.1.6 Fractional (grade) efficiency.....	10
1.1.7 Logistic representation of fractional efficiency	10
1.2 Pyrolysis.....	12
1.2.1 Types of biomass pyrolysis	12
1.2.2 Operating parameters for biomass pyrolysis	13
1.2.3 Stages of pyrolysis	14
1.2.4 Wood pyrolysis	15
1.3 Prototype	16
2 Goals and steps.....	18
3 Experimental campaigns	21
3.1 Overview of the experimental campaign	21
3.2 Pyrolysis parameters.....	22
3.3 Prototype characterization	23
3.3.1 Prototype parameters.....	23
3.3.2 Thermal characterization of the prototype	24
3.3.3 Hydrodynamic characterization	26
3.3.4 Mass balance and product recovery	28
3.3.5 Yields' comparison with Riaz et al.....	32
3.4 Test procedure.....	34
3.5 Pegasor experimental campaign	40
3.5.1 Pegasor instrument.....	40
3.5.2 Sampling circuit layout.....	41
3.5.3 Measurement shown.....	42
3.5.4 Comparison among the three sampling taps.....	43

3.6 ELPI®+ experimental campaigns	46
3.6.1 ELPI®+ instrument.....	46
3.6.2 Sampling circuit layout.....	48
3.6.3 Results and comments	52
4 Conclusions and future steps	58
APPENDIX A - Software assessment	59
Main VI	60
Lettura & zero.....	67
Driver mille funzioni.....	74
APPENDIX B - Sampling taps design.....	96
APPENDIX C – ELPI®+ measurements graphs.....	99
Bibliography	108
Image index	109
Tables index	112

Abstract

The Inertial Separator of Condensable Substances (ISCS), commercially developed under the name FumeCatch, is a technology intended to purify industrial exhaust fumes while simultaneously recovering condensable organic pollutants, offering a sustainable alternative to conventional abatement systems such as electrostatic precipitators, carbon beds, and incinerators. The purpose of the present work is to experimentally assess the particle collection efficiency of the cyclone separator installed in a first FumeCatch prototype, which operates as a slow biomass pyrolyzer, and to characterize the evolution of the aerosol produced along the pipeline connecting the pyrolysis oven to the cyclone.

To this end, six pyrolysis tests were performed under nominally repeatable operating conditions (maximum oven temperature of approximately 338 degrees Celsius, average heating rate of about 7 degrees Celsius per minute), with particle number size distributions measured at the oven outlet, cyclone inlet, and cyclone outlet using a Pegasor Particle Counter in three initial tests and a Dekati Electrical Low-Pressure Impactor (ELPI), coupled with an eDiluter conditioning unit, in three subsequent tests.

The results showed particle concentrations at the cyclone outlet consistently exceeding those at the inlet by up to two orders of magnitude, a behaviour inconsistent with the mass-balance assumptions of classical cyclone efficiency models, and attributable to the absence of a tangential inlet channel and to the presence of a water jacket and cold-flow injection altering the internal flow field. Overall by-product recovery across the six tests averaged 39.1 percent, limited chiefly by sealing deficiencies at the oven body and fan housing. It is concluded that the current cyclone does not function as an inertial classifier but rather as a nucleation-condensation stage, and that a redesign of the sealing system, cold-flow injection point, and cyclone geometry is required before a validated separation efficiency model can be established.

1 Inertial separator of condensable substances

The inertial separator of condensable substances, or ISCS, was developed in response to a common industrial issue. Many manufacturing processes, from cooking and rubber vulcanization to charcoal production and coffee roasting, generate fumes that contain condensable organic compounds. These compounds may be harmful, toxic, or even valuable. Conventional abatement technologies, such as electrostatic precipitators, activated carbon beds, incinerators, and cryogenic refrigeration systems, can be effective, but they often require high investment, complex operation, or demanding maintenance. Moreover, their separation efficiency is not always satisfactory for this type of exhaust stream. For this reason, FumeCatch was conceived as a sustainable and efficient alternative.

ISCS serves a dual purpose: it purifies exhaust fumes while simultaneously recovering pollutants. Separation is achieved by promoting the condensation of gaseous contaminants, particularly those with low vapor pressure. This innovative technology effectively reduces emissions by removing, in many cases, toxic and carcinogenic substances from the airstream before it is released into the atmosphere. (1)

Figure 1 shows a schematic of the ISCS. Hot fumes from the industrial process are immediately mixed with a cold flow. This mixing brings the volatile contaminants to saturation, triggering their condensation. The cold flow is introduced using a “nucleator”, which is designed to provide sufficient time and space for the nucleation, growth, and coagulation of liquid contaminant particles. Downstream of this localized condensation, an inertial separator removes the liquid particles from the gas stream, resulting in cleaner exhaust. A portion of the cleaned gas is sent to a refrigeration unit, where it is cooled to a temperature that promotes further condensation of volatile substances, while the remaining gas is recirculated back to the furnace to complete the loop. A first prototype was built using a high-efficiency cyclone — an inertial separator (Figure 2) (1)

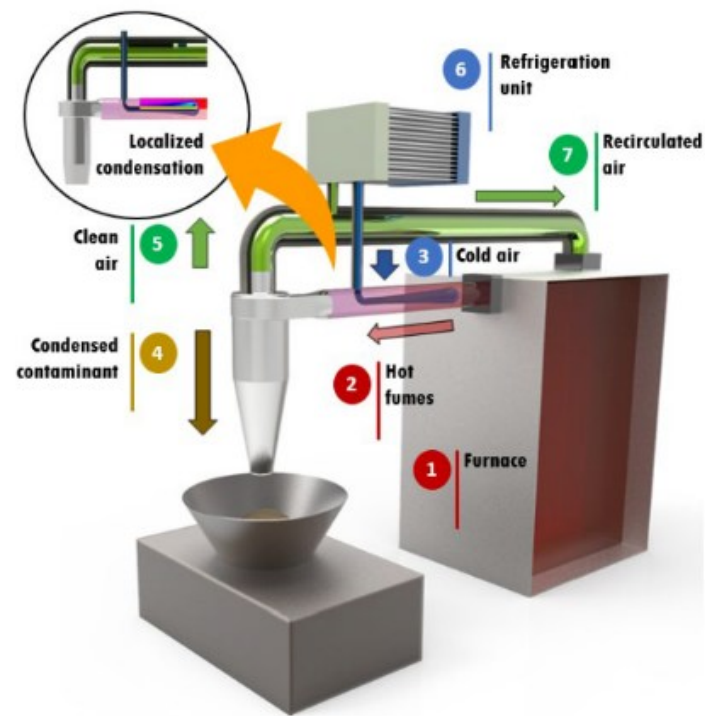
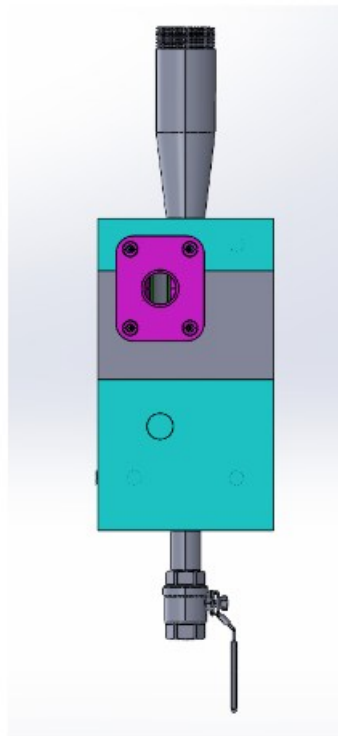
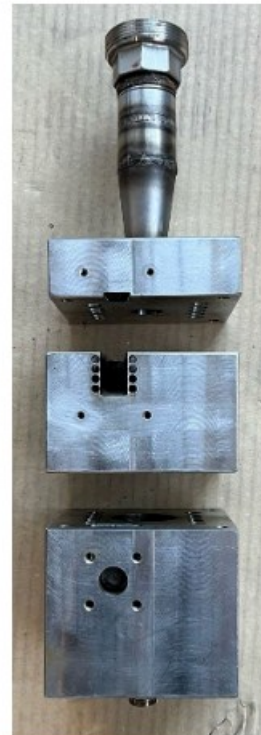


Figure 1



(a) Drawing



(b) Manufactured

Figure 2

ISCS can reduce maintenance costs, avoid interruptions in the production cycle for maintenance, recirculate the fumes without discharging them into the environment, collect condensed contaminants for recycling, adapt to different contaminants with different characteristics, be used for applications in mobile processes, be adopted on existing production lines. (2)

With ISCS one can separate organic vapor emissions in a vulcanization process or have a compact on-vehicle separator for asphalt paving machines or efficiently recover the oil from the wood pyrolysis process and even save the precious organic contaminants from the coffee roasting process to use them as intense aroma additives. (2)

ISCS is the new technology for efficient eco-friendly lightweight and maintenance-free separation of the organic compounds and exhaust fumes. (2)

1.1 Cyclone

A gas cyclone (reverse-flow, cylinder-on-cone design) is a centrifugal separator in which a particle-laden gas is introduced tangentially into a cylindrical body, generating a swirling flow with a double vortex: an outer downward vortex near the wall and an inner upward vortex that exits through a central “vortex finder.” Particles are driven towards the wall by centrifugal forces and then transported downwards to a dust outlet by the near-wall downward gas flow and gravity. (3)

Gas Cyclones and Swirl Tubes by Hoffmann and Stein describes the standard geometry with eight key dimensions: body diameter D , total height H , vortex finder diameter D_x , vortex finder length S , inlet height a and width b , conical section height H_c , and dust outlet diameter D_d . The same text distinguishes classical reverse-flow tangential cyclones from axial-entry swirl tubes, which employ vanes instead of tangential inlets but rely on the same centrifugal separation mechanism. (3)

1.1.1 Governing forces and flow field

The separation process is governed by a balance between centrifugal force, drag force and turbulent dispersion acting on particles in a swirling gas field. For a particle of diameter x at radial position r with tangential gas velocity v_θ , the outward centrifugal acceleration v_θ^2/r scales with x^3 through particle mass, whereas the inward drag force due to radial gas flow scales more closely with x (under Stokes drag). Consequently, large and dense particles are more easily driven to the wall, while very small particles are strongly influenced by turbulent fluctuations and may be lost through the vortex finder. (3)

The gas flow pattern in a reverse-flow cyclone is characterized by strong anisotropic turbulence and a radial pressure gradient, with near-free vortex behaviour ($v_\theta \propto 1/r$) in parts of the core and forced vortex regions near the wall. Hoffmann and Stein emphasize that accurate prediction of cyclone performance requires correct treatment of this complex flow (e.g. via Reynolds Stress Turbulence Models, RSTM) rather than simple, isotropic turbulence models. (3)

1.1.2 Pressure drops and energy consumption

The pressure drop consists of three main contributions: inlet losses, losses in the cyclone body, and losses in the vortex finder, with the latter typically dominating. Hoffmann and Stein note that for standard tangential-entry cyclones, wall friction primarily limits vortex intensity rather than directly setting the total pressure drop, while vortex finder losses can be an order of magnitude larger than inlet and body losses. (3)

Oranje et al. provide a detailed CFD-based optimization of Stairmand high-efficiency cyclones, showing that the vortex finder diameter is the single most influential geometric parameter for pressure drop. Increasing vortex finder diameter decreases tangential velocities and velocity gradients in the core, thereby reducing pressure loss, and pressure coefficient reductions up to about 28% were obtained compared with the original Stairmand design. (4)

1.1.3 Purpose and typical application of cyclones

Cyclones are widely used to remove particles from industrial gas streams for both environmental compliance and product recovery. Applications include dedusting in cement and mineral processing, fly ash removal from coal-fired boilers, particulate control in incineration plants, protection of downstream equipment (fans, compressors, turbines), and recovery of valuable solids such as catalysts in fluid catalytic cracking units (FCCU). (3) (5)

Wang's Air Pollution Control Engineering lists cyclones alongside bag filters, electrostatic precipitators, and wet scrubbers as key particle control devices, noting that cyclones offer low capital and maintenance costs, robustness, high-temperature capability, and suitability for aggressive gas environments. However, it also stresses that cyclones typically exhibit lower efficiency for fine particles below their cut size under low solids loading, and often higher-pressure losses than some alternative collectors. (5)

Beyond gas–solid separation, cyclones are widely used as demisters for removing liquid droplets from gas streams in natural gas processing, offshore platforms, compressor protection, and scrubber systems. Hoffmann and Stein indicate that “demisting cyclones” combine centrifugal separation with specific design features (roof skimmers, anti-creep skirts, vortex stabilizer plates, vortex breakers) to handle liquid films on walls and to avoid re-entrainment or short-circuiting of liquid into the gas outlet. (3)

In gas–liquid cyclones, liquid droplets coalesce on the wall film and form a continuous liquid phase that is drained via underflow piping, with proper underflow sealing and vortex breaking being critical for reliable performance. The same authors note that gas–liquid cyclones can effectively remove droplets $\geq 6\text{--}8\text{ }\mu\text{m}$ in many compressor-protection applications and can handle high droplet loadings when combined with knock-out drums. (3)

1.1.4 Cyclone operation with hot pyrolysis fumes

Fast or slow pyrolysis of biomass and sludge produces complex mixtures of permanent gases (CO , CO_2 , light hydrocarbons), condensable organic vapours (tar, acids, water), and solid or liquid aerosols (char fines, soot, molten or viscous droplets) whose properties depend strongly on reactor temperature, heating rate, feedstock, and quench strategy. For example, studies on “Chemical and physical characterization of aerosols from fast pyrolysis” show that pyrolysis aerosols are often multimodal, with both fine and coarse fractions, and can be sticky or prone to condensation upon cooling. (6)

Pyrolysis systems often use cyclones as primary particle separators, followed by condensers, electrostatic precipitators, or filters to remove residual fine aerosols and to collect pyrolysis oils. In this context cyclones are primarily tasked with removing non-condensable solids (char, ash, entrained bed material) and relatively large liquid droplets, while a fraction of condensable vapours passes through and is later condensed downstream. (7)

1.1.5 Global collection efficiency

Gas Cyclones and Swirl Tubes define the overall (global) separation efficiency η as the fraction of feed solids captured in the underflow (3)

Equation 1

$$\eta = \frac{M_c}{M_f} = 1 - \frac{M_e}{M_f}$$

where M_f is feed solids mass (or mass flow), M_c is captured underflow solids, and M_e is emitted overflow solids. This is obtained from the overall solids mass balance. (3)

Equation 2

$$M_f = M_c + M_e$$

In practice, η is determined by sampling and weighing two of the three streams (usually feed and overflow, or overflow and underflow) and then inferring the third via the mass balance. Hoffmann and Stein show that error propagation is minimized when the overflow solids stream is one of the measured quantities, due to typical magnitudes of measurement error and stream masses. (3)

1.1.6 Fractional (grade) efficiency

The grade-efficiency $\eta(x)$ is defined as the fraction of feed solids within a narrow size band $\left[x - \frac{1}{2}dx, x + \frac{1}{2}dx\right]$ that is captured by the cyclone. Using differential volume or mass density distributions of feed $f_f(x)$, captured $f_c(x)$ and emitted $f_e(x)$, Hoffmann and Stein derive the solids mass balance (3)

Equation 3

$$f_f(x)dx = f_c(x)dx + f_e(x)dx$$

which can be integrated over size to obtain cumulative distributions.

Grade efficiency is then:

Equation 4

$$\eta = \frac{M_c f_c(x)dx}{M_f f_f(x)dx} = \frac{f_c(x)}{f_f(x)} = 1 - \frac{f_e(x)}{f_f(x)}$$

where the last expression follows from the differential mass balance. The grade-efficiency curve is typically S-shaped, approaching zero for very small particles and unity for sufficiently large ones, with a cut-point x_{50} where $\eta(x_{50}) = 0.5$.

1.1.7 Logistic representation of fractional efficiency

Ioia and Leith (1990) propose representing cyclone fractional efficiency curves via a logistic function (8)

Equation 5

$$\eta(d) = \frac{1}{1 + \left(\frac{d_{50}}{d}\right)^p}$$

where d is aerodynamic particle diameter, d_{50} is the cut diameter (50% efficiency), and p is a logistic slope parameter that characterizes the sharpness of the cut. This formulation captures the sigmoid shape observed experimentally and allows compact representation of the entire grade-efficiency curve using just two parameters.

1.2 Pyrolysis

Biomass pyrolysis is a thermo-chemical decomposition process that converts organic matter into valuable products without oxygen. Biomass is a term utilized for all organic material stemming from vegetation and produced through photosynthesis, which converts carbon dioxide and water into organic matter. Biomass is produced from wood and wood wastes (64%), municipal solid waste (24%), agricultural waste (5%), and landfill gases (5%). (7)

The thermal decomposition of biomass produces bio-oil, gases, and char. The oil is obtained in the liquid recovery section of the process. Kaur performed an experiment by passing the vapor through the heat exchanger with ice-cold water in circulation to keep the temperature around 10 °C. The condensate was collected in the beaker and added to dichloromethane to extract the bio-oil. (7)

Upon cooling, pyrolysis vapours tend to form submicron aerosol droplets, especially when large amounts of carrier gas are present during condensation. These droplets are challenging to separate from the gas stream. Liquid spray scrubbing, using simple column scrubbers and venturi scrubbers, generates small spray droplets that collide with the bio-oil aerosols. However, venturi scrubbers require a high-pressure drop (>10kPa), which may only sometimes be feasible. Bio-oil is not a product of thermodynamic equilibrium during pyrolysis but is produced with short reactor times and rapid cooling or quenching from the pyrolysis temperatures. Bio-oils consist of multi-component mixtures of various-sized molecules resulting from the depolymerization and fragmentation of cellulose, hemicellulose, and lignin. The bio-oils are chemically mixture of (1) very volatile organic compounds (mainly hydroxyacetaldehyde, acetol, acetic acid, and methanol), (2) water, (3) monolignols, (4) polar compounds with moderate volatility (furans), (4) anhydrosugars (mainly levoglucosan), (5) extractive-derived compounds, (6) heavy polar compounds (likely oligomers derived from cellulose and hemicellulose), (7) heavy nonpolar compounds (lignin oligomers), and (8) MeOH-toluene insoluble (char). The quality and composition of bio-oil, a complex mix of oxygenated compounds, are significantly influenced by the type of biomass feedstock used and the type of pyrolysis. Different biomass sources, like wood or agricultural residues, impart unique characteristics to the bio-oil, affecting its properties and potential applications. Wastewater, industrial and sewerage wastes, and the food industry by-products are sources of pollution and health issues. Biomass pyrolysis aids in diminishing the wastes above. Biomass for energy production is globally accepted and is the main source of renewable energy in the EU. It accounts for 59% of the renewable energy consumption in 2021, according to the “Commission Report on bioenergy sustainability,” published as part of the State of the Energy Union Report 2023. (7)

1.2.1 Types of biomass pyrolysis

There are several types of biomass pyrolysis, e.g., slow, vacuum, fast, and flash pyrolysis. The difference between them is the temperature and the heating rate. Generally, fast pyrolysis is employed to maximize the liquid product yield, while slow pyrolysis is employed to maximize the solid product yield. An increase in temperature leads to an increase in the yield in fast pyrolysis, but there are more losses. The losses in slow or conventional and fast pyrolysis are

due to the leakages or the volatile products condensing inside the tubes. The losses in the slow pyrolysis are more than the fast pyrolysis. The temperature range for slow pyrolysis lies between 300 °C and 700 °C while for fast pyrolysis lies between 600°C and 1000°C. The target product for slow pyrolysis is biochar, while for fast pyrolysis is bio-oil. The heating rate is from 0.1 °C min⁻¹ to 10 °C min⁻¹ for slow pyrolysis, while for fast pyrolysis ranges from 10 °C min⁻¹ to 10000 °C min⁻¹. Slow pyrolysis takes up to an hour, while fast pyrolysis takes minutes. Slow pyrolysis is a batch process carried out at low temperatures and slow heating rates for long residence times. This process is more tolerant to the moisture content in the feedstock. Although most literature on slow pyrolysis discussed its use for producing solid fuel, this operation can also produce liquid fuels. (7)

1.2.2 Operating parameters for biomass pyrolysis

The yield and composition of pyrolysis oil depend on biomass composition and operating parameters of the process. Char is the solid product of pyrolysis, while bio-oil includes several chemical compounds. Char mainly comprises carbon (91-63%) and oxygen (30–10%). Because of its high carbon content, the char contains a high energy content and can generate heat for the process, prepare active carbon, improve soil fertility, and increase crops. Also, its large surface area can adsorb pollutants, and the physical or chemical activation processes can improve this feature. The pyrolysis temperature significantly affects biochar's physical, chemical, mineralogical, and surface characteristics due to the release of volatile compounds and the formation of intermediate melts. The most suitable biochar is produced at higher temperatures (550 °C and 650 °C) with lower atomic O/C and H/C ratios. Sawdust and rice husk biochar made at these temperatures also have a half-life exceeding 1000 years. The biogas is the incondensable gas of the process, mainly composed of carbon dioxide, methane, carbon monoxide, hydrogen, and light hydrocarbons. Biogas can be recuperated to industrial processes or biomass pyrolysis to increase the efficiency of the process. (7)

The main operating parameters for biomass pyrolysis are vapor residence time, heating rate, particle size, biomass composition, and feed rate. A higher heating rate causes a marked increase in liquid production in the pyrolysis of soybean cake in the fixed bed reactor. For the rapeseed pyrolysis, increasing the heating rate from 100 to 300 °C min⁻¹ increased the biomass decomposition by 58%. In other experiments, the oil yield was maximum, changing the heating rate from 100 to 500 °C min⁻¹. Tsai et al. observed an increase in oil yield when the pyrolysis temperature of the rice husk changed from 400 °C to 500 °C, from 11.3 % to 35.9 %, respectively. The increase in temperature causes a positive effect on the liquid yield, but at very high temperatures, the opposite effect is observed in most of the studies analysed. It occurs because there is secondary cracking of the volatiles at very high temperatures, which results in a higher gas yield. The vapours formed during the pyrolysis can suffer the secondary reactions of thermal cracking, condensation, and re-polymerization of char residue, decreasing the bio-oil yield. These problems can be avoided by introducing nitrogen in the process. Increasing the N₂ flow rate from 1 L/min to 2 L/min in pyrolysis of palm kernel shell in a fluidized bed reactor increased 14% bio-oil yield and reduced char and gas amounts. (7)

Islam studied the vapor residence time in the sugarcane bagasse pyrolysis in a fixed bed reactor and observed that an increase of vapor residence time from 5 s to 20 s decreases the liquid and char yields. In contrast, the gas yield increased. (7)

Biomass is a poor conductor of heat, and particle size influences biochar, bio-oil, and syngas yield. Smaller particles have a higher final pyrolysis temperature. The smaller the particle size, the lower the temperature difference between the interior and surface of the biomass particles, the more efficient the pyrolysis, and the lower the process temperature required to achieve a higher mass loss rate. Shen et al. observed an increase in bio-oil yield of 12–14 wt.% with a particle size reduction from 1.5 mm to 0.3mm in a fluidized bed reactor. (7)

The heat transfer limitation inside and outside larger particles causes a temperature gradient inside of them during their pyrolysis. The higher the pyrolysis temperature, the greater the temperature gradient inside the particles. This gradient causes a thermal hysteresis effect and a secondary reaction inside the particles that generate more char. (7)

Increasing the reaction time increases the yield of the char. However, the yield decreases if the reaction time exceeds a certain limit. Açikalin pyrolyzed pistachio shell at a holding time of 10–50 min. The liquid product yield was slightly affected by reaction times ranging from 10 min (52.96%) to 20 min (53.08%). (7)

Biomass consists of lignin, hemicellulose, cellulose, and a small fraction of inorganic matter whose percentage varies in the different biomass types. The higher the cellulose and hemicellulose contents, the higher the bio-oil yield. The same is not true for higher lignin content. We can summarize the pyrolysis behaviour of biomass's three most important components at 500 °C. Cellulose pyrolysis yields 18.7 % liquid, while hemicellulose pyrolysis yields 30.8 % liquid and the lignin generates a little liquid yield of 0.5%. (7)

Although carbon content in the char remains almost invariably around 95 wt.%, hydrogen and sulphur content slightly decrease as pyrolysis temperature increases, e.g., from 1.1 to 0.4 wt.% and 3.9 to 3.7 wt.%. The volatiles produced at low pyrolysis temperatures yield higher H₂ concentrations than those at higher temperatures. Additionally, as the steam-to-fuel ratio increases, the H₂ concentration rises while the CO concentration decreases. (7)

1.2.3 Stages of pyrolysis

The pyrolysis process happens in four stages. The water evaporates from the mass in the first stage (<100 °C). There is a mass loss in the second stage (100-T₀), while in the third stage (T₀-T), the wood releases the volatiles. The char generation occurs in the last stage of the pyrolysis (>T). The moisture is removed from the material in the first stage of pyrolysis. The temperature rises to evaporate the water content, producing the steam as an output. In the second stage of pyrolysis, also called the pyrolytic zone, the maximum decomposition of hemicellulose and cellulose occurs in the case of wood pyrolysis. In this zone, the application of continuous heat fragments higher molecular weight compounds into smaller molecular weight compounds. The temperature T₀ indicates the temperature in the pyrolysis till the second stage lasts, and after this temperature, the volatiles start to evaporate. The biomass releases the maximum volatile mass in the third zone until reaching temperature T. In the final pyrolysis stage, the remaining

biomass becomes biochar with rich carbon content as volatiles have already been released. As we increase the temperature above T , more volatile compounds evaporate, and secondary reactions may occur, breaking down the compounds into additional gases or oils. (7)

Ultimately, the fixed carbon percentage equals $100 - \Sigma (\text{moisture}\%, \text{volatile}\%, \text{char}\%)$. We can obtain the moisture content percentage by measuring the final and initial masses of the first stage. We can obtain the volatile matter percentage from the third stage and the char content from the fourth stage of the biomass pyrolysis. (7)

1.2.4 Wood pyrolysis

Lignin is a polymer of phenylpropane units containing three different aromatic ring substitution patterns: p-hydroxyphenyl (H), guaiacyl (4-hydroxy-3-methoxyphenyl, G) and syringyl (3,5-dimethoxy-4-hydroxyphenyl, S). Hardwood mainly consists of G and S units, while softwoods have high G and fewer S units. Analyses of the pyrolysis products of dimers, along with nuclear magnetic resonance analysis of the pyrolyzed lignin, revealed that α - and β -ether bonds are readily cleaved during the primary pyrolysis stage. Condensed (C-C) type linkages are stable during depolymerization of lignin macromolecules. When a stable radical is formed, cleavage of the ether linkages tends to proceed efficiently because the increased radical stability reduces the bond dissociation energy of the aromatic O-C bond. Proximate composition refers to four classes of substances such as volatile matter (VM), moisture (M), ash (A), and fixed carbon (FC) content of the sample. Wood sawdust (WSD) moisture content is low (3.1 %), while its high volatile matter is around 80.9 %. Ash content (residue) in the WSD is 3.4 %. The fixed carbon content in WSD is 12.7 %. In WSD, the amount of C and O is higher than H and N. Higher O content in biomass produces oxygenated liquid products during pyrolysis. Cellulose pyrolysis produced the highest CO due to higher carbonyl content. Lignin pyrolysis generated the highest CH₄ characterized by the largest higher heating value due to higher aromatic rings and methoxyl groups. The thermal degradation of cellulose, hemicellulose, and lignin in biomass leads to the formation of CO₂, CO, H₂, and other gaseous products. (7)

1.3 Prototype



Figure 3

FumeCatch prototype can act as a slow pyrolyzer using a cyclone as the inertial separator for condensable substances. This technology can purify the exhaust fumes but also aids in recovering the pollutants after they condense. Figure 3 shows the prototype with the chiller (on the left), heat exchanger with the expansion valve (the black cylinder with the red valve), oven that delivers 900 W of electric power for a consistent heating rate (the squared box on the top right), with a maximum temperature of about 330°C suitable for slow pyrolysis, and cyclone (the small rectangle at the left of the knobs).

Figure 4 shows the schematics of the prototype installed in our laboratory.

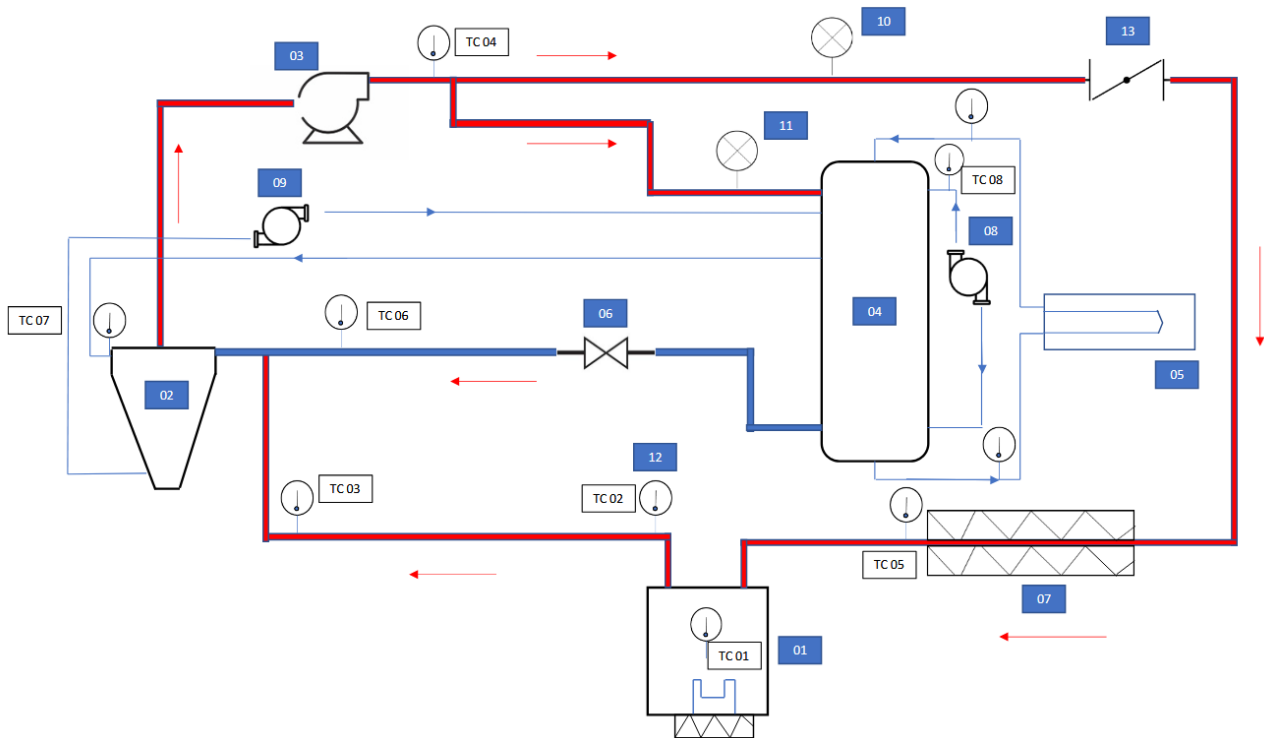


Figure 4

The above diagram describes the operating principle of the FumeCatch prototype. The red streams indicate the flow of the hot fumes, while the dark blue stream indicates the flow of the colder fumes.

A portion of the cleaner post-fan fumes is routed through the helical-coil heat exchanger for cooling, while the remainder recirculates to the oven, with flow rates determined via orifice plate pressure drops and the hot stream regulated by a software-controlled butterfly valve. The cycle persists until pyrolysis ceases.

The light blue streams indicate the water flow from the chiller to the heat exchanger and from the heat exchanger to the cyclone water jacket. This prototype of FumeCatch technology works in a closed loop

2 Goals and steps

The current experimental prototype presents three principal limitations that are deemed to affect the reliability and reproducibility of the measurements, and which should be addressed in future design iterations.

The first limitation concerns the integrity of the sealing system along the pipeline assembly. Leakage points were identified at multiple locations, with the most critical occurrences localised at the oven body and at the recirculation fan housing. These sealing deficiencies introduce the risk of uncontrolled air infiltration or fume leakage, potentially compromising the representativeness of the sampled aerosol and the overall mass balance of the system.

The second limitation pertains to the injection of the cold mass flow rate into the system. Specifically, the current configuration places it directly in the cyclone inlet section, which may result in incomplete mixing between the hot pyrolysis fumes and the cold flow.

The third limitation relates to the cyclone separator installed in the current prototype. No validated theoretical model or experimentally determined performance characterisation — in terms of cut-off diameter, collection efficiency curve, or pressure drop correlation — was provided for the specific cyclone geometry employed. The sole design parameter available for the inertial separator is its nominal volumetric flow rate, specified as $10 \text{ m}^3/\text{h}$. This absence of a reference performance model prevents a rigorous interpretation of the particle size distribution data acquired at the cyclone inlet and outlet and limits the quantitative assessment of the cyclone's separation efficiency under different operating conditions with respect to the one of the present studies.

Regarding the sealing deficiencies identified along the pipeline assembly, a comprehensive resolution would require extensive mechanical redesign, encompassing the oven body sealing system, the fan housing, and the mechanical interface between the fan and its drive motor. Given the scope of such modifications — which would effectively necessitate the development of an entirely new prototype — only containment measures were implemented within the framework of the present study, with the aim of limiting the extent of leakage without undertaking a full structural redesign. The presence of the sealing deficiencies precluded any systematic investigation of the influence of volumetric flow rate on the aerosol measurements, as the leakage extent was found to increase significantly with rising flow rate. Under the prevailing conditions, it was not possible to attain the nominal target flow rate of $10 \text{ m}^3/\text{h}$, as the associated leakage levels were deemed incompatible with the integrity of the sampled aerosol stream. Consequently, it was decided to conduct all experimental campaigns at a fixed, reduced mass flow rate, selected as the value at which the leakage contribution was sufficiently limited to ensure an acceptable degree of measurement repeatability and sample representativeness.

Concerning the injection point of the cold mass flow rate, the current configuration was found to deviate from the original design guidelines, which specified that the cold flow injection should be located along the pipeline section connecting the oven outlet to the cyclone inlet.

The as-built prototype does not comply with this specification, resulting in suboptimal mixing conditions between the hot pyrolysis fumes and the cold flow upstream of the cyclone.

Furthermore, the cyclone separator installed in the current prototype presents several compounding design issues. In addition to the presence of the water jacket and the cold flow injection — both of which alter the internal thermal and fluid dynamic conditions — the cyclone exhibits a fundamental structural deficiency at its inlet section: the absence of a dedicated tangential inlet channel to guide the incoming flow along the curved inner wall of the separator body. In a correctly designed cyclone, this geometrical feature is responsible for imparting the tangential velocity component to the entering fluid, thereby initiating the characteristic rotating motion about the cyclone axis that drives centrifugal particle separation. In the current configuration, the absence of such a guiding channel prevents the development of the swirling flow pattern, and the incoming aerosol is instead drawn directly toward the cyclone outlet section by the downstream fan, effectively bypassing the intended separation mechanism and rendering the cyclone aerodynamically non-functional under the present operating conditions.

The primary objective of the present work is the experimental assessment of the installed cyclone separator, with particular focus on its particle collection efficiency under the actual operating conditions of the prototype. To this end, particle number size distributions and concentrations are measured at both the cyclone inlet and cyclone outlet sections, enabling a direct quantitative evaluation of the separation performance across the full particle size range.

The secondary objective concerns the characterisation of the particle size distribution evolution along the pipeline section connecting the oven outlet to the cyclone inlet. This dataset is intended to serve a twofold purpose. First, it will provide the aerosol boundary conditions required for the aerodynamic design and performance prediction of a new cyclone separator, to be developed in a subsequent phase of the project. Second, it will allow an assessment of the effectiveness of the cold mass flow rate injection — to be implemented along the pipeline section in future prototype iterations — in promoting vapour nucleation and the associated particle formation and growth mechanisms. A targeted analysis of the particle size distribution upstream and downstream of the injection point will provide insight into whether the cold flow injection meaningfully enhances nucleation processes, thereby informing the optimisation of this design feature in the next generation of the prototype.

To fulfil the two research objectives, three dedicated sampling taps were designed and installed along the pipeline section connecting the oven outlet to the cyclone outlet, as described in the preceding paragraph. This arrangement enabled sequential aerosol characterisation at each of the three key locations — the oven outlet, the cyclone inlet, and the cyclone outlet — under reproducible operating conditions.

Particle concentration measurements were initially performed using the Pegasor Particle Counter; however, this instrument proved unsuitable for the specific requirements of the present application and was consequently excluded from further use. The ELPI®+ was subsequently adopted as the primary measurement instrument for all subsequent experimental campaigns, owing to its ability to resolve the full particle number size distribution

in real time, and its compatibility with the high-temperature sampling conditions imposed by the eDiluter™ upstream conditioning system.

Hence, these steps were taken: an experimental campaign using the Pegasor PPC, followed by an experimental campaign using the ELPI®+.

3 Experimental campaigns

3.1 Overview of the experimental campaign

The experimental activity was organised into six tests conducted under nominally identical operating conditions to ensure repeatability and to allow a consistent comparison among the measured aerosol data. The first three campaigns were performed in October 2025 using the Pegasor PPC, while the last three were carried out in December 2025 with the ELPI[®]+, which was adopted as the reference instrument for the subsequent measurements. For each test, the main operating parameters were kept constant as much as possible, including the inverter frequency, sample mass, and heating conditions, whereas the sampling location was varied among the oven outlet, cyclone inlet, and cyclone outlet to characterise the aerosol evolution along the prototype.

Table 1

Test ID	<i>TEST1</i>	<i>TEST2</i>	<i>TEST3</i>	<i>TEST4</i>	<i>TEST5</i>	<i>TEST6</i>
Date	23/10/2025	28/10/2025	31/10/2025	16/12/2025	17/12/2025	18/12/2025
Instrument	Pegasor PPC	Pegasor PPC	Pegasor PPC	ELPI [®] +	ELPI [®] +	ELPI [®] +
Sampling tap	Oven outlet	Cyclone inlet	Cyclone outlet	Oven outlet	Cyclone inlet	Cyclone outlet
Inverter frequency [Hz]	80.00	80.00	80.00	80.00	80.00	80.00
Sample mass [g]	140.42	140.20	140.26	140.20	140.25	140.25
t_{max} [°C]	337.00	344.00	327.00	337.00	338.00	345.00
Heating rate [°C/min]	6.83	6.93	6.99	6.82	7.29	7.27
Duration [min]	74.62	73.10	75.92	68.05	63.70	71.23

3.2 Pyrolysis parameters

This section summarises the main operating parameters used to characterise each pyrolysis test.

- Residence time [min] → This is the total time during which the biomass remains inside the oven under pyrolysis conditions. It represents the duration over which thermal decomposition, volatile release, and char formation can occur.
- $t_{\max}$ [°C] → This is the maximum oven temperature reached during the test. It is a key parameter because it determines the thermal severity of the pyrolysis process and strongly affects the relative yields of biochar, bio-oil, and gases.
- Heating-up time [min] → This is the time required for the oven to increase from the initial condition to $t_{\max}$. It defines the temporal length of the thermal ramp and is directly related to the heating dynamics of the experiment.
- Heating rate [°C/min] → This is the average temperature increase per unit time during the heating-up phase. It provides a measure of how rapidly the biomass is exposed to increasing thermal energy and is one of the key variables governing pyrolysis behaviour and product distribution.

3.3 Prototype characterization

3.3.1 Prototype parameters

- $TC01$ [°C] — Oven's internal temperature.
- $TC02$ [°C] — Oven's wall temperature.
- $TC03$ [°C] — Oven's outlet temperature.
- $TC04$ [°C] — Fan's outlet temperature.
- $TC05$ [°C] — Oven's inlet temperature.
- $TC06$ [°C] — Cyclone's inlet temperature (COLD FUMES).
- $TC07$ [°C] — Cyclone's water jacket temperature.
- $TC08$ [°C] — Heat exchanger's wall temperature.
- Q_f [m³/h] — Cold volumetric flow rate.
- Q_c [m³/h] — Hot volumetric flow rate.
- Δp_f [Pa] — Pressure drops across the cold volumetric flow rate branch.
- ρ_f [kg/m³] — Density downstream the fan.
- Δp_c [Pa] — Pressure drops across the hot volumetric flow rate branch.
- ρ_c [kg/m³] — Density downstream the fan.
- d_f [mm] — Orifice plate's diameter in the cold volumetric flow rate branch.
- d_c [mm] — Orifice plate's diameter in the hot volumetric flow rate branch.

Chiller and refrigerator's data

- $t_{\text{chilled water}}$ [°C] — 5.
- $p_{\text{chilled water}}$ [bar] — 2.

Inverter frequency

- [Hz] — 80.

3.3.2 Thermal characterization of the prototype

This section presents the thermal characterization of the prototype during a representative experimental run. The analysis focuses on the temporal evolution of the temperatures measured at the different points of the system, thereby providing a comprehensive description of the thermal transients occurring throughout the pyrolysis process. The figure also illustrates the discrete temperature checkpoints — set at 100 °C, 200 °C, 250 °C, and 300 °C on the primary oven thermocouple (TC01) — which constitute the reference milestones of the test procedure; the rationale and role of these checkpoints will be thoroughly discussed in the dedicated test procedure section. Attention is given to the evolution of the oven temperature, the corresponding heating rate, and the temperature differences observed along the sampling line, as these parameters govern the thermal boundary conditions under which aerosol generation and transport take place. In addition, it is worth noting that the chiller thermostat is maintained at a set-point of 5 °C throughout the experiment, which results in a steady operating temperature of approximately 8 °C inside the collection vessel and approximately 16 °C at the cyclone; the implications of this thermal conditioning strategy on aerosol collection efficiency will likewise be addressed in the test procedure section.

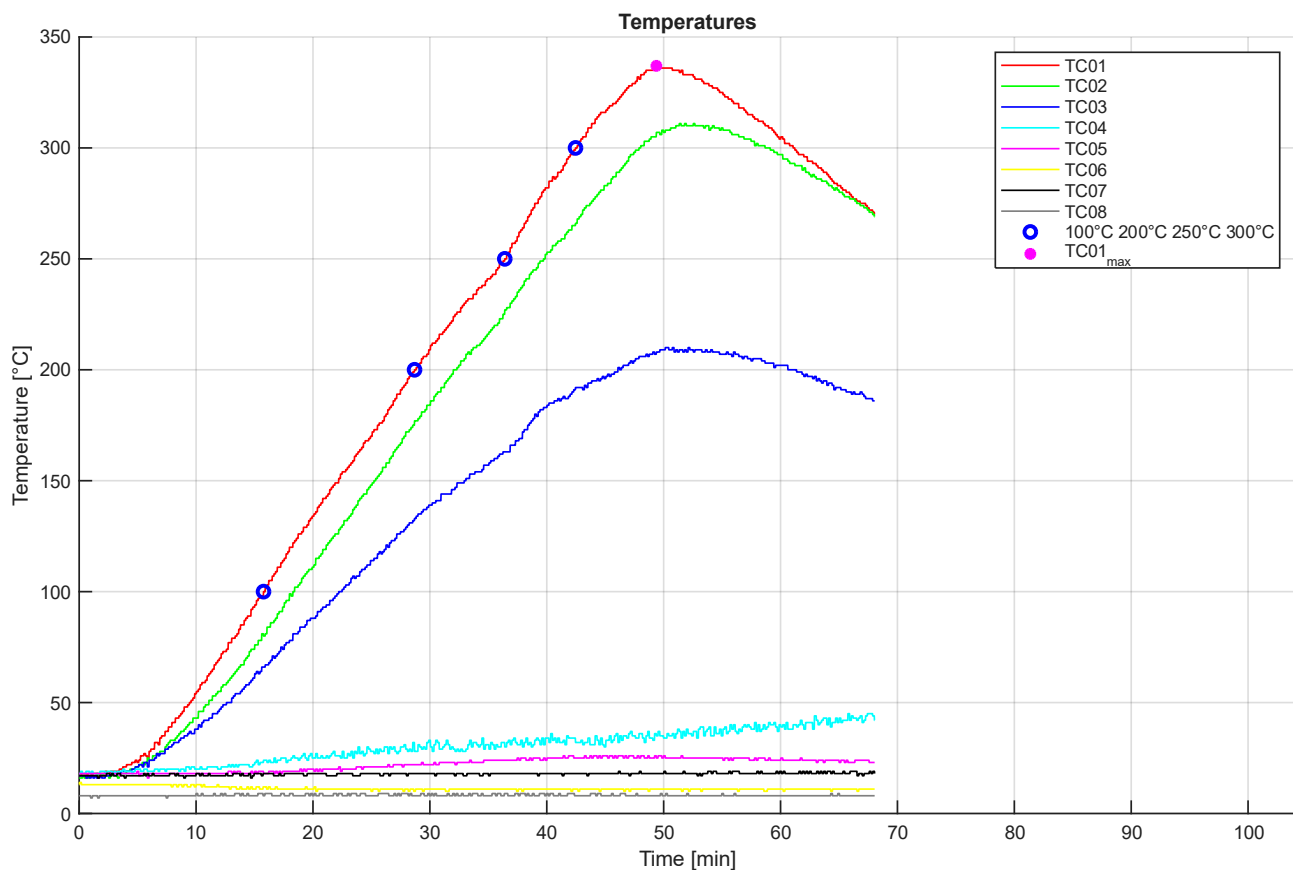


Figure 5

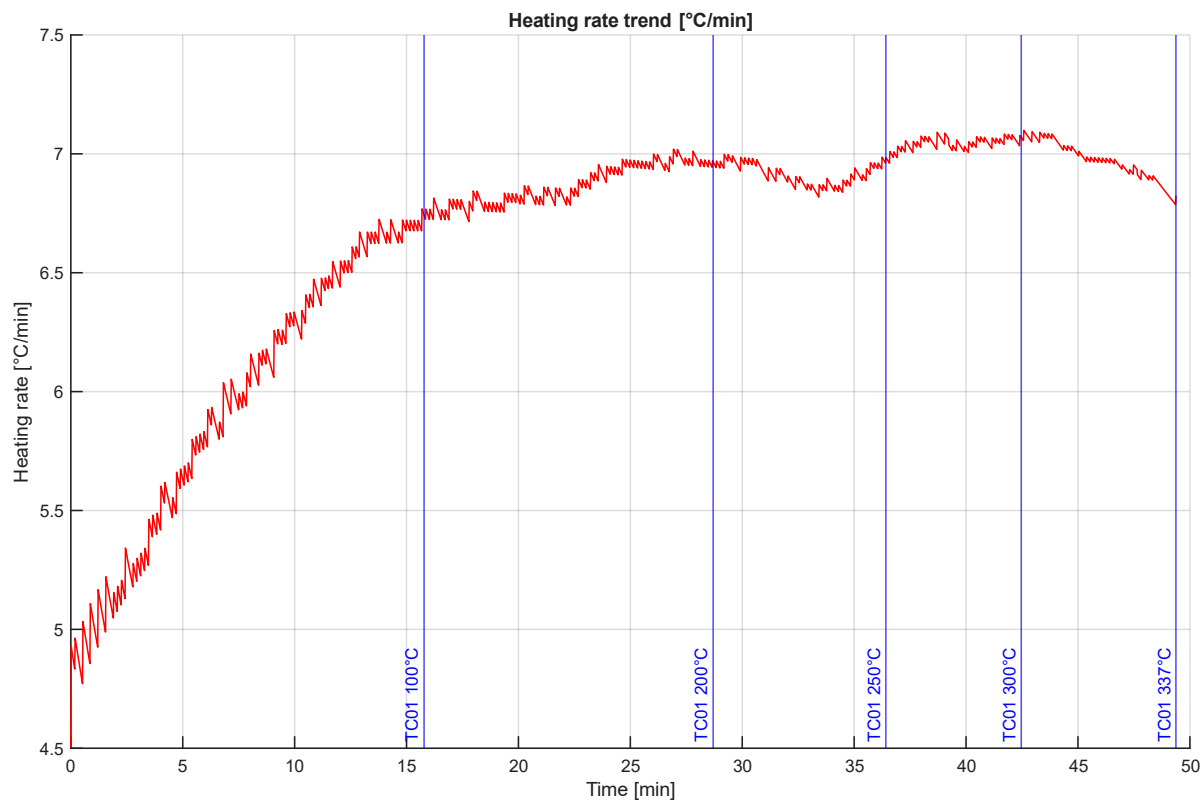


Figure 6

Table 2

PARAMETER	UNIT	Mean	Std. Dev.	N. (replicates)
<i>TC01_max</i>	°C	338.00	5.89	6
<i>Heating rate</i>	°C/min	7.02	0.19	6

The measured thermal conditions are consistent with a slow pyrolysis process. In particular, the prototype operated with an average heating rate of 7.02 °C/min and a maximum oven temperature of 338 °C, which fall within the range typically associated with slow pyrolysis of biomass.

Slow pyrolysis is described as a low-heating-rate process, generally performed between approximately 300 °C and 700 °C, with heating rates in the order of 0.1–10 °C/min, and where the prototype is explicitly identified as a slow pyrolyzer operating at a maximum temperature of about 340 °C.

The heating-rate profile also supports this interpretation, since it shows a gradual and stable thermal ramp rather than the rapid and intense heating typical of fast pyrolysis. In this sense, the process conditions suggest controlled biomass devolatilization rather than the short-residence, high-heating-rate regime used to maximize bio-oil.

3.3.3 Hydrodynamic characterization

At the operating frequency (80 Hz), the prototype generates a pressure drop across the detection points of approximately 569 Pa in the hot pipeline branch and 85 Pa in the cold pipeline branch, respectively. Therefore, a total volumetric flow rate of approximately $5 \text{ m}^3/\text{h}$ is produced. This flow rate is divided into two components: the hot volumetric flow rate, recirculated through the oven, and the cold volumetric flow rate, directed toward the heat exchanger, as reported in the Prototype Parameters table (Table 1). The hot contribution is approximately $3.5 \text{ m}^3/\text{h}$, whereas the cold contribution is approximately $1.5 \text{ m}^3/\text{h}$, as shown in the figure below.

Table 3

MASS FLOW RATES' DATA	Frequency [Hz]	80.00
	d_hot [mm]	8.00
	d_cold [mm]	8.00
	$\Delta p_{f_mean_value}$ [Pa]	85.00
	$\Delta p_{c_mean_value}$ [Pa]	568.65
	$Q_{cold_mean_value}$ [m³/h]	1.41
	$Q_{hot_mean_value}$ [m³/h]	3.58
	$Q_{tot_mean_value}$ [m³/h]	4.99

Table 4

$\Delta p_{f_mean_value}$ [Pa]	85.00 ± 4.28
$\Delta p_{c_mean_value}$ [Pa]	568.65 ± 46.11
$Q_{cold_mean_value}$ [m³/h]	1.41 ± 0.04
$Q_{hot_mean_value}$ [m³/h]	3.58 ± 0.09

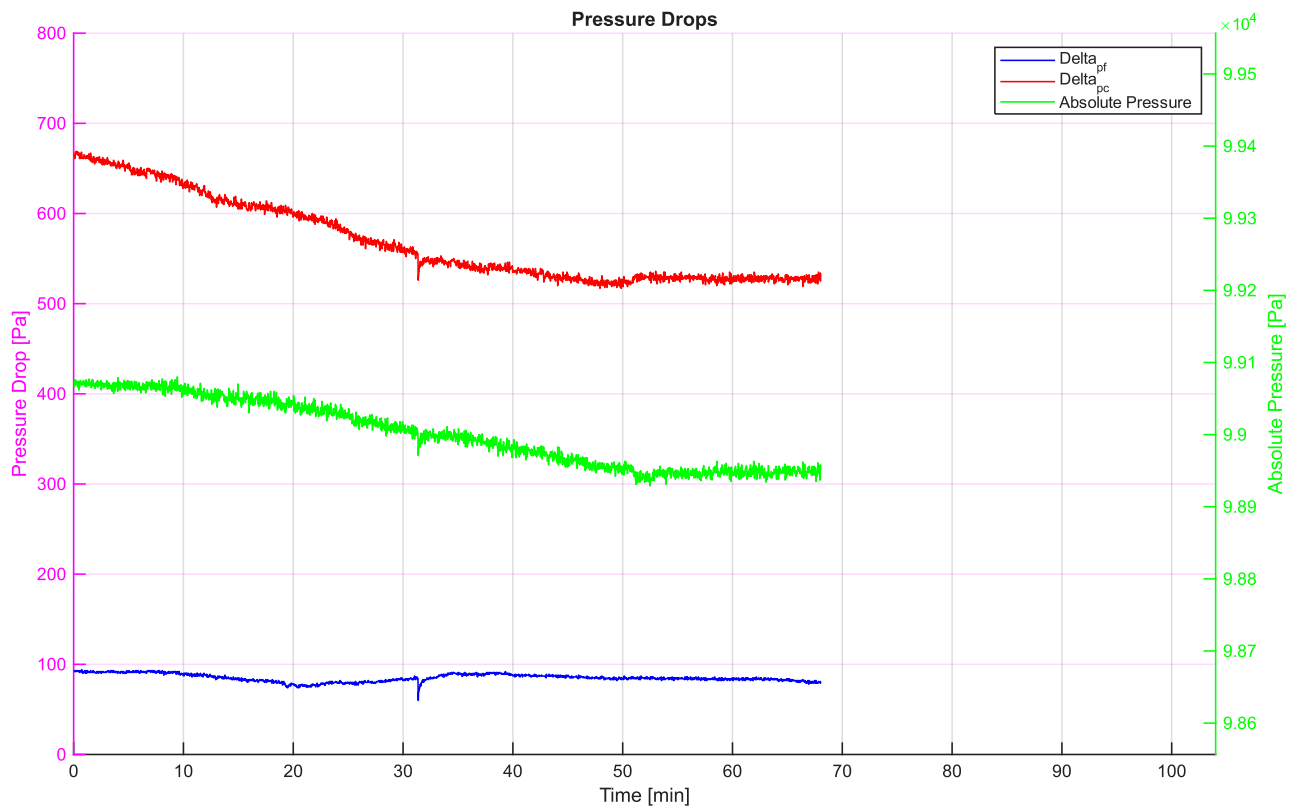


Figure 7

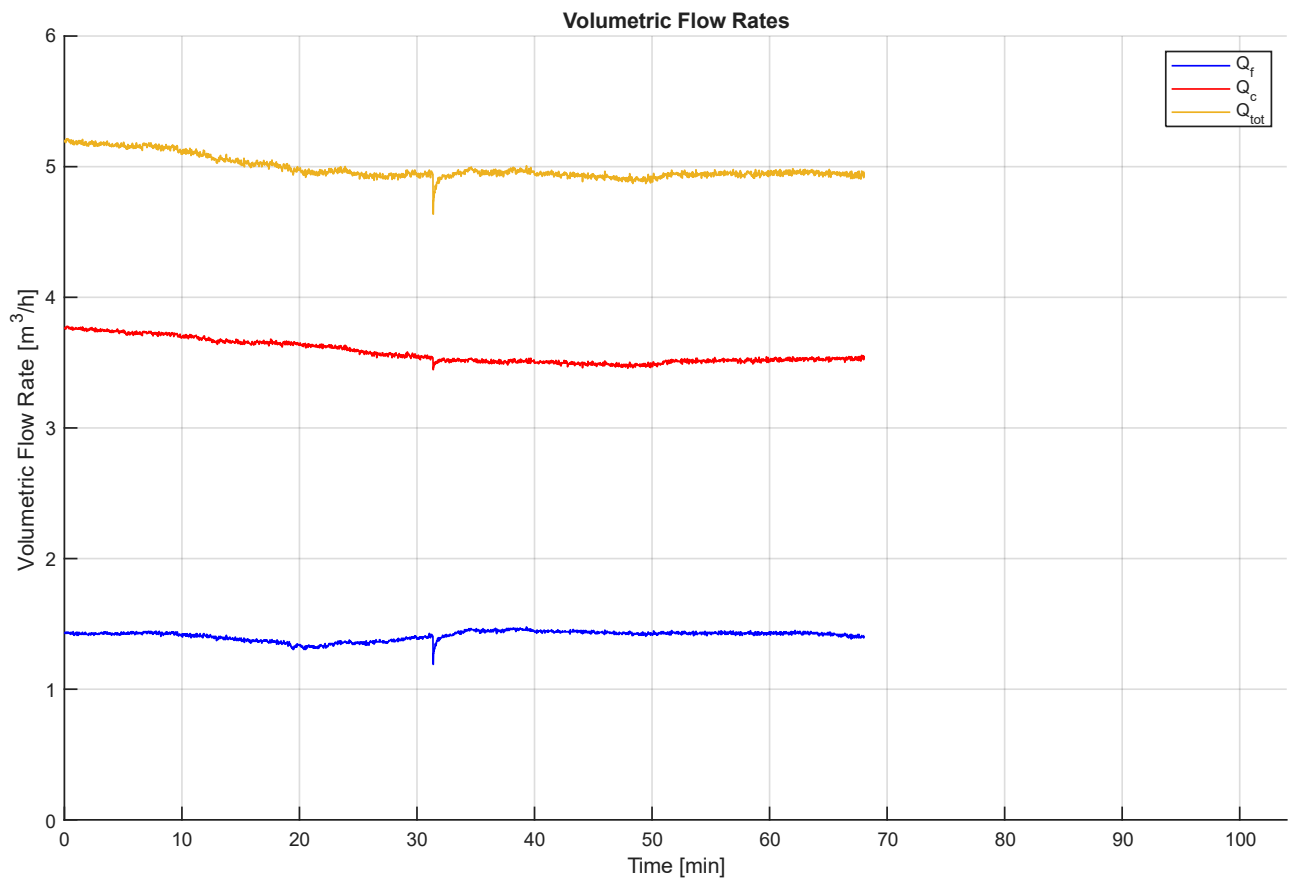


Figure 8

3.3.4 Mass balance and product recovery

In this section, the mass balance of each experimental run is closed by accounting for the main recovered streams of the pyrolysis process and by quantifying the fraction of material that is not directly recovered. The initial sample mass is partitioned into char, collected bio-oil, and an unaccounted fraction; in physical terms, this unaccounted mass corresponds mainly to non-condensable gases (CO , CO_2 , CH_4 , H_2) and to prototype-related losses, especially leakages throughout the system, as well as vapour escape, incomplete condensation, and deposits retained in the reactor, pipes, or condensation train. Char yield is defined as the ratio between char mass and sample mass, while bio-oil yield is the ratio between the collected liquid fraction and the sample mass; total recovery is then the sum of char and bio-oil relative to the initial feed and serves as the main indicator of mass-balance closure. This interpretation is consistent with the literature, which reports that pyrolysis vapours can form persistent aerosols, that a fraction of oil may remain in condensers or separators as deposits, and that the remaining unrecovered fraction is associated with gases and system losses.

Test inputs and outputs

- Sample mass [g].
- Char mass [g].
- Bio-oil mass [g].
- Total by-products mass [g].
- Unaccounted mass [g].
- Char yield [%].
- Bio-oil yield [%].
- Total recovery [%].

Table 5

	TEST1	TEST2	TEST3	TEST4	TEST5	TEST6
Sample mass [g]	140.42 ± 0.15	140.2 ± 0.15	140.26 ± 0.15	140.2 ± 0.15	140.25 ± 0.15	140.25 ± 0.15
Char mass [g]	21.8 ± 0.15	33.32 ± 0.15	33.66 ± 0.15	35.07 ± 0.15	36.21 ± 0.15	36.98 ± 0.15
Bio-oil mass [g]	23.15 ± 0.15	20.91 ± 0.15	22.44 ± 0.15	13.74 ± 0.15	29.82 ± 0.15	21.71 ± 0.15
Total by-products mass [g]	44.95 ± 0.21	54.23 ± 0.21	56.1 ± 0.21	48.81 ± 0.21	66.03 ± 0.21	58.69 ± 0.21
Unaccounted mass [g]	95.47 ± 0.26	85.97 ± 0.26	84.16 ± 0.26	91.39 ± 0.26	74.22 ± 0.26	81.56 ± 0.26
Char yield [%]	15.52%	23.77%	24.00%	25.01%	25.82%	26.37%
Bio-oil yield [%]	16.49%	14.91%	16.00%	9.80%	21.26%	15.48%
Total recovery [%]	32.01%	38.68%	40.00%	34.81%	47.08%	41.85%

Explicit uncertainty bounds strengthen the interpretation of the test-to-test variability observed in the char yield, which ranges from 15.52% in TEST1 to 26.37% in TEST6. Because this spread (approximately 11 percentage points) is far larger than what could plausibly arise from an instrumental uncertainty of only ± 0.15 – 0.26 g on the underlying masses, the observed variability in char yield must be attributed to genuine differences in the pyrolysis process or operating conditions across tests, rather than to measurement noise or an artifact of weighing precision.

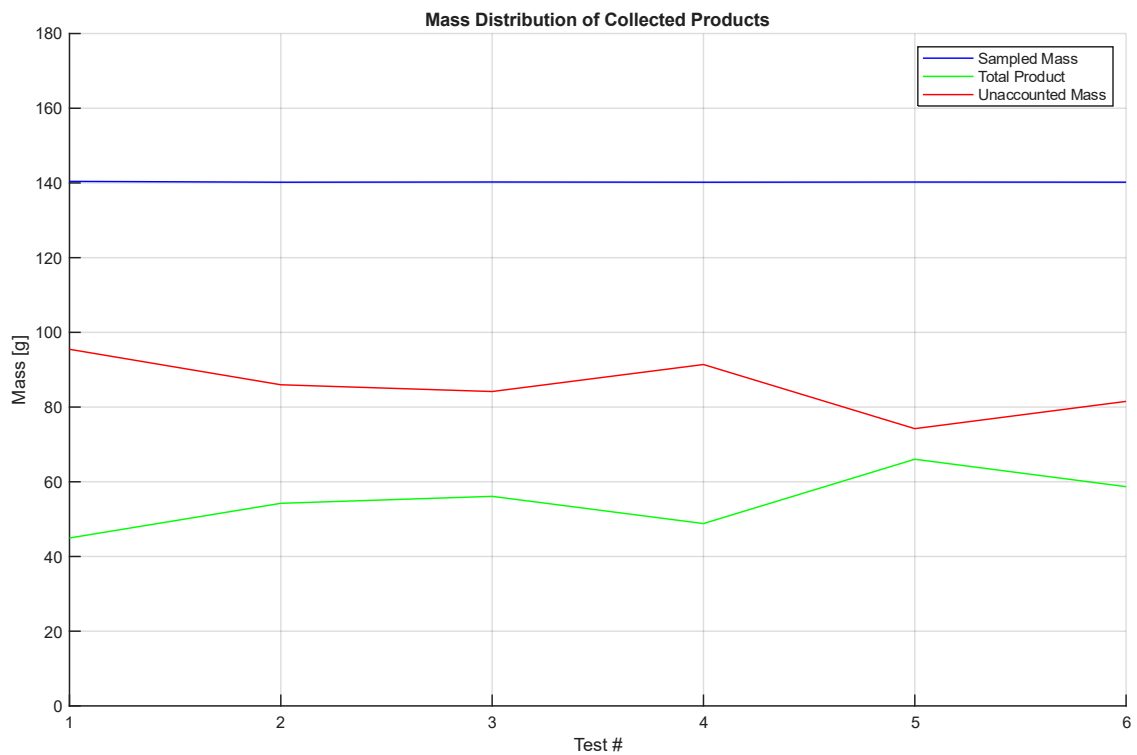


Figure 9

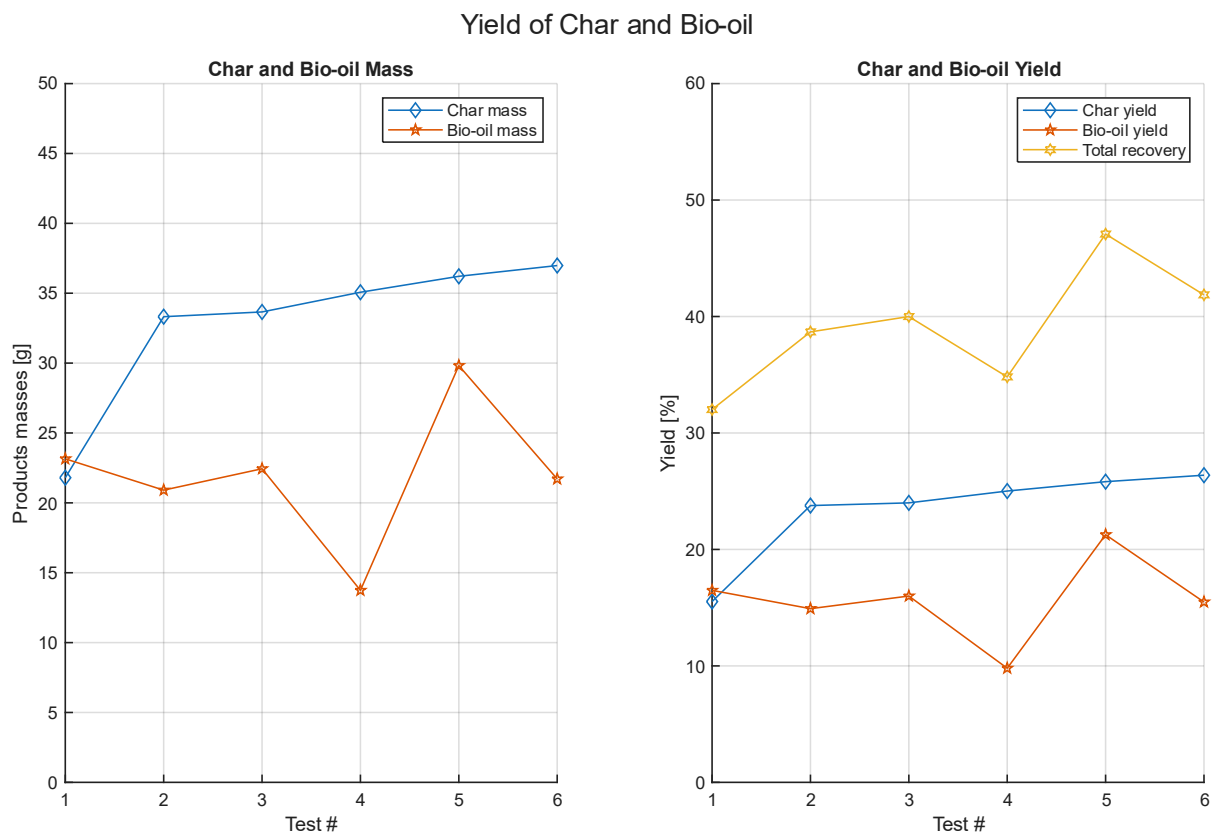


Figure 10

Figure 10 shows the significant influence of leakages on the collected bio-oil mass — which is composed predominantly of condensable volatile compounds formed during the thermochemical decomposition of wood sawdust — explains the low collection efficiencies, reaching at best only 47.08%. The formation of submicron bio-oil aerosol droplets upon cooling of the pyrolysis vapours, combined with the presence of substantial carrier gas flow and the absence of an efficient aerosol separation system, further contributes to the loss of condensable species along the pipeline and within the cyclone. The relatively modest improvement in bio-char collection following the implementation of containment measures in the oven also aligns with the expected behaviour of slow pyrolysis, in which solid-phase products are inherently less sensitive to minor gas-phase losses than the highly volatile liquid fraction. These considerations therefore support the conclusion that the prototype's sealing deficiencies and the limitations of the installed cyclone separator are the primary causes of the poor bio-oil recovery observed in the present experimental campaign.

3.3.5 Yields' comparison with Riaz et al.

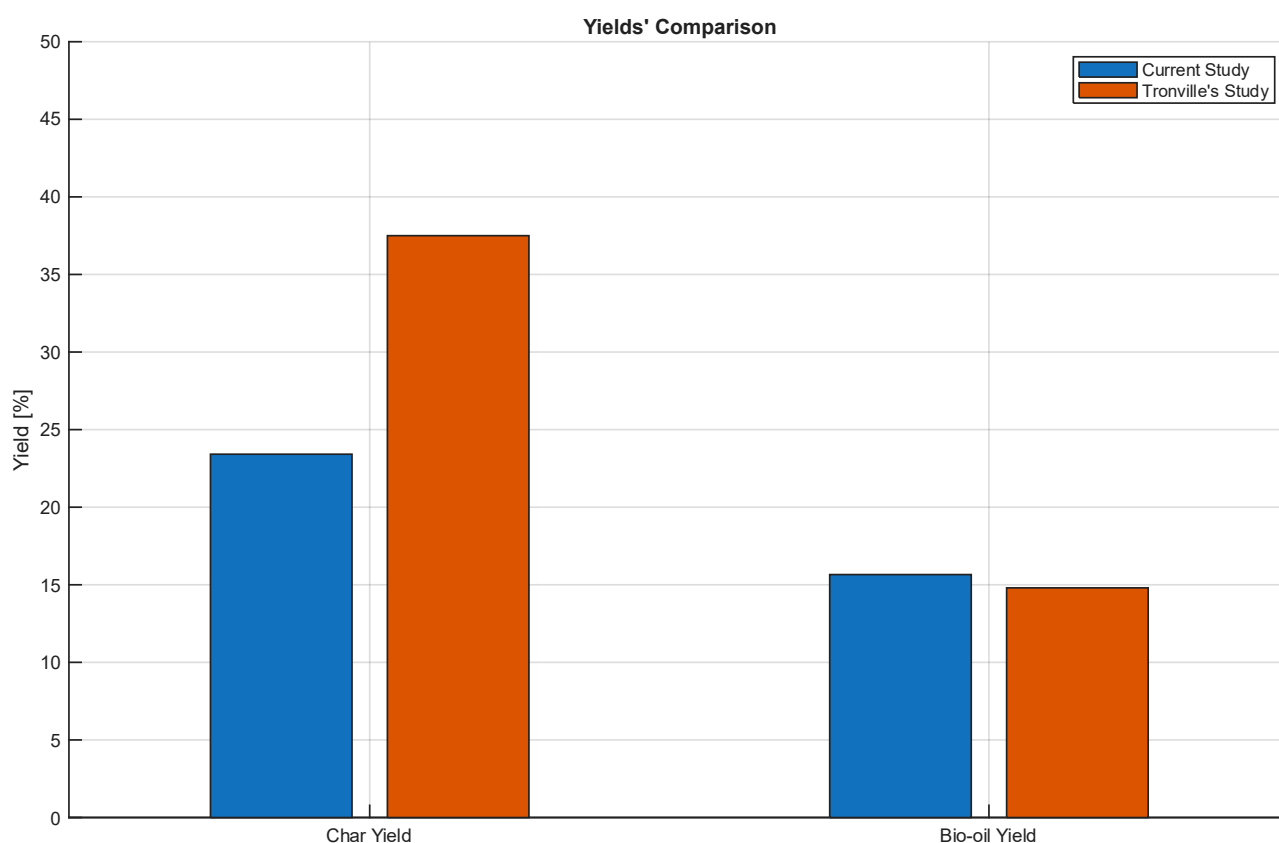


Figure 11

The experimental results obtained in the present work can be compared to those reported by Riaz et al., who conducted slow pyrolysis of wood sawdust using the FumeCatch prototype equipped with a chiller maintaining the heat exchanger wall temperature below 8 °C. In their chiller experiment, an initial biomass mass of 140.4 g yielded a char mass of 52.6 g and a bio-oil mass of 20.8 g, corresponding to a total by-products mass of 73.4 g and a reported collection efficiency of 52.3%.

Regarding the solid fraction, the char yield reported by Riaz et al. with the chiller corresponds to approximately 37.5 wt.% of the initial biomass mass (52.6 g / 140.4 g). In the present experiments, char yields ranged from 15.52% (TEST1) to 26.37% (TEST6), with an average of approximately 23.4%. These values are systematically lower than the reference result, suggesting either differences in the thermal cycle applied, the maximum oven temperature reached, or the moisture and volatile matter content of the biomass batch used. It should be noted that the reference paper states a maximum oven temperature of approximately 340 °C and a slow heating rate, and any deviation in these parameters in the present setup could significantly affect char yield.

The bio-oil yield reported by Riaz et al. with the chiller amounts to approximately 14.8 wt.% (20.8 g / 140.4 g). In the present tests, bio-oil yields ranged from 9.80% (TEST4) to 21.26% (TEST5), with a mean value of approximately 15.7%, which is broadly consistent with the reference value. The considerable variability across the six tests — particularly the low recovery

in TEST4 and the comparatively high value in TEST5 — may be attributed to differences in condensation efficiency, potential liquid losses during collection, or variability in the biomass feedstock moisture content between runs.

The total by-products recovery in the present work ranged from 32.01% (TEST1) to 47.08% (TEST5), with an average of approximately 39.1%, compared to the 52.3% collection efficiency reported by Riaz et al. Given that both sets of experiments were conducted on the same FumeCatch prototype and under comparable cooling conditions — with TC07 averaging 16 °C at the cyclone water jacket and TC08 maintained at approximately 8 °C at the heat exchanger wall in both cases — the observed gap cannot be attributed to differences in either the hardware configuration or the thermal operating point of the condensation system. The discrepancy is therefore more likely related to run-to-run operational variability, such as differences in the butterfly valve opening position, the fume flow rate split between the recirculation and heat exchanger streams, or variability in the biomass feedstock moisture and volatile matter content between batches. The unaccounted mass — encompassing non-condensable syngas, uncollected condensable vapours, and residual leakages from the fan shell — ranged between approximately 53 wt.% and 68 wt.% across the present tests. Riaz et al. themselves acknowledged that liquid leakage from the fan shell was only partially mitigated by the chiller, confirming that complete mass balance closure is not achievable with the current prototype configuration regardless of operating conditions. A more systematic logging of all operational parameters across repeated runs would be necessary to isolate the dominant sources of variability and draw more definitive conclusions.

3.4 Test procedure

Prior to initiating any measurement campaign, a series of preparatory operations and functional verification procedures must be carried out to ensure the correct and reliable operation of either the Pegasor PPC or the ELPI®+ instrument.

From an auxiliary equipment standpoint, while the Pegasor PPC does not require any setup procedures, the ELPI®+ requires connection to a dedicated vacuum pump, which maintains the low-pressure conditions necessary for proper aerosol classification within the cascade impactor stages. Concurrently, the eDiluter™ must be connected to a pressurised air supply line, with a minimum operating pressure of 7 bar, to sustain the ejector dilution mechanism and ensure a stable and controlled dilution factor throughout the measurement.

Once the hardware connections have been established and the system has reached thermal and fluidic steady-state conditions, two mandatory **routine verification procedures** must be performed before measurements can commence:

1. **Zeroing Procedure** — The instrument performs an automatic zeroing of all electrometer channels in the absence of aerosol flow. This step is essential to establish a stable electrical baseline for each detection stage, thereby eliminating any offset contributions from electronic noise or residual charge accumulation on the impactor substrates.
2. **Charger Functionality Verification** — The correct operation of the unipolar corona charger is verified to confirm that particles entering the impactor are charged to the expected, reproducible level. This step is critical, as the accuracy of the particle number concentration measurements is directly dependent on the charge imparted to the aerosol particles upstream of the impactor.

Only upon successful completion of both verification procedures, with all diagnostic parameters within the acceptable operational thresholds, may the instrument be considered ready for particle size distribution acquisition.

At the commencement of each experimental run, the thermal conditioning circuit is brought to operational readiness prior to aerosol sampling. The chiller unit is activated first, with its set-point configured at a temperature of about 5 °C and the circuit operating pressure below 3 bar (its circulation pump is engaged to drive the chilled water flow through the heat exchanger).

The thermal stabilisation of the heat exchanger is continuously monitored by means of a dedicated thermocouple data acquisition unit (TC-08), which records the heat exchanger wall temperature as the primary indicator of steady-state thermal conditions.

Once the TC-08 thermocouple readings have stabilised at approximately $8 \pm 1^{\circ}\text{C}$, confirming that the heat exchanger has reached its steady-state thermal condition, pump (9) is engaged to direct the low-temperature water from the heat exchanger to the water jacket surrounding the cyclone body, thereby initiating active thermal management of the cyclone through forced liquid cooling.

The coolant circulating within the cyclone jacket is monitored by thermocouple TC-07, which records the water temperature at this stage of the circuit and serves as the primary indicator of the thermal steady-state condition of the cyclone wall. This cooling stage is essential to maintain the cyclone operating temperature within the desired range ($17 \pm 1^\circ\text{C}$), ensuring consistency of the aerosol conditions at the cyclone inlet and outlet during the measurement campaign. The evolution of TC07 and TC08 over the full duration of the experiment is shown in Figure 12, while the internal architecture of the cyclone body and the routing of the water flow tubes within the jacket are illustrated in Figure 13.

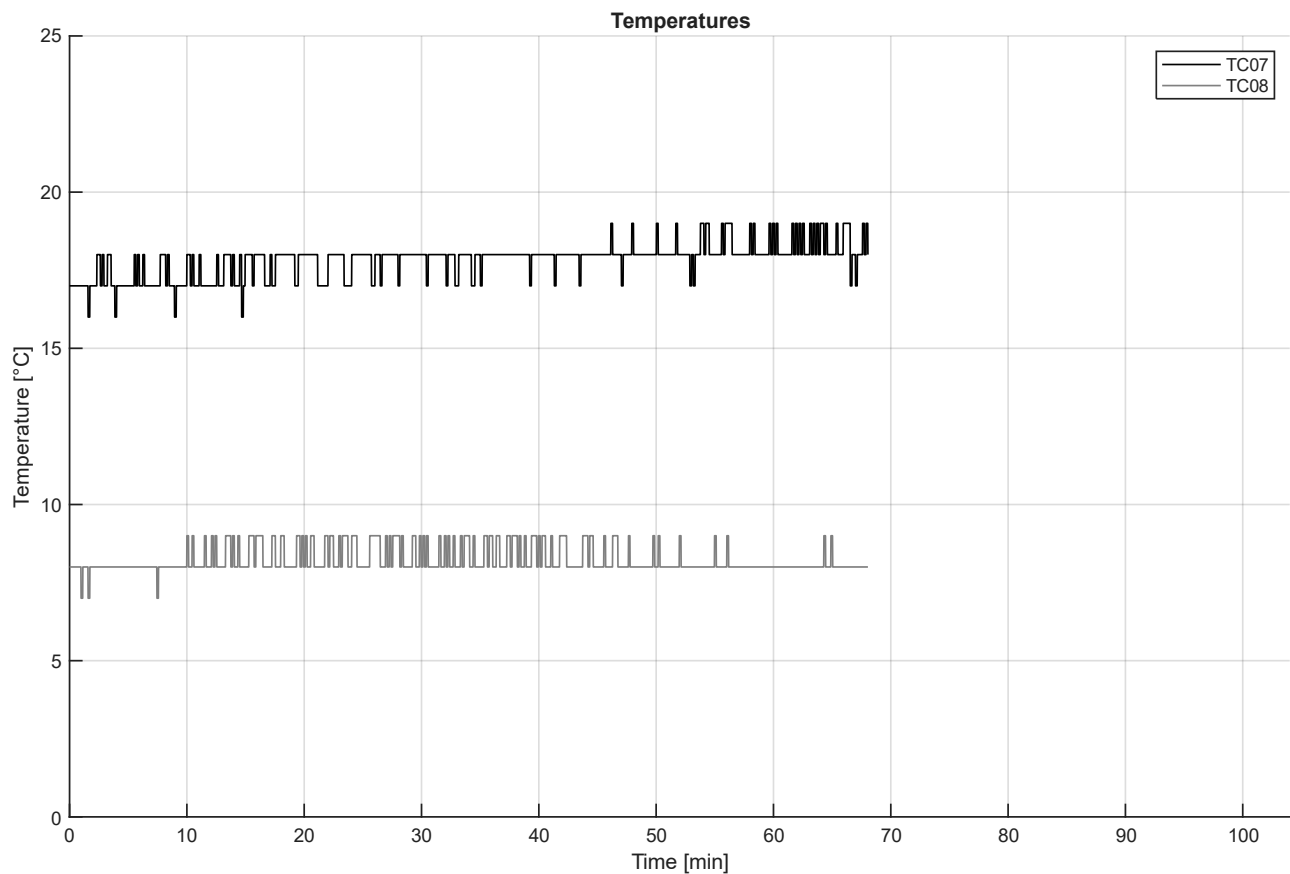


Figure 12

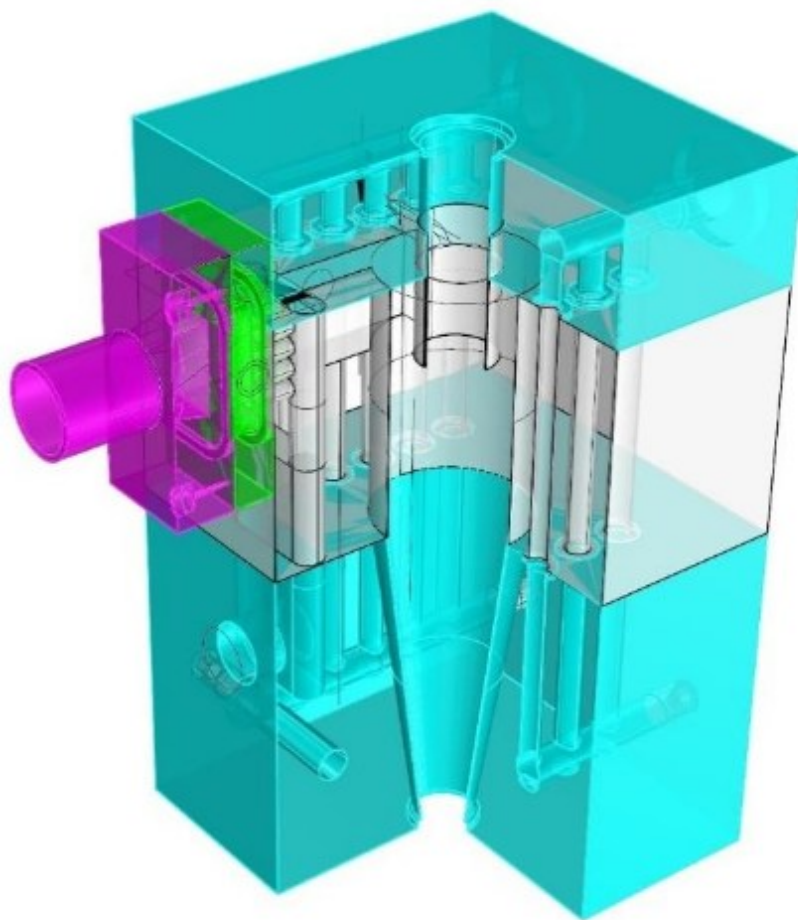


Figure 13

When measuring with ELPI[®]+, concurrently with the thermal stabilisation of the cooling circuit, the eDiluter[™] is powered on and allowed to heat up to its target operating temperatures prior to the commencement of aerosol sampling. The temperature set-points of both the sampling line and the dilution air within the eDiluter[™] are configured depending on the specific position of the active sampling tap along the pipeline connecting the oven outlet to the cyclone inlet.

The reference thermal condition for this configuration is provided by thermocouple TC-03, which continuously monitors the gas temperature at the oven outlet. To prevent any partial condensation or precipitation of gaseous compounds — such as condensable organic vapours or water vapour — within the eDiluter[™] sampling line during aerosol transport, the internal temperature set-points of the instrument are defined by adding a margin of 20 °C above the maximum temperature recorded by TC-03. This conservative thermal offset ensures that the sampled stream remains entirely in the vapour phase throughout its transit through the eDiluter[™], thereby preserving the integrity of the aerosol sample and preventing the formation of condensation artefacts that would otherwise bias the particle size distribution measured by the ELPI[®]+

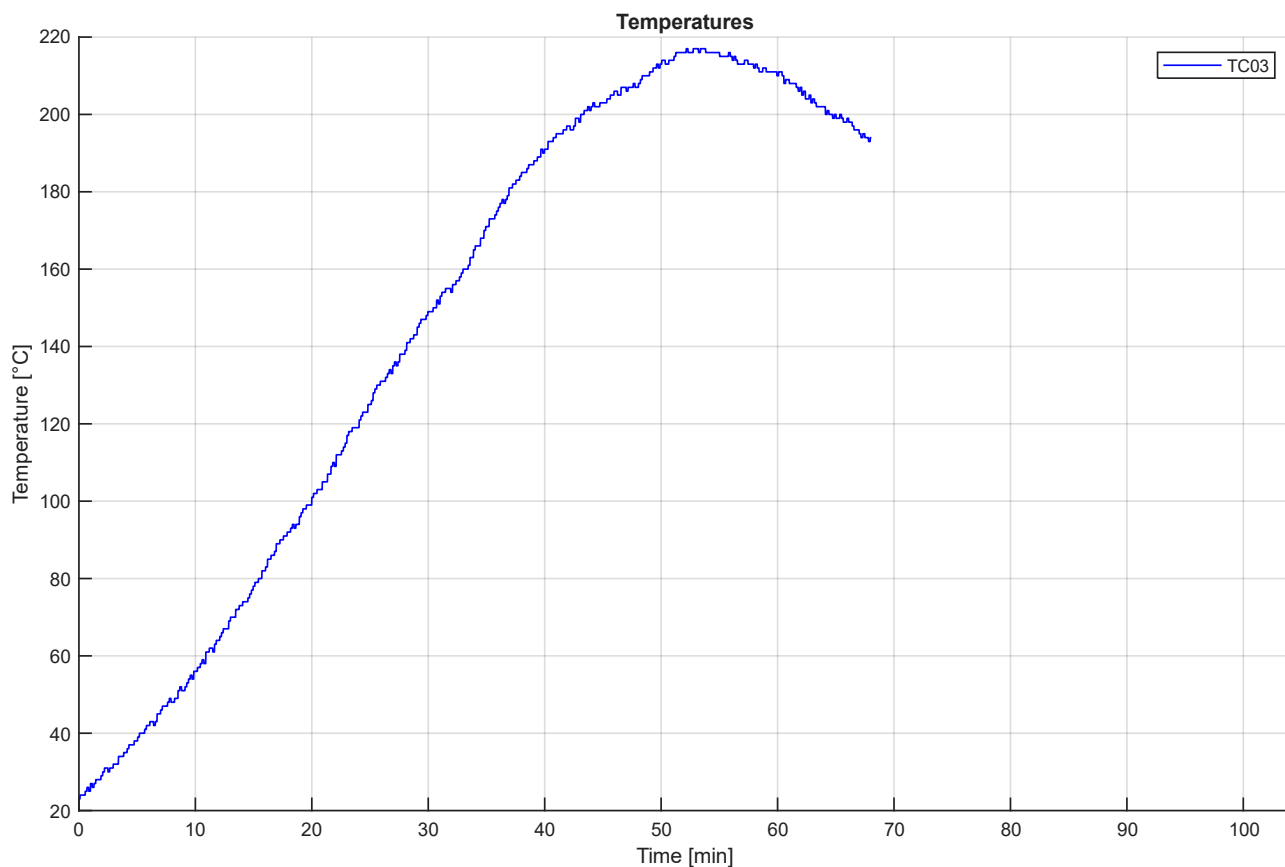


Figure 14

Once the cyclone has reached its target operating temperature, the wood sawdust sample is prepared. The material is first weighed ($140.21 \pm 0.15g$) on a precision balance and manually inspected to remove any macroscopic impurities, then loaded into the oven. The prepared sample as arranged in the container prior to oven insertion is shown in Figure 15.



Figure 15

Upon confirmation that all thermal boundary conditions are stable, either the Pegasor or the eDiluter™ hot sampling line is connected to one of the sampling taps along the pipeline. The oven heating resistance is then activated along with the fan (inverter frequency = 80 Hz), and either Pegasor or ELPI®+ data acquisition is simultaneously initiated, enabling continuous real-time monitoring of the particle size distribution evolution from the onset of the thermal process.

In the initial phase of the experiment, particle concentrations detected by both Pegasor and ELPI®+ remain low, with the measured signal attributed predominantly to residual contaminants such as ash deposits and oxide scaling from previous experimental sessions, rather than to freshly generated pyrolysis aerosol.

It was decided to monitor the particle number concentration as a function of particle aerodynamic diameter at discrete, representative temperature conditions in the oven — monitored by thermocouple TC-01 — namely at 100 °C, 200 °C, 250 °C, and 300 °C, in order to assess the evolution of the particle size concentration as a function of the thermal state of the system throughout the experimental campaign.

Figure 16 illustrates these checkpoint temperatures and the maximum temperature along the TC01 temperature trend.

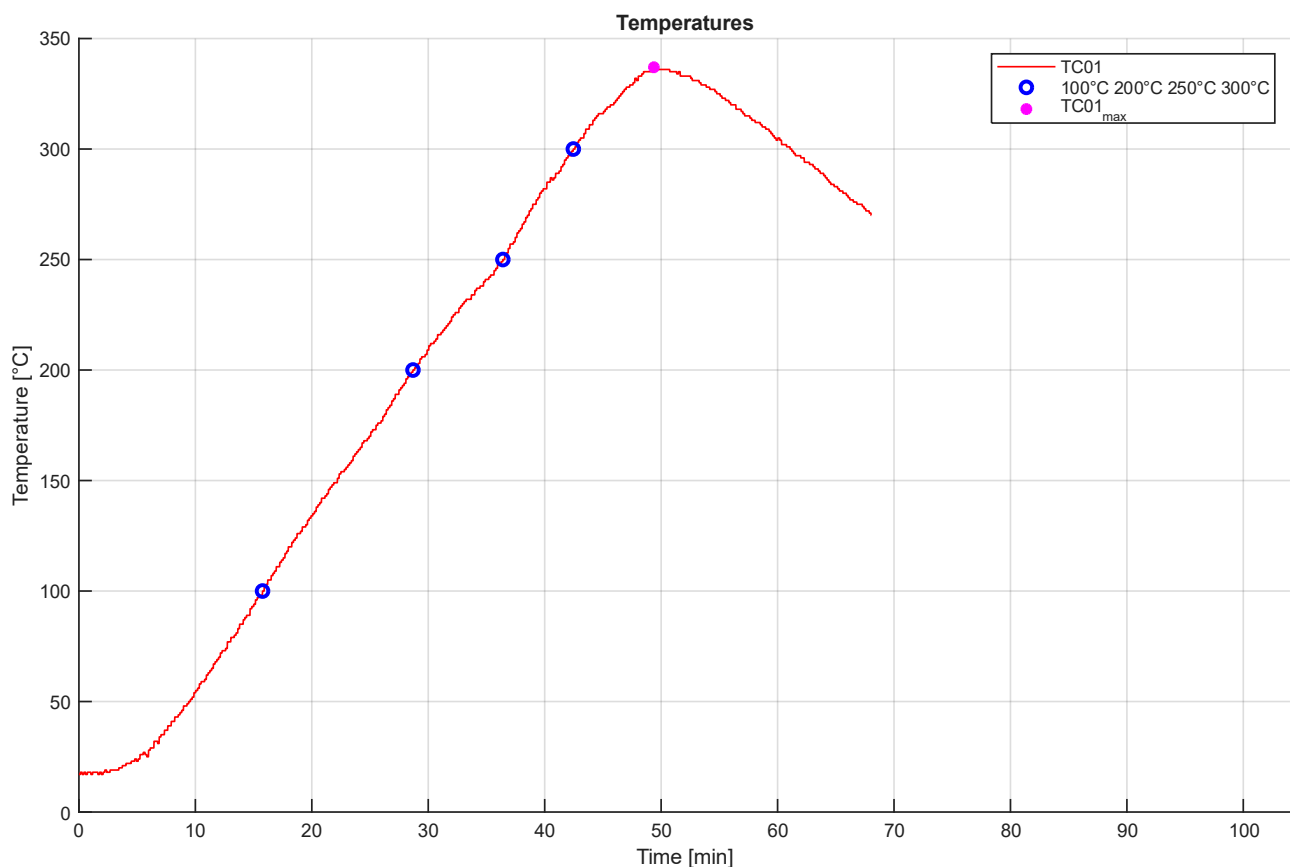


Figure 16

The selection of the four checkpoint temperatures — 100 °C, 200 °C, 250 °C, and 300 °C — is consistent with the sequential stages of the biomass pyrolysis process described in the present text. The first stage of pyrolysis occurs below 100 °C and is associated with the removal of

moisture from the biomass, during which no significant release of organic volatile compounds is expected. The checkpoint at 100 °C therefore corresponds to the transition from the drying stage to the onset of thermochemical decomposition and marks the temperature above which pyrolysis fumes and condensable vapours begin to appear in the sampling line.

The subsequent checkpoints at 200 °C and 250 °C fall within the range of temperatures over which the second and third pyrolysis stages occur, during which hemicellulose and cellulose are progressively decomposed into smaller, volatile organic molecules and the first substantial fraction of the bio-oil-related aerosol is generated. These temperatures thus represent intermediate monitoring points along the pyrolysis temperature ramp, enabling the characterisation of the particle size distribution evolution as the amount and complexity of the emitted volatiles increase.

The final checkpoint at 300 °C lies at the lower boundary of the temperature range defined for slow pyrolysis (300–700 °C) in the reference text, which is the regime targeted in the present experimental campaign. At this temperature, the release of volatiles is well established, while the formation of more stable, heavier components and the onset of char-forming reactions become increasingly significant. Collectively, the four selected checkpoints therefore provide a physically coherent and representative basis for assessing the evolution of the particle size distribution as a function of the thermal state of the system throughout the slow pyrolysis process.

Throughout the duration of the experiment, the oven temperature increases approximately linearly. The oven remains active until no droplets exit the cyclone, after which the char and bio-oil are weighed.

The experiment can be considered complete once the particle concentration has returned to a level comparable to that observed at the beginning of the test, hence the total duration of each experimental run is approximately 60 minutes.

3.5 Pegasor experimental campaign

3.5.1 Pegasor instrument¹

The Pegasor Particle Counter (PPC) is a complete, stand-alone particle number measurement system. The instrument is intended for real-time monitoring of particle emissions from combustion sources, including engine and vehicle exhaust, industrial stacks, and other high-temperature aerosol sources. At the core of the PPC is the patented Pegasor PPS-G2 particle sensor, which enables simultaneous measurement of particle number (PN) concentration, lung-deposited surface area (LDSA), particle mass (PM) concentration, and median particle size within a single, integrated measurement platform.

The PPS-G2 sensor operates based on electrical detection of aerosol particles, implementing the patented "escaping current" technique. In this method, particles entering the sensor are first electrically charged and subsequently detected through the measurement of the electrical current carried out of the sensing volume by the charged particles as they exit — hence the designation "escaping current". A defining characteristic of this detection principle is its flow-through design, which ensures that charged particles do not deposit on the internal surfaces of the sensor during measurement.

The PPC has been specifically engineered for high-temperature measurement applications, enabling direct aerosol sampling from sources at temperatures of up to 200 °C. To this end, the PPS-G2 sensor is internally heated and operates at elevated temperatures throughout the measurement. An integrated heated Volatile Particle Remover (VPR) is included within the unit to ensure the efficient removal of volatile organic compounds (VOCs) and humidity from the aerosol sample prior to detection. The combination of the heated sensor module and the integrated VPR eliminates the requirement for external sample dilution, thereby improving measurement sensitivity and simplifying the overall system setup. Connection to the emission source is made by means of a heated sampling line, supplied with the instrument as standard.

¹ All technical data referenced above are sourced exclusively from the official Pegasor Oy product page available at pegasor.fi/particle-instruments/pegasor-particle-counter/

3.5.2 Sampling circuit layout

Given that the Pegasor PPC does not require any pre-measurement setup or thermal stabilisation procedures prior to the commencement of data acquisition, the instrument was connected directly to the sampling tap of interest without any preliminary preparatory operations. The resulting configuration is illustrated in the figure below.



Figure 17

Here it is shown linked to the oven outlet sampling tap.

3.5.3 Measurement shown

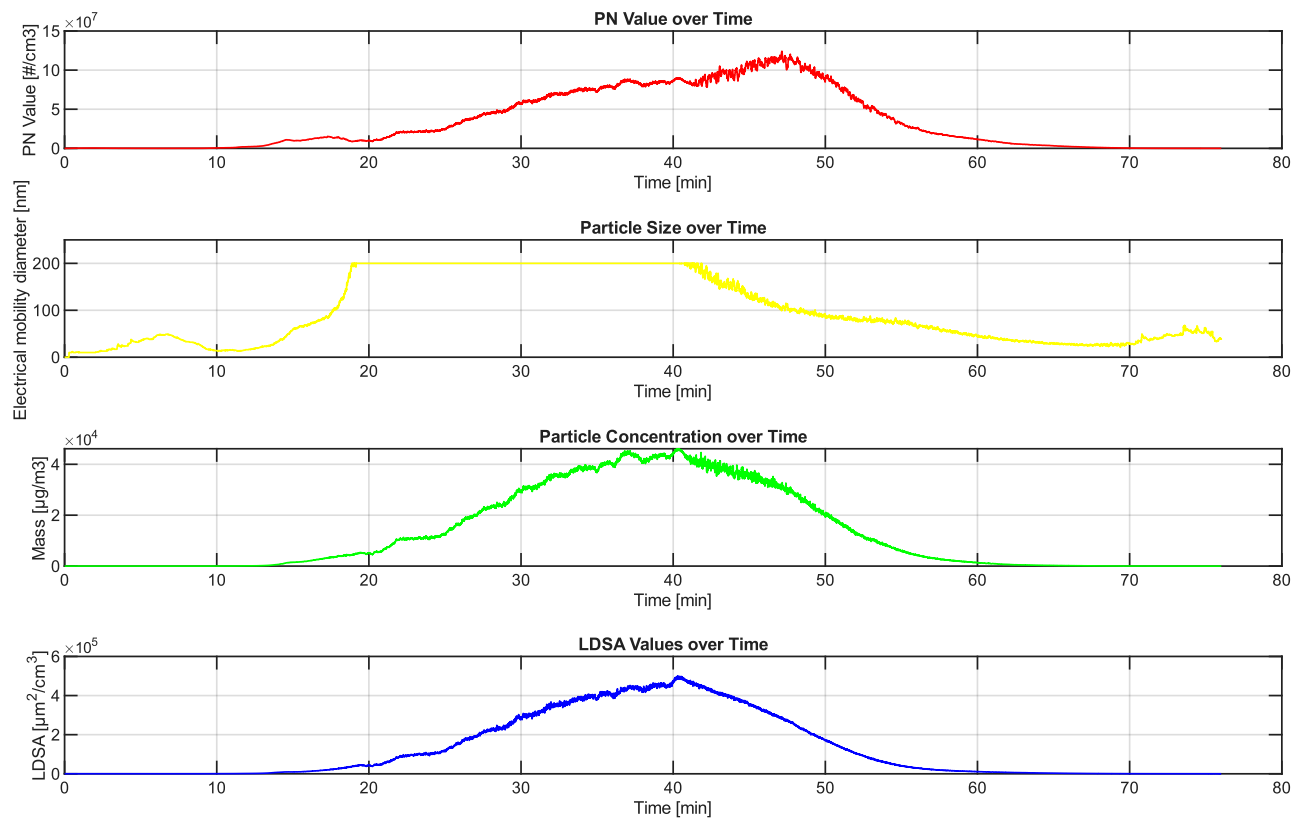


Figure 18

Pegasor PPC measurements at the cyclone outlet during Test 6 reveal a clearly structured temporal evolution of the aerosol across all four measured quantities — particle number concentration (PN), mean particle size, mass concentration, and lung-deposited surface area (LDSA) — over a total measurement duration of 75.92 minutes.

Moreover, it is consistent with the classical pyrolysis sequence reported in the literature, which can be broadly divided into a drying stage, a pyrolytic or active devolatilization stage, and a final char-forming stage. During the initial interval, the signal remains comparatively low and can be associated with the moisture evaporation and early heating period; subsequently, the marked increase in particle number concentration, mass concentration, and LDSA corresponds to the main devolatilization interval, when the biomass releases the maximum amount of volatile matter. In this phase, the literature also indicates that aerosols may be generated as primary aerosols during pyrolysis or, more importantly for cooled vapours, as secondary aerosols through condensation and repolymerization during vapor cooling. The final decline in the measured aerosol metrics is therefore compatible with the depletion of volatile precursors and the onset of the char-forming stage, when most condensable material has already been released.

3.5.4 Comparison among the three sampling taps

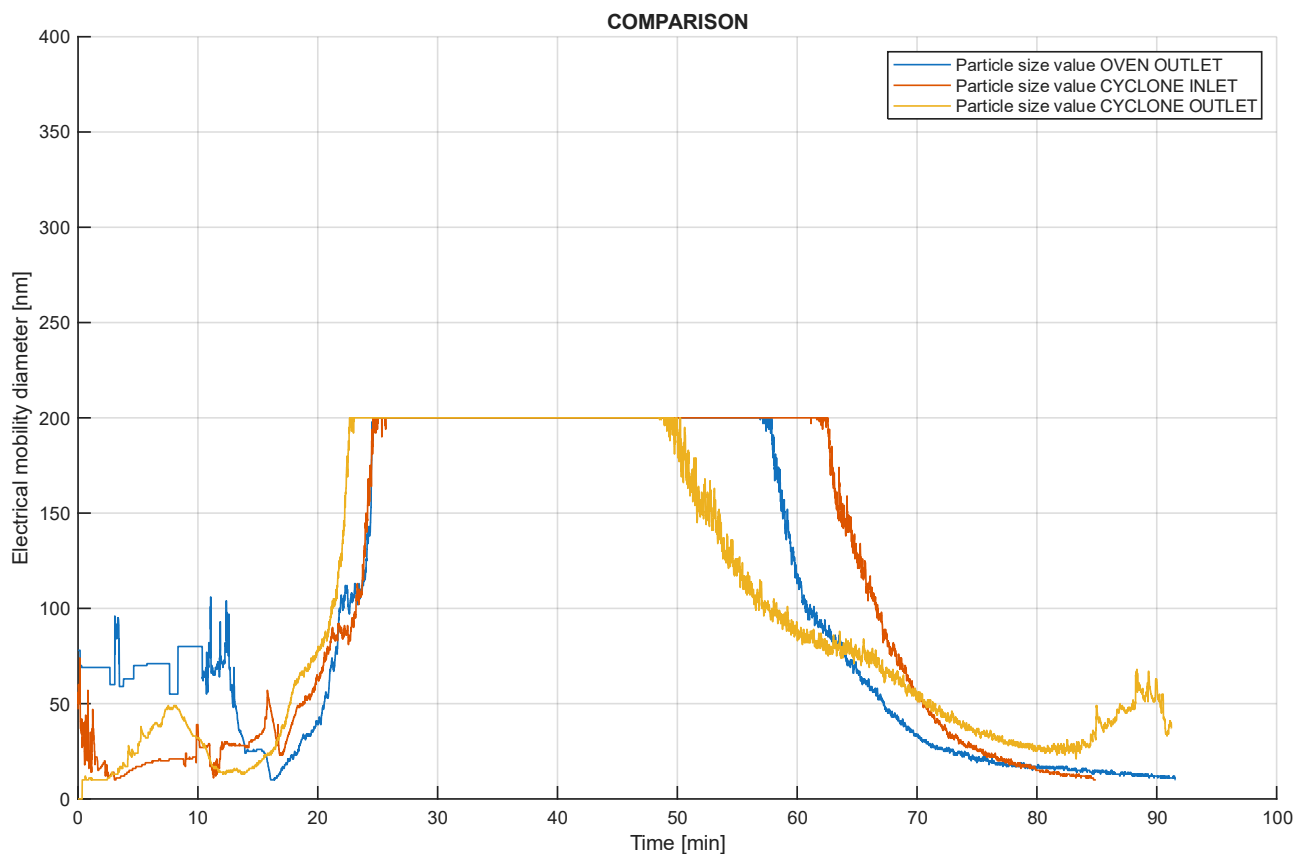


Figure 19

The figure illustrates the temporal evolution of the electrical mobility diameter reported by the Pegasor PPC at the three sampling positions — oven outlet, cyclone inlet, and cyclone outlet — over the full duration of the experimental campaign.

It should be noted that the data recorded during the first approximately 15 minutes of the experiment are not representative of the pyrolysis aerosol and should therefore be considered physically meaningless in the context of the present analysis. During this initial phase, the oven temperature has not yet reached the threshold required to initiate biomass pyrolysis, and the particles detected by the instrument are attributed predominantly to residual contaminants — such as ash deposits and oxide scaling from previous experimental sessions — rather than to freshly generated pyrolysis aerosol.

A critical observation regarding the remainder of the dataset is the saturation of the particle size signal at 200 nm across all three measurement positions for an extended period between approximately 25 and 60 minutes into the experiment. This plateau is not physically representative of the actual particle size distribution present in the sampling line; rather, it reflects a fundamental instrumental limitation of the Pegasor PPC: the upper boundary of the detectable median particle size is capped at 200 nm, beyond which the instrument is unable to report a physically meaningful size value. Consequently, during the most active phase of the pyrolysis process — when the highest volatile production and aerosol generation are expected

— the Pegasor PPC is effectively operating outside its reliable measurement range, and the recorded size values are saturated and therefore unreliable.

This limitation has two important implications. First, it prevents any quantitative assessment of the particle size evolution during the peak pyrolysis phase, which is precisely the interval of greatest scientific interest for the objectives of the present study. Second, and more critically, it renders the Pegasor PPC unsuitable for characterising an aerosol population in which particle sizes are expected to exceed 200 nm during a substantial portion of the experiment, as is the case in biomass pyrolysis.

These observations constitute the primary technical justification for the replacement of the Pegasor PPC with the ELPI[®]+, which resolves the full particle number size distribution across aerodynamic diameter classes up to **10 μm** , and is therefore capable of characterising the aerosol population throughout the entire duration of the pyrolysis experiment without saturation.

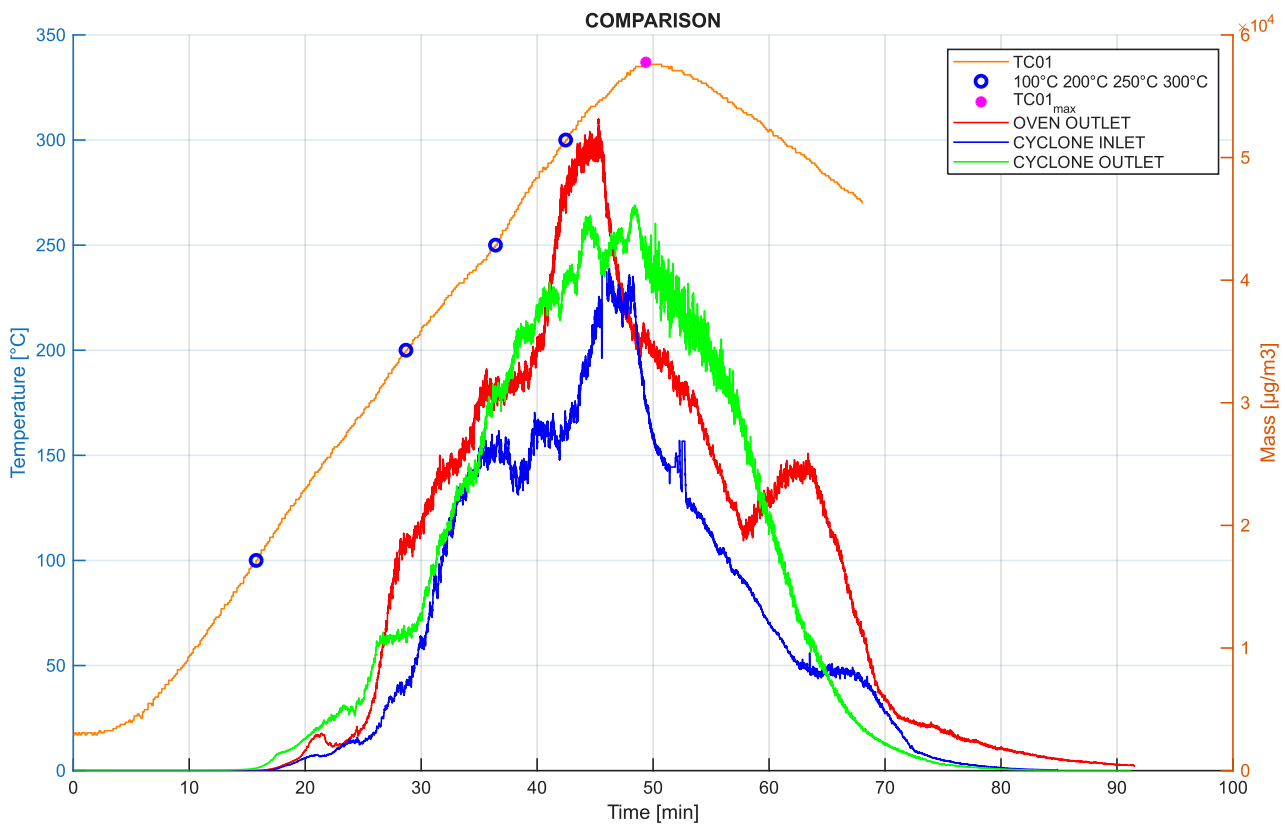


Figure 20

Notwithstanding its dimensional limitations, the Pegasor PPC proved useful as a qualitative indicator of the relative particle mass concentration at each of the three sampling positions throughout the experiment, as illustrated in Figure 20. In particular, the data reveal that the particle mass concentration measured at the cyclone outlet is consistently higher than that recorded at the cyclone inlet over the most significant portion of the experiment. This counter-intuitive result generates the concrete suspicion that the installed cyclone is not operating as an inertial separator in any meaningful sense but rather acting predominantly as a heat exchanger. This behaviour is attributed to the combined effect of three concurrent factors: the

presence of the water jacket surrounding the cyclone body, which actively cools the internal gas flow; the cold mass flow rate injection upstream of or within the cyclone; and the structural deficiency at the inlet section, which — as discussed in the preceding section — prevents the development of the swirling flow pattern necessary for centrifugal particle separation. Under these conditions, the primary effect of the cyclone on the aerosol stream appears to be thermal rather than aerodynamic: the cooling induced by the water jacket and cold injection promotes condensation of volatile compounds onto pre-existing particles within the cyclone volume, leading to particle growth and an effective increase in the measured particle mass concentration at the cyclone outlet relative to its inlet.

3.6 ELPI®+ experimental campaigns

3.6.1 ELPI®+ instrument²

The Dekati® Electrical Low-Pressure Impactor (ELPI®+) is a real-time aerosol particle size spectrometer designed and manufactured by Dekati Ltd. (Tampere, Finland). The instrument enables continuous measurement of particle number size distribution and concentration across a size range of **6 nm to 10 µm**, at a temporal resolution of up to **10 Hz**. Its broad measurement range, combined with the ability to perform simultaneous physical collection of particulate matter, renders the ELPI®+ a versatile tool for aerosol characterisation in both controlled laboratory environments and field measurement campaigns.

The ELPI®+ operates on the combined principles of unipolar electrical charging, aerodynamic size classification by inertial impaction, and real-time electrometric detection. The measurement process can be described in three sequential stages:

1. Particle Charging

The aerosol sample is drawn into the instrument at a flow rate of 10 L/min and directed through a unipolar corona charger. Within this charger, particles acquire a well-defined and reproducible electrical charge, the magnitude of which is a known function of particle size. This conditioning step is fundamental to the quantitative nature of the subsequent detection.

2. Aerodynamic Size Classification

Following charging, the aerosol enters a cascade impactor operating under low-pressure conditions. The impactor consists of 14 electrically insulated collection stages, each designed to capture particles above a specific aerodynamic cut-off diameter. Particle deposition on each stage is governed by inertial impaction: as the aerosol flow accelerates through the nozzles of each stage, particles with sufficient inertia deviate from the streamlines and impact upon the collection substrate, while smaller particles remain entrained in the flow and proceed to the subsequent stage. In this manner, the particle population is fractionated by aerodynamic diameter across the 14 stages.

3. Electrometric Detection

Each impactor stage is connected to a dedicated, highly sensitive electrometer. As charged particles deposit upon a given stage, the accumulated charge generates an electrical current that is continuously measured in real time. Since the charge carried by each particle is a known function of its size, the current signal from each stage is directly proportional to the particle number concentration within the corresponding size fraction. The array of electrometer signals is processed by an onboard computer system, yielding the real-time particle number size distribution.

² All technical data referenced above are sourced from the official Dekati Ltd. product documentation, including the eDiluter™ Model Range Brochure (2024) and the Dekati® eDiluter™ Product Range page, available at dekati.com.

Since the FumeCatch operates at elevated temperatures, the use of the e-Diluter was also required to ensure accurate measurements while preventing potential damage to the instrument: The eDiluter™ operates on the basis of **two-stage ejector dilution**, wherein the aerosol sample is progressively diluted and thermally conditioned before reaching the measurement instrument. The operating sequence is as follows:

1. First Dilution Stage (Heated)

The aerosol sample enters the system through the inlet and is introduced into the first dilution stage, which operates at an elevated, user-defined temperature. This heated stage performs the initial dilution of the hot aerosol sample and is critical for preventing unwanted condensation and nucleation artefacts that would otherwise distort the measured particle size distribution. The dilution at this stage is achieved through an **ejector diluter** mechanism: pressurised, purified dilution air — itself heated — is supplied at high velocity around a large ejector nozzle, inducing a pressure drop that draws the sample flow through the nozzle. The raw sample is instantaneously and homogeneously mixed with the dilution airflow upon entry.

2. Second Dilution Stage (Ambient Temperature)

Following the first stage, the partially diluted sample proceeds to the second dilution stage, which operates at room temperature. This stage further dilutes the aerosol and allows it to cool in a controlled manner to near-ambient conditions. As in the first stage, an ejector diluter with additional sheath air flow is employed. The combination of a large ejector nozzle geometry and sheath air minimises particle losses within the system, with a particle penetration efficiency exceeding 90% for particles smaller than 200 nm.

3. Sample Output

The fully conditioned and diluted sample exits the system at stable ambient temperature and pressure, with an output flow rate of 50–80 lpm. This makes the eDiluter™ compatible with virtually all commercially available particle measurement instruments. The dilution factor of each stage is independently adjustable over a range of 1:5 to 1:30, yielding a total two-stage dilution factor between 1:25 and 1:900.

3.6.2 Sampling circuit layout



Figure 21

Figure 21 illustrates the measurement station as configured during the experimental campaigns. The workstation running the main LabVIEW Virtual Instrument (VI) is visible, through which all acquisition parameters are monitored and logged in real time. Also shown is the vacuum pump, which is connected to the ELPI®+ outlet and is responsible for maintaining the sub-atmospheric pressure conditions required for correct aerodynamic particle classification within the cascade impactor stages of the instrument.

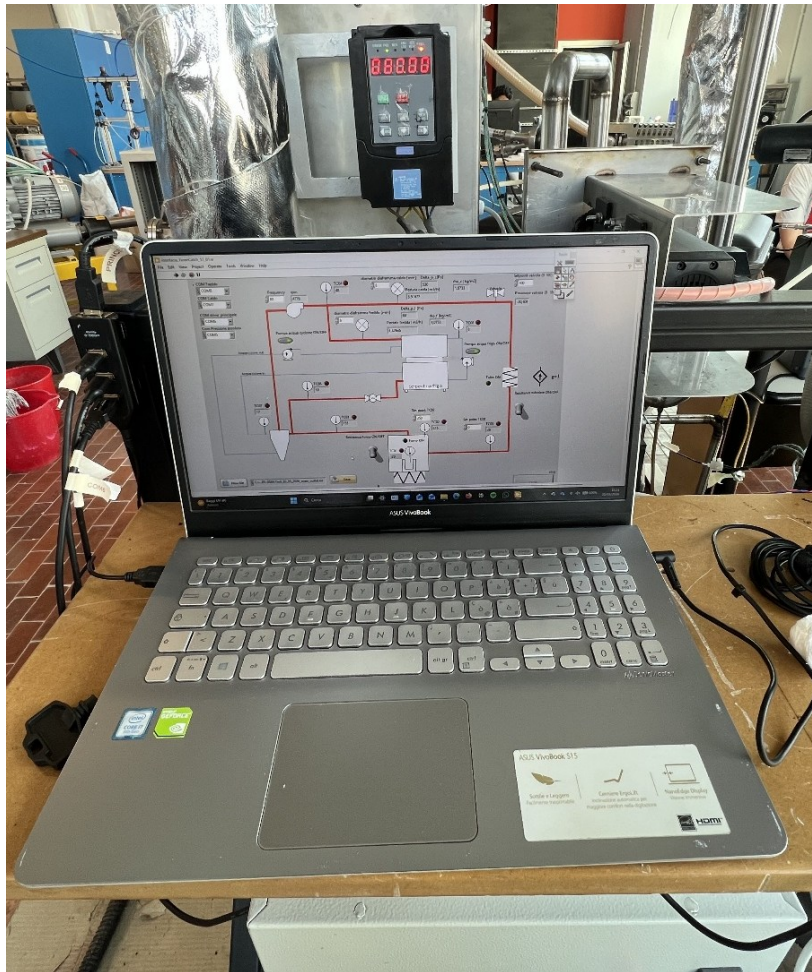


Figure 22



Figure 23



Figure 24



Figure 25

Figures 24 and 25 illustrate the measurement setup as operational during an experimental campaign. The workstation running the dedicated ELPI®+ acquisition software is shown, displaying the real-time particle number size distribution recorded by the instrument during active sampling. The ELPI®+ unit itself is visible in its installed configuration, together with the eDiluter™, which is positioned upstream of the ELPI®+ inlet and performs the thermal conditioning and two-stage dilution of the aerosol sample prior to its introduction into the impactor stages.



Figure 26



Figure 27

3.6.3 Results and comments

This section first presents the cumulative particle concentration for each diameter as a function of time, highlighting the time instant at which a given temperature checkpoint is reached. This constitutes the first significant evidence of the difference between particle concentration at the inlet and at the outlet, indicating a substantial increase in particle concentration at the outlet.

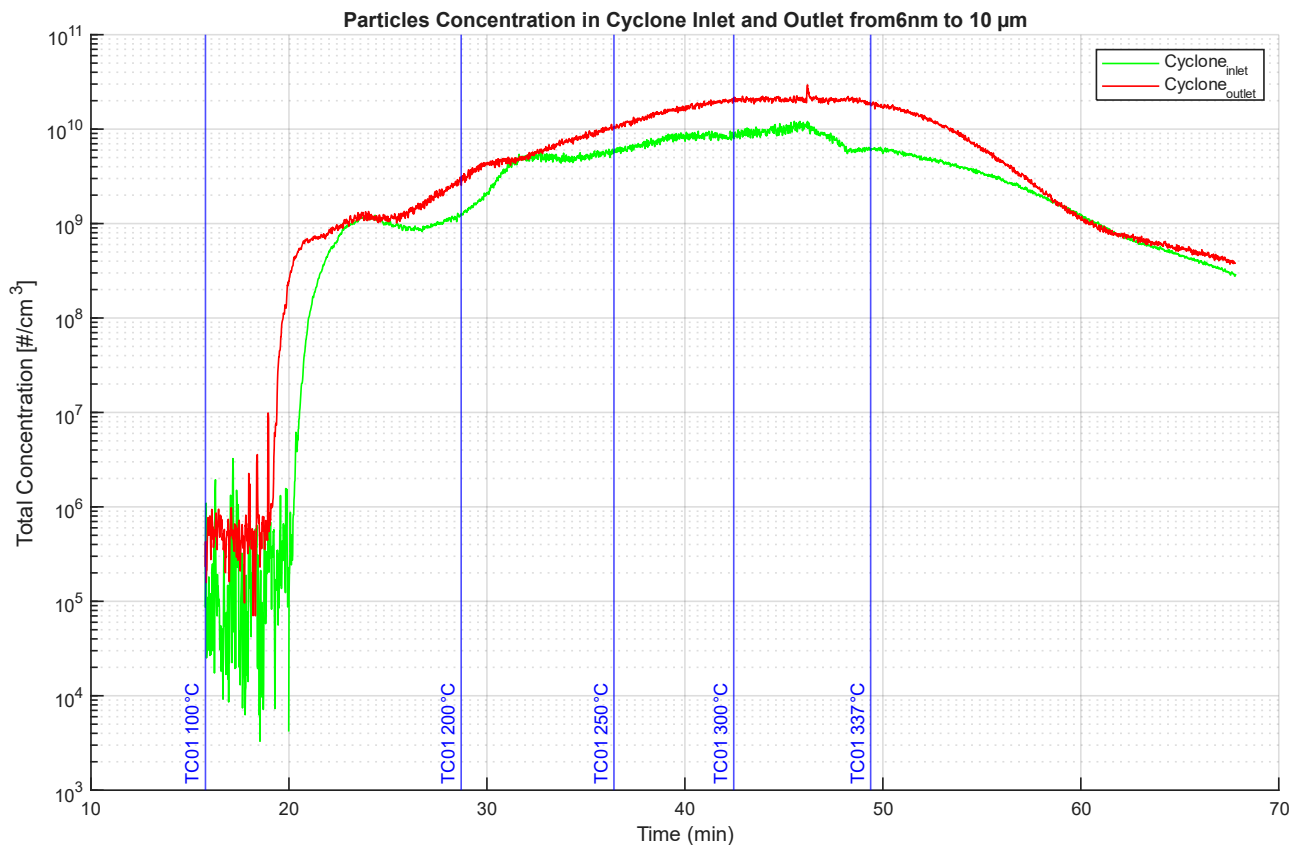


Figure 28

Only the most significant particle concentration is presented, namely that corresponding to 300°C, since at this temperature checkpoint, the highest concentration is observed at both the inlet and the outlet relative to the other checkpoints.

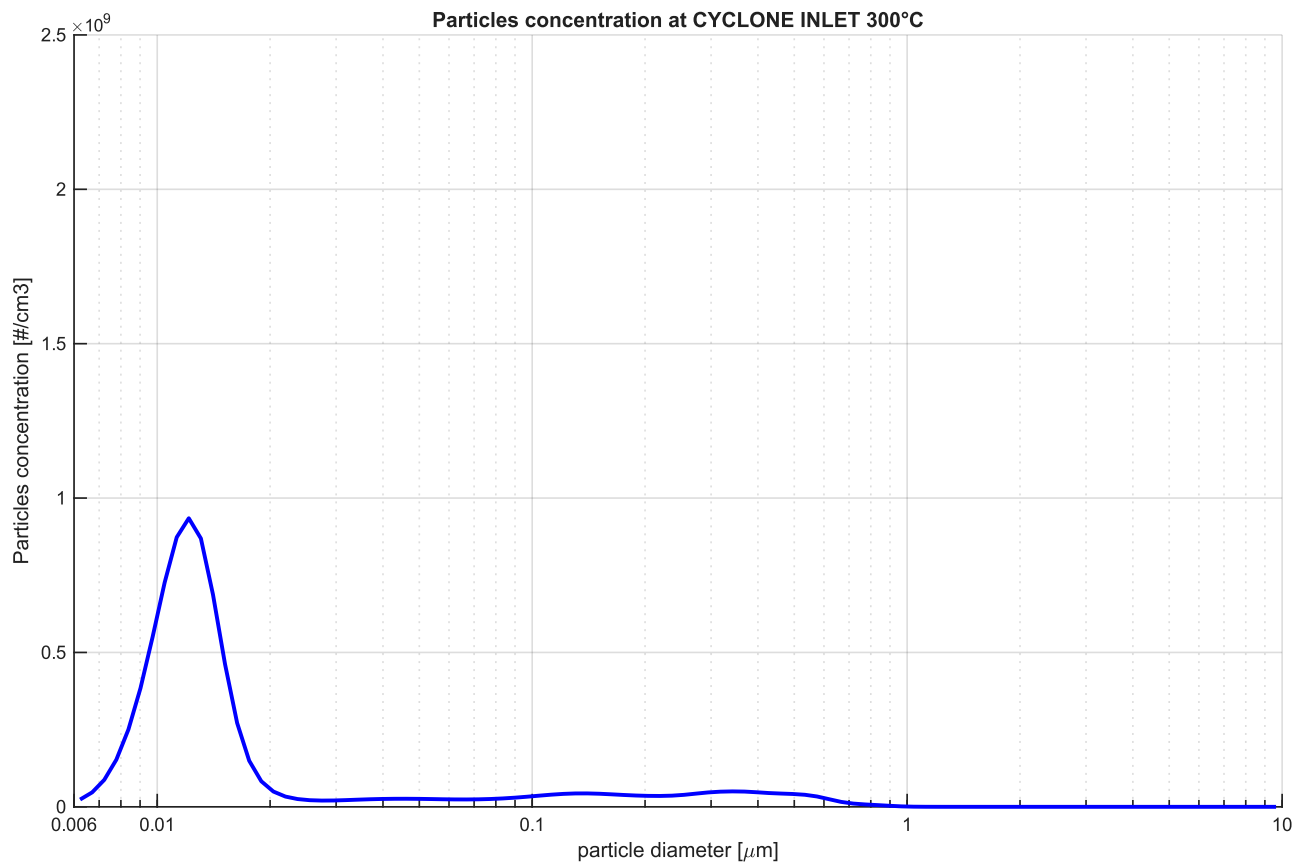


Figure 29

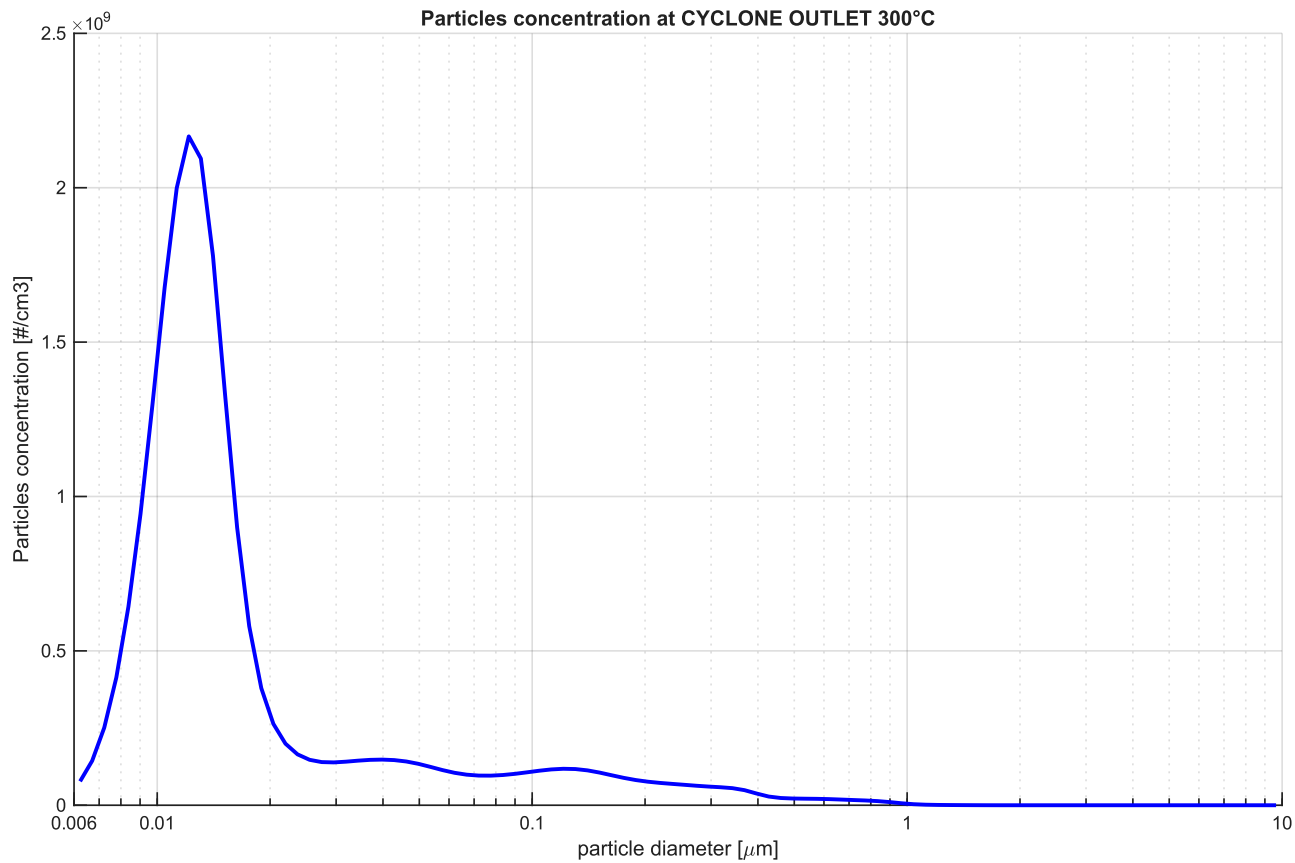


Figure 30

Dirgo & Leith 1985, Iozia & Leith 1989/1990, Zhao 2010, Hoffmann & Stein's *Gas Cyclones and Swirl Tubes* confirms that a physically meaningful cyclone "collection efficiency" cannot be defined for this dataset, because every classical model assumes that outlet concentration is always lower than or equal to inlet concentration; outlet spectra show up to two orders of magnitude higher particle number concentration than the inlet at all four temperatures, which is inconsistent with the underlying mass-balance assumption of any cyclone theory. This strongly supports treating the cyclone, under these operating conditions, as a condensation/nucleation stage rather than an inertial separator. (8) (9) (10)

Every fractional-efficiency theory (Lapple, Barth, Leith–Licht, Dietz, and their later refinements by Iozia–Leith and Muschelknautz) defines collection efficiency as $\eta = 1 - \frac{N_{out}}{N_{in}}$ or, in dimensionless form, as a logistic function of the ratio d/d_{50} . These formulations are built on the physical premise that particles can only be removed from the gas stream, never generated inside it — the force balance underlying the static-particle and time-of-flight approaches only accounts for centrifugal separation of pre-existing particles, not for in-situ nucleation or condensation. (8) (9) (10) (11)

In the following picture a better view of the particle's concentration both at cyclone's inlet and outlet is given.

Particles concentration at CYCLONE INLET 300°C

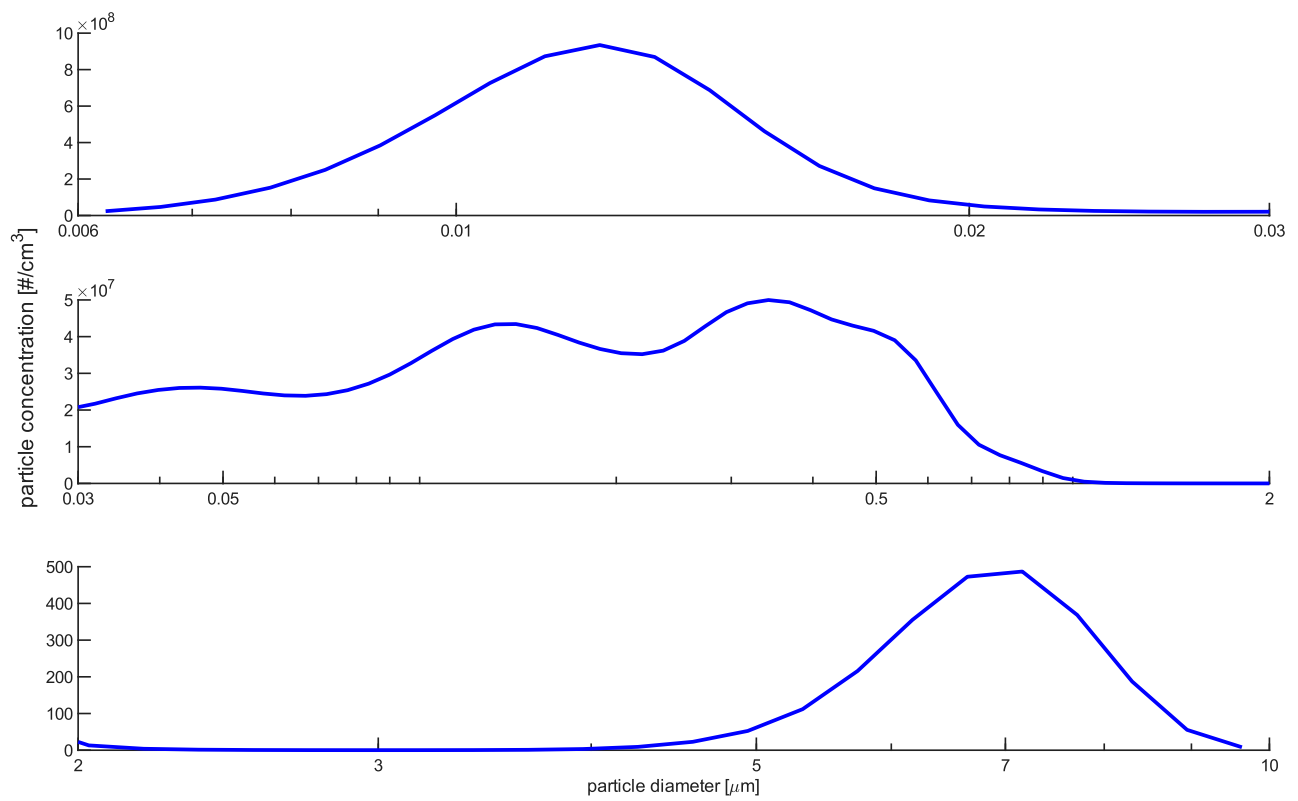


Figure 31

Particles concentration at CYCLONE OUTLET 300°C

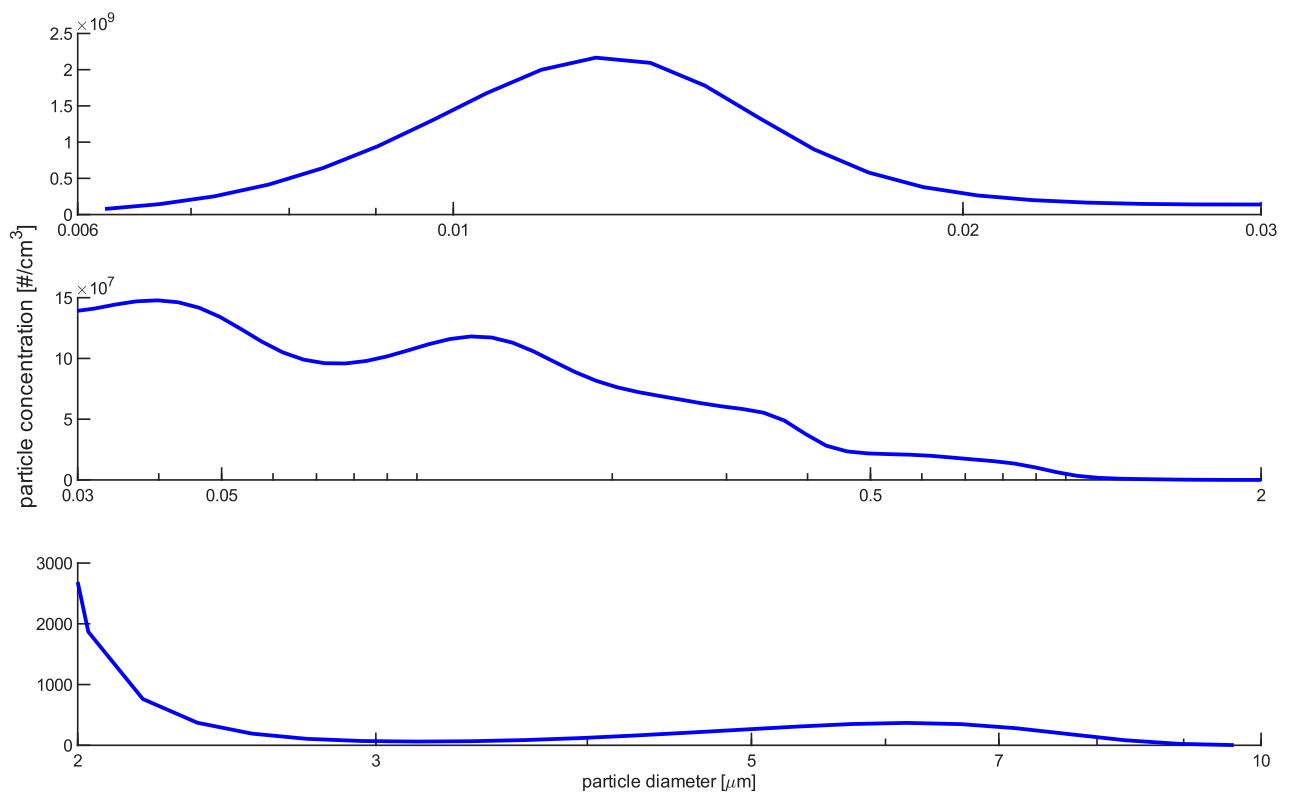


Figure 32

The shape of outlet spectra is consistent with homogeneous nucleation/condensation rather than mechanical separation. This pattern — a new, dominant nanoparticle mode appearing only at the outlet and growing steeply with temperature — is the classic signature of vapor supersaturation and homogeneous/heterogeneous nucleation occurring as hot, volatile-laden gas contacts a colder surface or a cold injected stream, rather than of inertial classification of pre-existing particles. The literature on cyclone gas dynamics also notes that any internal temperature gradient or additional gas injection changes the local flow and residence-time pattern in ways the classical models do not capture, reinforcing that a mechanistic reinterpretation (condenser-like behaviour) is more consistent with these data than a cyclone. (3) (10)

As far as the cold injection effect is concerned, the monotonic increase of the ultrafine outlet peak with increasing hot-side temperature (100→300°C) is consistent with more vapours being available to condense/nucleate when it meets the cold injection stream, which would support the idea that the cold stream is inducing condensation. In addition to the cold injection stream there is also the water jacket effect on the cyclone's walls, that induces a temperature gradient all over the cyclone's body. Hence, both mechanisms intensify local cooling and promote supersaturation of the pyrolysis vapours. (7) (12)

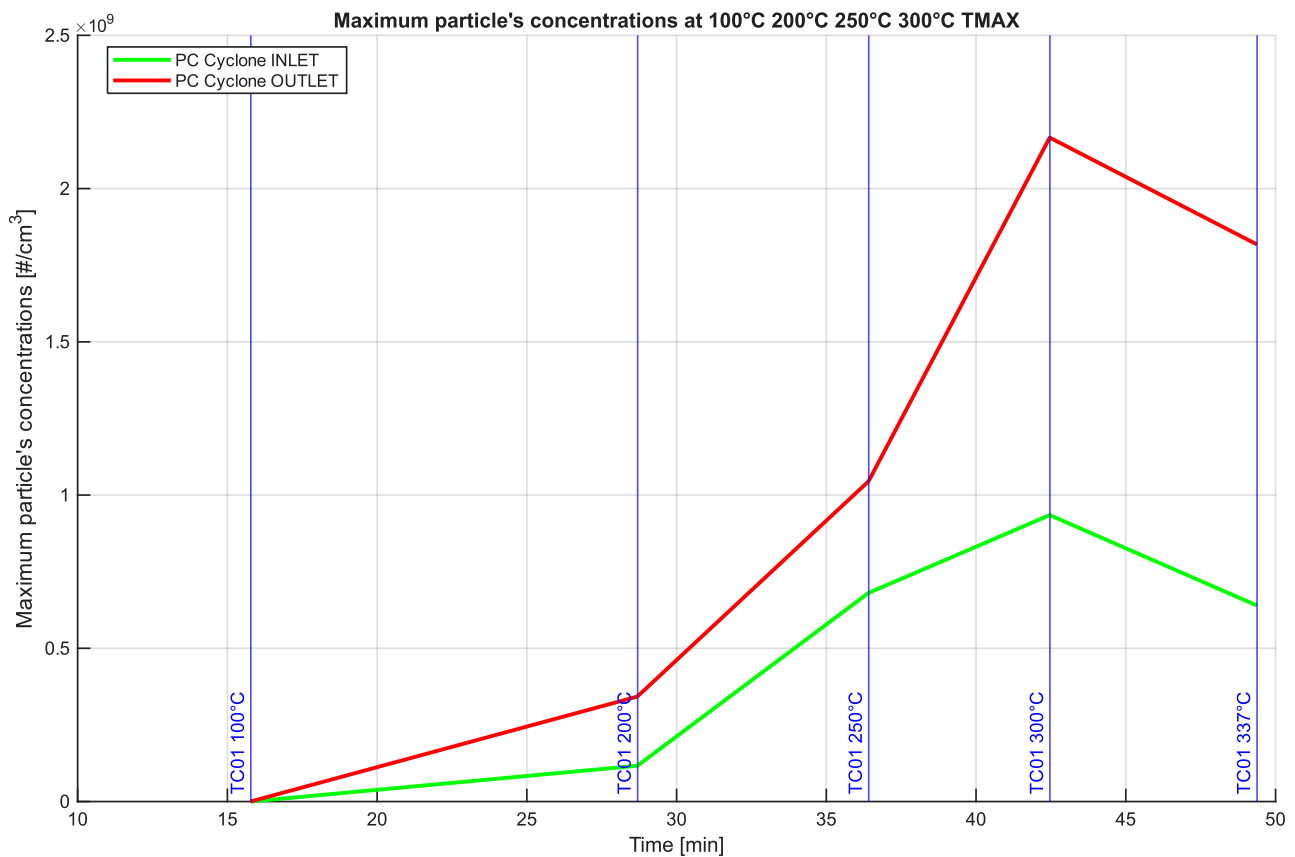


Figure 33

The monotonic increase of the ultrafine outlet peak with hot-side temperature (100→300 °C) is consistent not only with the greater availability of condensable vapours released at higher pyrolysis temperatures, but also with the exponential rise of the equilibrium partial pressure of the pyrolytic compounds with temperature, as described by the Clausius–Clapeyron relation;

upon contact with the cold injected flow, this results in a markedly higher supersaturation ratio, which is the controlling variable for the nucleation rate in classical homogeneous nucleation theory. To conclude, a plausible cause of the observed particle formation is the coupled effect of the cold-flow injection and the water-jacket cooling, which may jointly increase local vapor supersaturation and thereby promote secondary nucleation and condensation; however, the present experiments do not allow the individual contribution of each mechanism to be isolated.

4 Conclusions and future steps

The experimental campaigns demonstrate that the present prototype cannot, in its current configuration, be used for a rigorous case study and requires substantial redesign before further quantitative testing can be considered reliable. The overall by-product recovery remained low across all six tests (32.0%–47.1%, mean $\approx$ 39.1%), a result attributable primarily to sealing deficiencies and to the intrinsic limitations of the installed cyclone separator.

Redesign of the oven should prioritise an improved sealing and insulation system, since the oven body was identified as one of the two most critical leakage locations and directly limits biochar recovery. Equally critical is the sealing system at the recirculation fan housing and at the mechanical interface between the fan and its drive motor, where the unsealed shaft passage constitutes a leakage path for hot fumes and condensable vapours whenever the fan casing is pressurised; this interface, together with the oven body, represents the most severe source of condensable-phase losses in the prototype. The water circulation pumps supplying the chiller and the cyclone jacket are not identified in the current data as a source of gas-phase leakage and are therefore not part of the sealing redesign priority.

The cold mass flow rate should be injected along the pipeline section connecting the oven outlet to the cyclone inlet, rather than directly at the cyclone inlet as currently implemented, to allow sufficient residence time for nucleation, growth, and coalescence of condensable vapours prior to separation; this corresponds to the original design intent, from which the as-built prototype currently deviates.

Finally, the cyclone — which under present conditions behaves more as a heat exchanger than as an inertial separator, owing to the combined effects of the water jacket, the cold injection point, and the absence of a tangential inlet channel — should be redesigned in accordance with established cyclone theory and validated geometric models.

Once these modifications have been implemented, the characterisation of the redesigned cyclone becomes the appropriate next step. The present experimental campaign was necessarily conducted at a single, fixed, reduced operating point ($\sim 5 \text{ m}^3/\text{h}$ total flow, against a nominal design value of $10 \text{ m}^3/\text{h}$), because sealing deficiencies caused leakage to increase disproportionately with flow rate, precluding any systematic variation of this parameter. With the sealing and cyclone redesign completed, it would be relevant to investigate the correlation between separation efficiency and volumetric flow rate, by independently varying the recirculated (hot) flow rate, the cold flow rate, and the temperature of the cold injection, thereby generating the performance characterisation (cut-off diameter, collection efficiency curve, pressure-drop correlation) that is currently unavailable for this cyclone geometry.

APPENDIX A - Software assessment

Appendix A is fundamental to the present work, as it documents the software that enables the prototype to be operated and monitored. It describes the computational routines used to evaluate the volumetric flow rate in the pipeline branches and the control interface through which the prototype can be remotely commanded by assigning the desired temperature set-points and other operating variables. This section is therefore essential not only for understanding how the prototype is controlled in practice, but also for ensuring the repeatability and interpretability of all subsequent experimental campaigns. Without this software layer, neither the regulation of the operating conditions nor the implementation of further tests and maintenance interventions would be possible.

The machine is controlled through the LabView software titled “INTERFACCIA FUME CATCH 17_01”. Each sensor, together with the DC motor that actuates the butterfly valve, the inverter and the AC motor of the fan and the two heating resistors, is connected to an Arduino microcontroller that interfaces with the software. The system is composed of the following VI which operate concurrently:

- Main VI → this module enables the evaluation of the mass flow rate within the system, the monitoring of temperature values at critical points, and the regulation of the mass flow rate directed either toward the refrigerator or the oven by controlling the valve position. It also manages the activation and deactivation of the pumps associated with the refrigerator and the cyclone to ensure uniform temperature distribution, the switching on and off the oven resistor and that located along the inlet branch, and, finally, it generates a data file that records all the monitored parameters for each performed.
- Lettura & zero → this subVI it is designed to continuously acquire and verify signals from pressure sensors. It features three string monitors, one for each sensor, which display the respective pressure readings in real time.
- Globale sensore pressione (G.S.P.) → this subVI manages the variables associated with the pressure measurements, respectively corresponding to the cold flow (Δp_{FREDDO} , $p_{ASSOLUTA}$) pipeline branch (directed toward the refrigerator) and the hot flow (Δp_{CALDO}) pipeline branch (recirculating). Within this subVI, the COM port of each sensor can be selected, and for each signal, the following parameters are displayed: pressure value, the “pendenza” and the “zero”. This subVI interacts directly with the “Lettura&zero”. The user may also stop the execution of this subVI and simultaneously the one of “Lettura&zero”.
- Global mille funzioni (G.M.F.) → While G.S.P. handles pressure-related variables, G.M.F. is responsible for temperatures (coming from the thermocouples reading), the valve position control, the oven resistors, the inverter, the pumps. Additionally, this module generates the header of the data file produced and stored during each execution.
- Driver mille funzioni (D.M.F.) → This subVI performs real-time verification of the proper functioning of the thermocouples, valve, resistors and pumps. Furthermore, it manages communication with the Arduino microcontroller regarding all components.

Main VI

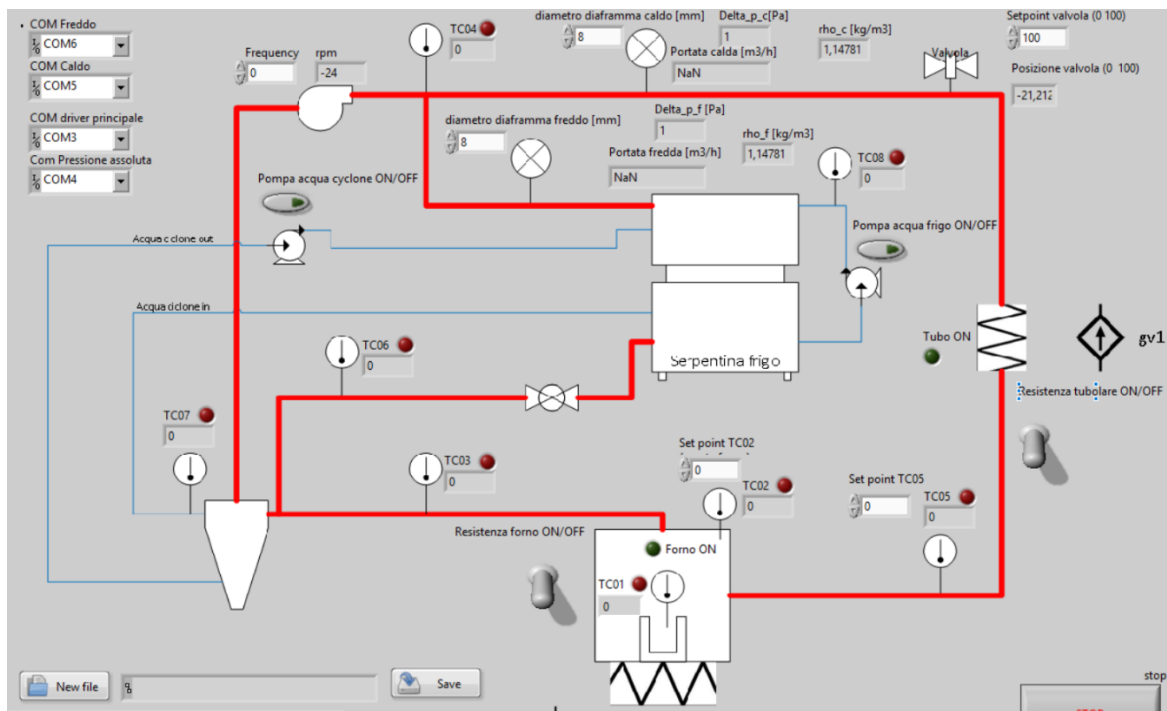


Figure 34

It consists of several block diagram and begins with a timed loop, synchronized with the Arduino clock. This loop contains a stacked sequence structure composed two main sections:

- Section 0 → “CASE 1 - Fase di comunicazione”. This section manages all the communication links with the entities stored in G.M.F. subVI. Starting from the left side of the block diagram, the following components are present:
 - ERRORE LETTURA TC → This handles warning signals related to the thermocouples. From G.M.F. the signal “NaN#” (# = 1, 2, 3, ..., 8) is received and simultaneously displayed in the same interface thanks to the use of a global variable. The same procedure applies to subsequent variables.

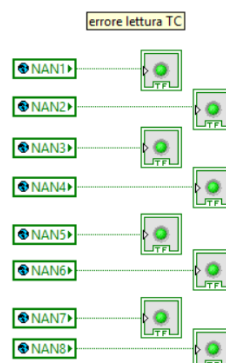


Figure 35

- TEMPERATURE → These elements receive from G.M.F. the signal of each thermocouple.

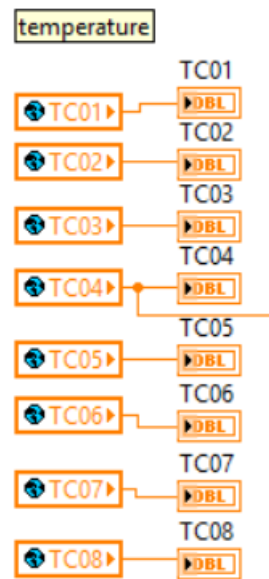


Figure 36

- RESISTENZE → These controls allow the user to switch ON or OFF the oven and the pipeline resistances.

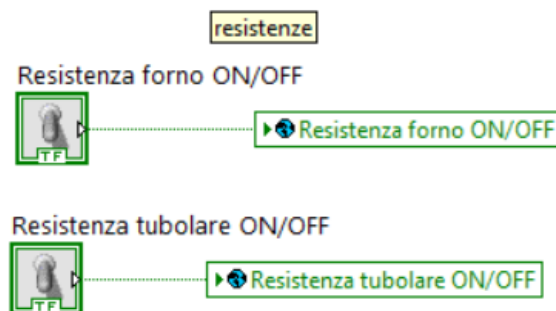


Figure 37

- RESISTENZA FORNO → This indicator, received from G.M.F., provides a warning signal showing whether the oven resistor is active. (this check is performed in D.M.F. at section 18).
- RESISTENZA TUBOLARE → This indicator, also received from G.M.F., displays whether the oven' inlet resistor is on. (this check likewise occurs in D.M.F., section 19).

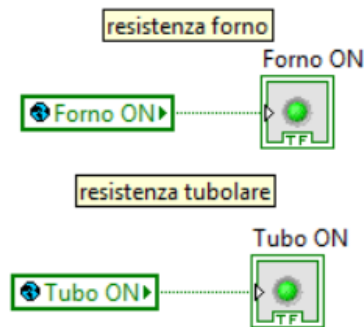


Figure 38

- POMPA ACQUA E CIRCOLATORE → These controls enable the user to activate or deactivate the two pumps: one located in the fridge, ensuring continuous water mixing to improve heat exchange, and another dedicated to the cyclone water jacket, serving the same purpose.

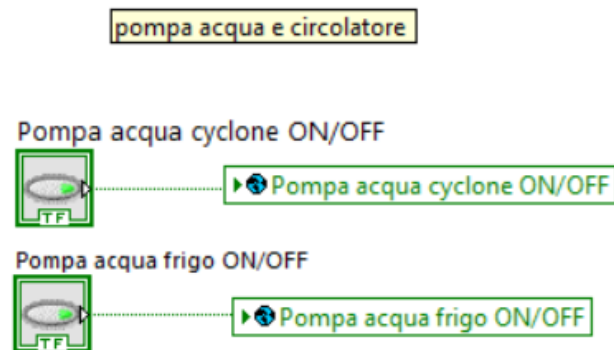


Figure 39

- FAN RPM EVALUATION → Basing on the net's frequency and the properties of the fan's AC motor, along with the inverter frequency, the software estimates the actual rotational speed of the fan.

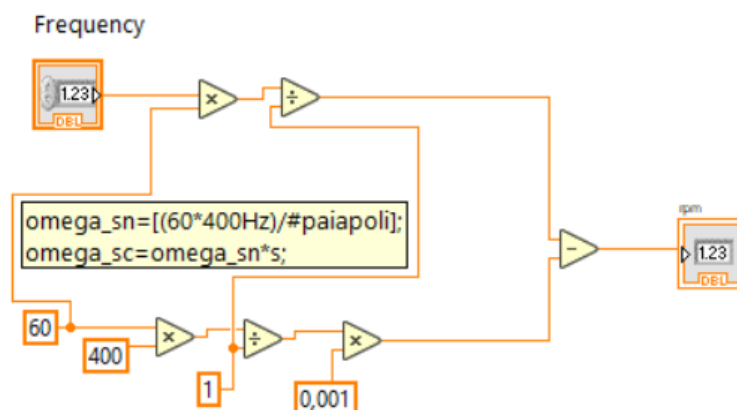


Figure 40

- SETPOINT RESISTENZA TUBOLARE → This function acquires the temperature setpoint for the oven's inlet resistance, which the user specifies in the numeric control "Set point TC05". The corresponding value is then transmitted to D.M.F. (see section 16).
- SETPOINT RESISTENZA FORNO → This function acquires the temperature setpoint for the oven's resistance, which the user specifies in the numeric control "Set point TC02". The corresponding value is then transmitted to D.M.F.

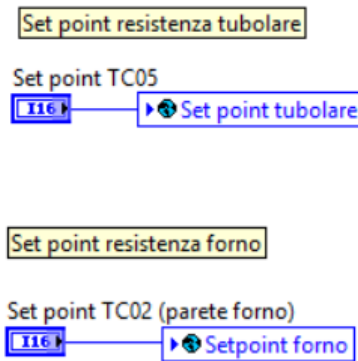


Figure 41

- SETPOINT VALVOLA → This parameter allows the user to define the valve position, thereby determining the fraction of mass flow rate directed either toward the fridge or back to the oven. The variable is designated as "set point valvola (0 100)". The entered value is multiplied by 6,6 and divided by 140; the resulting output must fall within the range 140-800. This value is sent to G.M.F. through the global variable "VALVOL" and subsequently to D.M.F. Within this latter, the received value is displayed in the numeric indicator "valvola" while the Arduino output is presented in the string monitor "setpoint valvola". (Section 10 of D.M.F.).

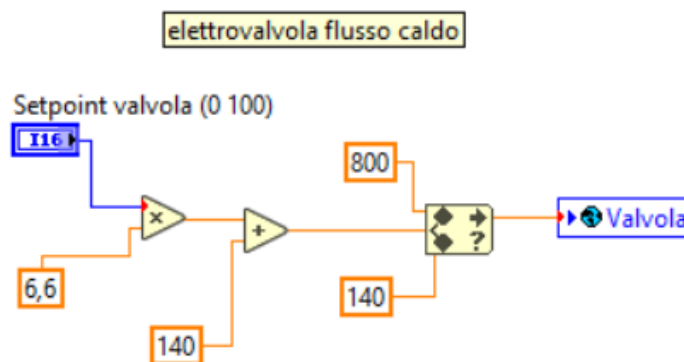


Figure 42

- MASS FLOW RATE EVALUATION → The final part of the section 0 comprises two computational modules devoted to the evaluation of the cold and hot mass flow rate. The methodology complies with ASME MFC-14M-2003 standard for all the relevant formulae, while the iterative algorithm adheres to the BS EN ISO 5167-

1:2003. The iterative procedure is based on the knowledge of the dynamic viscosity μ_1 , the density ρ_1 , the duct diameter D , the orifice plate's diameter d and the pressure drop across this device Δp . Pretending the fluid circulating in the pipeline to be air, its viscosity is evaluated according to the Sutherland's law³, its density according to the ideal gases law, and the pressure drop is measured through the orifice device. Every cycle the procedure reduces the error on the first guess choice of Re the Reynold number.

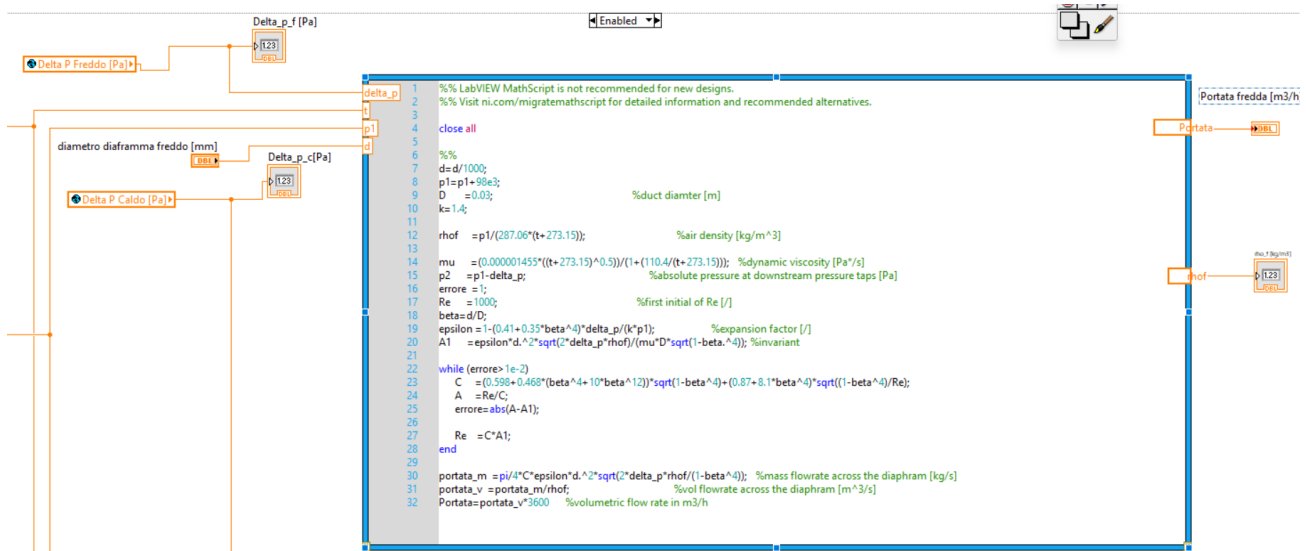


Figure 43

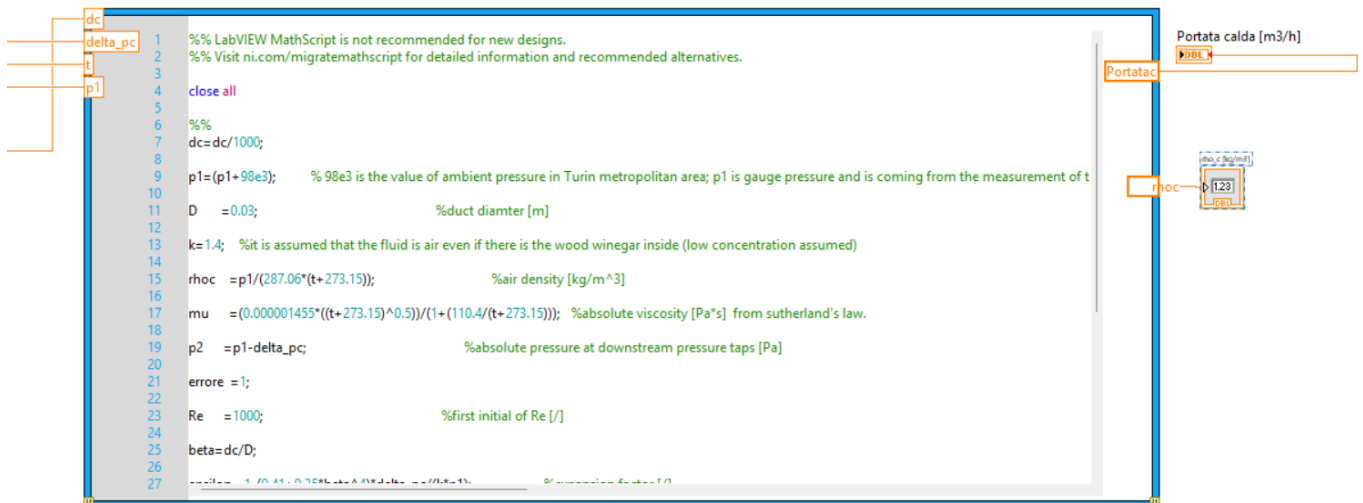


Figure 44

³ Sutherland's law is an empirical formula used to calculate the dynamic viscosity of a gas as a function of temperature.

- Section 1 → is responsible for data acquisition during system operation. When the user enters the command “new file”, the data acquisition procedure is initiated. In this section, a stacked sequence structure governs the execution of the process:

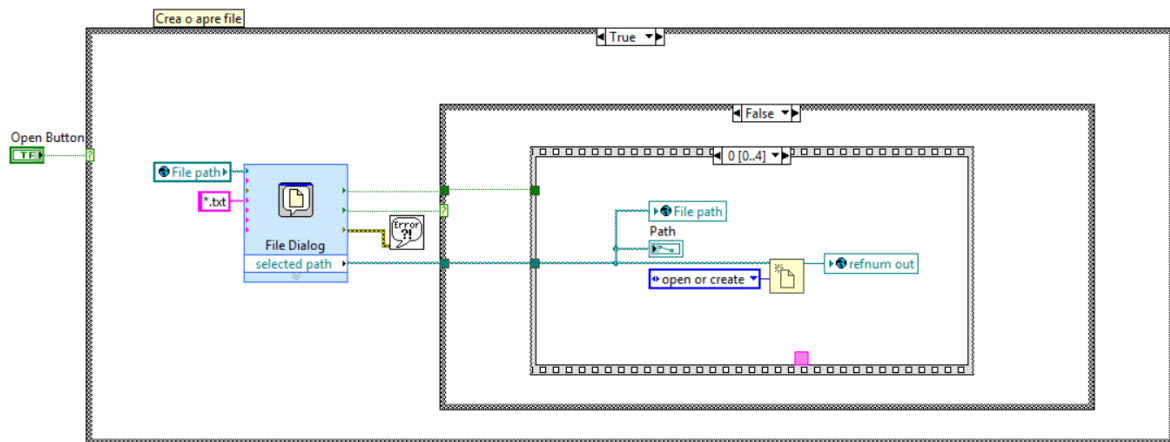


Figure 45

- Section 0 → This section, named “crea o apre file”, is executed only when its Boolean condition is true, that is, when the user has pressed the “new file” button. In the G.M.F. subVI, all variables to be stored and the file header are maintained. When the user presses the “new file” button, the file dialog operator opens a dialog window in which the user must specify the file path. If the user closes this window without selecting a path, an error message is generated; otherwise, once the path is selected, the “exist” branch returns false and the execution proceeds to a new stacked sequence structure:
 - Section 0 → The selected path, defined through the file dialog box, is passed to the open/create/replace file operator, which accordingly opens, creates, or replaces the file. This path is also displayed in the user interface above the label “prototipo fumeCatch”. The open/create/replace file operator takes the path as input and, via the “operation” branch, configures whether the file must be opened or created. It returns a refnum-out containing all information associated with the target file, which is then passed to and used within G.M.F.
 - Section 1 → In this section, a property node is used to read or write the properties of a given reference. It is configured to keep the save button in the user interface disabled until the user explicitly presses it and changes its status. This behaviour is required when a file with the same name already exists, that is, when an overwrite operation may occur. In this way, the user must perform a deliberate action before enabling the save function.
 - Section 2 → This part sets the header of the new file.txt. A string vector containing the header is received from G.M.F. and converted into a spreadsheet-style string by the array-to-spreadsheet-string operator. The resulting header string is then passed to Section 3 for writing to the file.

- Section 3 → Once the file.txt has been confirmed as new, the header is written to the file using the write-to-text-file operator. This operator receives both the file path and the header string as inputs, and performs the actual write operation.
- Section 4 → closes the file and stores it in the path previously specified.
- Section 1 → This section is executed only when the user presses the save button in the interface, that is, when the corresponding Boolean condition is true. Under this condition, the section starts and performs the associated save procedure. Within this section, a stacked sequence structure is implemented, consisting of two sequentially executed sub-sections that organize the save operations in a deterministic order:

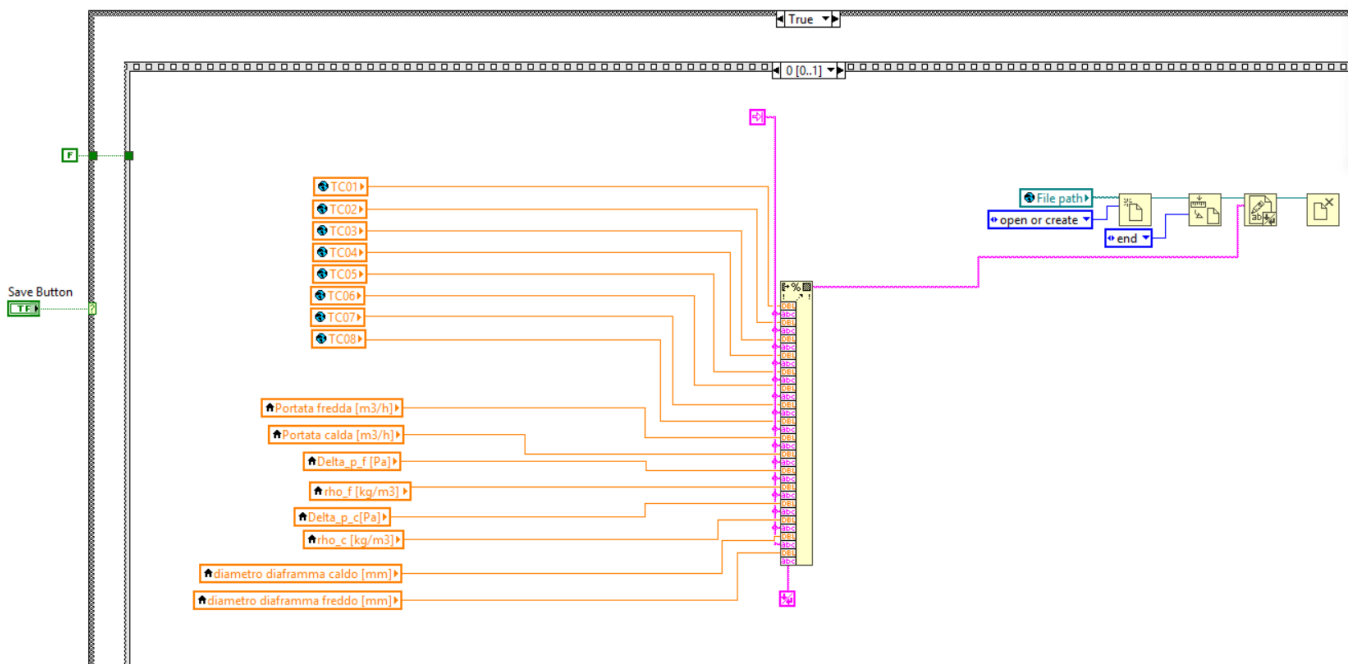


Figure 46

- Section 0 → This section prepares the data entities for saving, arranging them according to the predefined header structure. The write operation is positioned to begin on a new line after the header, thereby preventing any overwrite, which is achieved using the set-file-position operator configured with the "end" constant. All variables designated for storage are formatted as tab-delimited strings using the format-into-string operator and a tab constant, ensuring consistent spacing and alignment.
- Section 1 → waits for 500ms.

Lettura & zero

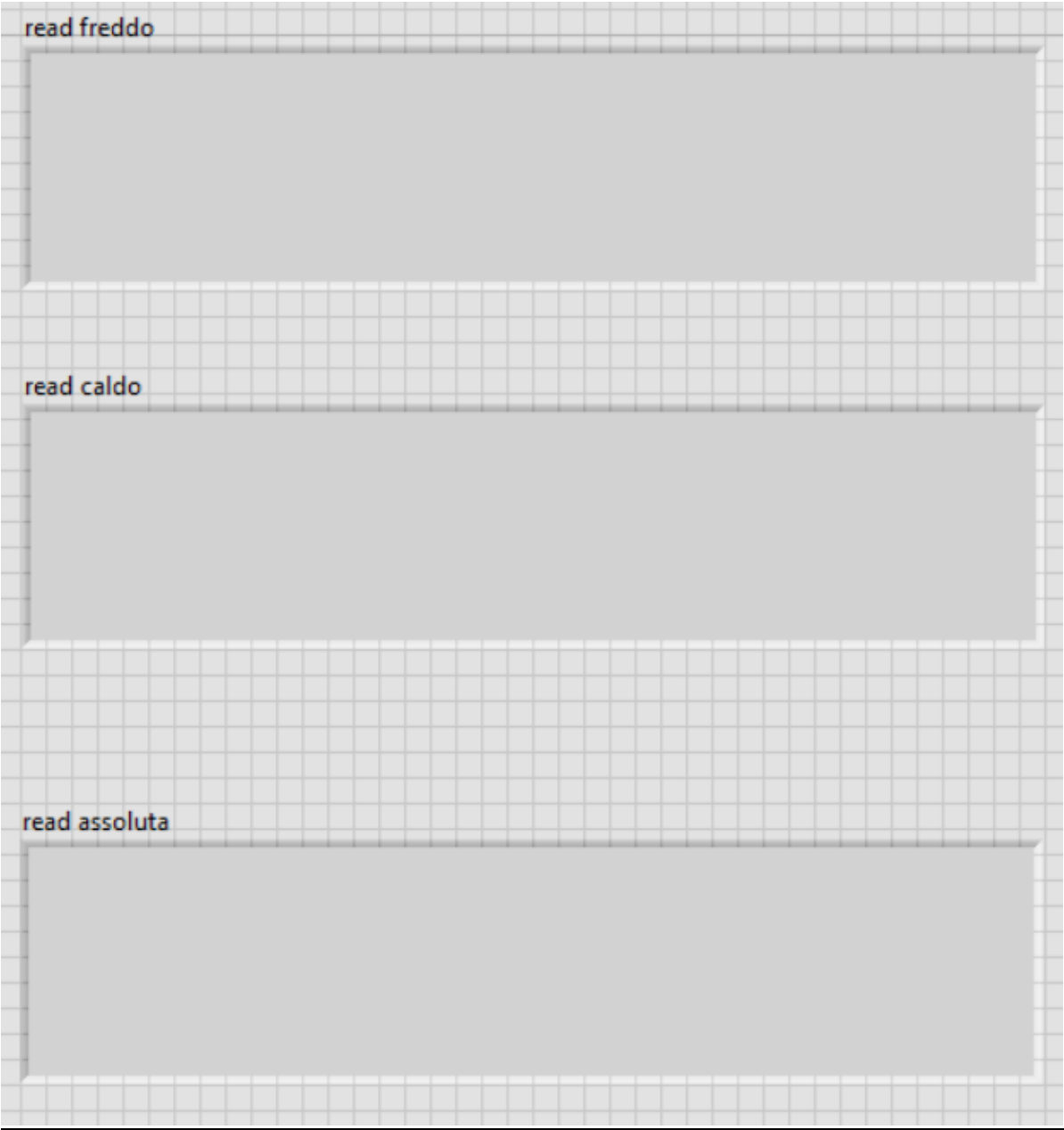


Figure 47

It is a stacked sequence structure and consists of the following sections sequentially executed:

- 0 section → This section initializes communication with the relevant USB ports using the VISA configure serial port operator. The ports targeted are those providing pressure signals: COM PRESSIONE FLUSSO CALDO, COM PRESSIONE FLUSSO FREDDO, and COM PRESSIONE ASSOLUTA.

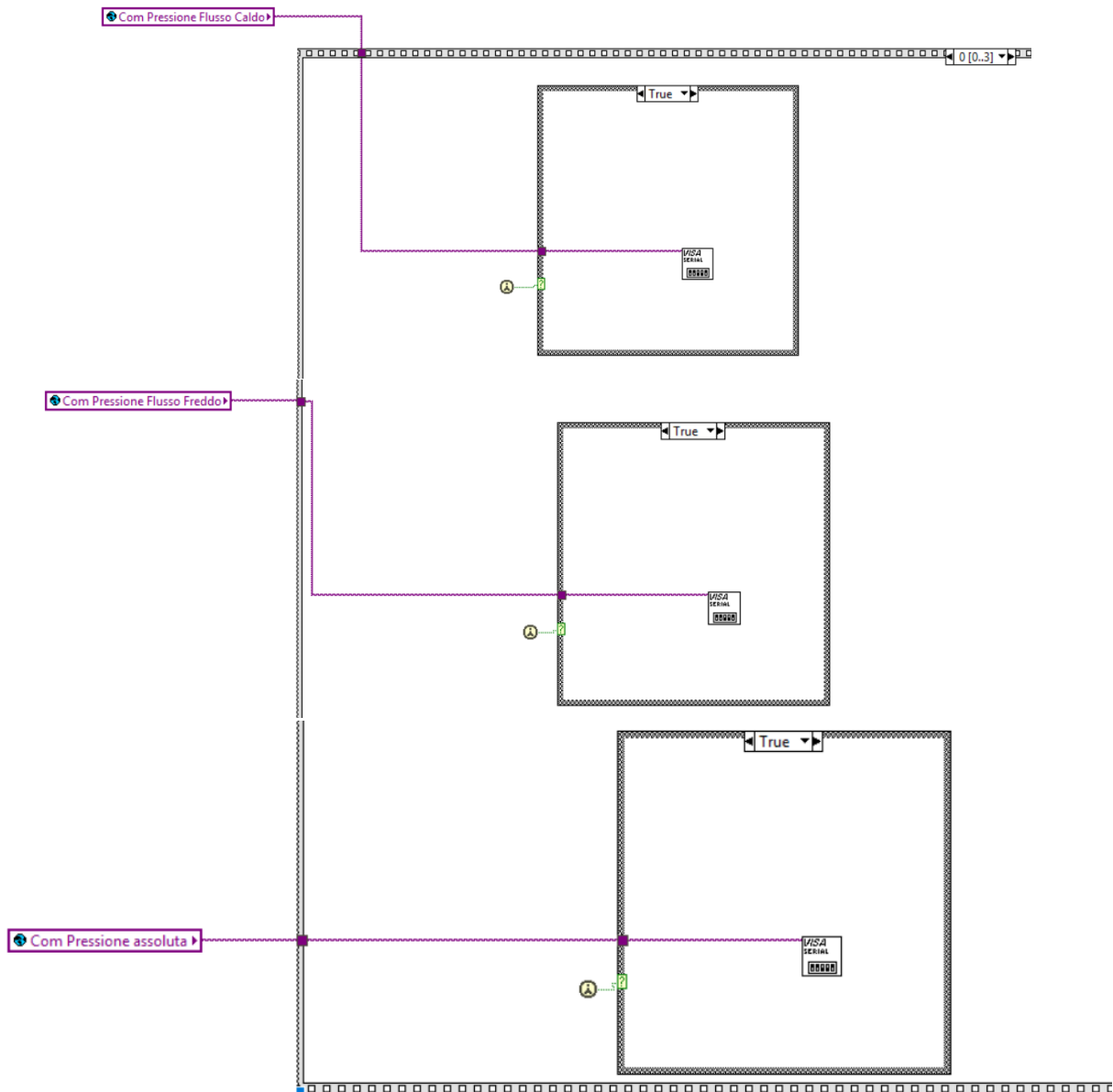


Figure 48

- Section 1 → it delays the next execution of 2000ms.

- Section 2 → This performs the reading and resetting of the sensors. It employs a timed loop that, in turn, encapsulates an inner stacked sequence structure for sequential execution.

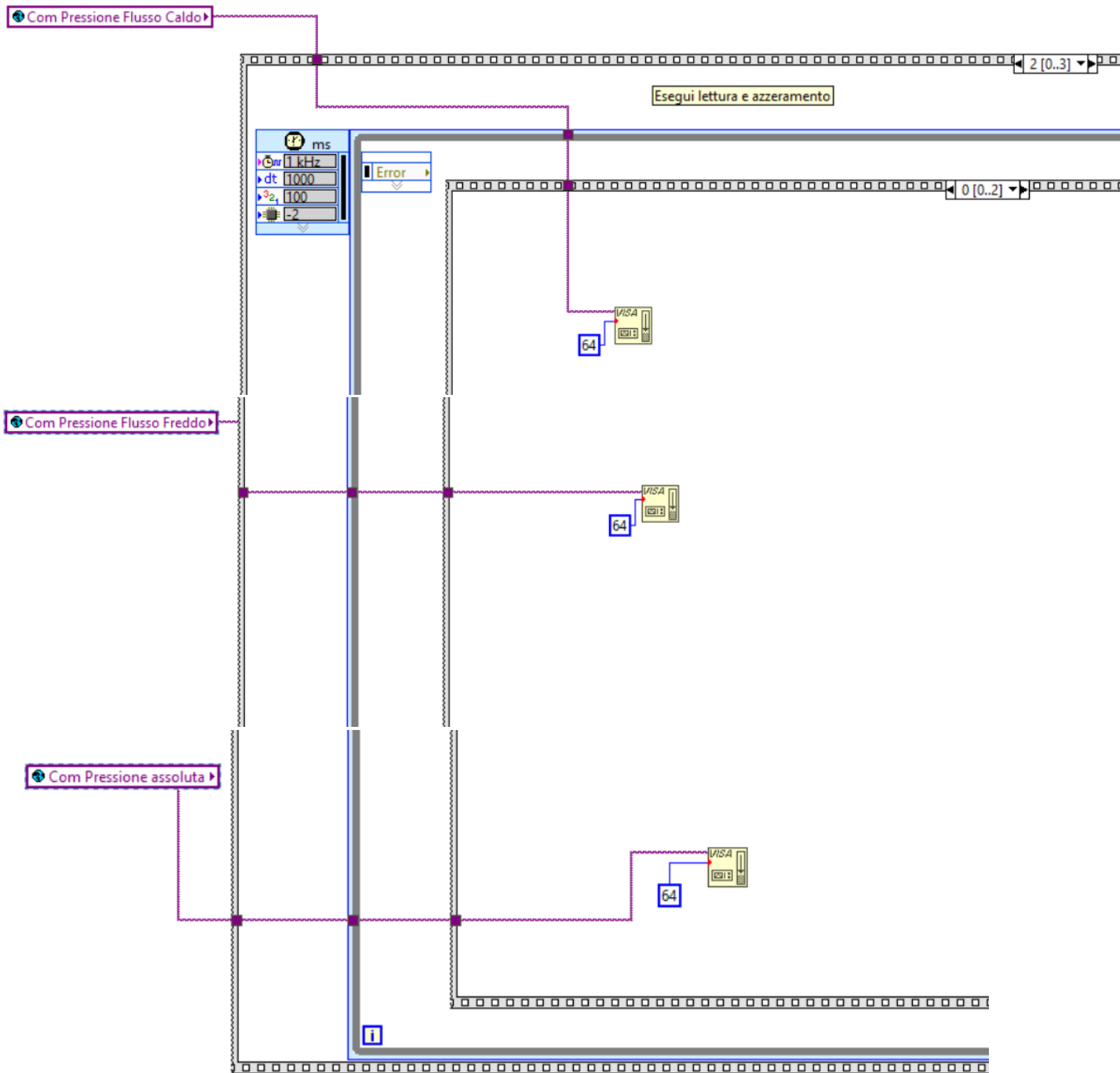


Figure 49

- Section 0 → This step resets the buffer memory used for communication between LabVIEW and the Arduino by means of the VISA flush I/O buffer operator. This operation clears any residual data in the buffer, ensuring that subsequent data exchanges start from a clean state.
- Section 1 → The command "@ABLL" is transmitted to the Arduino, which responds by executing the corresponding actions defined within its switch

structure. Upon receipt, the Arduino⁴ acquires the sensor signal and forwards it to LabVIEW, where the VISA read operator captures the incoming string data. Three signals arrive from the respective Arduinos, each encoding the pressure value, slope ("pendenza"), and zero offset for its sensor. These strings are then processed by the match pattern operator to extract only the relevant numerical values, which are subsequently displayed in the string monitors.

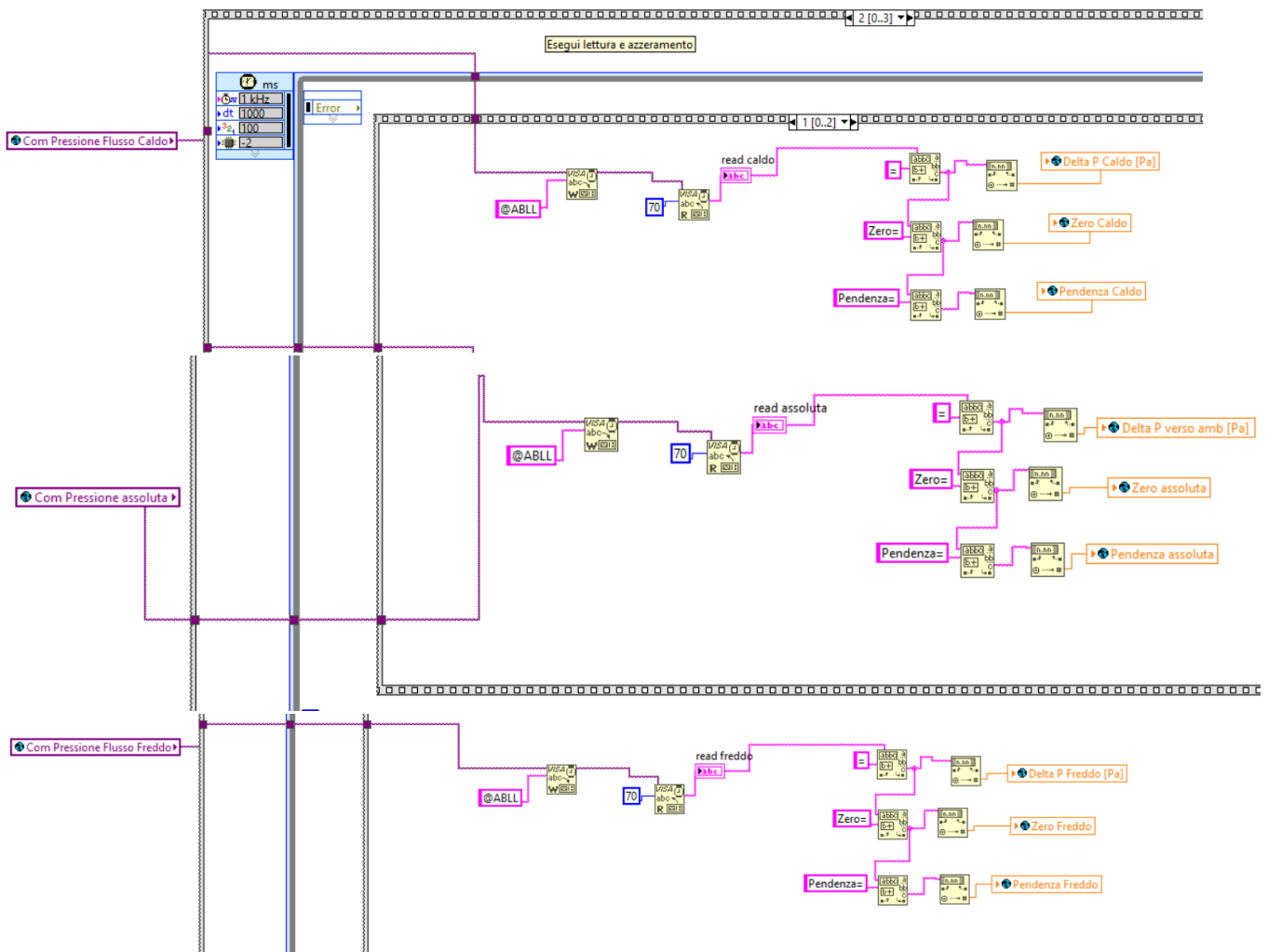


Figure 50

⁴ There is an Arduino linked to each sensor, so for each of them there is a software respectively named: "Sensore_pressione_FREDDO/CALDO/ASSOLUTA".

```

if (Serial.available() > 0)
{
  com = Serial.read();          // Prendo dalla seriale il primo carattere per la comunicazione
  delay(2);
  if (com == '@')
  {
    ID1 = Serial.read();        // Prendo dalla seriale il primo carattere che definisce l'indirizzamento
    delay(2);
    ID2 = Serial.read();        // Prendo dalla seriale il secondoo carattere che definisce l'indirizzamento
    delay(2);
    if (ID1 == 'A' && ID2 == 'B')
    {
      Comando1 = Serial.read(); // Prendo dalla seriale il primo carattere che mi definisce il comando
      delay(2);
      Comando2 = Serial.read(); // Prendo dalla seriale il secondo carattere che mi definisce il comando
      delay(2);

      //Serial.println(Comando1);
      //Serial.println(Comando2);

      if (Comando1 == Comando2)
      {
        Argomento = Serial.readStringUntil('\n'); //Prendo il resto del contenuto della seriale
      }
      else
      {
        Comando1 = 'N'; // Comando Nullo
      }
    }
    else
    {
      Argomento = Serial.readStringUntil('\n'); //Prendo il resto del contenuto della seriale
      Comando1 = 'N'; // Comando Nullo
      Argomento = "";
    }
    delay(2);
  }
}

```

Figure 51

```

case 'L' : //it executes the reading of the sensor

  lettura_ponte = (A_hx711.read());

  Serial.print("Pressione [Pa]=");
  press_attuale = press_min + (press_max - press_min)*((lettura_ponte - lettura_min_media)/(lettura_max - lettura_min_media)); // [Pa]
  Serial.print(press_attuale);
  Serial.print(" Zero=");
  Serial.print(lettura_min_media);
  Serial.print(" Pendenza=");
  Serial.println((press_max-press_min)/(lettura_max-lettura_min_media));

  break;

```

Figure 52

- Section 2 → This section executes only if the user issues a reset command from the G.S.P. interface for the sensors. Specifically, pressing the "Azzerare manometro caldo/freddo/assoluta" button triggers its activation; otherwise, it is bypassed. Upon activation, LabVIEW transmits the "@ABZZ" command to each Arduino, instructing it to reset the current pressure reading to zero.

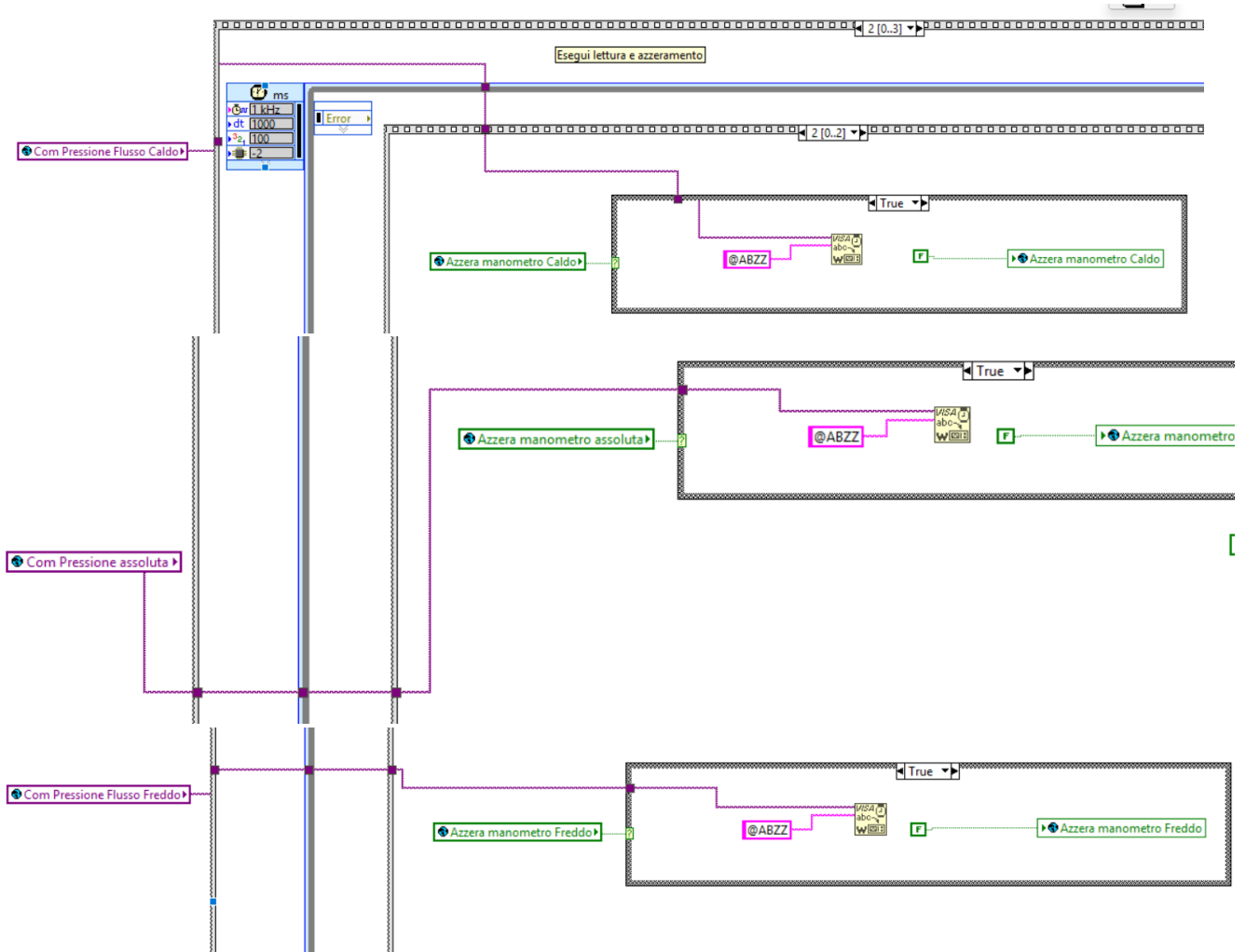


Figure 53

```

case 'Z' : //it executes the calibration of the sensor as far as its zero is concerned

    lettura_min=0; //resetting of the variable to allow a proper evaluation of the new zero;

    lettura_min_media=0;

    for (i=0; i<size; i++) {
        lettura_min[i]=0;
    }

    for (i=0; i<size; i++) {

        lettura_min[i] = (A_hx711.read());
        /*Serial.print(i);
        Serial.print("\t");
        Serial.println(lettura_min[i]);*/

    }

    for (i=0; i<size; i++){

        lettura_min = lettura_min + lettura_min[i];
        /*Serial.print(i);
        Serial.print("\t");
        Serial.print(lettura_min[i]);
        Serial.print("\t");
        Serial.println(lettura_min);*/

    }

    lettura_min_media = lettura_min/size;
    //Serial.println(lettura_min_media);

    break;

```

Figure 54

- Section 3 → at last here is closed the communication with each COM thanks to the operator named visa close.

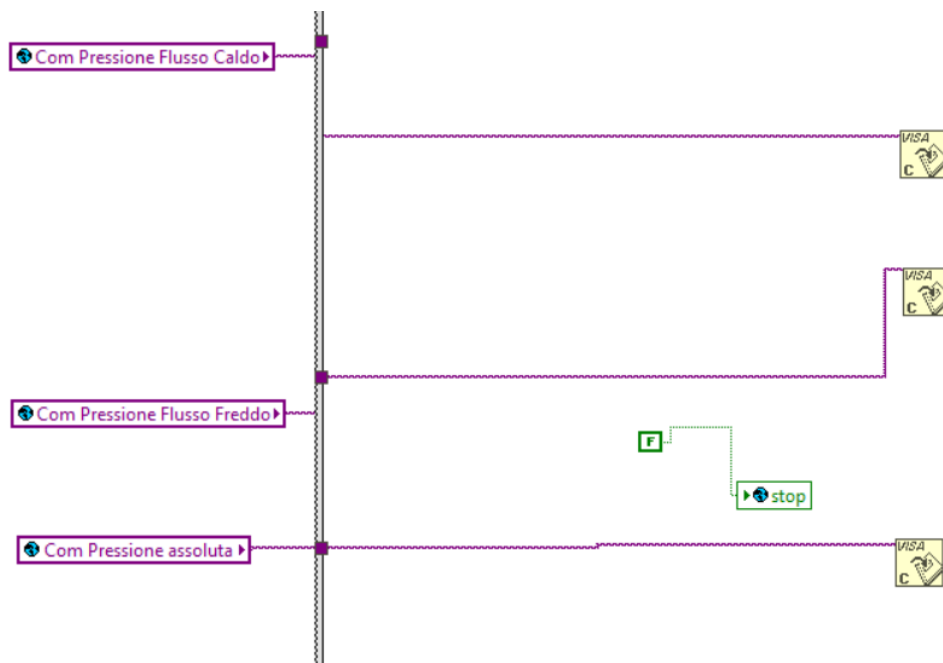


Figure 55

Driver mille funzioni

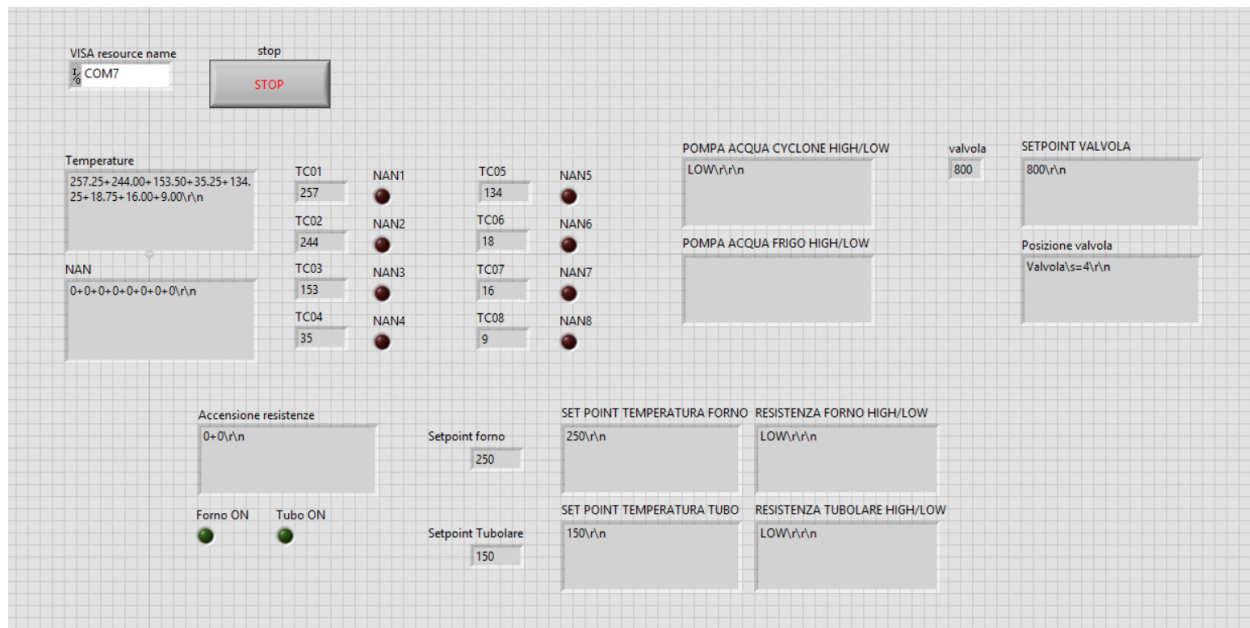


Figure 56

In this subVI one can have a look, through a series of string monitors, at the following entities:

- TEMPERATURE → it collects all the thermocouple readings.
- NaN → it tells whether the thermocouples are reading any “NaN”.
- SETPOINT VALVOLA → it shows the value inputted by the user for the valve position.
- POSIZIONE VALVOLA → it displays the actual valve position.
- POMPA ACQUA CYCLONE HIGH/LOW → it makes visible the actual status of the cyclone pump.
- POMPA ACQUA FRIGO HIGH/LOW. → it makes visible the actual status of the fridge pump.
- ACCENSIONE RESISTENZE → it displays the actual status of the resistances (oven and pipe).
- SETPOINT TEMPERATURA FORNO → here appears the value wanted by the user for the oven resistance.
- SETPOINT TEMPERATURA TUBO → here appears the value wanted by the user for the pipe resistance.
- RESISTENZA FORNO HIGH/LOW → it shows the actual status of the oven’s resistance.
- RESISTENZA TUBO HIGH/LOW → it shows the actual status of the pipe’s resistance.

While through the double monitors is possible to control the temperature detected by the thermocouples:

- TC01 → oven resistance.
- TC02 → inside the oven.
- TC03 → cyclone inlet (hot fumes).
- TC04 → fan outlet.

- TC05 → oven inlet.
- TC06 → cyclone inlet (cold fumes).
- TC07 → cyclone inlet (cooling water).
- TC08 → fridge (wall).

Each double monitor is paired with a Boolean indicator that signals whether the thermocouple is reporting a "NaN" value; such readings are excluded from data acquisition regardless.

Finally, the communication port (COM) for these entities can be configured to receive the corresponding signals, with this port linked to the G.M.F. subVI.

Communication commences with a case structure that branches based on the value from the first call operator.

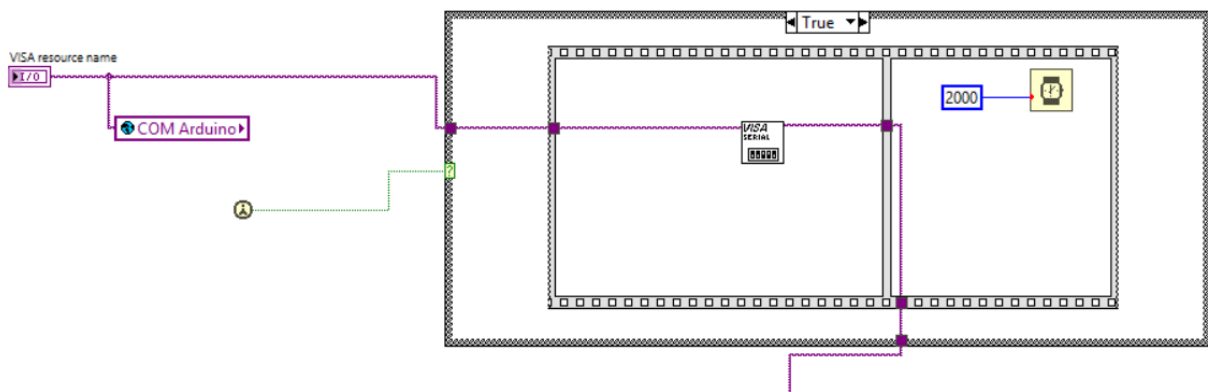


Figure 57

- If TRUE, the signal enters a flat sequence structure: the first frame configures serial port communication using the VISA configure serial port operator, followed by a two-second delay, then proceeds to a subsequent flat sequence structure.
- If FALSE (indicating a subsequent call), the signal bypasses the initial setup and enters directly into the final flat sequence structure.

This final flat sequence structure comprises two frames: the first contains all instructions for communicating with the Arduino, while the second closes the communication.

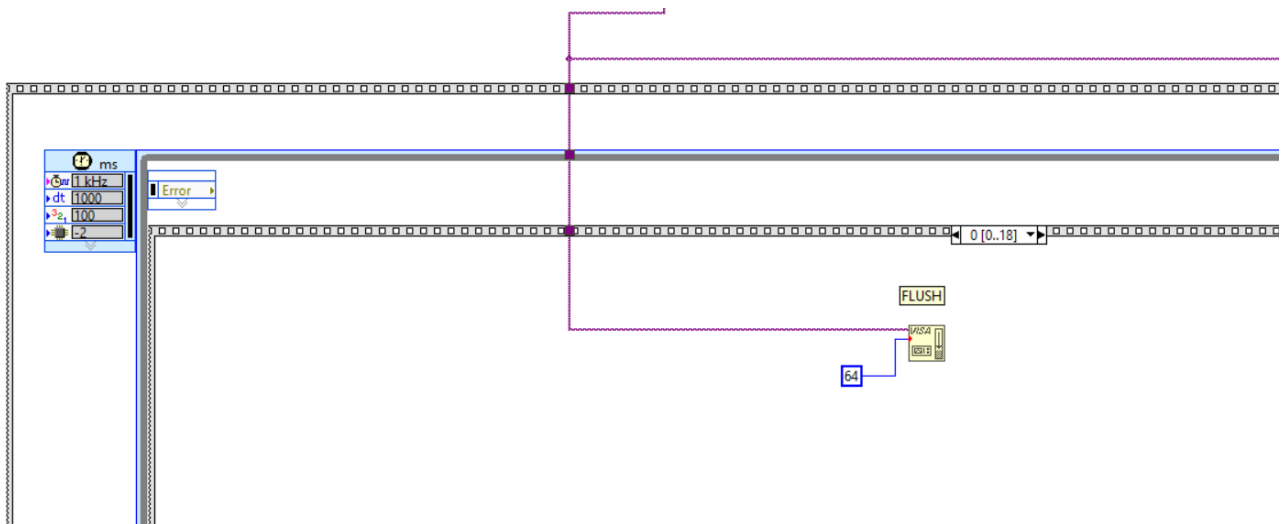


Figure 58



Figure 59

The first frame employs a timed loop that, in turn, incorporates a stacked sequence structure to manage the operations sequentially.

- Section 0 → This step resets the communication buffer using the VISA flush I/O buffer operator, which clears the memory used by LabVIEW to send commands to the Arduino. In this way, any residual data is removed before Arduino reads new commands and executes the corresponding actions.
- Section 1 → This step commands the reading of each thermocouple via the VISA write operator, which transmits the "@AHLL" instruction to the Arduino.

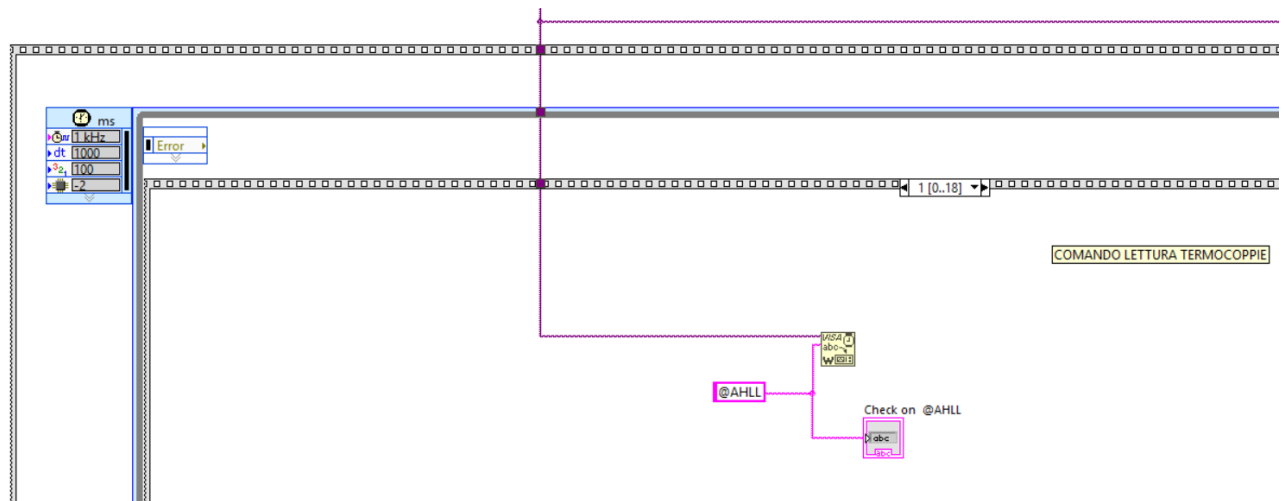


Figure 60

```
case 'L' :

risposta=60;
digitalWrite(REDE, HIGH); //abilito 485
redeon=millis();

Serial.print(temp1a);
Serial.print('+');
Serial.print(temp2a);
Serial.print('+');
Serial.print(temp3a);
Serial.print('+');
Serial.print(temp4a);
Serial.print('+');
Serial.print(temp5a);
Serial.print('+');
Serial.print(temp6a);
Serial.print('+');
Serial.print(temp7a);
Serial.print('+');
Serial.println(temp8a); //it is important that after the last value printed it form a new line otherwise cannot communicate with LabView.

FLAGT=1;
break;
```

Figure 61

- Section 2 → delays the execution of the next section of 25ms.
- Section 3 → This step reads the temperature values from each thermocouple, as acquired by the Arduino⁵. These values are stored in the G.M.F. subVI and simultaneously displayed in the string monitors within the D.M.F. subVI and the main user interface.

⁵ The Arduino file related to the thermocouples etc... is named AF0020_1_5

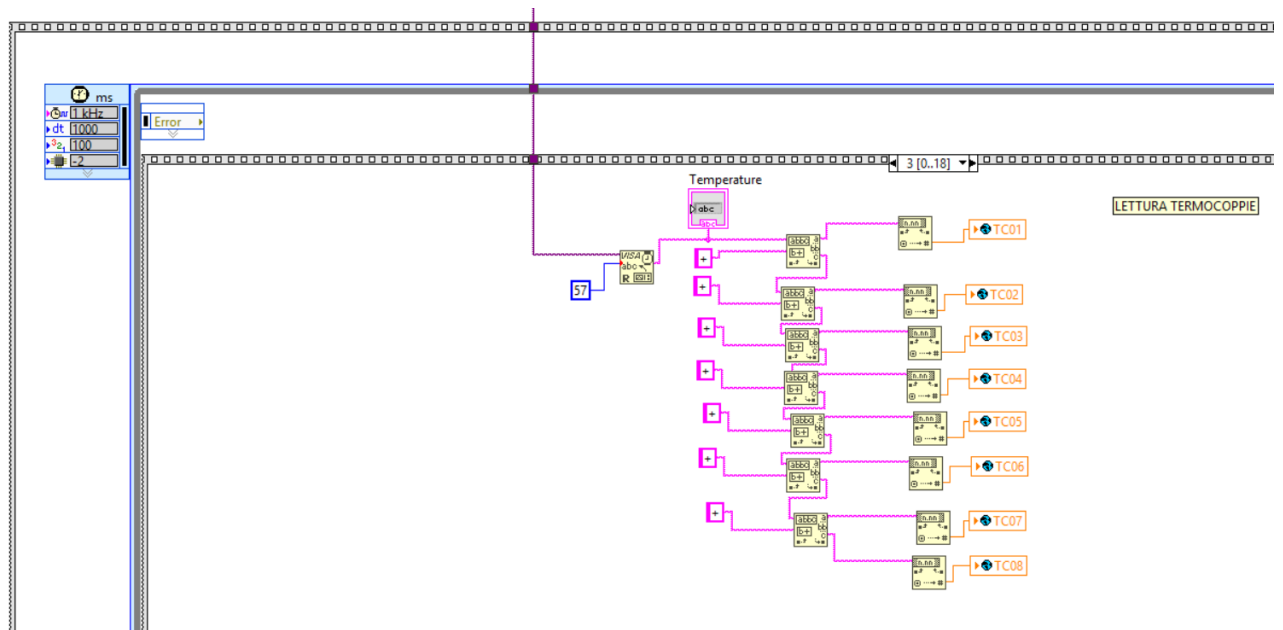


Figure 62

- Section 4 → delays the execution of the next section of 65ms.
- Section 5 → brings the value of each thermocouple from G.M.F. and send them to D.M.F. showing them in the double monitors.

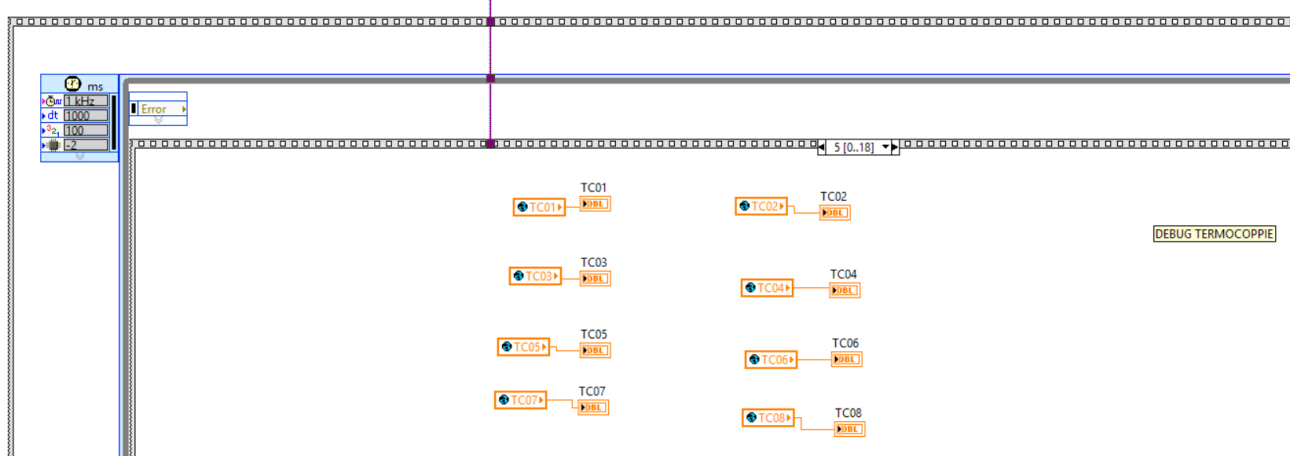


Figure 63

- Section 6 → This step transmits the "@AHRR" command to the Arduino, which uses an index variable "x" to sequentially check the readings from each thermocouple across cycles. At startup, "x" is zero; in the first cycle, it increments to 1 to check the first thermocouple, then to 2 for the second, and so on up to 8, after which it resets to zero for continuous cycling. The "x" variable selects the thermocouple under evaluation: at initialization, Arduino stores the current reading in variables "temp#" (# = 1 to 8), copies it to "temp#a", and checks for "NaN". If "NaN" is detected, the corresponding counter "ns#" is incremented, and reading continues until a valid (non-NaN) value is obtained, at which point it is stored in "temp#" and output.

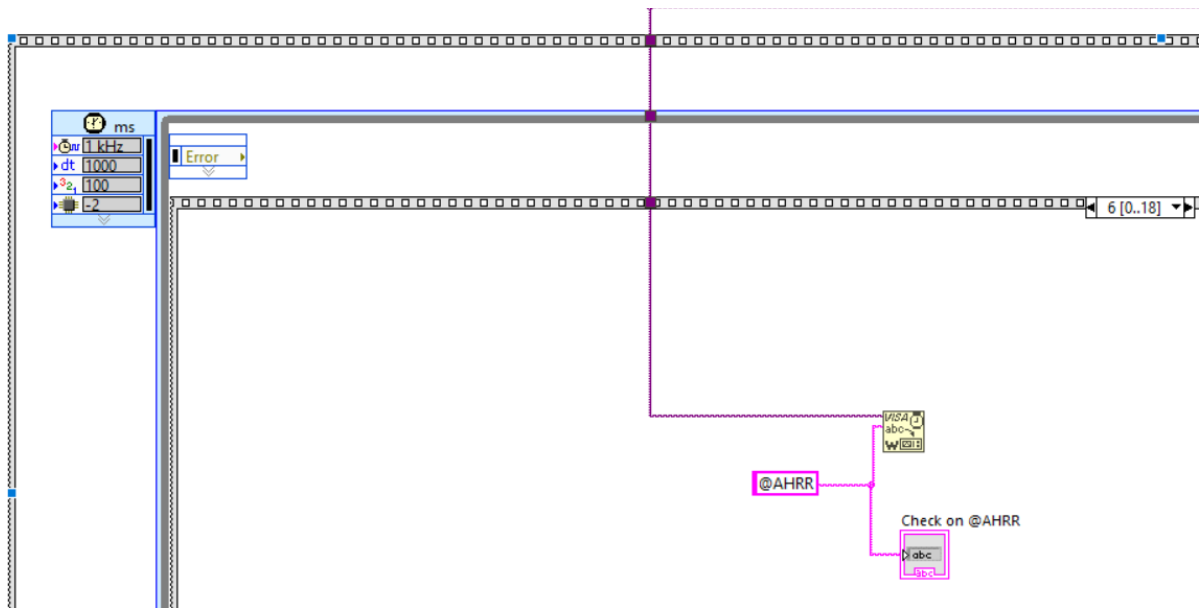


Figure 64

```
case 'R' :

    risposta=60;
    digitalWrite(REDE, HIGH);    //abilito 485
    redeon=millis();

    Serial.print(ns1>maxRetries);
    Serial.print('+');
    Serial.print(ns2>maxRetries);
    Serial.print('+');
    Serial.print(ns3>maxRetries);
    Serial.print('+');
    Serial.print(ns4>maxRetries);
    Serial.print('+');
    Serial.print(ns5>maxRetries);
    Serial.print('+');
    Serial.print(ns6>maxRetries);
    Serial.print('+');
    Serial.print(ns7>maxRetries);
    Serial.print('+');
    Serial.println(ns8>maxRetries);

    break;
```

Figure 65

```

/*LETTURA RESISTENZE*/

if (FLAG1==1) { //it means that the first acquisition is completed and so the new ones must be accomplished

    ns1=0;
    ns2=0;
    ns3=0;
    ns4=0;
    ns5=0;
    ns6=0;
    ns7=0;
    ns8=0;

    x++;

    if (x == 1) {
        temp1 = thermocouple1.readCelsius();
        while (isnan(temp1)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
            temp1 = thermocouple1.readCelsius();
            ns1++;
        }
        temp1a = temp1;
    }

    if (x == 2) {
        temp2 = thermocouple2.readCelsius();
        while (isnan(temp2)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
            temp2 = thermocouple2.readCelsius();
            ns2++;
        }
        temp2a = temp2;
    }
}

```

Figure 66

```

if (x == 3) {
    temp3 = thermocouple3.readCelsius();
    while (isnan(temp3)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp3 = thermocouple3.readCelsius();
        ns3++;
    }
    temp3a = temp3;
}

if (x == 4) {
    temp4 = thermocouple4.readCelsius();
    while (isnan(temp4)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp4 = thermocouple4.readCelsius();
        ns4++;
    }
    temp4a = temp4;
}

if (x == 5) {
    temp5 = thermocouple5.readCelsius();
    while (isnan(temp5)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp5 = thermocouple5.readCelsius();
        ns5++;
    }
    temp5a = temp5;
}

if (x == 6) {
    temp6 = thermocouple6.readCelsius();
    while (isnan(temp6)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp6 = thermocouple6.readCelsius();
        ns6++;
    }
    temp6a = temp6;
}

```

Figure 67

```

}

if (x == 7) {
    temp7 = thermocouple7.readCelsius();
    while (isnan(temp7)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp7 = thermocouple7.readCelsius();
        ns7++;
    }
    temp7a = temp7;
}

if (x == 8) {
    temp8 = thermocouple8.readCelsius();
    while (isnan(temp8)) { //se lettura termocoppia restituisce NaN aggiunge 1 al contatore di NaN e restituisce la temperatura del ciclo precedente
        temp8 = thermocouple8.readCelsius();
        ns8++;
    }
    temp8a = temp8;
    x=0;
}

```

Figure 68

- Section 7 → delays of 5ms the next execution.
- Section 8 → This step reads the validation results performed by the Arduino, specifically the "ns#" counter variable for each thermocouple. If "ns#" exceeds zero, it indicates that the thermocouple detected a "NaN" reading, triggering the activation of the corresponding NaN indicator light in the G.M.F. subVI adjacent to each numerical display. The same NaN detection and indicator logic is replicated in the D.M.F. subVI.

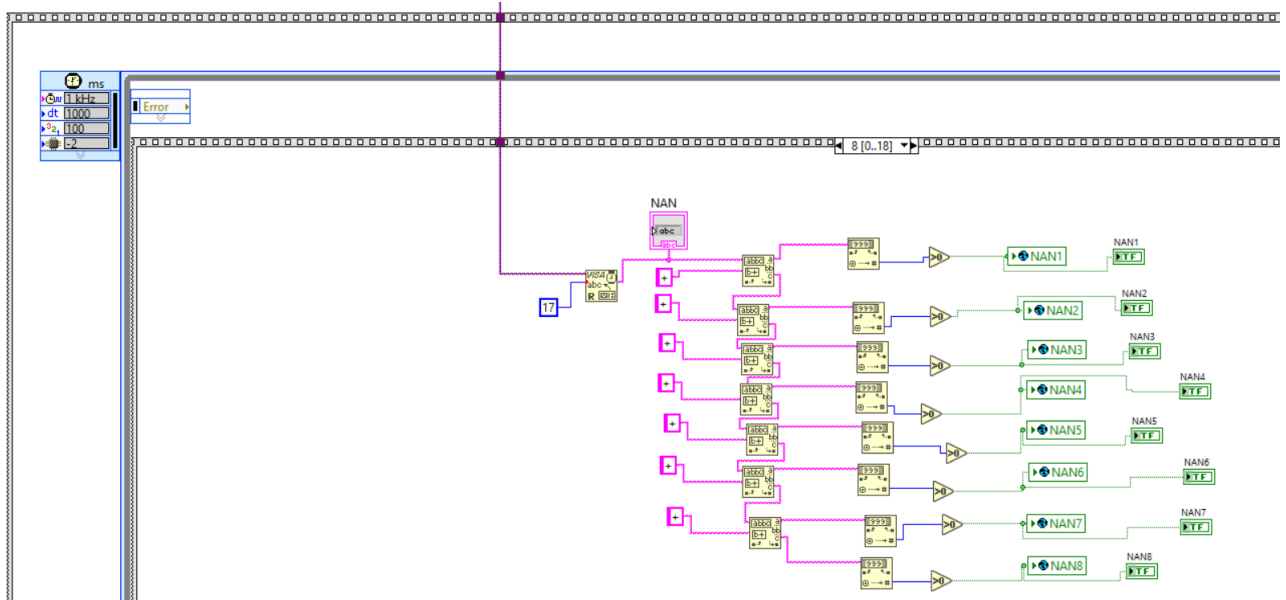


Figure 69

- Section 9 → delays the next execution of 65ms.
- Section 10 → This section handles the acquisition of the valve position as specified by the user. Entry into the stacked sequence structure is controlled by the "is value changed" operator: if false, no action is taken; if true, execution proceeds into the stacked sequence structure.

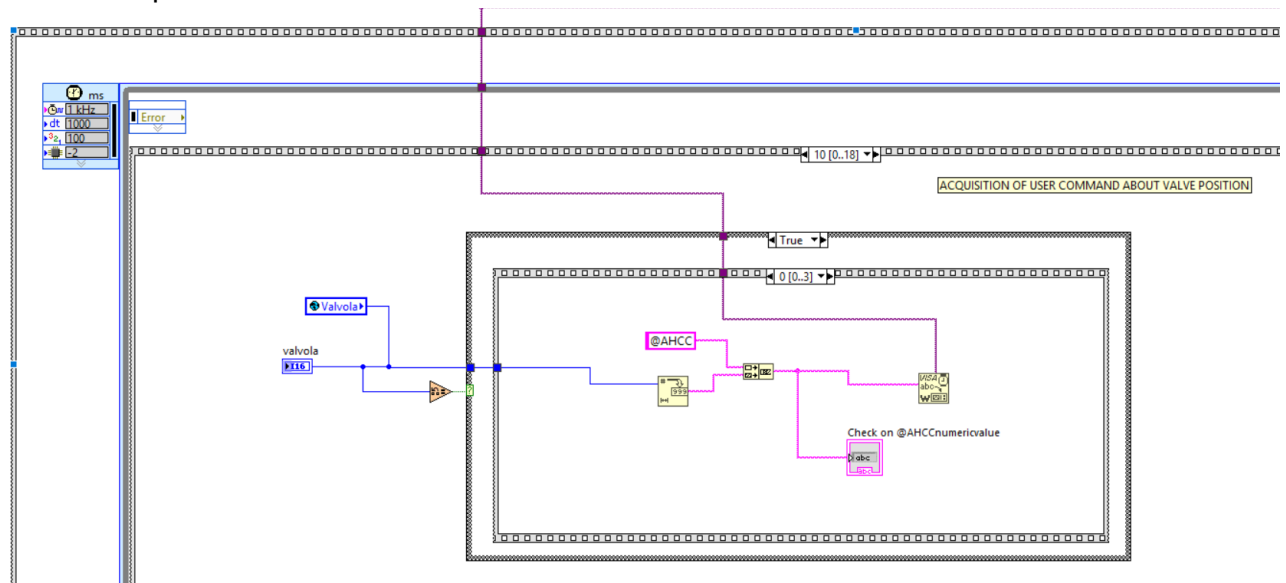


Figure 70

- Section 0 → This section retrieves the user-input valve opening value and converts it into a decimal string format. The value originates from the numeric control "setpoint valvola" in the user interface and is linked to both the G.M.F. and D.M.F. subVIs under the name "valvola". It then constructs the command for transmission to the Arduino using the concatenate string operator, forming "@AHCC(valueofthevalveopening)". Upon receipt, the Arduino stores this value in the "SET3" variable (initialized to 800) and outputs it.

```
case 'C' :  
  
    risposta=10;  
    digitalWrite(REDE, HIGH);  
    redeon=millis();  
  
    set3= arg.toInt();  
    Serial.println(set3);  
  
break;
```

Figure 71

- Section 1 → 5ms of delay.
- Section 2 → reads what Arduino gives back and in turns prints the value of "SET3" variable in the D.M.F as "setpoint valvola" and in G.M.F. as "valvol".

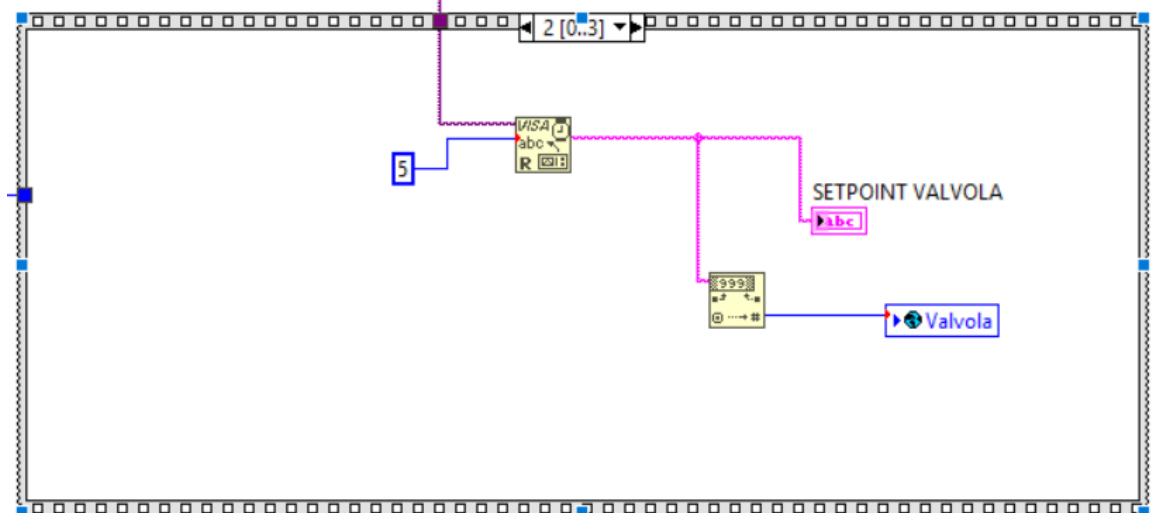


Figure 72

- Section 3 → again a delay of 15ms.
- Section 11 → checks on valve actual position. It is a stacked sequence structure:

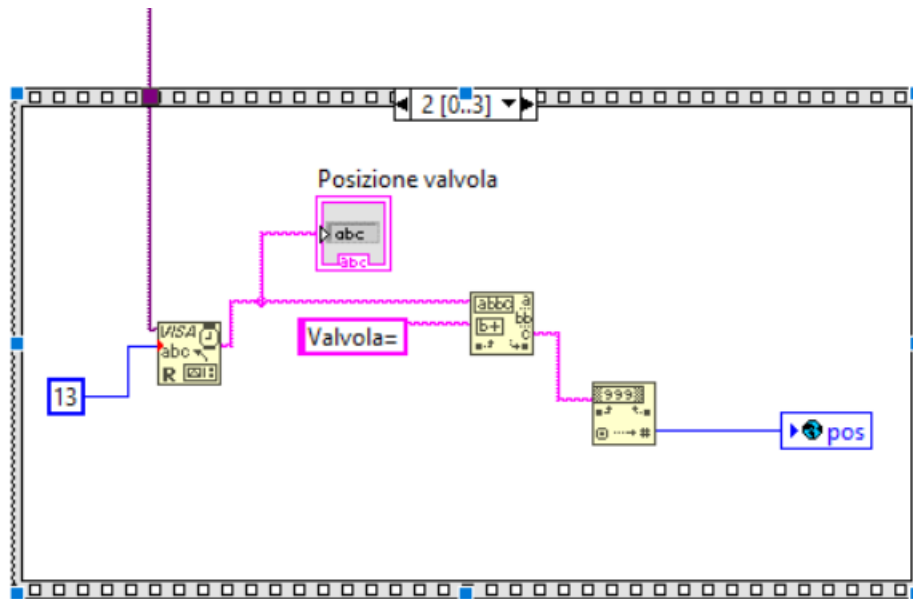


Figure 75

- Section 3 → 15ms.
- Section 12 → it is related to the control of the oven's resistance: the user turns the resistance ON/OFF from the interface, then here:

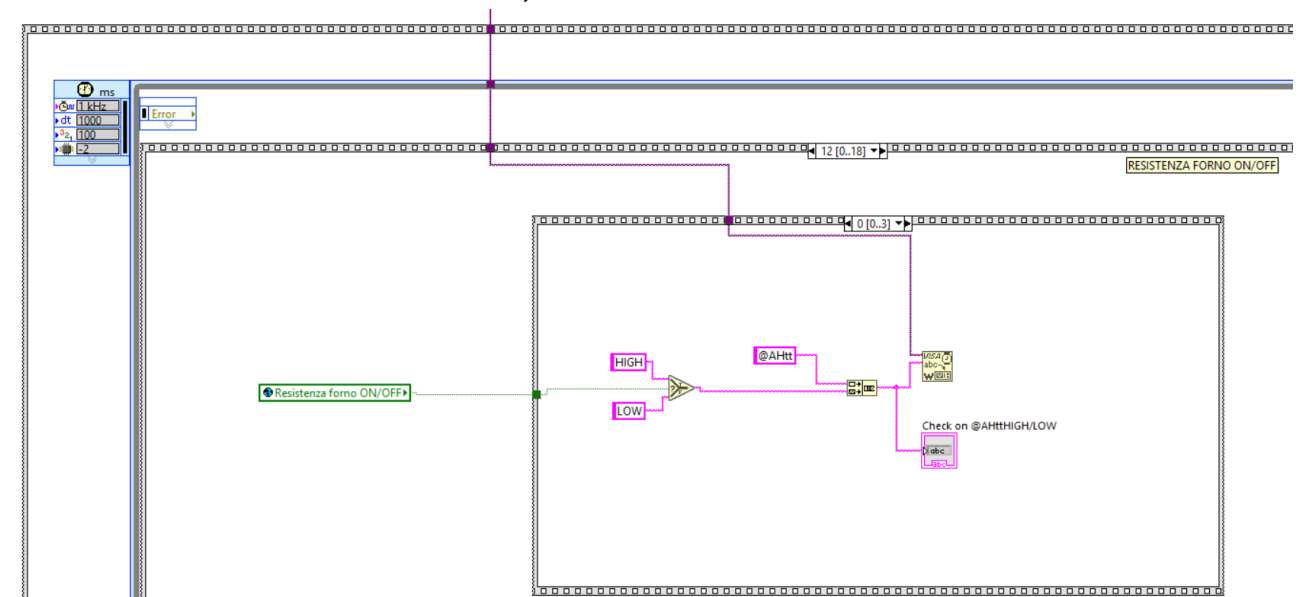


Figure 76

- Section 0 → it is sent to Arduino the command “@AHtt(HIGH/LOW)”.

```

case 't' :

    risposta=10;
    digitalWrite(REDE, HIGH);
    redeon=millis();

    comando_res=arg;
    Serial.println(comando_res);

break;

```

Figure 77

```

/*Controllo resistenza forno*/
//executed at each cycle without being called from LabView

if (comando_res == "HIGH") {

    if ((temp2a < set) && (temp2a < Tmax1)) {

        digitalWrite(res, HIGH);

    } else {

        digitalWrite(res, LOW); //in case that temp2a > set it turn the resistor off

    }

} else {

    digitalWrite(res, LOW);

}

```

Figure 78

- Section 1 → 5ms.
- Section 2 → in D.M.F., in the string monitor named “RESISTENZA FORNO HIGH/LOW” is printed the actual status of the resistance.

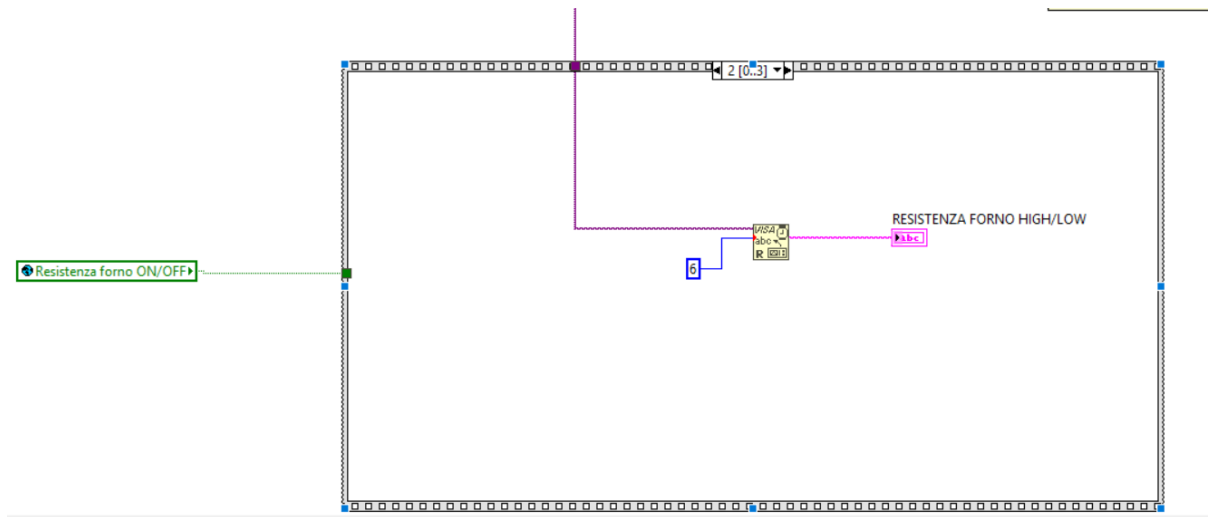


Figure 79

- Section 3 → 15ms.
- Section 13 → it is related to the control of the pipe's resistance: the user turns the resistance ON/OFF from the interface, then here:

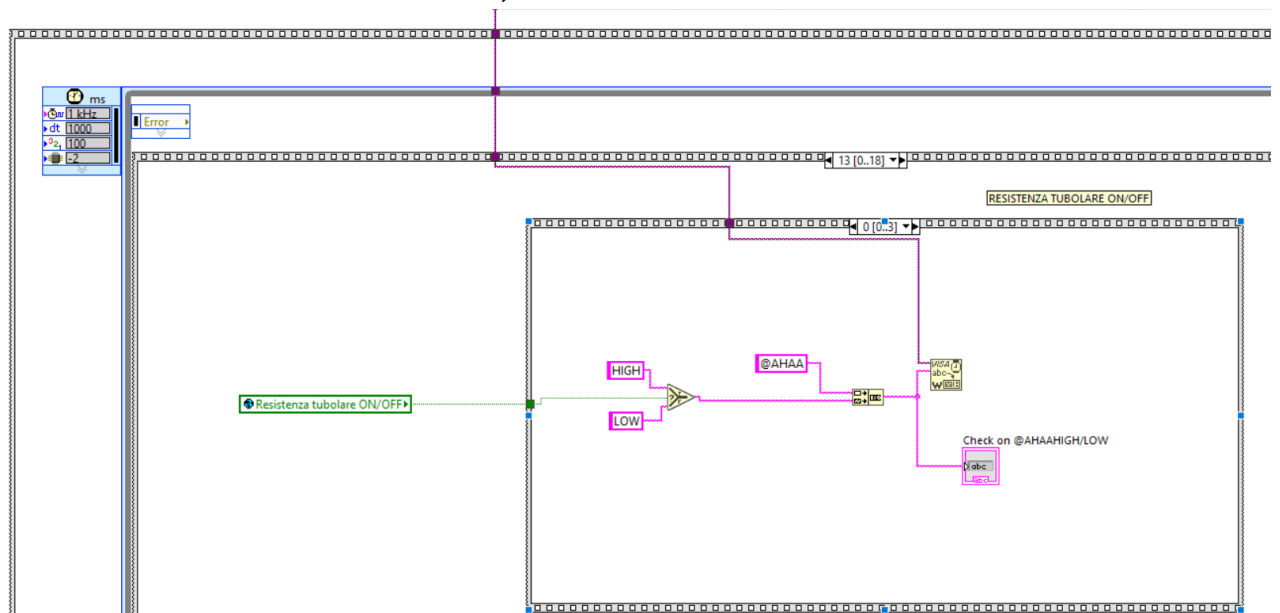


Figure 80

- Section 0 → it is sent to Arduino the command “@AHAA(HIGH/LOW)”.

```

case 'A' :
  risposta=10;
  digitalWrite(REDE, HIGH);
  redeon=millis();

  comando_res2=arg;
  Serial.println(comando_res2);

break;

```

Figure 81

```

/*Controllo resistenza tubolare*/

if (comando_res2 == "HIGH") {

  if ((temp5a < set2) && (temp5a < Tmax2)) {

    digitalWrite(res2, HIGH);

  } else {

    digitalWrite(res2, LOW); //in case that temp5a > set2 it turn the resistor off

  }

} else {

  digitalWrite(res2, LOW);

}

```

Figure 82

- Section 1 → 5ms.
- Section 2 → in D.M.F., in the string monitor named “RESISTENZA TUBOLARE HIGH/LOW” is printed the actual status of the resistance.

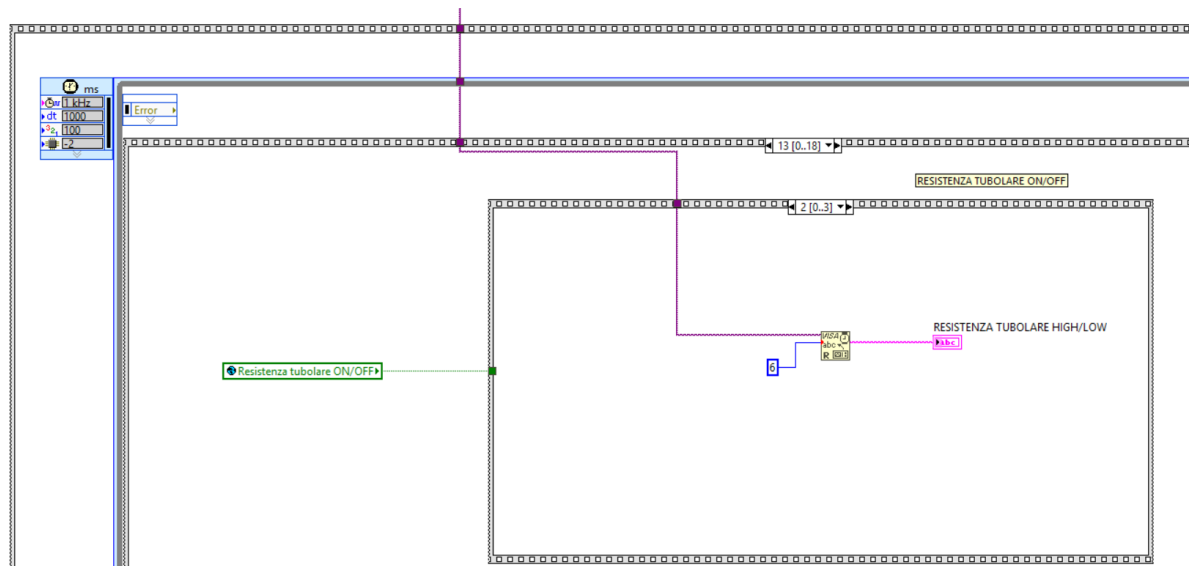


Figure 83

- Section 3 → 15ms.
- Section 14 → it is related to the control of the cyclone's pump: the user turns the pump ON/OFF from the interface, then here:

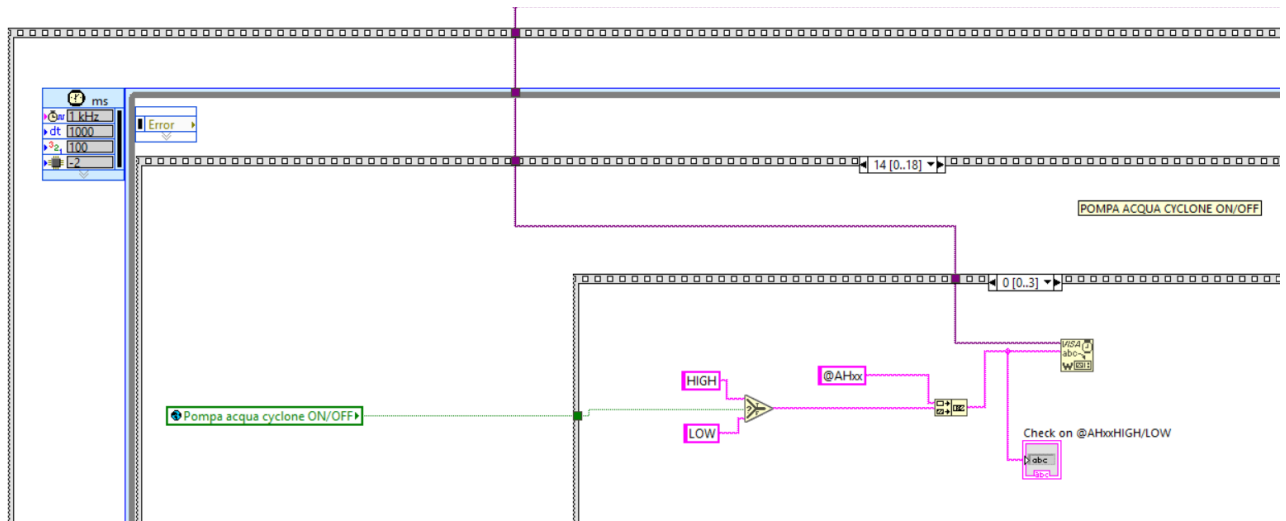


Figure 84

- Section 0 → it is sent to Arduino the command “@AHxx(HIGH/LOW)”.
- Section 1 → 5ms.
- Section 2 → in D.M.F., in the string monitor named “POMPA ACQUA CYCLONE HIGH/LOW” is printed the actual status of the resistance.

```
case 'x' :  
  
    risposta=10;  
    digitalWrite(REDE, HIGH);  
    redeon=millis();  
  
    comando_pompa_cyclone=arg;  
    Serial.println(comando_pompa_cyclone);  
  
break;
```

Figure 85

```
/*CONTROLLO POMPA ACQUA CYCLONE*/

if (comando_pompa_cyclone == "HIGH") {

    digitalWrite(pompa_c, HIGH);

} else {

    digitalWrite(pompa_c, LOW);

}
```

Figure 86

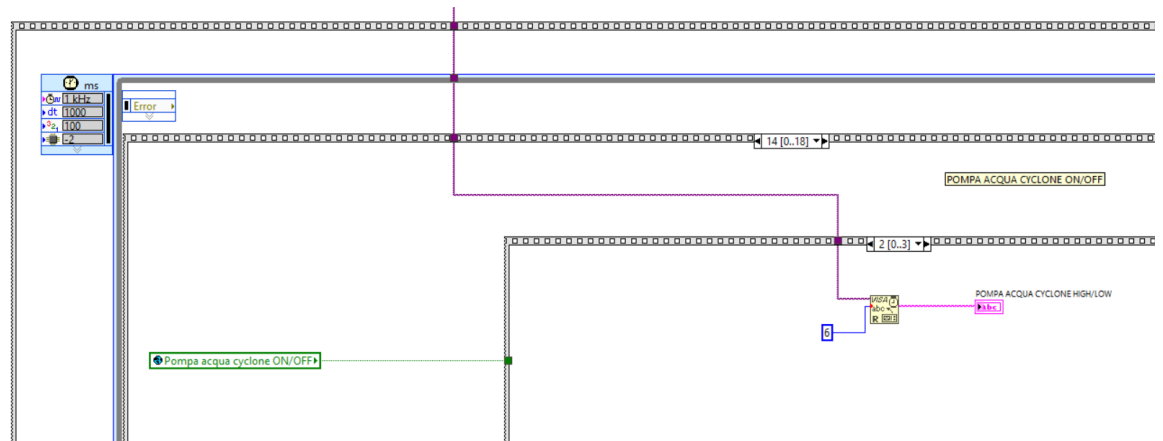


Figure 87

- Section 3 → 15ms.
- Section 15 → it is related to the control of the fridge's pump: the user turns the pump ON/OFF from the interface, then here:

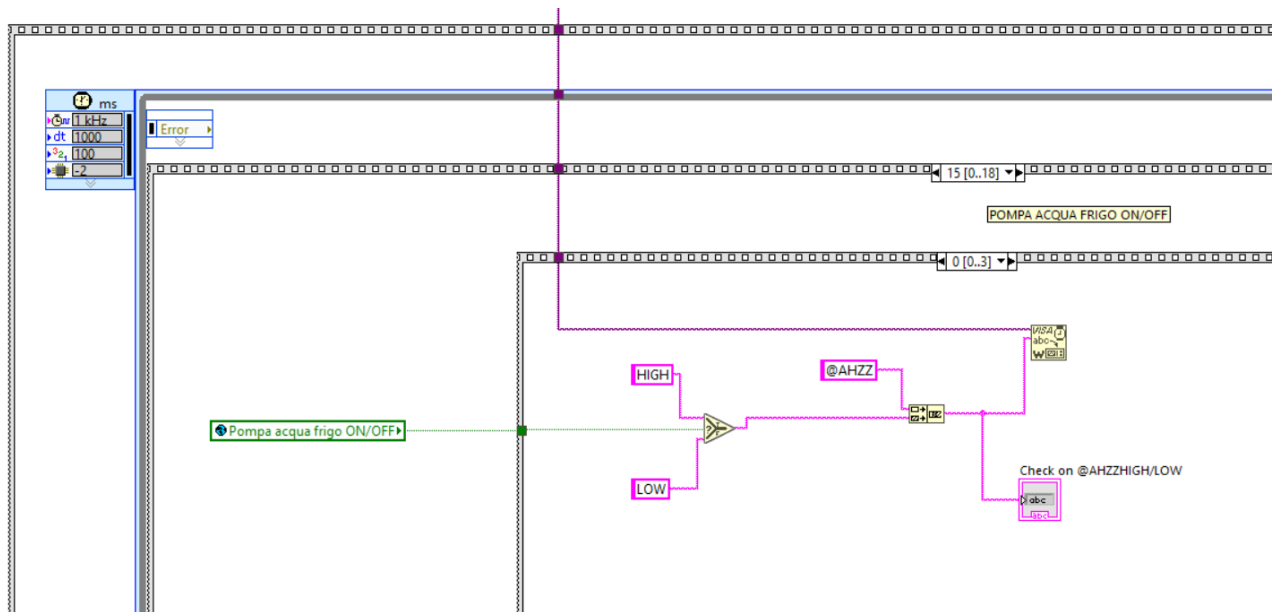


Figure 88

- Section 0 → it is sent to Arduino the command “@AHZZ(HIGH/LOW)”.

```
case 'Z' :
    risposta=10;
    digitalWrite(REDE, HIGH);
    redeon=millis();

    comando_pompa_frigo=arg;
    Serial.println(comando_pompa_frigo);

    break;
```

Figure 89

```
if (comando_pompa_frigo == "HIGH") {
    digitalWrite(pompa_f, HIGH);
} else {
    digitalWrite(pompa_f, LOW);
}
```

Figure 90

- Section 1 → 5ms.
- Section 2 → in D.M.F., in the string monitor named “POMPA ACQUA CYCLONE HIGH/LOW” is printed the actual status of the resistance.

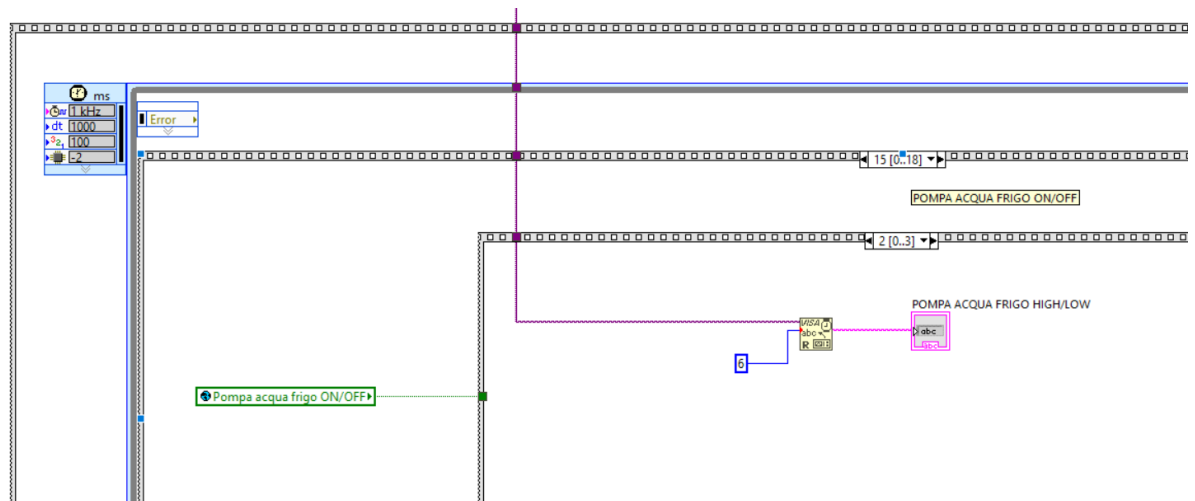


Figure 91

- Section 3 → 15ms.
- Section 16 → sets the temperature of the oven's inlet branch resistance: the user can choose a temperature for the resistance through the interface in the numeric control named "set point TC05" linked to G.M.F. (set point tubolare) and D.M.F. (set point tubolare). The execution of this section starts only if the user changes the values of the "setpoint TC05" or it is the startup as the previous sections:

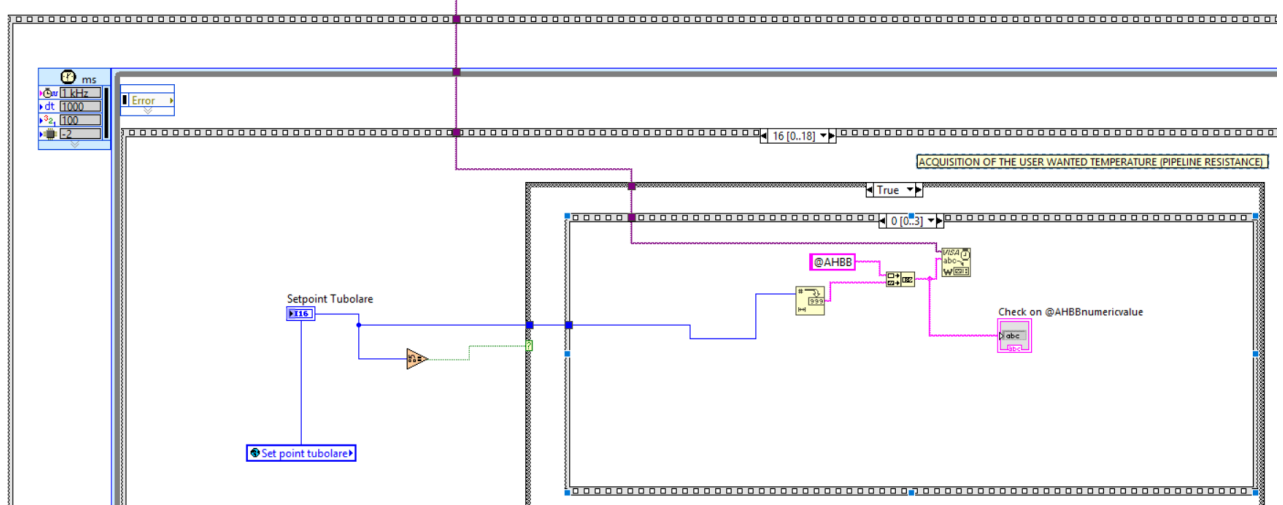


Figure 92

- Section 0 → sends the command “@AHBB(set point tubolare)” to Arduino.

```
case 'B' :  
    risposta=10;  
    digitalWrite(REDE, HIGH);  
    redeon=millis();  
  
    set2=arg.toInt();  
    Serial.println(set2);  
  
break;
```

Figure 93

- Section 1 → 5ms.
- Section 2 → in the D.M.F. in the string monitor named “set point temperature tubo” and in G.M.F. in the numerical indicator “set point tubolare” it is shown the actual value imposed by the user.

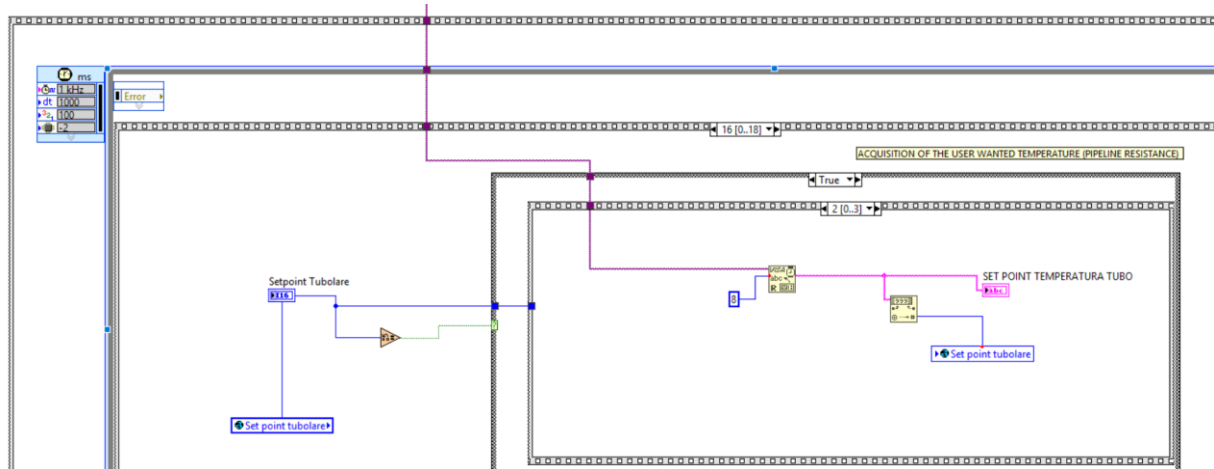


Figure 94

- Section 3 → 15ms.
- Section 17 → sets the temperature of the oven's resistance: the user can set a temperature for the resistance through the interface in the numeric control named “set point TC02” linked to G.M.F. (setpoint forno) and D.M.F. (set point temperature forno). The execution of this section starts only if the user changes the values of the “setpoint TC05” or it is the startup as the previous sections:

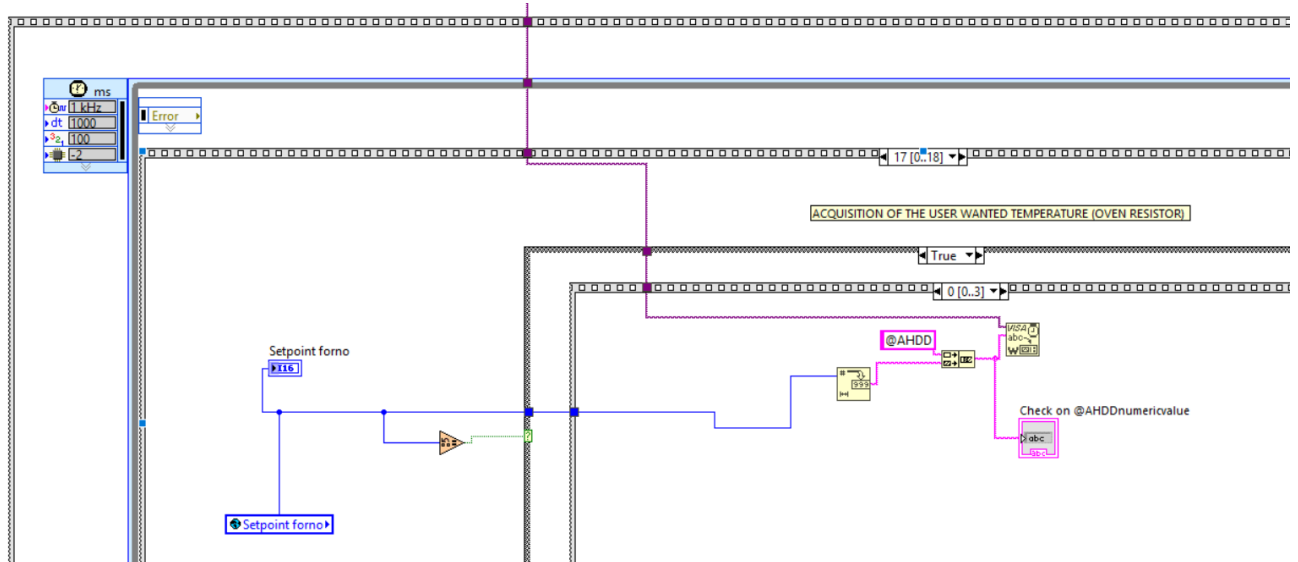


Figure 95

- Section 0 → sends the command “@AHDD(set point tubolare)” to Arduino.

```
case 'D' :
    risposta=10;
    digitalWrite(REDE, HIGH);
    redeon=millis();

    set=arg.toInt();
    Serial.println(set);

    break;
```

Figure 96

- Section 1 → 5ms.
- Section 2 → in the D.M.F. in the string monitor named “set point temperature forno” and in G.M.F. in the numerical indicator “setpoint forno” it is shown the actual value imposed by the user.

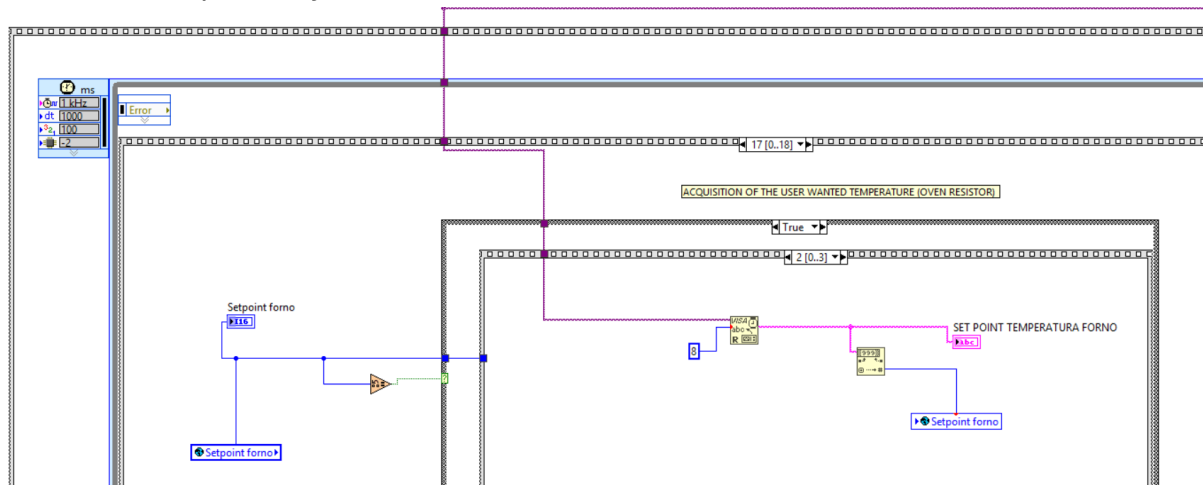


Figure 97

- Section 3 → 15ms.
- Section 18 → starts directly with a stacked sequence structure. It checks the status of the resistances, either they are on or off:

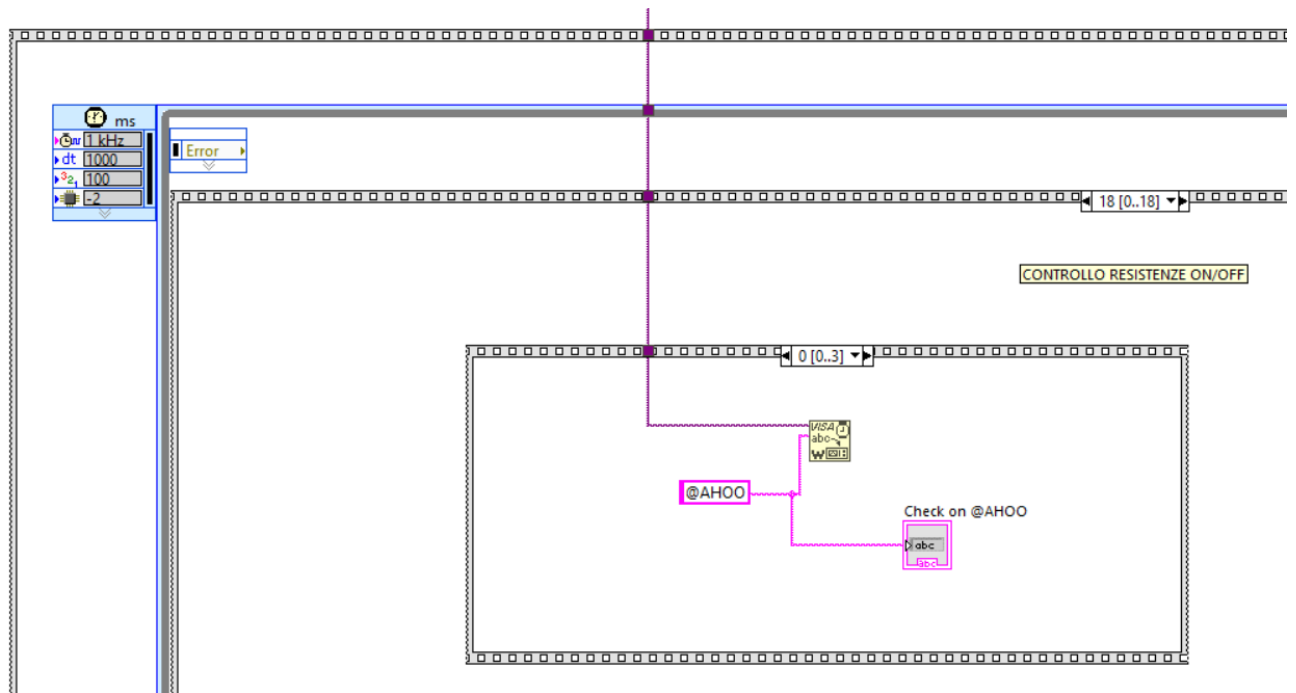


Figure 98

- Section 0 → sends the command “@AHOO”.

```
case '0' :
    risposta=20;
    digitalWrite(REDE, HIGH);
    redeon=millis();

    Serial.print(digitalRead(res));
    Serial.print('+');
    Serial.println(digitalRead(res2));

    break;
```

Figure 99

- Section 1 → 5ms. At this point Arduino prints the status of the pins to which are linked the resistances: “res + res2”, they can be either high or low then either 1 or 0.
- Section 2 → reads what Arduino prints and displays it in the string monitor named “accensione resistenze” in the D.M.F. subVI, then checks if “res>0 and res2>0” and if true turns on two warning lights in G.M.F. named respectively “Forno on” and “tubo on” and simultaneously also in D.M.F. with two identical warning lamps.

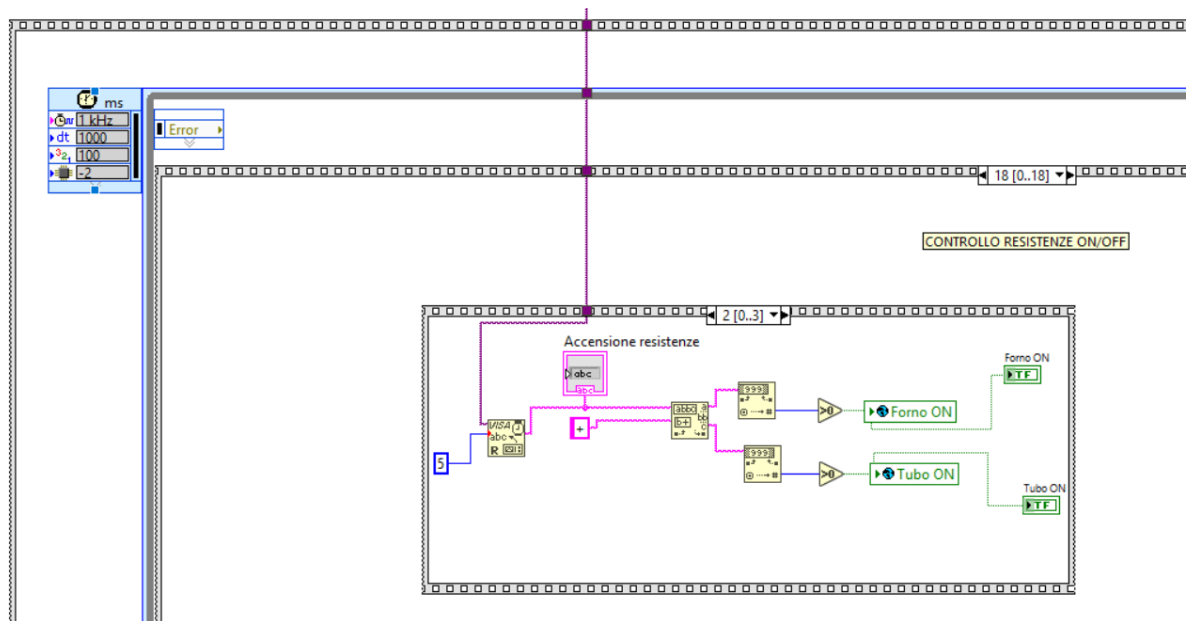


Figure 100

- In the end it closes the communication with Arduino.

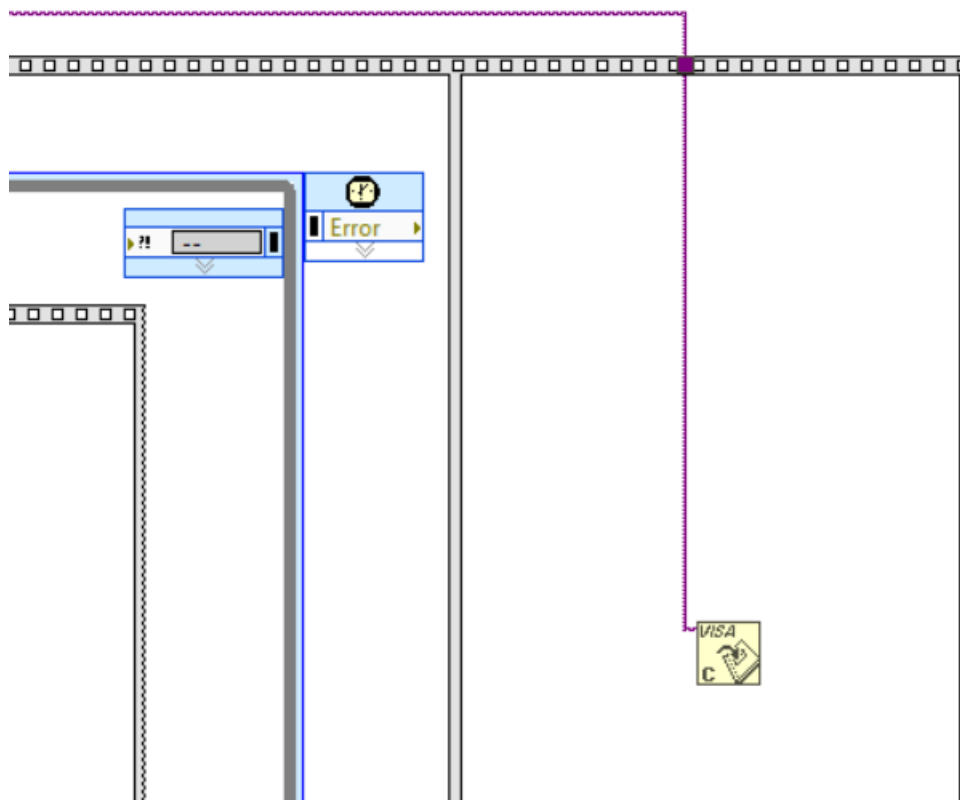


Figure 101

APPENDIX B - Sampling taps design

One of the primary objectives of the experimental campaign is the characterisation of the particle size distribution at successive positions along the pipeline connecting the oven outlet to the cyclone separator. To this end, three dedicated sampling taps were designed and installed at key locations along the pipeline under investigation: the first at the oven outlet, the second at the cyclone inlet, and the third at the cyclone outlet. This arrangement enables sequential aerosol characterisation at each of the three measurement positions, providing the dataset necessary for both the spatial mapping of the aerosol population along the sampling line and the quantitative assessment of the cyclone separation performance.

As anticipated in the Goals and Steps section, the Pegasor PPC was the first instrument to be deployed in the experimental campaign. Accordingly, the three sampling taps were initially designed and dimensioned to accommodate the Pegasor sampling head specifically.

The geometry of each tap was defined to satisfy three concurrent requirements: to ensure the correct positioning of the sampling head at the centreline of the pipeline cross-section, so as to avoid aerosol sampling within the hydrodynamic boundary layer where flow conditions and particle concentration profiles may differ from those in the bulk flow; to guarantee a complete and airtight seal between the sampling head and the pipeline wall, preventing both fume leakage toward the external environment and spurious air infiltration into the sampled stream, either of which would compromise the representativeness of the measured particle concentration and size distribution.

The sampling tap assembly was conceived to ensure pipeline integrity under two distinct operative configurations: with and without the measurement instrument connected.

When no instrument is connected to a given sampling tap, airtight sealing of the pipeline is maintained by means of a threaded stopper incorporating an internal Perfluoroelastomer (FFKM) O-ring, as illustrated in the figures below. This configuration prevents any fume leakage or air infiltration at unused sampling positions throughout the duration of the experimental campaign.

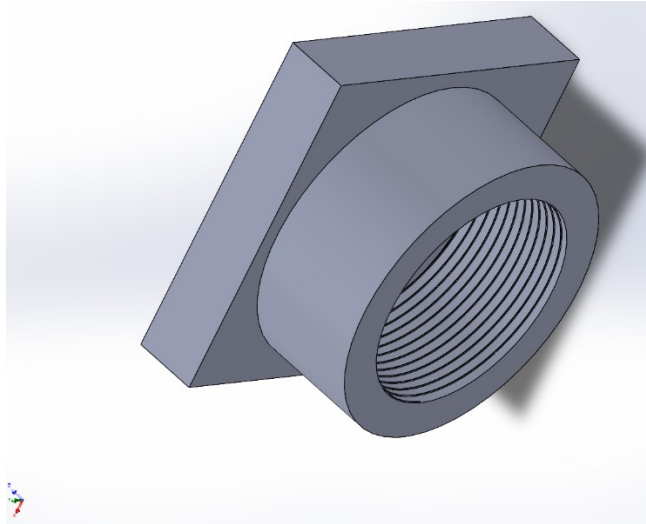


Figure 102

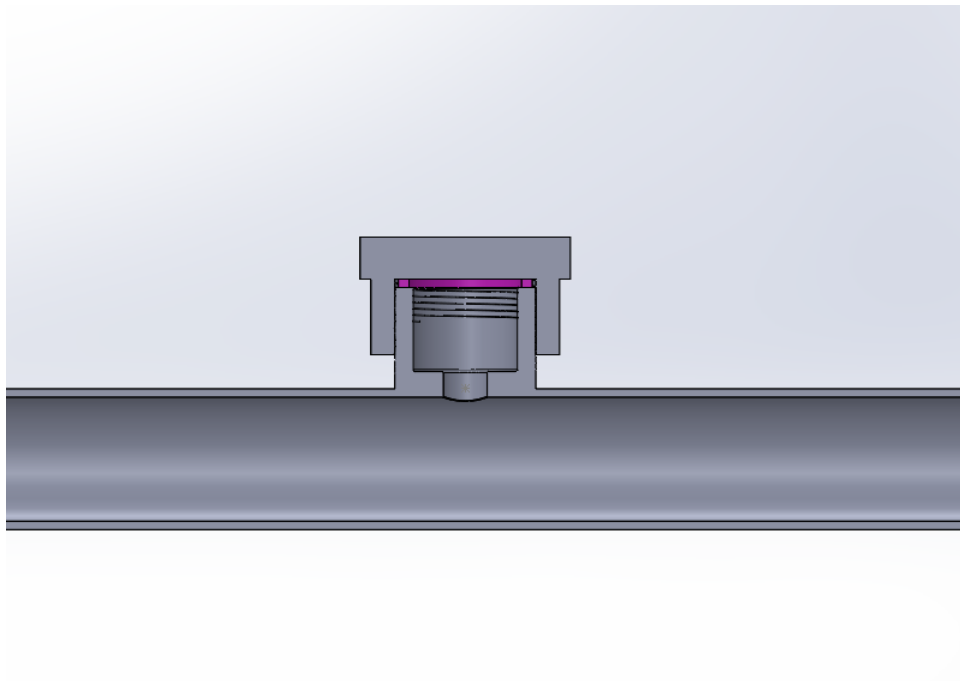


Figure 103

When the instrument sampling line is to be connected to one of the taps, the following assembly procedure is adopted. A hollow stainless-steel cylinder, featuring an external threaded surface and a squared head, is screwed into the internally threaded stainless steel sampling tap body by means of its squared head, through which the instrument sampling head is inserted. Prior to tightening, a hollow cylindrical gasket in Fluorocarbon (Viton®) elastomer is interposed between the hollow cylinder and the internal walls of the sampling tap. As the hollow cylinder is progressively screwed into the tap, the gasket is axially compressed and radially expanded, forcing it to conform tightly against the internal walls of the sampling tap and the outer surface of the instrument sampling head simultaneously. This mechanical compression of the Viton® gasket ensures a robust and reliable double-interface seal,

maintaining the pressure integrity of the pipeline with respect to the external environment during aerosol sampling operations.

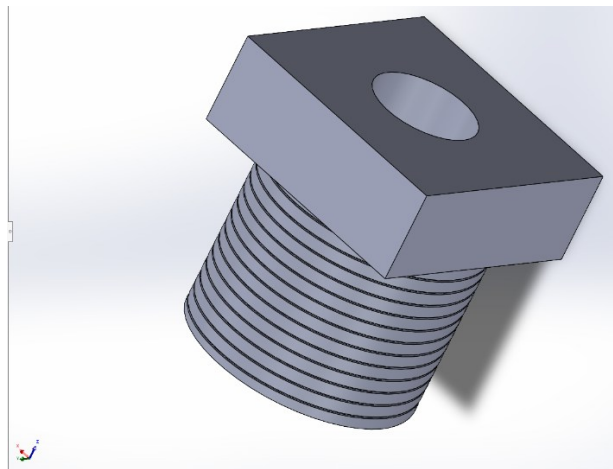


Figure 104

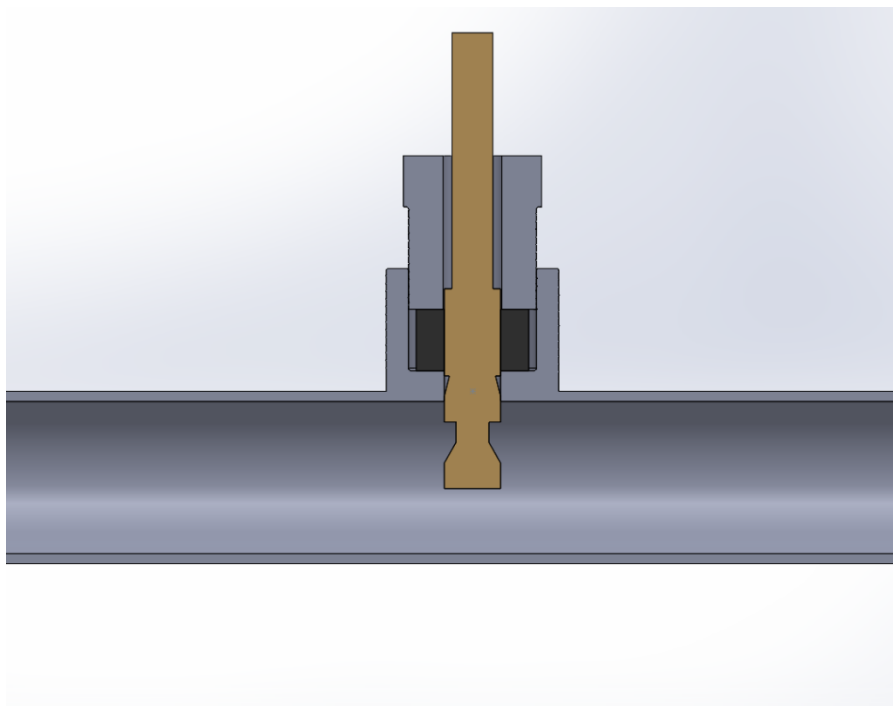


Figure 105

To accommodate the ELPI®+ sampling head on the same sampling taps, only a minor modification of the previous configuration was required. Specifically, the hollow cylinder with the squared head was provided with an internal thread, allowing the ELPI®+ sampling head to be screwed directly onto it. An additional O-ring was installed between the ELPI®+ sampling head and the hollow cylinder to ensure airtight sealing and prevent any infiltration of external air.

APPENDIX C – ELPI[®]+ measurements graphs

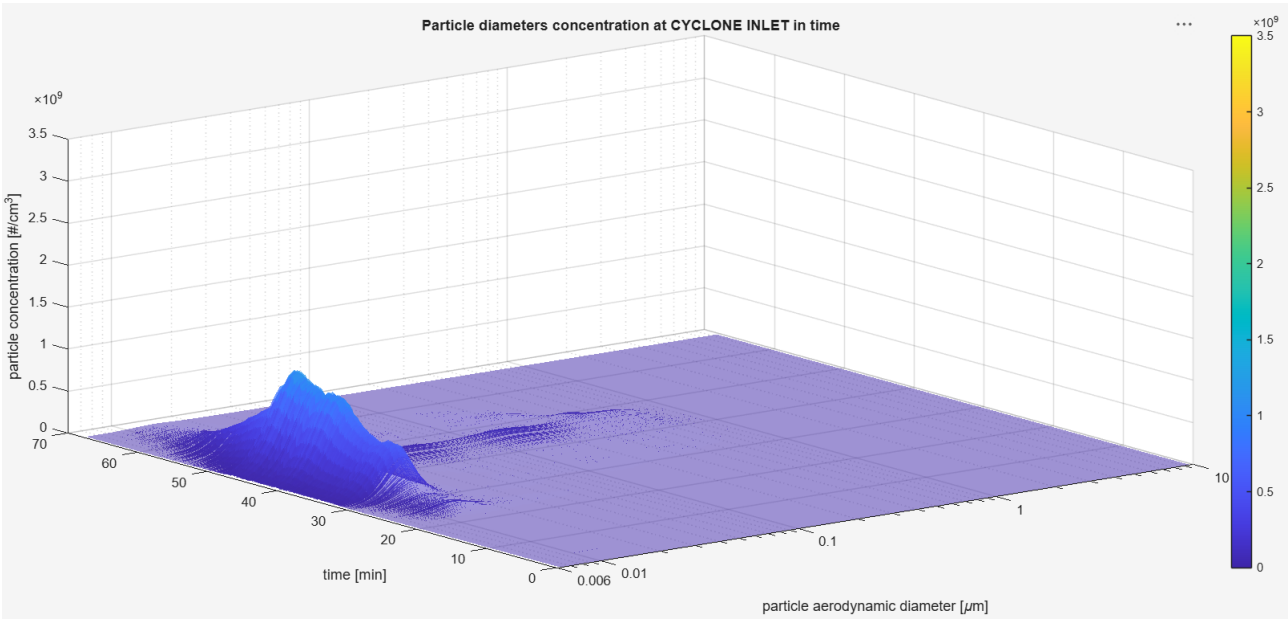


Figure 106

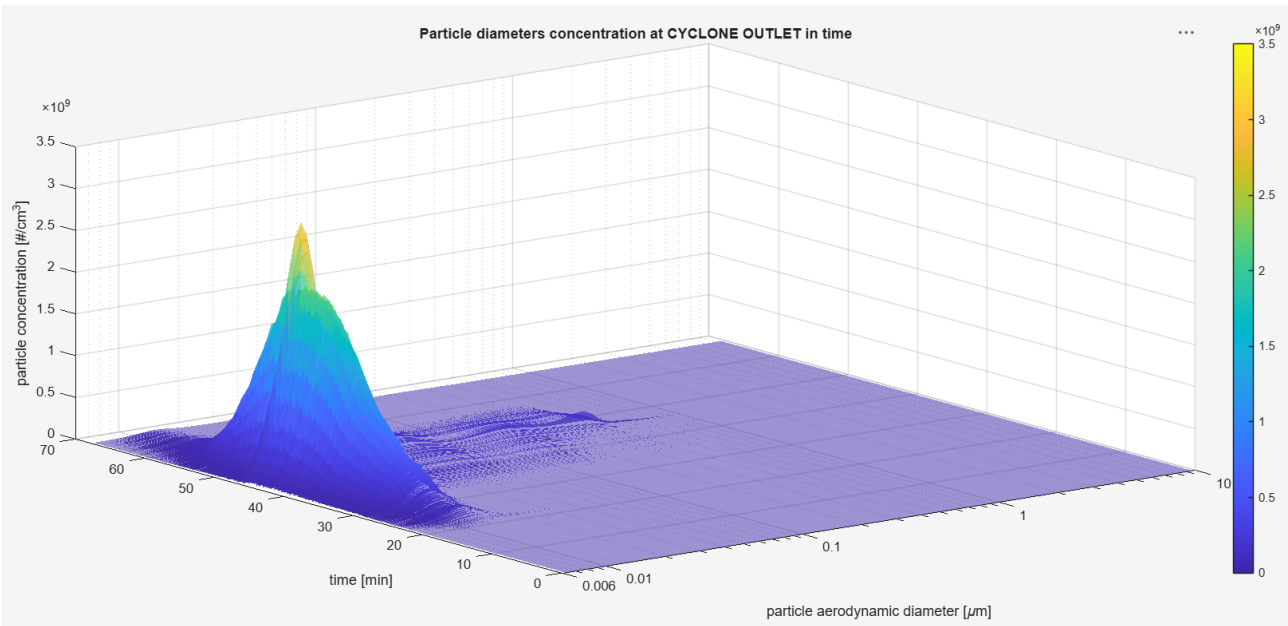


Figure 107

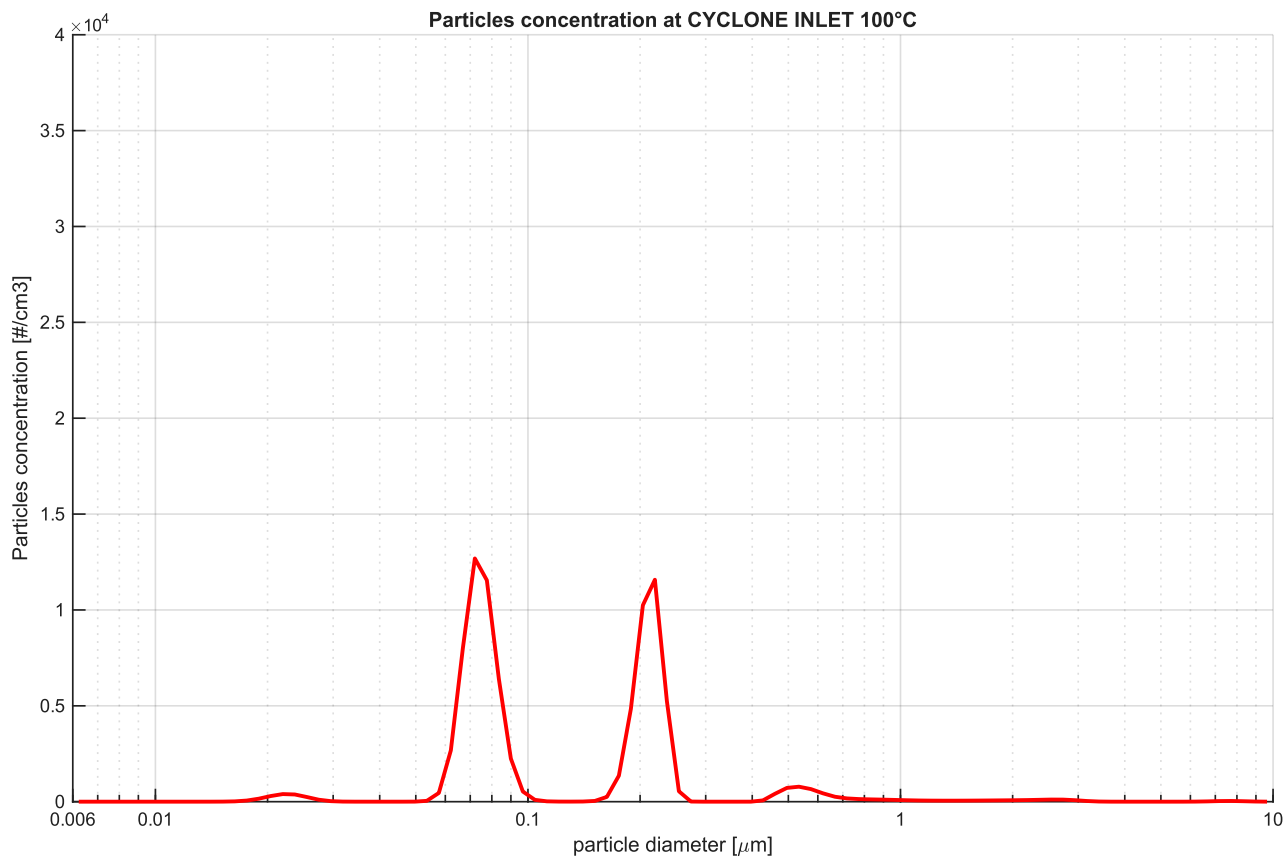


Figure 108

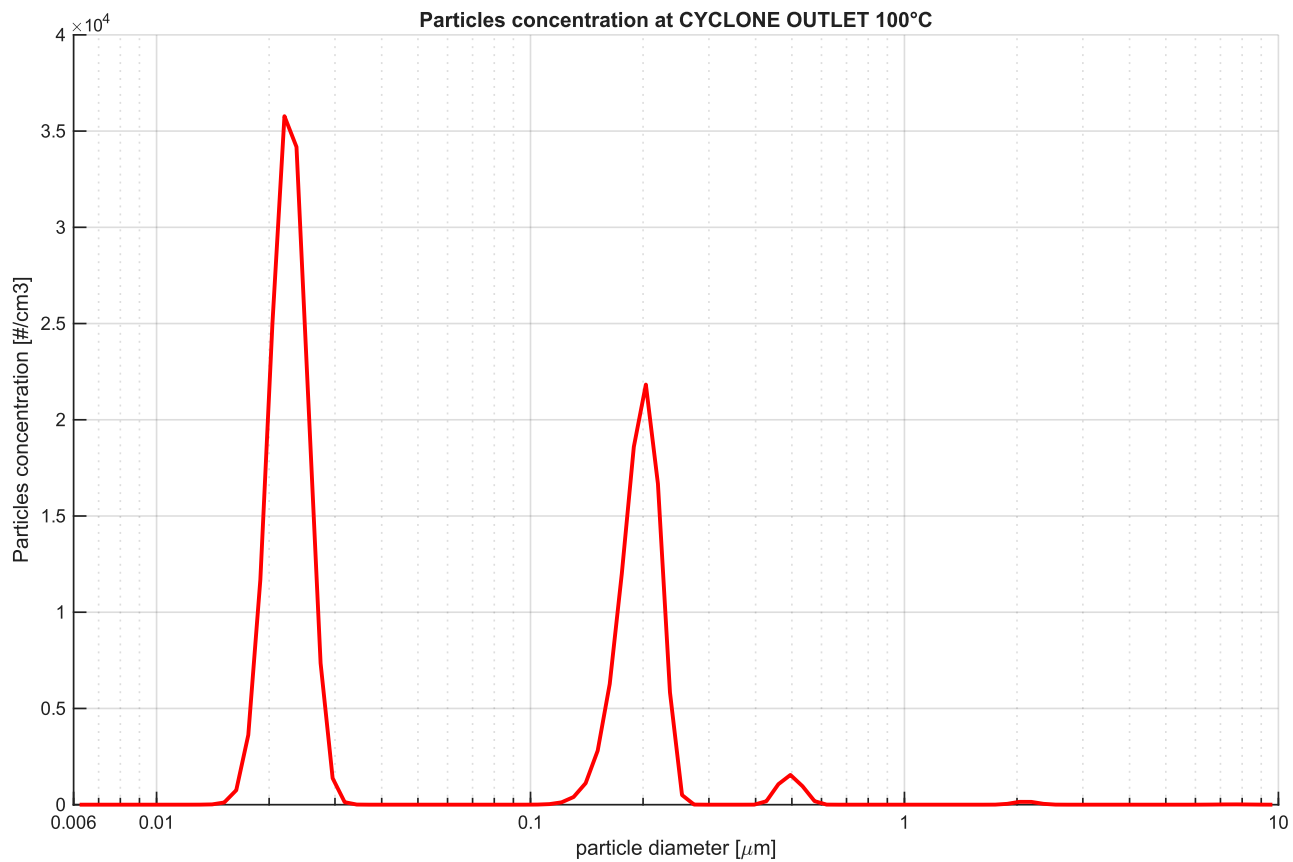


Figure 109

Particles concentration at CYCLONE INLET 100°C

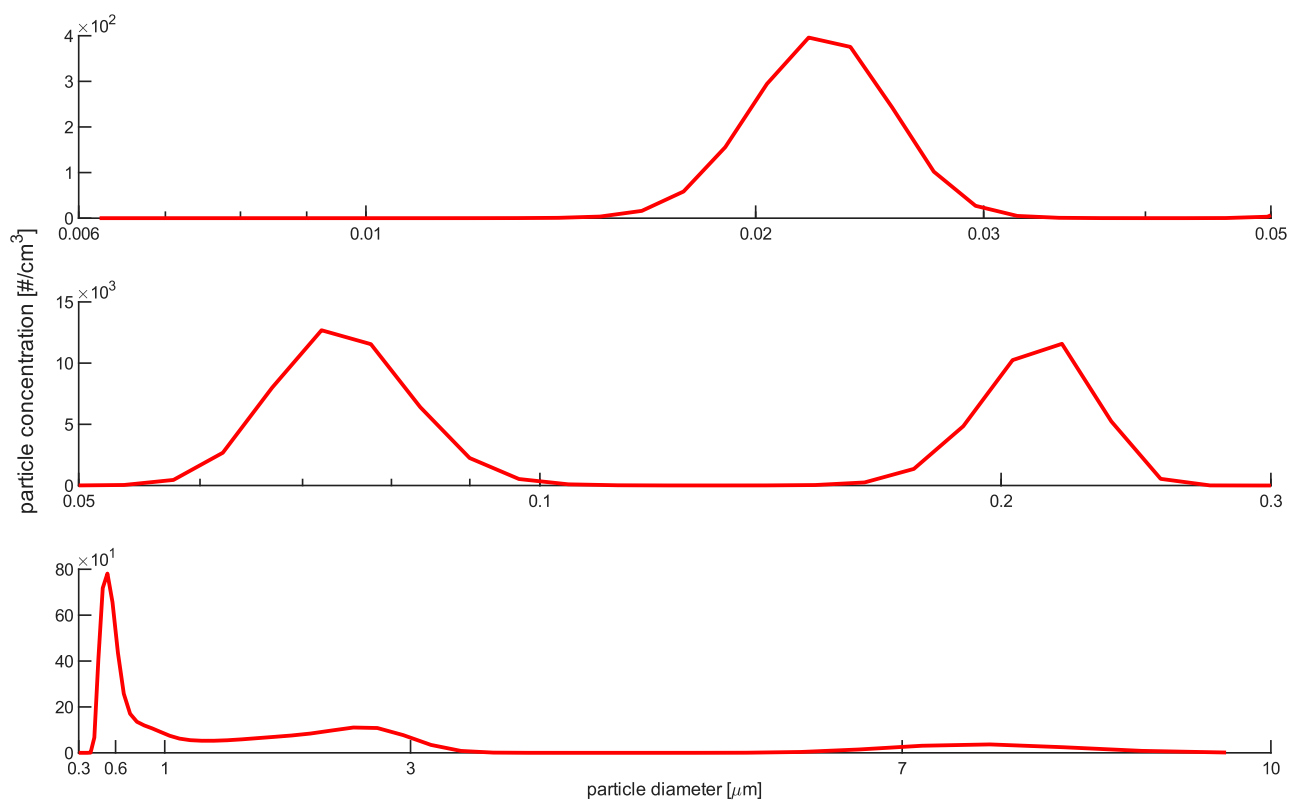


Figure 110

Particles concentration at CYCLONE OUTLET 100°C

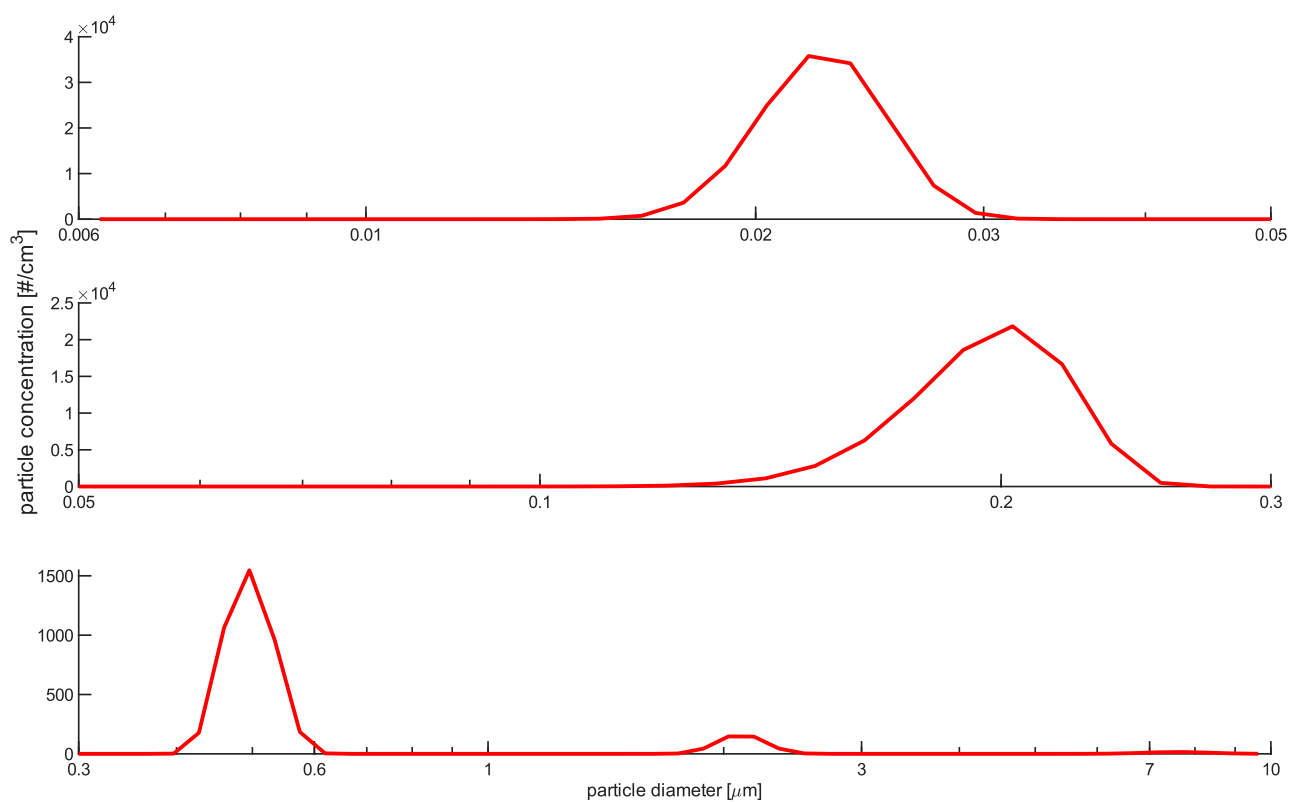


Figure 111

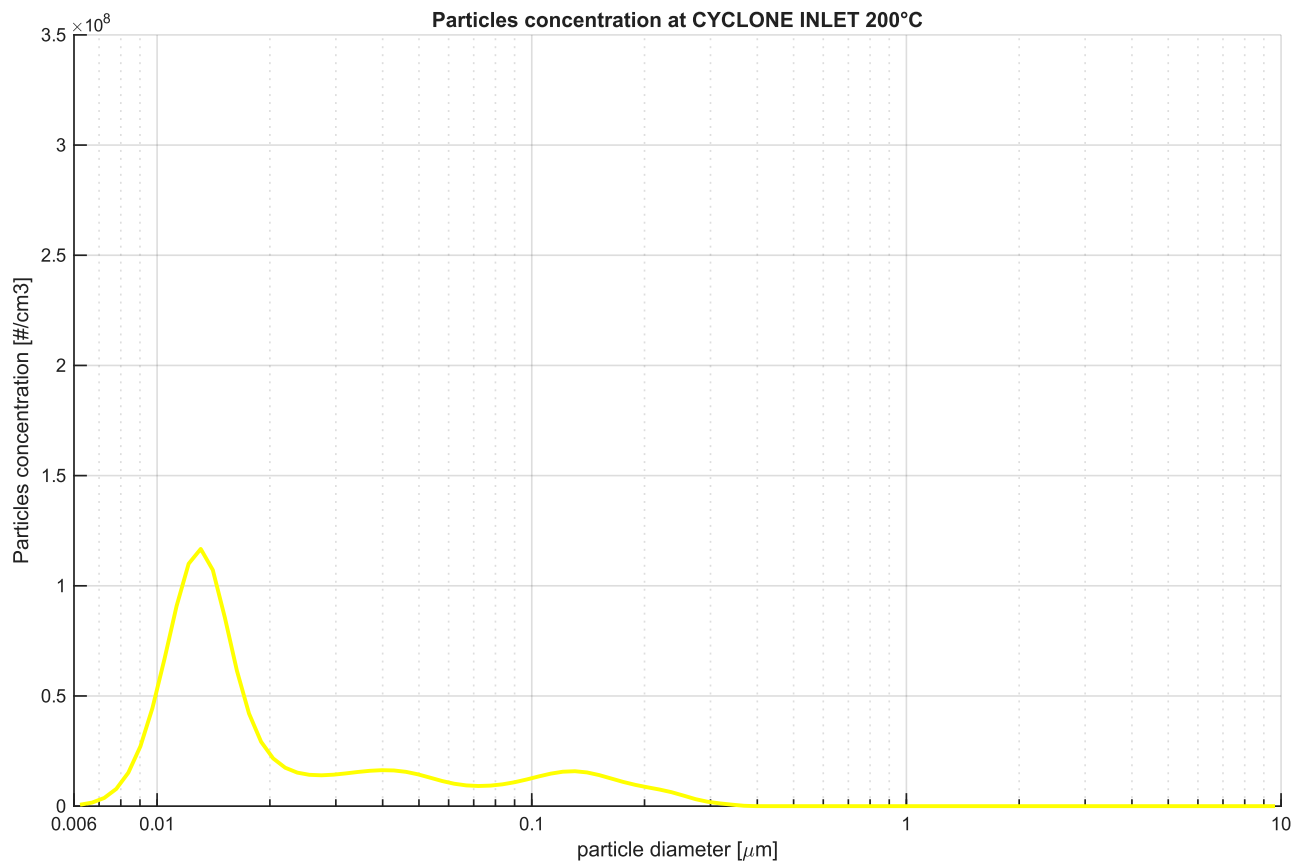


Figure 112

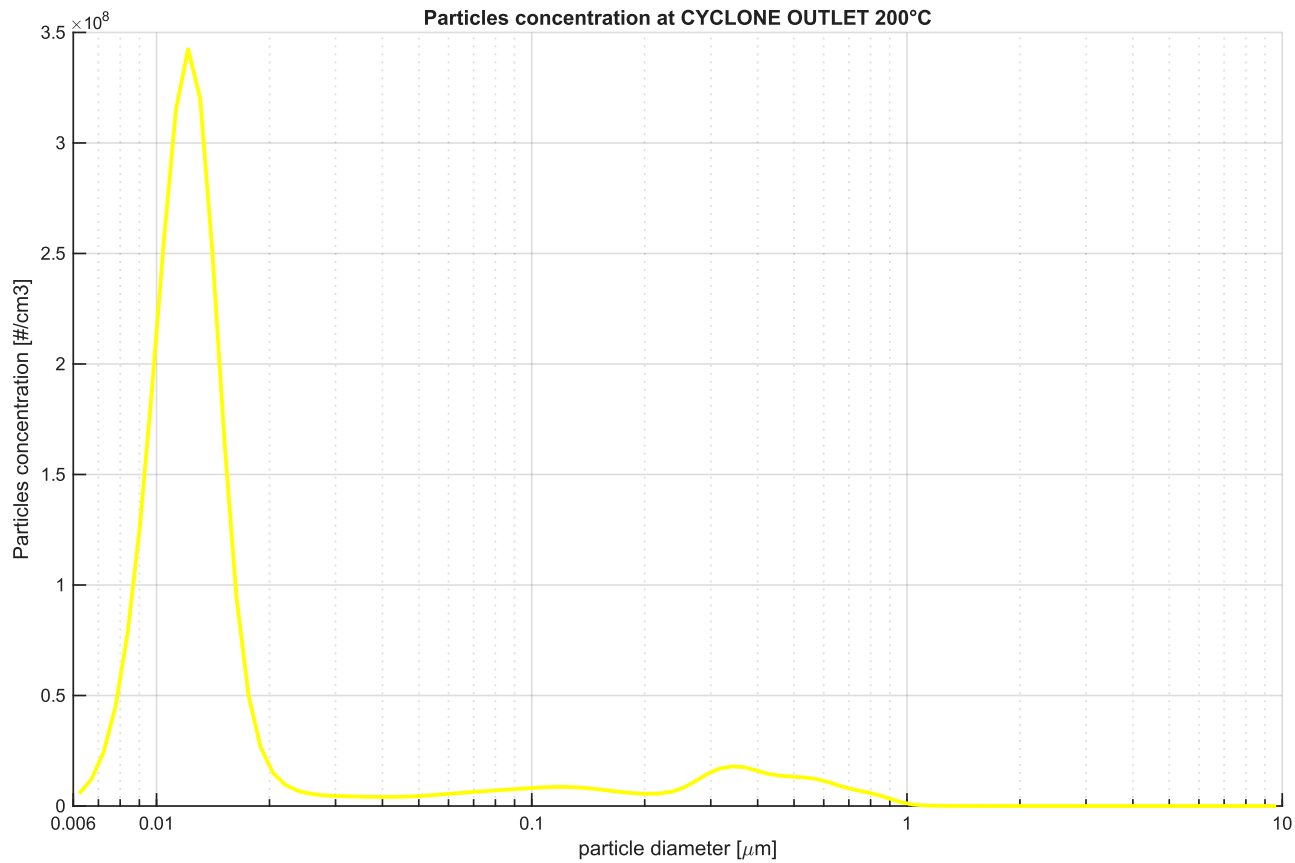


Figure 113

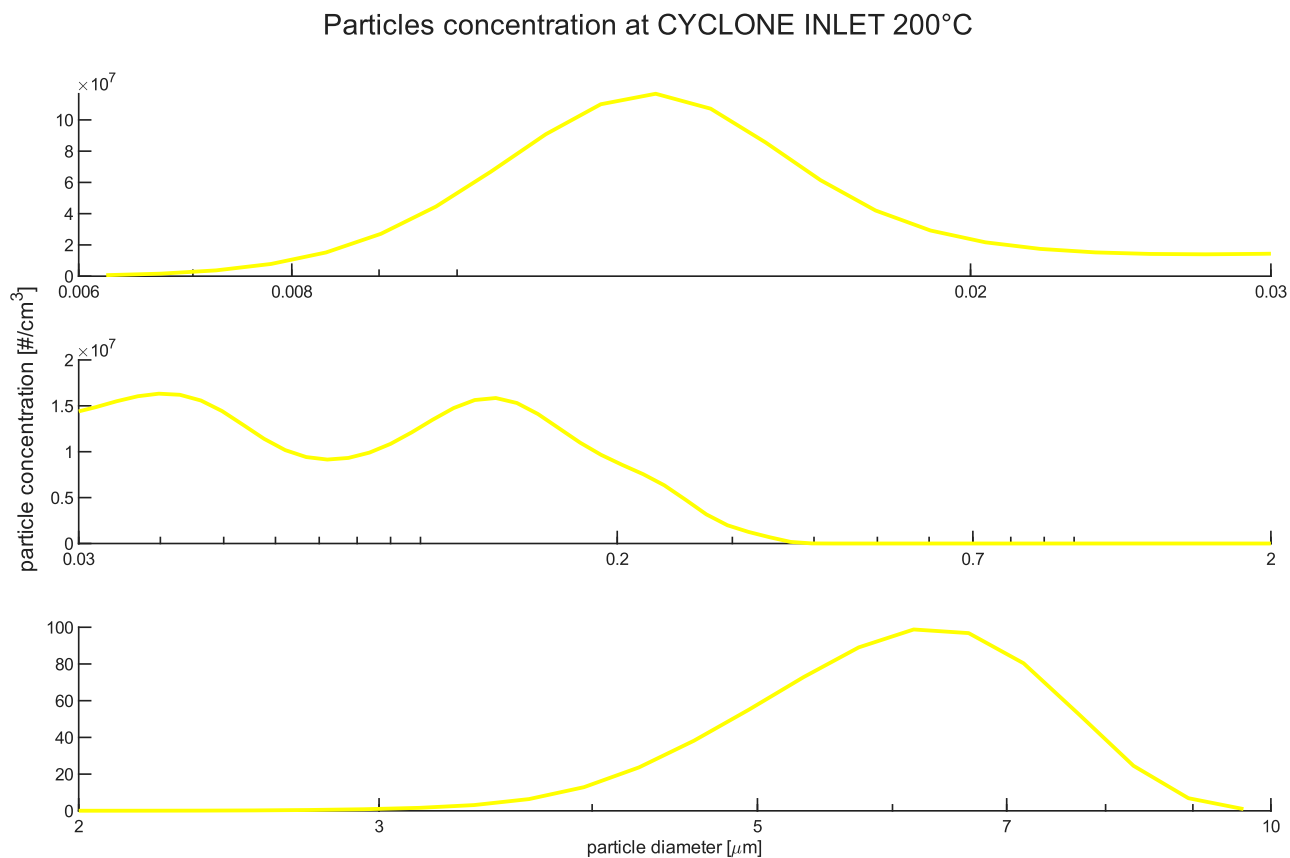


Figure 114

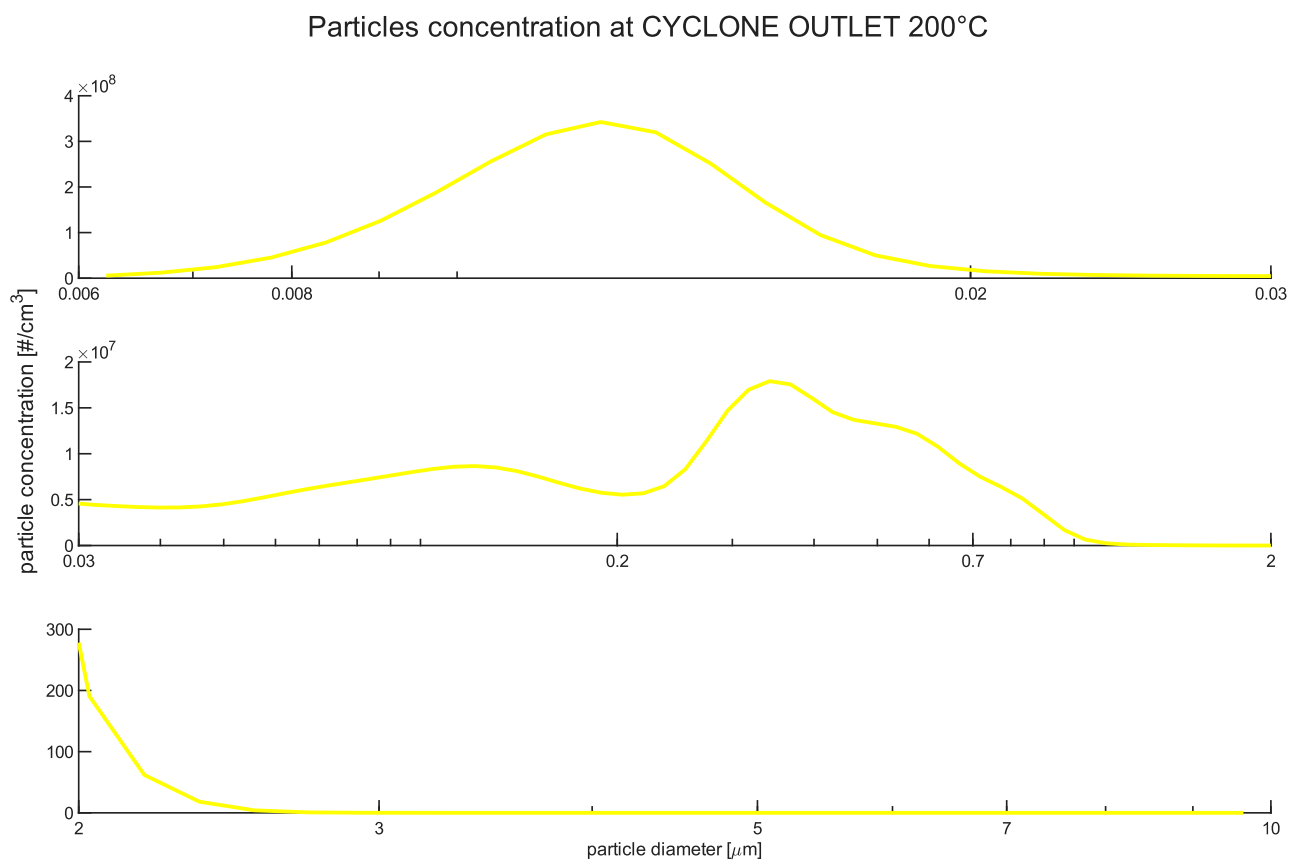


Figure 115

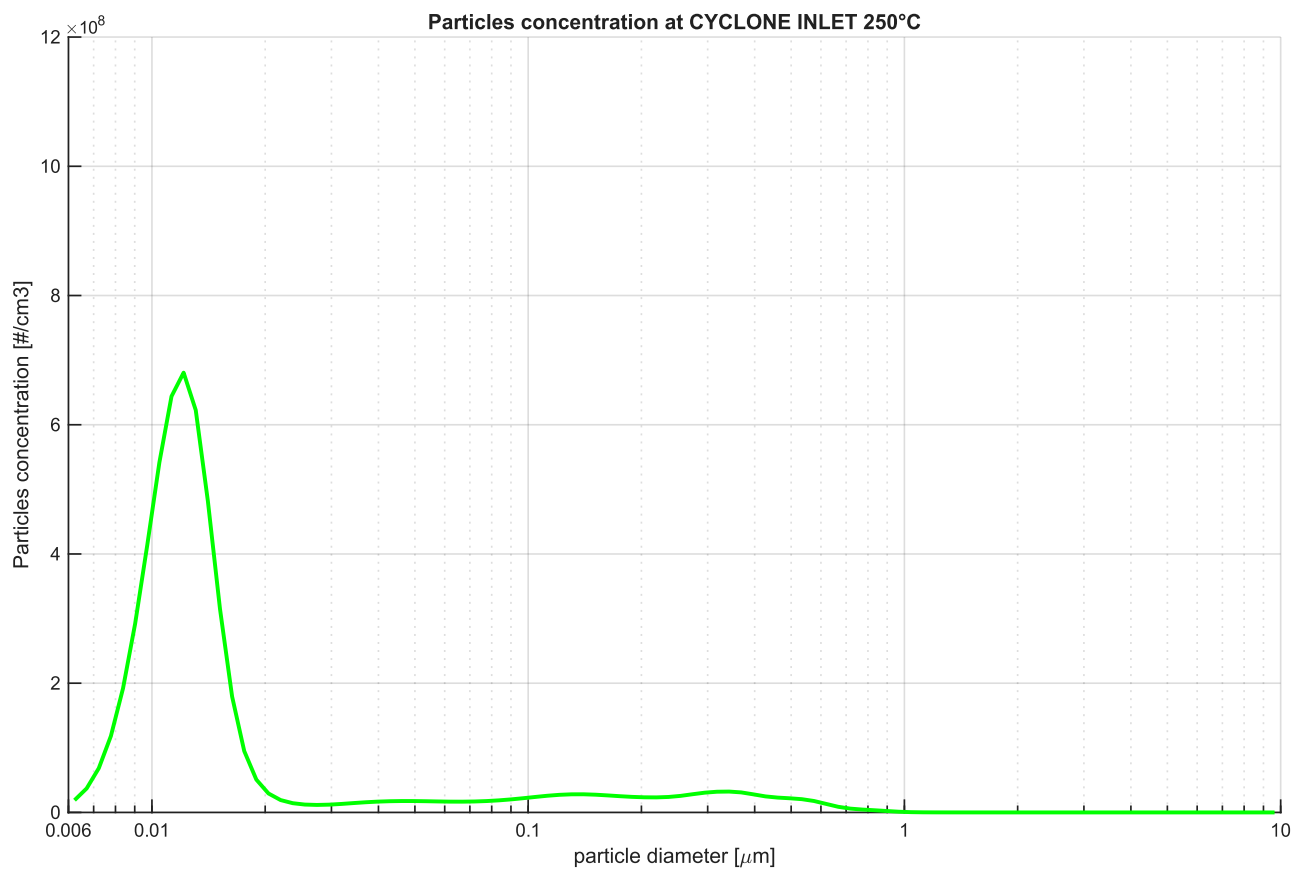


Figure 116

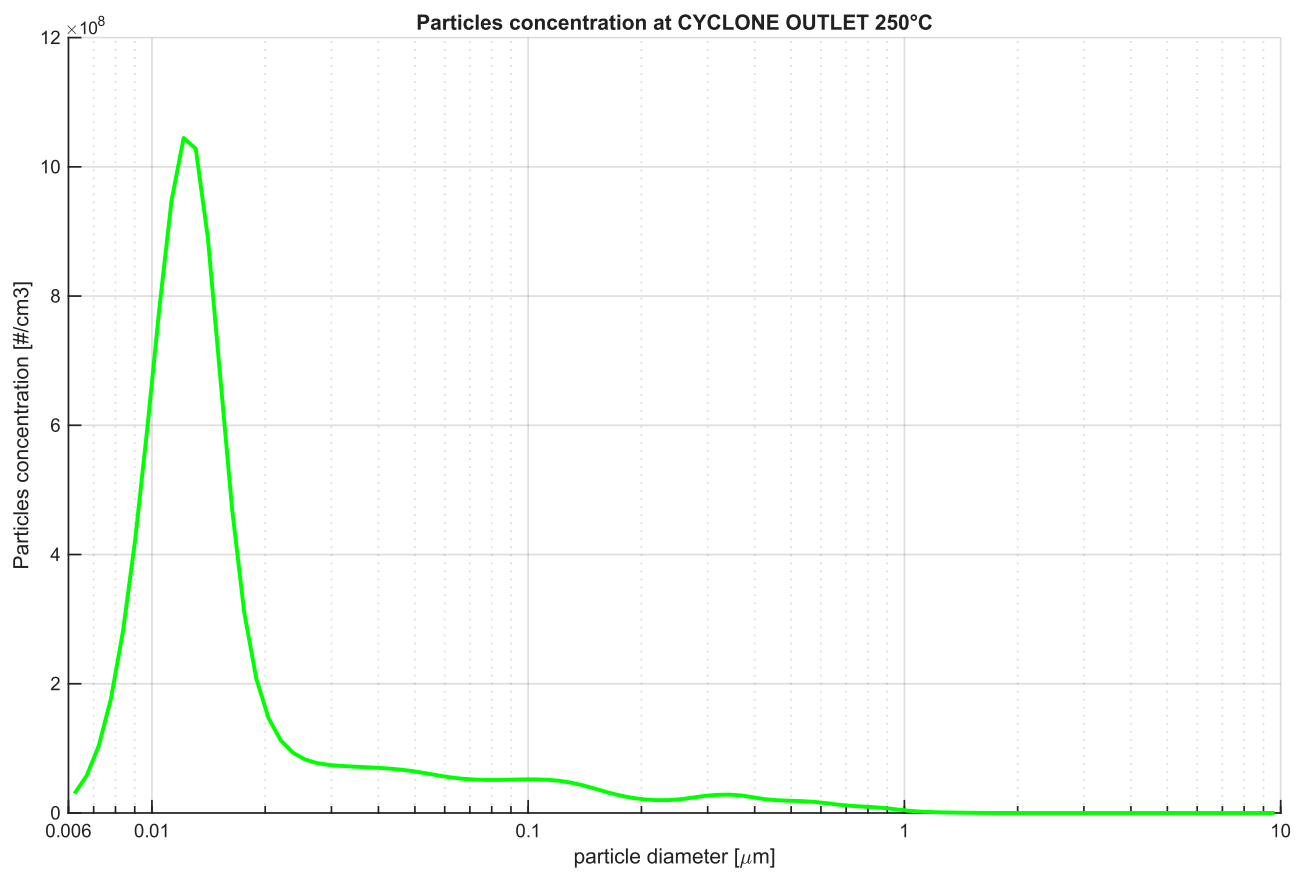


Figure 117

Particles concentration at CYCLONE INLET 250°C

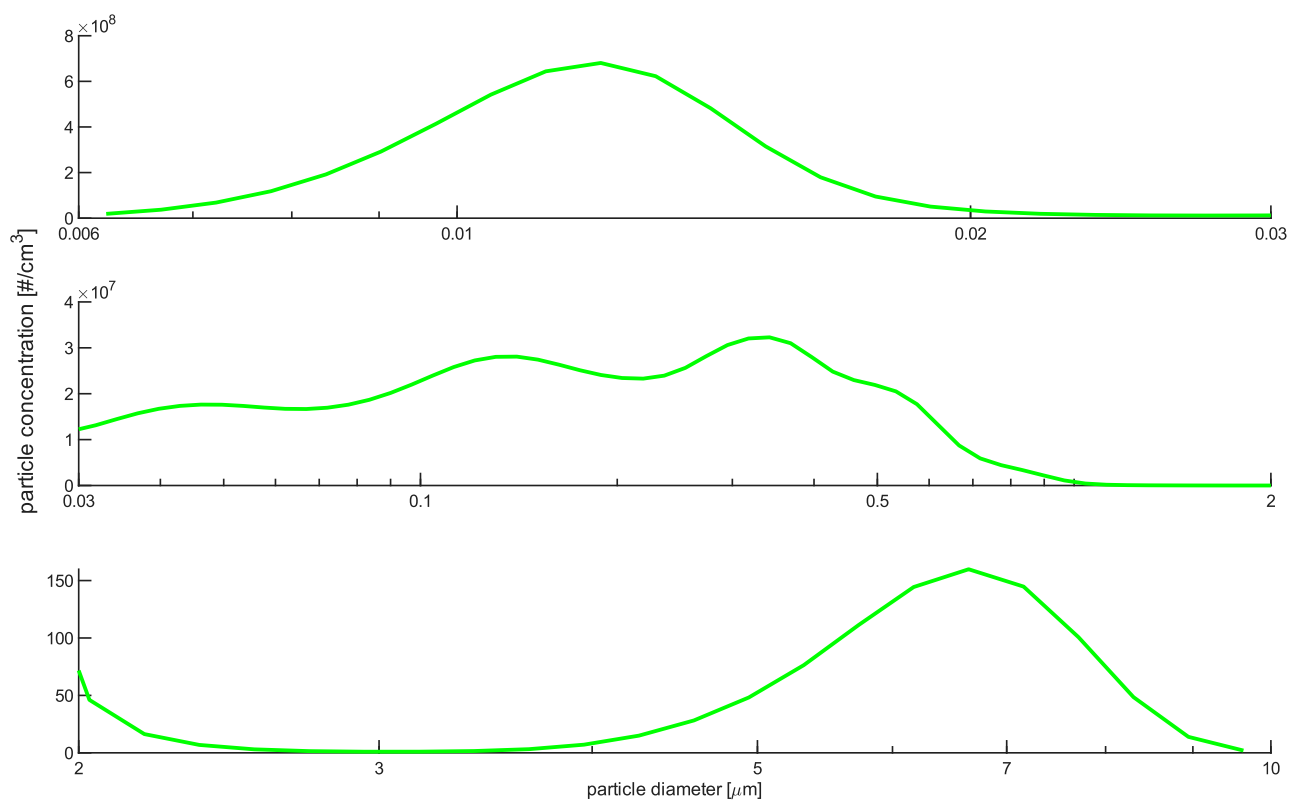


Figure 118

Particles concentration at CYCLONE OUTLET 250°C

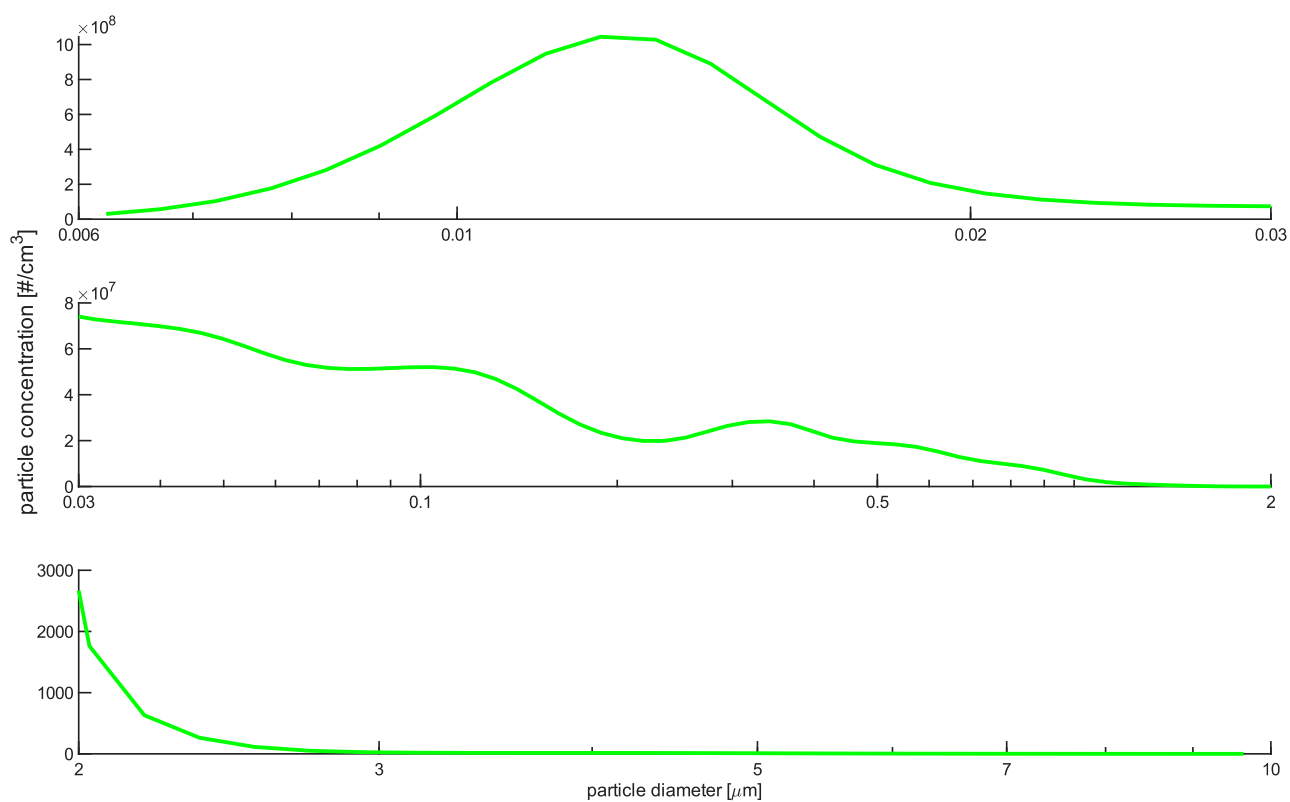


Figure 119

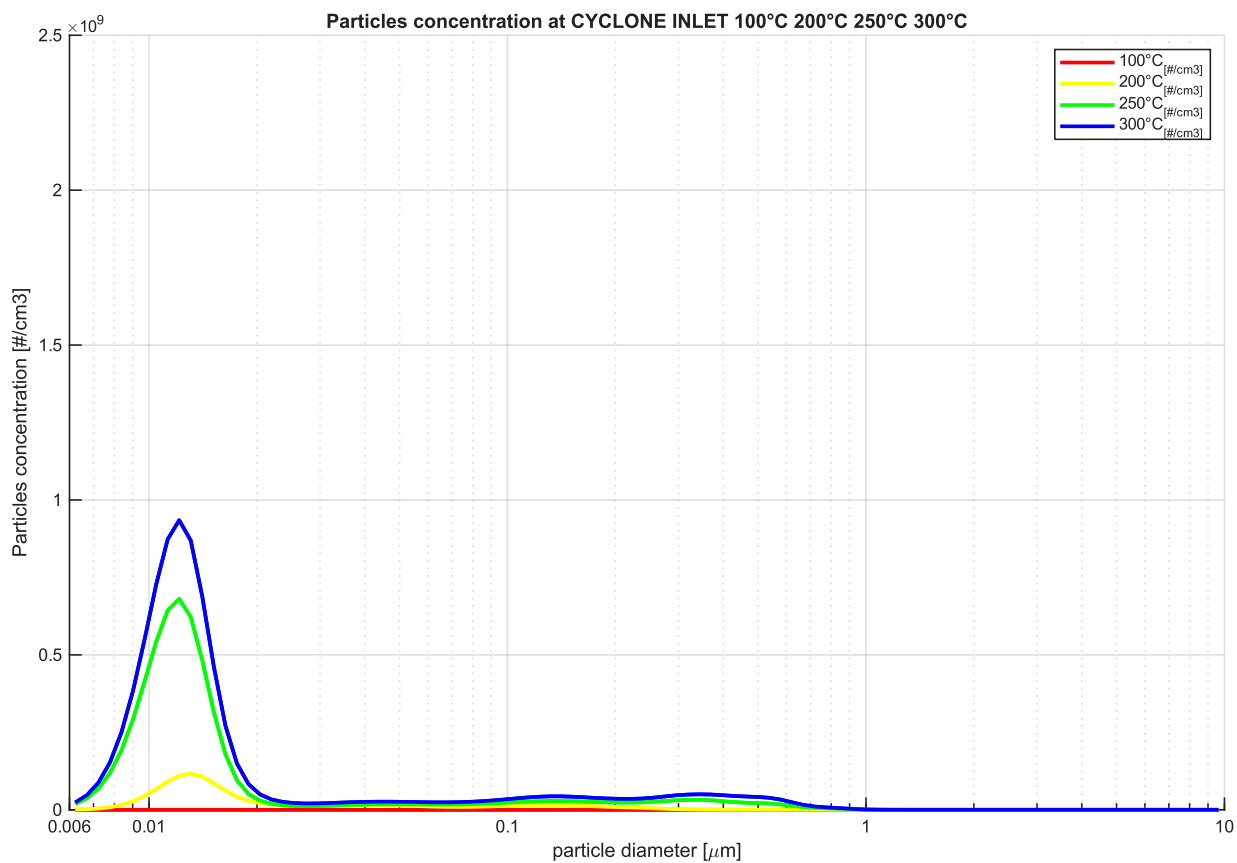


Figure 120

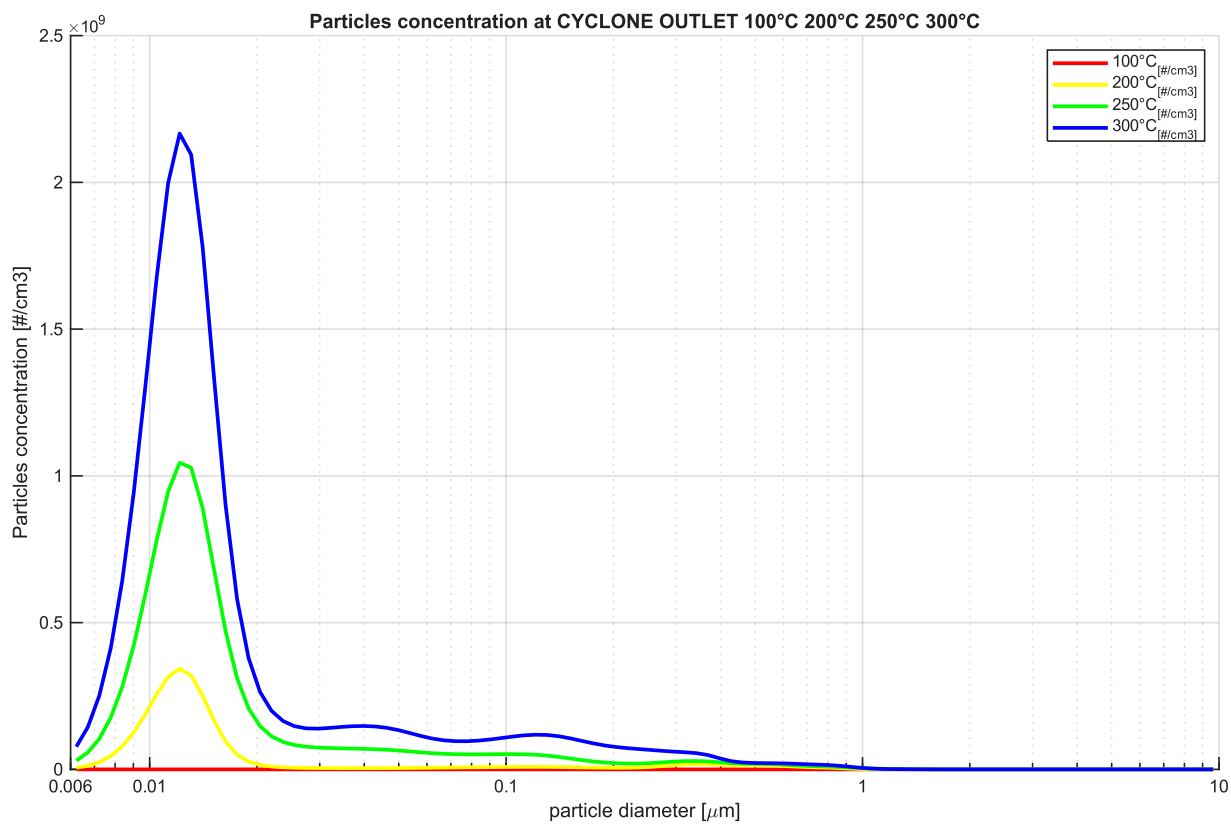


Figure 121

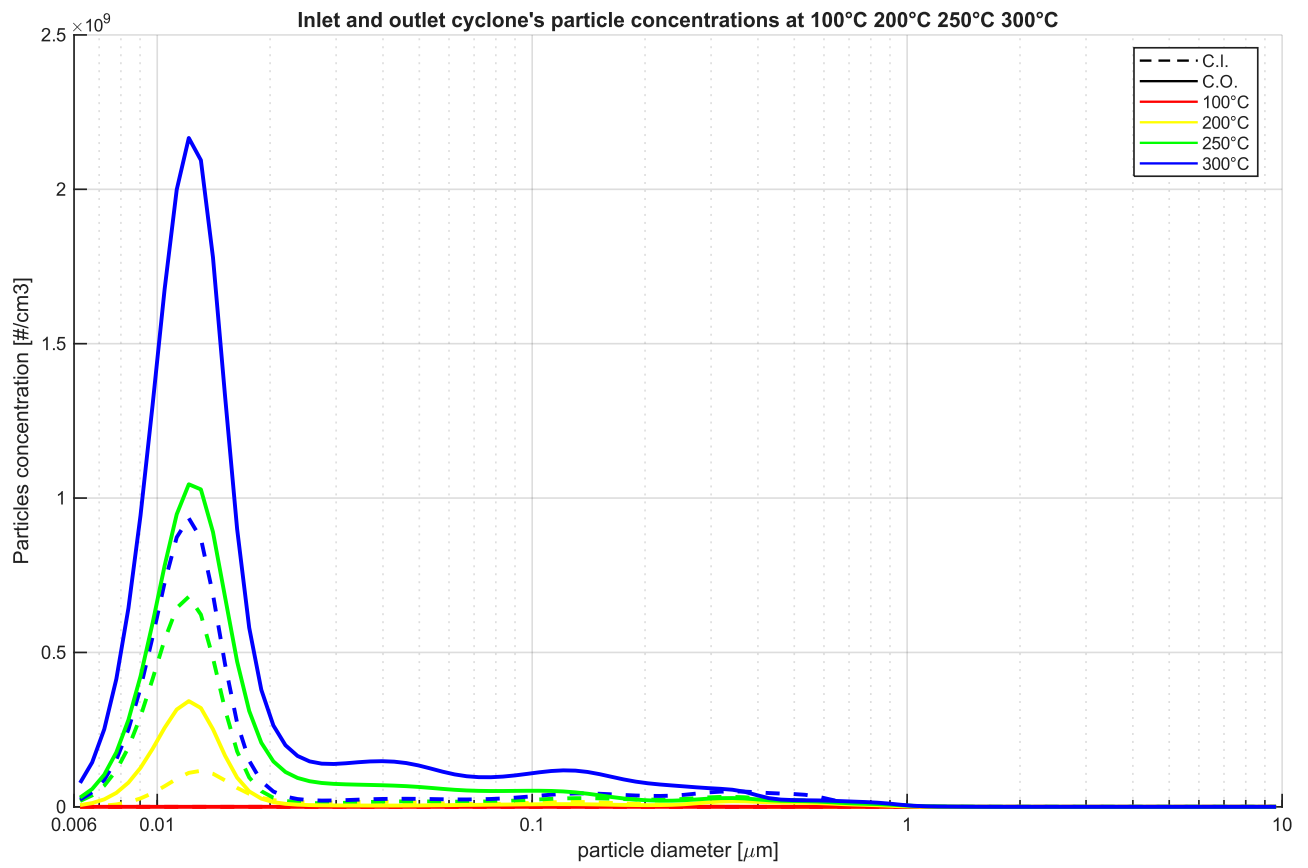


Figure 122

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Image index

Figure 1.....	6
Figure 2.....	6
Figure 3.....	16
Figure 4.....	17
Figure 5.....	24
Figure 6.....	25
Figure 7.....	27
Figure 8.....	27
Figure 9.....	30
Figure 10.....	30
Figure 11.....	32
Figure 12.....	35
Figure 13.....	36
Figure 14.....	37
Figure 15.....	37
Figure 16.....	38
Figure 17.....	41
Figure 18.....	42
Figure 19.....	43
Figure 20.....	44
Figure 21.....	48
Figure 22.....	49
Figure 23.....	49
Figure 24.....	50
Figure 25.....	50
Figure 26.....	51
Figure 27.....	51
Figure 28.....	52
Figure 29.....	53
Figure 30.....	53
Figure 31.....	55
Figure 32.....	55
Figure 33.....	56
Figure 34.....	60
Figure 35.....	60
Figure 36.....	61
Figure 37.....	61
Figure 38.....	62
Figure 39.....	62
Figure 40.....	62
Figure 41.....	63
Figure 42.....	63

Figure 43.....	64
Figure 44.....	64
Figure 45.....	65
Figure 46.....	66
Figure 47.....	67
Figure 48.....	68
Figure 49.....	69
Figure 50.....	70
Figure 51.....	71
Figure 52.....	71
Figure 53.....	72
Figure 54.....	73
Figure 55.....	73
Figure 56.....	74
Figure 57.....	75
Figure 58.....	76
Figure 59.....	76
Figure 60.....	77
Figure 61.....	77
Figure 62.....	78
Figure 63.....	78
Figure 64.....	79
Figure 65.....	79
Figure 66.....	80
Figure 67.....	80
Figure 68.....	80
Figure 69.....	81
Figure 70.....	81
Figure 71.....	82
Figure 72.....	82
Figure 73.....	83
Figure 74.....	83
Figure 75.....	84
Figure 76.....	84
Figure 77.....	85
Figure 78.....	85
Figure 79.....	86
Figure 80.....	86
Figure 81.....	87
Figure 82.....	87
Figure 83.....	88
Figure 84.....	88
Figure 85.....	89
Figure 86.....	89

Figure 87	89
Figure 88.....	90
Figure 89.....	90
Figure 90.....	90
Figure 91.....	91
Figure 92.....	91
Figure 93.....	91
Figure 94.....	92
Figure 95.....	92
Figure 96.....	93
Figure 97.....	93
Figure 98.....	94
Figure 99.....	94
Figure 100	95
Figure 101	95
Figure 102	97
Figure 103	97
Figure 104	98
Figure 105	98
Figure 106	99
Figure 107	99
Figure 108	100
Figure 109	100
Figure 110	101
Figure 111	101
Figure 112	102
Figure 113	102
Figure 114	103
Figure 115	103
Figure 116	104
Figure 117	104
Figure 118	105
Figure 119	105
Figure 120	106
Figure 121	106
Figure 122	107

Tables index

Table 1	21
Table 2	25
Table 3	26
Table 4	26
Table 5	29