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Design and Characterization of the Aerosol Sampling and
Vacuum System of the University of Vienna's Aerosol
Observatory

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Abstract

Aerosols significantly influence Earth's climate by interacting with incoming and outgoing electromagnetic radiation and affecting cloud formation and characteristics. Furthermore, aerosol particles can have a negative impact on human and animal health. Especially hazardous are high concentrations of small particles in densely populated areas. Consequently, monitoring urban aerosol particle concentrations is of great importance to public health protection and exposure assessment as well as climate research.

The University of Vienna's Aerosol Observatory (AerObs), located on the rooftop of the Faculty of Physics building, is equipped with instruments that monitor the ambient number concentration of particulate matter smaller than $2.5\text{ }\mu\text{m}$ in diameter (PM_{2.5}). Since 2024, the University of Vienna has been part of the Aerosols, Clouds and Trace Gases Research Infrastructure (ACTRIS) and has been recognized as a National Facility. For the particle concentration measurement, ambient aerosol is sampled with an inlet and transported with stainless steel tubes to measuring devices such as Condensation Particle Counters (CPCs) that monitor the particle number concentration. However, through various effects, particles can be lost within the sampling system. As a result, particle concentrations of transported aerosol differ from those in ambient air. To determine the "true" ambient aerosol particle number concentration, the particle losses attributable to the sampling system and thus the sampling efficiency must be characterized. In this thesis, the PM_{2.5} transport system of the AerObs is theoretically as well as experimentally characterized for particle losses using monodisperse silver particles. The theoretical characterization is conducted, using the Particle Loss Calculator software (PLC), whereas the experimental characterization is performed with the TSI Aerosol Electrometer 3068B and four Grimm 5410 CPCs with cutoff diameters of 4.5 nm, 7 nm and two at 10 nm. Silver particles are generated with the Catalytic Instruments Silver Particle Generator (SPG). A Differential Mobility Analyzer (RAX-DMA) selects a narrow electrical mobility diameter range from the polydisperse silver aerosol, thereby extracting a monodisperse aerosol fraction. Thus, the size-dependent transport efficiency of the PM_{2.5} transport system is assessed. Furthermore, the splitting performance of the flow splitters, incorporated into the PM_{2.5} sampling system, is determined using the TSI Aerosol Electrometer 3068B and two TSI 3772-CEN CPCs.

Additionally, to fulfill the requirements of ACTRIS, the AerObs must provide adequate flow and vacuum for the numerous existing devices and potential additions. Therefore, the performance of the new MINK MV 0060 D Synchro Dry claw vacuum pumps within the AerObs vacuum system is characterized for various inlet flow rates. To further determine which component configurations and dimensions achieve a sufficient vacuum level in the exhaust line, the frictional pressure losses for various setups are calculated using a self-developed algorithm. This provides a calculated pressure distribution within the entire PM_{2.5} sampling, exhaust and vacuum system. In addition, the absolute pressure is measured using Jumo Delos SI 488, at two points of the vacuum system to confirm the validity of the calculations.

Results show that experimentally measured and theoretically predicted transport efficiencies agree, over the investigated diameters between 7.5 and 300 nm. Particle losses increase with decreasing particle diameters due to diffusion. Depending on the transport line through which they flow, approximately 14 to 30 % of silver particles with electrical mobility diameters of 7.5 and 9 nm are deposited on the walls of the transport system. It is also observed that the Catalytic Stripper incorporated upstream of one of the CPCs reduces the transport

efficiency of silver particles by an additional 15 to 25 % depending on particle size. Furthermore, experiments show that the three-way splitters used in the setup exhibit no significant preference for any branch when dividing the aerosol. In addition, particle losses attributable to the splitters are negligible, because they lie within the uncertainty of the measurement.

The pressure analysis shows that the vacuum pumps provide sufficient vacuum for the planned AerObs extension, provided the exhaust lines have an adequate diameter. Perfluoroalkoxy alkane (PFA, 1/2 inch) tubes are well suited for the required vacuum downstream of the incorporated critical orifices and measurement devices, which require a pressure below approximately 500 hPa to ensure a constant flow rate. Additionally, the pressure distribution analysis identified a considerable pressure loss in the connected Catalytic Instruments' Catalytic Vapor Filter - 400 (CVF-400) that depends on whether the device is switched on or off, suggesting that the increased temperature of the CVF-400 increases the flow rate, which increases frictional pressure losses.

Kurzfassung

Aerosole beeinflussen das Erdklima maßgeblich durch ihre Wechselwirkung mit einfallender und ausgehender elektromagnetischer Strahlung sowie durch ihren Einfluss auf die Bildung und Eigenschaften von Wolken. Darüber hinaus können Aerosolpartikel negative Auswirkungen auf die Gesundheit von Mensch und Tier haben. Besonders gefährlich sind hohe Konzentrationen kleiner Partikel in dicht besiedelten Gebieten. Folglich ist die Überwachung urbaner Aerosolpartikelkonzentrationen von großer Bedeutung für den Schutz der öffentlichen Gesundheit und die Klimaforschung.

Das Aerosol-Observatorium (AerObs) der Universität Wien, das sich auf dem Dach des Gebäudes der Fakultät für Physik befindet, ist mit Instrumenten ausgestattet, welche die Umgebungskonzentration von Partikeln mit Durchmessern kleiner als $2.5\ \mu\text{m}$ (PM_{2.5}) messen. Seit 2024 ist die Universität Wien Teil der Forschungsinfrastruktur Aerosols, Clouds and Trace Gases Research Infrastructure (ACTRIS) und wurde als nationale Einrichtung (National Facility) anerkannt. Zur Messung der Partikelkonzentration wird Umgebungsaerosol mit einem Einlass angesaugt und über Edelstahlrohre zu Messgeräten wie Kondensationspartikelzählern (Condensation Particle Counters, CPCs) transportiert, die die Partikelkonzentration messen. Durch verschiedene Effekte können jedoch Partikel innerhalb des Einlasssystems verloren gehen. Dadurch unterscheiden sich die Partikelkonzentrationen des transportierten Aerosols von jenen der Umgebungsluft. Um die „wahre“ Partikelkonzentration der Umgebungsluft zu bestimmen, müssen die durch das Einlasssystem verursachten Partikelverluste und somit die Einlasseffizienz charakterisiert werden.

In dieser Arbeit wird das PM_{2.5}-Transportsystem des AerObs sowohl theoretisch als auch experimentell für Verluste von Silberpartikeln charakterisiert. Die theoretische Charakterisierung erfolgt mittels der Particle Loss Calculator Software (PLC), während die experimentelle Charakterisierung mit dem TSI Aerosol Elektrometer 3068B sowie vier Grimm 5410 CPCs mit Cutoff-Durchmessern von 4.5 nm, 7 nm und zweimal 10 nm durchgeführt wird. Silberpartikel werden mit dem Catalytic Instruments Silver Particle Generator (SPG) erzeugt. Ein Differenzieller Mobilitätsanalysator (RAX-DMA) selektiert einen schmalen Bereich elektrischer Mobilitätsdurchmesser und isoliert so aus polydispersem Silberaerosol ein monodisperses Aerosol. Auf diese Weise wird die größenabhängige Transporteffizienz des PM_{2.5}-Transportsystems ermittelt. Darüber hinaus wird die Aufteilungsleistung der im PM_{2.5}-Einlasssystem verbauten Flussteilers (Flow Splitter) mithilfe des TSI Aerosol Elektrometer 3068B und zweier TSI 3772-CEN CPCs bestimmt.

Um zudem die Anforderungen von ACTRIS zu erfüllen, muss das AerObs ausreichende Volumenstromstärke und Vakuum für die zahlreichen bestehenden Geräte sowie mögliche künftige Erweiterungen bereitstellen. Daher wird die Leistung der neuen MINK MV 0060 D Synchro Dry Klauenvakuumpumpen im Vakuumsystem des AerObs für verschiedene Einlass- Volumenstromstärken charakterisiert. Um darüber hinaus zu bestimmen, welche Bauteilkonfigurationen und -dimensionen ein ausreichendes Vakuumniveau in der Abluftleitung erzielen, werden die Reibungsdruckverluste für verschiedene Konfigurationen mithilfe eines selbst entwickelten Algorithmus berechnet. Daraus ergibt sich eine berechnete Druckverteilung innerhalb des gesamten PM_{2.5}-Einlass-, Abluft- und Vakuumsystems. Zusätzlich wird der absolute Druck mittels Jumo Delos SI 488 Drucksensoren an zwei Punkten des Vakuumsystems gemessen, um die Gültigkeit der Berechnungen zu bestätigen.

Die Ergebnisse zeigen, dass im untersuchten Größenbereich von 7.5 bis 300 nm die experimentell gemessenen und die theoretisch vorhergesagten Transporteffizienzen übereinstimmen, wobei die Partikelverluste bei kleineren Größen aufgrund von Diffusion zunehmen. Je nach durchflossener Transportleitung lagern sich etwa 14 bis 30 % der Silberpartikel mit elektrischen Mobilitätsdurchmessern von 7.5 und 9 nm an den Wänden des Transportsystems ab. Zudem wird beobachtet, dass der Catalytic Stripper, der stromaufwärts eines der CPCs eingebaut ist, die Transporteffizienz von Silberpartikeln je nach Partikelgröße um weitere 15 bis 25 % reduziert. Des Weiteren zeigen die Experimente, dass die im Aufbau verwendeten Dreiwege-Flussteiler bei der Aufteilung des Aerosols keine signifikante Präferenz für einen bestimmten Zweig aufweisen. Darüber hinaus sind die den Flussteilern zuzuschreibenden Partikelverluste vernachlässigbar, da sie innerhalb der Messunsicherheit liegen.

Die Druckanalyse zeigt, dass die Vakuumpumpen ausreichendes Vakuum für die geplante Erweiterung des AerObs bereitstellen, sofern die Abluftleitungen einen ausreichenden Durchmesser aufweisen. 1/2-Zoll-Schläuche aus Perfluoralkoxy-Polymer (PFA, 1/2 inch) sind gut für das erforderliche Vakuum stromabwärts der verbauten kritischen Düsen und Messgeräte geeignet, die einen Druck von unter etwa 500 hPa benötigen, um eine konstante Durchflussrate zu gewährleisten. Zusätzlich identifizierte die Druckverteilungsanalyse einen erheblichen Druckverlust im angeschlossenen Catalytic Vapor Filter - 400 (CVF-400), der davon abhängt, ob das Gerät ein- oder ausgeschaltet ist, was darauf hindeutet, dass die erhöhte Temperatur des CVF-400 zu einer höheren Volumenstromstärke und somit zu größeren Reibungsdruckverlusten führt.

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1 Introduction and Motivation

1.1 Aerosols

Aerosols are liquid or solid particles suspended in a carrier gas. In Earth's atmosphere, aerosol particle sizes typically range from $0.002\text{ }\mu\text{m}$ to more than $100\text{ }\mu\text{m}$. This definition includes both the suspended particles and the gas (Hinds and Zhu, 2022). There are types of aerosol, which depend on the physical form and other properties of the particles, such as bioaerosols, clouds, dust, fumes, mist, fog, smog, smoke and spray (Hinds and Zhu, 2022). Aerosols are produced either by the conversion of gases into particles (secondary aerosol) or by the breakdown of solid or liquid particles into smaller fragments, which are emitted into the atmosphere (primary aerosol) (Kulkarni, 2011).

1.1.1 Impact of Atmospheric Aerosols on the Climate

Depending on properties such as concentration, size, chemical composition, albedo, refractive index, surface structure, as well as the properties of their surroundings, atmospheric aerosols have different effects on our climate (IPCC, 2021). The impact on Earth's radiative energy budget originates from direct aerosol-radiation interactions, such as scattering, absorption and reflection of incident radiation, or indirect aerosol effects emerging from changes in cloud droplet sizes and concentrations, as well as the resulting shift of water content in the atmosphere caused by the change in the abundance of cloud condensation nuclei (CCNs) and of ice nucleating particles (INPs) (IPCC, 2021).

Although some atmospheric aerosols (e.g. black carbon) are estimated to warm Earth's climate, aerosols in general have a net cooling effect. Sulfate aerosols have a major impact on Earth's radiation budget. Due to their effective scattering of solar radiation, high transmittance of longwave radiation and the ability to effectively act as CCNs and thus increase the albedo of clouds, they significantly cool the Earth's surface (IPCC, 2021). Figure 1 shows the effective radiative forcing (ERF) and change in global mean surface air temperature (GSAT) from component emissions between 1750 to 2019. Greenhouse gases such as CO_2 , CH_4 and N_2O contribute to positive radiative forcing, while aerosols such as those containing SO_2 , organic carbon, and ammonia have a cooling effect (IPCC, 2021).

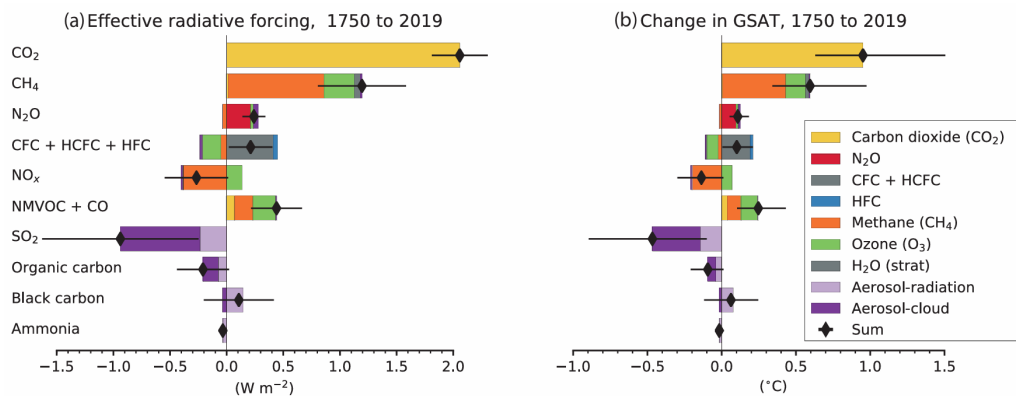


Figure 1: Contribution to effective radiative forcing (ERF, in W m^{-2}) (left) and global mean surface air temperature (GSAT) change (in $^{\circ}\text{C}$) (right) from component emissions between 1750 and 2019, based on CMIP6 models (Thornhill et al., 2021). Error bars indicate the uncertainty range, while black diamonds denote the total effect. Reprinted from IPCC (2021), Chapter 6, Figure 6.12.

Another aerosol type, mineral dust, which constitutes the largest fraction of atmospheric aerosols by mass, exerts a net radiative effect of $-0.2 \pm 0.5 \text{ Wm}^{-2}$ on Earth's energy budget, with a 90 % confidence interval (Kok et al., 2023).

As a result of the high complexity of meteorological and climatological processes, combined with interactions governing aerosol transport, nucleation, sedimentation and radiation, there are substantial uncertainties in both ERF and the change in GSAT. The collection of large amounts of accurate and reliable data is crucial for the correct assessment of the influence of aerosols and trace gases on Earth's climate.

1.1.2 Impact of Atmospheric Aerosols on Human Health

Aerosols can have diverse consequences for human health. These effects may be beneficial in nature, such as in the case of sea spray aerosols (SSA) and asthma medication. SSAs contain dipalmitoylphosphatidylcholine (DPPC), which is an important component of human lung surfactant and accumulates on the surface layer of the sea (Van Acker et al., 2021). In medical aerosol therapy, DPPC is commonly used as an excipient, enhancing the active ingredient's absorption and therapeutic efficacy, suggesting a link between the marine processes and human health (Van Acker et al., 2021). In the case of asthma medication, bronchodilators are nebulized, inhaled and thus transported to the bronchi, treating bronchoconstrictions and bronchial hypersensitivity which relieve asthmatic symptoms such as wheezing and breathlessness (Arfin et al., 2023). Since asthma is a chronic, incurable disease affecting more than 300 million people worldwide and causing approximately 180 thousand deaths annually, bronchodilators play a crucial role in improving both the quality of life and life expectancy of patients (Arfin et al., 2023).

However, some abundant aerosol types are hazardous to human health. Dust storms, forest fires and volcanic eruptions are extreme, yet realistic examples of powerful natural events that release significant amounts of particulate matter (PM) that can be detrimental to human health. The PM concentration in close proximity to these environments is astoundingly high, exceeding 0.1 gm^{-3} (Mustafa et al., 2019). However, particles from those emissions can also be transported thousands of kilometers. Exposure to PM smaller than $2.5 \mu\text{m}$ (PM_{2.5}) from the 2023 Canadian wildfires alone, is estimated to have contributed to 3 400 - 7 400 acute deaths in North America and 37 800 - 90 900 chronic deaths in North America and Europe (Zhang et al., 2025). In 13 European countries studied, Wang et al. (2020) estimate a yearly total of almost 42 thousand deaths, which are attributed to the exposure to Saharan dust in the region. Furthermore, bioaerosols such as pollen, fungi spores, viruses and bacteria can exacerbate a multitude of allergic symptoms, illnesses and serious respiratory infections, which may lead to death (Kallawicha et al., 2024). Tarín-Carrasco et al. (2021) estimate that 904 000 premature deaths per year are linked to PM_{2.5} in Europe alone. In one climate change scenario, described by the Representative Concentration Pathway 8.5 (RCP8.5), which expects radiative forcing change to reach 8.5 Wm^{-2} in 2100, by the year 2050, this mortality rate is expected to increase by 73% (Tarín-Carrasco et al., 2021). This climate change pathway is described as the worst-case scenario.

Anthropogenic emissions of PM, such as from industrial, residential, commercial and transportation sources, further affect human life. Silva et al. (2016) estimate the contribution of anthropogenic PM_{2.5} to 2 230 000 deaths per year globally, while 1 070 000 deaths per year emerge from East Asia. Globally, the highest mortality of an estimated 675 000 deaths per year is attributable to residential and commercial emissions, while in North America land transportation dominates in terms of total anthropogenic PM_{2.5} mortality.

Furthermore, global land transportation impacts anthropogenic ozone production, which is associated with an estimated 493 000 deaths per year (Silva et al., 2016). Therefore, reliable measurements of the number concentration, composition and size of airborne particles, especially in densely populated areas, such as cities like Vienna, are not only of scientific interest, but also provide valuable information for the potential improvement of our quality of life.

However, simply detecting particles is not enough to reliably determine the actual ambient particle number concentration and thus the magnitude of processes affecting Earth's climate and Human health. In practice, aerosol is sampled through an inlet and transported via tubing to a measuring device. During this process aerosol particles can be deposited on the walls due to mechanisms such as diffusion, gravitational settling and inertial deposition. The particle losses are strongly dependent on particle size and density, flow velocity and the geometry of the sampling system. These effects result in a decrease in the overall particle number concentration, as well as a significant change in the size distribution reaching the measurement instruments (compared to the "true" ambient number concentration and size distribution). If left uncharacterized, this discrepancy would introduce a systematic error into any further analysis of climate or health impacts. Therefore, the characterization and correction of particle losses in aerosol sampling systems is highly important for the collection of reliable and accurate atmospheric data.

1.2 The Aerosol Observatory (AerObs)

The Aerosol Observatory (AerObs) of the University of Vienna Aerosol Physics and Environmental Physics Research Group is a research observatory on the roof of the University building of the Physics Faculty, Boltzmanngasse 5, Vienna. It was renovated between 2019 and 2023 and is currently being further developed.

As of now, the AerObs consists of one PM_{2.5} and one PM₁₀ inlet, which allow the sampling of particulate matter of sizes smaller than 2.5 μm and 10 μm , respectively. The PM_{2.5} line is equipped with four butanol-based Grimm 5410 Condensation Particle Counters (Grimm CPCs) with different cutoff diameters as well as one TSI CPC 3750 installed in a Scanning Mobility Particle Sizer (SMPS) arrangement. The CPCs, which are incorporated into the PM_{2.5} line, measure the number concentration of aerosol particles of sizes ranging from 4.5 nm to 2.5 μm , while a gas concentration analyzer (Picarro) continuously measures the concentration of trace gases (CO, CO₂, H₂O and CH₄). The PM₁₀ sampling line transports particles to devices which measure optical particle characteristics such as light scattering and absorption, as well as the aerodynamic diameter of particles of sizes ranging from 0.3 μm up to 10 μm .

The latest objectives of the AerObs includes the continuous measurement of aerosol and trace gas concentrations and characteristics, as well as the provision of infrastructure to enable collaborations with external measurement campaigns, which can use the aerosol sampling and transport system of the AerObs for independent studies. For the latter objective, three additional inlets are planned. The construction of a Nano-CPC inlet is also under consideration.

The goal of the AerObs vacuum system is the provision of a stable and sufficiently low vacuum for the instruments and the sampling system itself. The sampling line of the AerObs is designed to minimize particle losses within the given constraints of the building. To obtain unbiased data of particle concentrations and optical properties, sampling losses must be considered and corrected for in the data. This acts as a basis for the accurate analysis of the impact of aerosols on the climate and on human health. These efforts are motivated, in part, by the status of AerObs at the University of Vienna as an ACTRIS National Facility, alongside broader institutional and scientific priorities.

This leads to the research questions that will be answered during this thesis:

- What are the required dimensions and performances of the sampling and vacuum system of the University of Vienna's new Aerosol Observatory, to provide adequate inlet flow and sufficient vacuum for the continuous operation of the measurement instrumentation, as well as the establishment of measurement infrastructure for collaborative campaigns?
- How representative are the measured particle size distributions of "true" ambient conditions, taking into account aerosol particle losses in the sampling system?

2 Theoretical Background

2.1 Flow Mechanics

On the subject of flow and its properties, an important distinction between compressible and incompressible fluids must be made. Compressibility describes the ability of a fluid to change its volume, thus changing its density, due to a uniform pressure acting upon the medium, without a change in temperature (Glück, 1988). Because compressible fluids have the ability to compress and expand, they behave very differently from incompressible fluids. An example of an incompressible fluid would be water, while gases such as air are compressible fluids (Glück, 1988). Since aerosols are defined as particles suspended in a carrier gas, the focus will be on compressible fluids (Hinds and Zhu, 2022).

2.1.1 Gas Streamlines

Streamlines are visualizations of the flow of an infinitesimally small packet of fluid and are therefore always tangential to the velocity direction at any given moment. They can be recreated by using a visible tracer such as smoke (Kulkarni, 2011). Generally, suspended particles follow the gas streamlines. Especially smaller particles that have little inertia, are often capable of following the streamlines, even if the flow direction changes. Heavier particles, however, possess more inertia and are unable to follow curved streamlines and are thus often deposited on the walls and lost (Hinds and Zhu, 2022). Figure 2 shows the gas streamlines around a circular object.

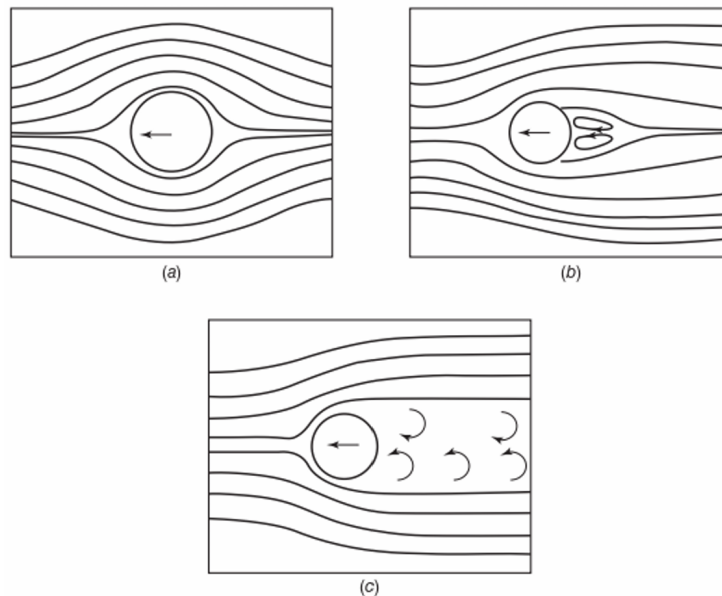


Figure 2: The gas streamlines around a round obstacle with different flow behaviors, (a) laminar flow, (b) turbulent flow with small Reynolds number, (c) turbulent flow with large Reynolds number. Reprinted from Hinds and Zhu (2022) with permission. The arrow inside the obstacle indicates the obstacle's direction of motion, while the arrows to its right depict eddies.

2.1.2 Flow Regimes

Flowing fluids interact very differently with obstacles, depending on the flow regime. There are three defined flow regimes: a characteristic feature for *laminar flow* is the smooth circumvention of gas streamlines around an obstacle and their return to the original paths downstream. If there is no obstacle, the streamlines are parallel and no spontaneous mixing occurs. Under *turbulent flow* conditions, the obstacle generates a turbulent wake characterized by chaotic eddies and vortices (Hinds and Zhu, 2022). Under turbulent conditions in a pipe, a spontaneous formation of eddies arises, mixing the gas and the streamlines circulate back. Additionally, there exists a *transitional boundary layer*, in which the fluid exhibits a combination of laminar and turbulent behavior. Fluid in the transitional regime is sensitive to even small disturbances, high friction or obstacles in the flow. Additionally, the behavior of fluids in the transitional regime is dependent on the previous fluid motion, remaining laminar, if no turbulence took place earlier and vice versa (Kulkarni, 2011).

Flow regimes can be classified using the Reynolds number. The Reynolds number is a dimensionless number that helps characterize the flow around obstacles or through a pipe. It indicates whether the flow is laminar or turbulent and quantifies the behavior of the flow. Equal Reynolds numbers signify the similarity of the flow patterns of streamlines around obstacles with different sizes, for different fluids or velocities, as long as a geometrical similarity is given (Hinds and Zhu, 2022). Figure 2 portrays the fluid flow around a circular obstacle. (a) shows the behavior of laminar flow, (b) shows the turbulent regime with small Reynolds number and (c) shows the behavior of an entirely turbulent flow.

The Reynolds number also depends on the flow geometry (for example flow in a pipe or flow in free space), the geometry of the object and the viscosity of the fluid (Kulkarni, 2011). For the calculation of the Reynolds number, it is necessary to use the correct diameter as the characteristic dimension d_c . For an aerosol particle with diameter d_p flowing through a circular tube with inner diameter d , two different Reynolds numbers can be calculated, depending on the chosen characteristic dimension. Choosing the inner diameter of the tube as the characteristic dimension determines the Reynolds number of the flow inside the tube, whereas choosing the particle diameter, calculates the Reynolds number of the flow around the aerosol particle (Kulkarni, 2011). When calculating the particle losses through an aerosol transport system, the flow behavior inside the tube is of interest, rather than the behavior of the flow around individual particles.

Equation 1 shows the Reynolds number Re of a fluid flowing through a circular pipe, where U is the mean velocity of the fluid, d is the inner diameter of the circular pipe, ρ is the density of the fluid and ν and μ is the kinematic and dynamic viscosity, respectively (Kulkarni, 2011).

$$Re = \frac{Ud}{\nu} = \frac{Ud\rho}{\mu} \quad (1)$$

Additionally, the flow profile differs for laminar and turbulent conditions. For laminar conditions, shown in Figure 3a, the flow profile is a paraboloid with the maximum velocity U_{max} at the center of the pipe. The maximum velocity U_{max} is twice the mean flow velocity in laminar conditions (Equation 2) (Glück, 1988).

$$U = \frac{U_{max}}{2} \quad (2)$$

In the case of turbulent flow, shown in Figure 3b, the velocity profile is flattened out because of the radial movement of the gas molecules. It follows Equation 3 where r is the radial coordinate, d is the inner diameter of the pipe and n is derived from the Darcy friction factor f with the relation $n = \frac{1}{\sqrt{f}}$ (Glück, 1988).

$$U = U_{max} \left[1 - \frac{2r}{d} \right]^{1/n} \quad (3)$$

Figures 3a and 3b show the flow velocity profile (described in Equations 2 and 3) for laminar and turbulent conditions in a tube, respectively (Glück, 1988).



Figure 3: Flow velocity profiles of two different flow regimes: (a) depicts the flow profile of laminar flow and (b) depicts the flow profile of turbulent flow. Reprinted from Glück (1988).

Inside a pipe, Reynolds numbers below 2000 indicate a laminar flow regime (Kulkarni, 2011). The transitional regime is characteristic of Reynolds numbers from 2000 up to 4000, while Reynolds numbers above 4000 indicate turbulence. Figure 4 shows simulations of the transitional flow with $Re = 2400$ through a pipe (Lahiri and Volokh, 2024) performed with two different models (infinite viscous strength vs finite viscous strength). The color indicates the fluid velocity in x-direction inside the pipe. On the right, the cross sectional cut of the pipe is portrayed, showing the higher velocity in x-direction in the center of the pipe but also the difference in the behavior of the gas between the conventional and modified Navier-Stokes simulation models. The spontaneous emergence of chaotic eddies is visible in the simulation of the modified Navier-Stokes model, while smooth streamlines with constant velocities can be seen in the conventional Navier-Stokes model simulation.

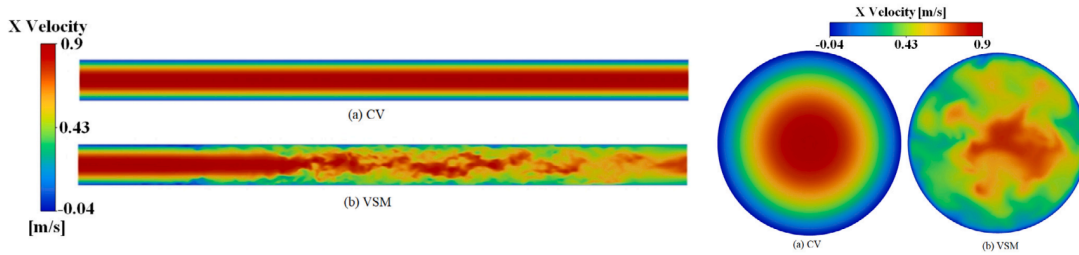


Figure 4: Simulations of fluid flowing through a pipe with $Re = 2400$ (transitional regime) and of the fluid velocity. (a) and (b) differ by the model used for the simulations, where CV and VSM are abbreviations for the conventional Navier-Stokes model with infinite viscous strength and the modified Navier-Stokes model with finite viscous strength, respectively. The colors indicate the velocity: warmer colors indicate higher velocities while colder colors indicate lower velocities. Reprinted from Lahiri and Volokh (2024).

2.1.3 Mass and Volumetric Flow

During steady flow through a pipe, the mass flow $\dot{m} = \frac{dm}{dt}$ remains constant, even if the inner diameter of the pipe or the fluid temperature changes. This ensures the conservation of mass in and out of an imaginary volume (Glück, 1988). The mass flow rate $\dot{m}$ can also be determined by the volumetric flow rate $\dot{V}$ or Q and the density of the fluid ρ , which can be expressed with the pressure p , specific gas constant R and temperature T of the fluid (Çengel and Cimbala, 2014):

$$\dot{m} = \rho \cdot \dot{V} = \frac{p}{R \cdot T} \cdot Q. \quad (4)$$

2.1.4 Pressure of Flowing Media

The relation between pressure, elevation and velocity is given by the Bernoulli equation (Equation 5). It states that the sum of kinetic, potential and flow energy of a steady incompressible flow is constant along a streamline, while frictional effects and compressibility are negligible (Çengel and Cimbala, 2014).

$$\int \frac{dP}{\rho} + \frac{U^2}{2} + gz = \text{constant} \quad (5)$$

The Bernoulli equation for unsteady, compressible flow is (Çengel and Cimbala, 2014):

$$\int \frac{dP}{\rho} + \int \frac{\partial U}{\partial t} ds + \frac{V^2}{2} + gz = \text{constant}. \quad (6)$$

These two equations are very useful for the analysis in fluid mechanics. Note that frictional effects, viscous effects and heat transfer are assumed to be negligible and the equation only holds along a streamline, which implies that turbulent flow conditions and flow sections involving machines or devices that disrupt the streamlines are not determinable by the Bernoulli equations (Çengel and Cimbala, 2014). To incorporate frictional effects, the pressure loss inside a pipe with length L and diameter d in laminar conditions can be calculated with the Darcy-Weisbach equation (Equation 7) (Çengel and Cimbala, 2014):

$$\Delta P_L = f \frac{L}{d} \frac{\rho U_{avg}^2}{2} \quad (7)$$

where U_{avg} is the average velocity of the flowing fluid and f is the Darcy friction factor of the pipe. The Darcy friction factor f varies based on the geometry of the pipe. For laminar condition and a circular pipe, the Darcy friction factor is (Çengel and Cimbala, 2014):

$$f = \frac{64}{Re}. \quad (8)$$

The Darcy-Weisbach equation is used to calculate the pressure drop in turbulent conditions as well. However, the Darcy friction factor f is different for turbulent conditions and can be determined by the Colebrook equation (Çengel and Cimbala, 2014):

$$\frac{1}{\sqrt{f}} = -2.0 \log_{10} \left(\frac{\epsilon/d}{3.7} + \frac{2.51}{Re\sqrt{f}} \right). \quad (9)$$

The roughness ϵ varies for different pipe materials and is typically provided by tables in mm, which supply values with high uncertainties. The relative roughness ϵ/d depends on the inner diameter of the pipe. From this equation the Moody chart is drawn, visualizing the relation between the Darcy friction factor, the Reynolds number and the relative roughness ϵ/d . The Moody diagram, as well as a table, including values for roughness of pipes of different materials, are depicted in Figure 5.

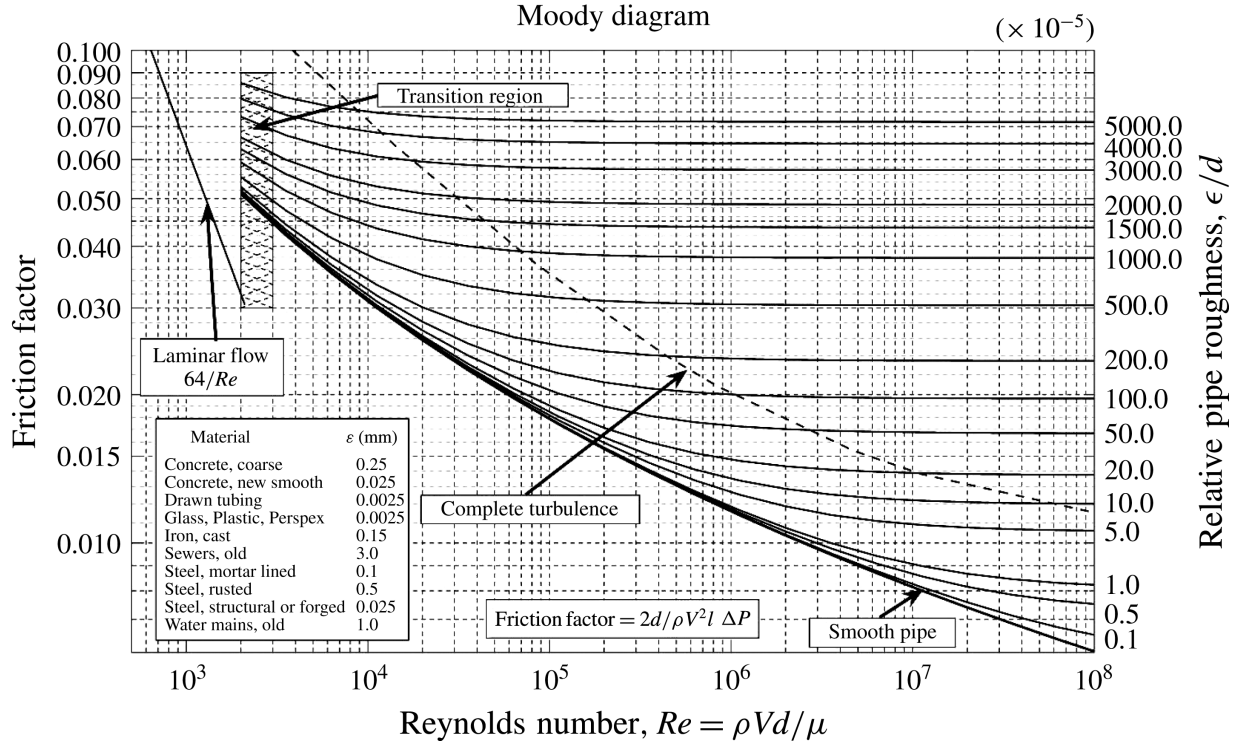


Figure 5: Moody diagram, which relates the friction factor to the Reynolds number, for different parameters for relative pipe roughness. Reprinted from Moody (1944).

The Colebrook equation is implicit in f and must be solved iteratively (Çengel and Cimbala, 2014). An explicit relation, which provides results within a 2 percent discrepancy of the ones obtained from the Colebrook equation, is given by Haaland (1983) (Equation 10):

$$\frac{1}{\sqrt{f}} \cong -1.8 \log_{10} \left[\frac{6.9}{Re} + \left(\frac{\epsilon/d}{3.7} \right) \right]. \quad (10)$$

2.1.5 Critical Orifices

Critical orifices are essential for inlet designs, since they decouple the upstream mass flow rate from the conditions downstream of the critical orifice, as long as the pressure ratio is critical (< 1.8929 for air) (Babu, 2021). Therefore, the mass flow rate depends solely on the upstream pressure, fluid temperature and orifice diameter. Criticality for air is achieved when the ratio between the upstream pressure P_0 and downstream pressure P^* is above the value expressed in Equation 11.

$$\frac{P_0}{P^*} = \left(\frac{\gamma + 1}{2} \right)^{\frac{\gamma}{\gamma - 1}} = 1.8929 \quad \text{with} \quad \gamma = 1.4 \quad (11)$$

Considering a critical pressure ratio, the fluid velocity through the orifice equals the Mach number $M = 1$ of the medium (Babu, 2021). To calculate the mass flow $\dot{m}$ through a choked (flow constricted) nozzle, where the flow velocity reaches the speed of sound at the narrowest point, Equation 12 is used, where C_d is the coefficient of discharge, p_0 is the upstream pressure, A^* is the cross sectional throat area of the nozzle, T_0 is the upstream temperature, $\gamma = 1.4$ is the specific heat ratio for air and R is the specific gas constant of air.

$$\dot{m} = \frac{C_d p_0 A^*}{\sqrt{T_0}} \sqrt{\frac{\gamma}{R} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (12)$$

The discharge coefficient C_d of a critical orifice with a diameter ratio $\beta = d/D$ and the Reynolds number Re_D with respect to larger diameter D is calculated with the Reader-Harris/Gallagher equation and lies between 0.6 and 0.85 for most critical orifices (Reader-Harris and Sattary, 1998).

2.2 Aerosol Mechanics

2.2.1 Definitions of Efficiencies

The following paragraph will summarize the definitions of multiple types of efficiencies related to aerosol sampling from (Brockmann, 2011), shown in Figure 6. All efficiencies described in this paragraph are size-dependent.

Aspiration Efficiency η_{asp}

The aspiration efficiency is defined as the concentration ratio between particles of a defined size, entering the inlet, and particles present in the ambient sampling environment of the same defined size (Brockmann, 2011).

Transmission Efficiency η_{trans}

The transmission efficiency is defined as the concentration ratio between particles of a defined size that are transmitted to the rest of the sampling system, and the total aspirated particles of that size (Brockmann, 2011).

Inlet Efficiency η_{inlet}

The inlet efficiency is defined as the product of the aspiration efficiency and the transmission efficiency. It is the fraction of ambient particles, which are aspirated and are able to follow the path of the inlet to the transport system (Brockmann, 2011).

$$\eta_{inlet} = \eta_{asp} \eta_{trans} \quad (13)$$

Transport Efficiency $\eta_{transport}$

The transport efficiency is defined as the fraction of particles of a certain size that enter the transport system, are not deposited on the walls, and can be detected by the measurement device, taking into account all flow elements installed in the transport line and all relevant loss mechanisms (Brockmann, 2011). It is the product of all transport efficiencies of individual flow elements and deposition mechanisms $\eta_{flow\ element, mechanism}$ (Brockmann, 2011).

$$\eta_{transport} = \prod_{\text{flow elements}} \prod_{\text{mechanisms}} \eta_{\text{flow element, mechanism}} \quad (14)$$

Sampling Efficiency η_{sample}

The sampling efficiency is defined as the product of the inlet efficiency and the transport efficiency. It describes the overall efficiency of the sampling system and is calculated as the concentration of particles of a defined size that reach the measurement device, divided by the concentration of ambient particles of the same size (Brockmann, 2011).

$$\eta_{sample} = \eta_{inlet} \eta_{transport} \quad (15)$$

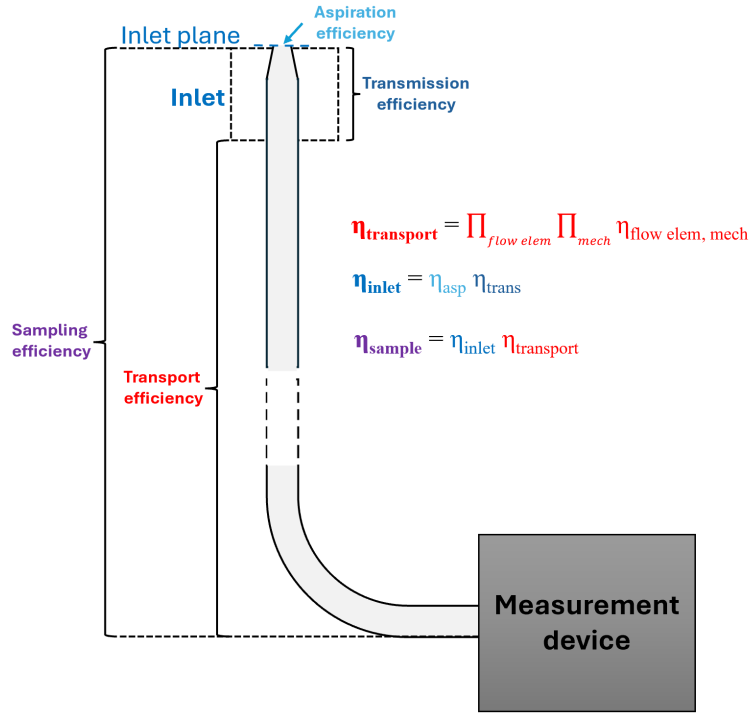


Figure 6: A sketch of an arbitrary sampling system to visualize the definitions of the various efficiencies related to aerosol sampling and transport. The dashed box defines the dimensions of the inlet, while the light blue dashed line defines the inlet plane.

2.2.2 Sampling and Measurement

The accurate analysis of the representative ambient concentration, chemical composition and size distribution of airborne particles presents itself as an essential, yet challenging task in environmental aerosol research. Some measurement methods require the introduction of an ambient aerosol sample into a measurement instrument. Other measurement techniques introduce the detector to the aerosol sample, abandoning the necessity of an aerosol transport system (Hinds and Zhu, 2022). Furthermore, a distinction is made between sampling from moving air, and from still air. Sampling from moving air requires either relatively high unidirectional wind speeds, or, more typically, the placement of the measurement device on a moving base, e.g. an airplane or a helicopter.

Sampling from Moving Air

For moving air, representative sampling of ambient aerosol is established under isokinetic sampling conditions, if the velocity U_0 of the fluid before entering the inlet is equal to the average fluid velocity U inside the inlet (Hinds and Zhu, 2022). Isokinetic sampling defines the equality of velocities inside and outside a sampling probe, while isoaxial sampling describes an alignment of the gas streamlines normal to the inlet plane. Together, they ensure that no particles are lost at the inlet plane and translate to an aspiration efficiency of 100 % (Brockmann, 2011). Figure 7 (c) illustrates the principle of isokinetic and isoaxial sampling, in which the average fluid velocity U inside the sampling probe is equal to the ambient fluid velocity U_0 and the probe direction equals the direction of flow. The gas streamlines that align with the direction of the sampling probe, remain unchanged (Hinds and Zhu, 2022). Achieving perfectly isokinetic conditions during sampling is unrealistic. Super-isokinetic sampling, where $U > U_0$ or sub-isokinetic sampling, where $U < U_0$ is more likely and causes a particle-inertia-dependent sampling bias (Hinds and Zhu, 2022).

Since the inertia of a particle is dependent on its size and density, a normalized diameter, called the aerodynamic diameter d_a is introduced. There, the density and shape are standardized to $\rho_0 = 1000 \text{ kgm}^{-3}$ and a sphere, while the diameter of the particle is adjusted to ensure identical settling velocities V_{TS} (Hinds and Zhu, 2022). Equation 16 describes the relationship between the aerodynamic diameter d_a , the volume equivalent diameter d_e (describes the diameter of a sphere with the same volume as the original, non-spherical particle) and density ρ_p of the particle, and its shape factor χ (Hinds and Zhu, 2022).

$$d_a = d_e \left(\frac{\rho_p}{\rho_0 \chi} \right)^{1/2} \quad (16)$$

Figure 7 shows how the sampling bias occurs in the case of anisokinetic and misaligned sampling. Misalignment and super-isokinetic sampling lead to the depletion of high-inertia particles, while sub-isokinetic sampling introduces more high-inertia particles into the probe, leading to their enrichment compared to particles with less inertia (Hinds and Zhu, 2022).

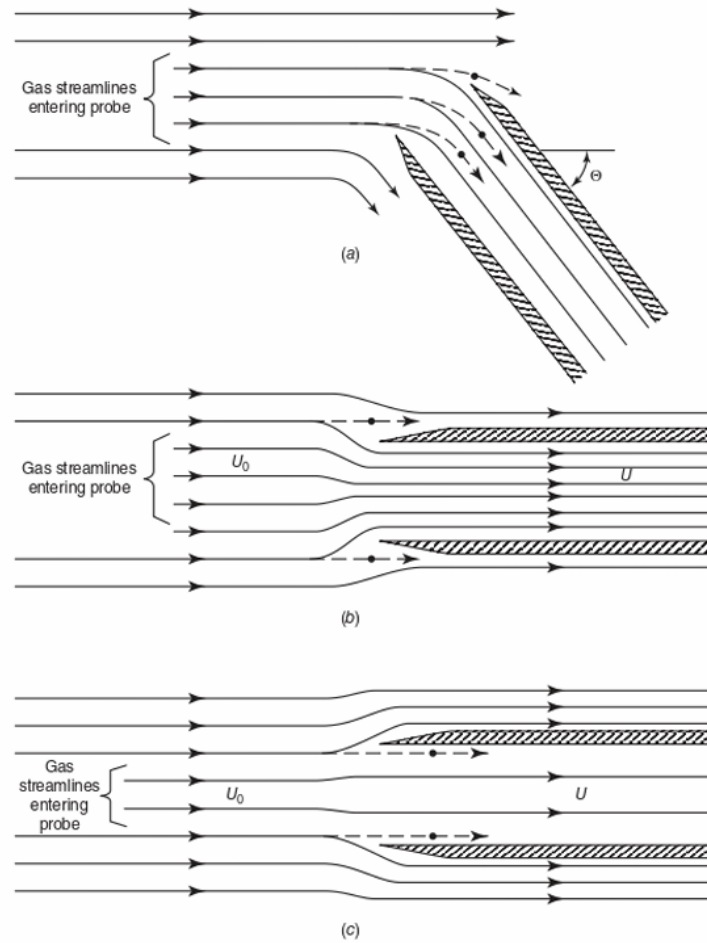


Figure 7: Illustration of three sampling cases and the consequent sampling bias. (a) shows the case of isokinetic but anisoaxial sampling, where particles with high inertia are underrepresented compared to low-inertia particles. (b) shows the case of super-isokinetic and isoaxial sampling, where again high-inertia particles are depleted and (c) shows the case of sub-isokinetic and isoaxial sampling, resulting in overrepresentation of high-inertia particles, compared to low-inertia particles. Reprinted from Hinds and Zhu (2022) with permission.

The Stokes number can be used to calculate whether a particle with relaxation time τ is affected by the possible sampling bias arising from anisokinetic sampling, for the sampling inlet (Equation 17). The relaxation time τ describes the time an aerosol particle needs to adapt to an external force (Hinds and Zhu, 2022).

$$Stk = \frac{\tau U_0}{d_s} = \frac{\rho_p d_p^2 C_c U_0}{18\mu d_s} \quad (17)$$

where d_s is the characteristic sampling diameter in m, d_p is the particle diameter in m, ρ_p is the particle density in kgm^{-3} , μ is the dynamic viscosity in $\text{kgm}^{-1}\text{s}^{-1}$ and U_0 is the fluid velocity before sampling in ms^{-1} . According to Hinds and Zhu (2022), anisokinetic sampling losses are negligible if the velocity ratio during sampling is between 0.2 and 5 ($0.2 < U_0/U < 5$) while the inlet Stokes number is $Stk < 0.01$.

For anisokinetic isoaxial sampling, Belyaev and Levin (1974) present an equation (Equation 18) to calculate the ratio between the particle concentration inside the sampling probe C and the particle concentration outside the sampling probe C_0 . Equation 18 relates the concentration ratio to the velocity ratio $\frac{U_0}{U}$ and the Stokes number Stk of the sampling probe.

$$\frac{C}{C_0} = 1 + \left(\frac{U_0}{U} - 1 \right) \left(1 - \frac{1}{1 + (2 + 0.62U/U_0)Stk} \right) \quad (18)$$

Figure 8 shows the concentration ratio $\frac{C}{C_0}$ of particles inside and outside the sampling probe, depending on the square root of the inlet Stokes number Stk , for different velocity ratio values $\frac{U_0}{U}$. Both Equation 18 and Figure 8 indicate that the concentration ratio $\frac{C}{C_0}$ is 1, only if the velocity ratio $\frac{U_0}{U}$ is 1 (isokinetic sampling) or Stk is 0 (particle diameter or density is zero) (Belyaev and Levin, 1974; Hinds and Zhu, 2022).

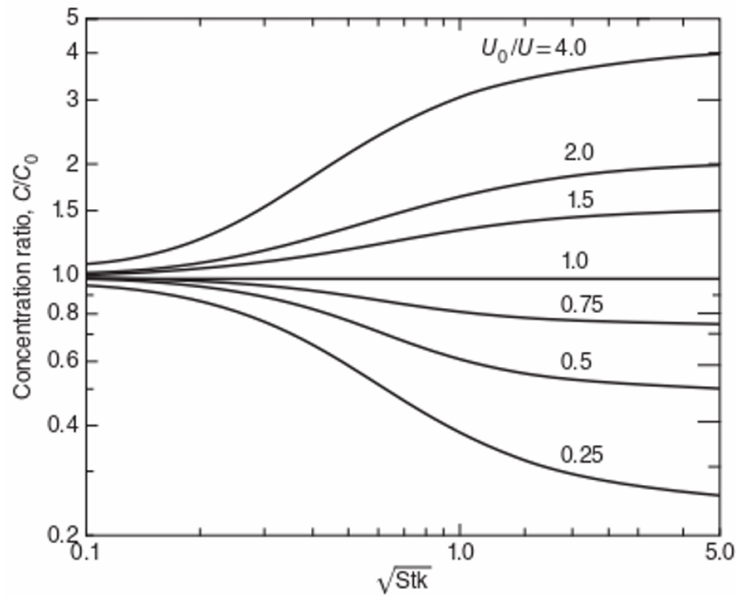


Figure 8: Particle concentration ratio plotted against the square root of the Stokes number for different velocity ratios, during isoaxial sampling. Reprinted from Hinds and Zhu (2022) with permission.

Sampling from Still Air

Isokinetic sampling from still air is not possible since the velocities would have to be zero to be equal and thus no sampling would occur. Therefore, a sampling bias, created by the settling velocity and inertia of the particle is inevitable (Hinds and Zhu, 2022). The terminal settling velocity V_{TS} of a spherical particle with a relaxation time τ in s, a diameter d in m and density ρ_p in kgm^{-3} is given by,

$$V_{TS} = \tau g = \frac{\rho_p d^2 C_c g}{18\mu} \quad (19)$$

for $Re \leq 1.0$, with C_c as the Cunningham slip correction factor and μ in $\text{kgm}^{-1}\text{s}^{-1}$ as the dynamic viscosity of the medium (Raynor et al., 2011). The Cunningham slip correction factor is calculated with Equation 20:

$$C_c = 1 + \frac{\lambda}{d_p} \left[2.33 + 0.966 \exp \left(-0.499 \frac{d_p}{\lambda} \right) \right], \quad (20)$$

where λ is the mean free path of the gas molecules and d_p is the particle diameter (Kim et al., 2005). According to Hinds and Zhu (2022), for a sampling inlet design, as is shown in Figure 7, the bias for sampling probes in any orientation, arising from the particle settling velocity V_{TS} is negligible when:

$$U \geq 25 V_{TS} \quad (21)$$

The settling velocity causes a sampling bias when the average inlet velocity U is low and the inlet opening is facing upwards (Hinds and Zhu, 2022). In that case high-inertia particles are overrepresented (Hinds and Zhu, 2022).

Sampling in still air with a sampling probe can also cause a sampling bias due to the inertia of the particle. Particles are accelerated as they approach an inlet along its curved streamline. If they have enough inertia, the particles will be unable to follow the inlet dimensions, colliding with the inlet walls. Especially larger particles, or particles with a higher density are affected by this effect (Hinds and Zhu, 2022). According to Hinds and Zhu (2022), the bias caused by inertial effects is negligible if the probe diameter D_s in mm, particle relaxation time τ in s and the flow rate Q in m^3h^{-1} follow the relation:

$$D_s \geq 10 \left(\frac{Q\tau}{4\pi} \right)^{1/3} \quad (22)$$

Inlets designed for sampling from still air are often configured as inertial classifiers. Particles are classified by their inertia by setting up a defined flow rate and introducing an obstacle such as an impactor plate, a bend, or a split into multiple flows that separates particles with different inertia. Particles with sufficiently high inertia will escape the main flow, while particles with low inertia will continue following the gas streamlines. Four types of inertial classifiers are depicted in Figure 9. This process results in a sigmoidal curve with a cutoff aerodynamic diameter $d_{a,50}$, where 50 % of the particles with that aerodynamic diameter follow the gas streamlines, while the remaining 50 % cannot (Marple and Olson, 2011).

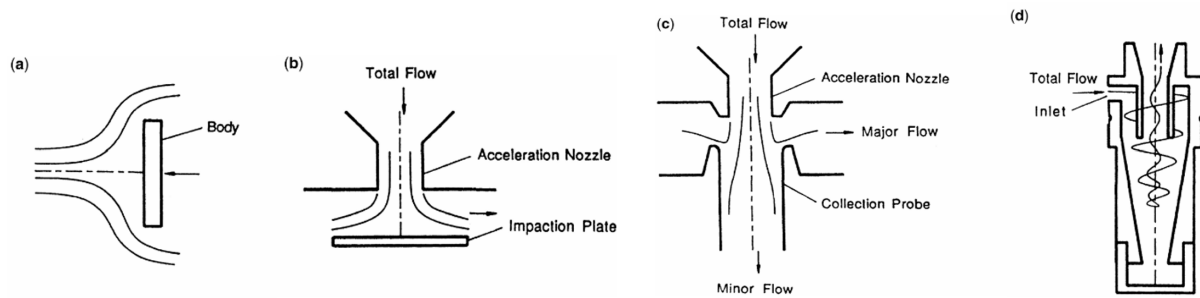


Figure 9: Four types of inertial classifiers: (a) body impactor, (b) conventional impactor, (c) virtual impactor, and (d) cyclone. Adapted from Marple and Olson (2011) with permission.

2.2.3 Particle Deposition Mechanisms

Aerosol particles inside the transport line are affected by multiple loss mechanisms. The severity of the deposition effect this effect depends on the particle characteristics, such as size and density, but also the dimensions and geometry of the transport line itself. Common deposition mechanisms are (Brockmann, 2011):

- Diffusional deposition
- Gravitational settling
- Inertial deposition at a bend
- Inertial deposition at flow constrictions
- Turbulent inertial deposition
- Electrostatic deposition
- Thermophoretic deposition
- Diffusiophoretic deposition

Since the effects of the last four deposition mechanisms are negligible within the scope of this thesis, they will not be discussed in further detail. Furthermore, turbulent conditions are avoided in the transport line of the AerObs. Therefore only the deposition effects during laminar flow conditions will be discussed. Temperature differences in the AerObs sampling system are insignificant, minimizing thermophoretic losses. Additionally, the transport line is constructed from stainless steel tubing, ensuring conductivity, thus avoiding electrostatic losses.

Diffusional Deposition

Small suspended particles will undergo Brownian motion, leading to net diffusive flux from regions of higher particle concentration to lower concentration. Particles that make contact with the walls of the transport line will be deposited. This leads to a smaller concentration of particles near the walls, compared to the center of the tube. Therefore, diffusion acts as a particle flow from the center of the pipe towards the walls. The magnitude of this effect differs between turbulent and laminar conditions as well as the particle diameter d_p (Brockmann, 2011).

The diffusion coefficient D is an important factor in determining the magnitude of diffusional deposition and can be calculated with Equation 23:

$$D = \frac{k_b T C_c}{3\pi\mu d_p} \quad (23)$$

where k_b is the Boltzmann constant, T is the temperature of the medium, C_c is the Cunningham slip correction factor, μ is the dynamic viscosity of the medium and d_p is the particle diameter (Hinds and Zhu, 2022).

Equations 24 and 25 present the relationship between the transport efficiency $\eta_{tube,diff}$ and $\xi = \frac{\pi D L}{Q}$ with the particle diffusion coefficient D , the tube length L and the volumetric flow rate Q , while considering only diffusional deposition for laminar flow in a cylindrical tube (Gormley and Kennedy, 1948).

$$\eta_{tube,diff} = 1 - 2.56\xi^{2/3} + 1.2\xi + 0.177\xi^{4/3} \quad \text{for } \xi < 0.02 \quad (24)$$

$$\eta_{tube,diff} = 0.819e^{-3.657\xi} + 0.097e^{-22.3\xi} + 0.032e^{-57\xi} \quad \text{for } \xi > 0.02 \quad (25)$$

The majority of losses of smaller particles are attributed to diffusional deposition and generally increase with decreasing flow rate Q .

Gravitational Settling

Larger aerosol particles are strongly affected by gravity and settle on the lower walls of non-vertical sampling lines. The transport efficiency of a laminar flow of particles through a circular tube at an inclination, while only considering gravitational settling losses, can be calculated with Equation 26, where L is the tube length, d is the inner diameter of the tube, V_{ts} is the gravitational settling velocity, θ is the inclination angle and U is the mean flow velocity of the medium (Heyder and Gebhart, 1977).

$$\eta_{tube,grav} = 1 - \frac{2}{\pi} \left[2\kappa \sqrt{1 - \kappa^{2/3}} - \kappa^{1/3} \sqrt{1 - \kappa^{2/3}} + \arcsin(\kappa^{1/3}) \right] \quad \text{where } \kappa = \frac{3}{4} \frac{L}{d} \frac{V_{ts}}{U} \cos \theta \quad (26)$$

Equation 26 assumes a parabolic flow distribution and is limited to

$$\frac{V_{ts} \sin \theta}{U} \ll 1. \quad (27)$$

This implies that the average fluid velocity should be significantly greater than the axial component of the gravitational settling velocity (Heyder and Gebhart, 1977). If the criterion is not satisfied, a dependence on the flow direction exists in an inclined tube, implying that particle losses due to gravitational settling are different for uphill and downhill flow. In addition, it is apparent from Equation 26 that in the case of a vertical tube, no particles are lost due to gravitational settling.

However, in vertically aligned tubes, the Saffman force exists: This force drives particles towards the walls during downward flow, while upward flow drives particles away from the walls. This is caused by the velocity gradient of the flow inside a circular tube and the unequal pressure acting on the particle. This effect is negligible for particles smaller than 15 μm (Brockmann, 2011).

Inertial Deposition in a Bend

Changing the direction of flow with a bend in the sampling line may result in particle losses due to inertial deposition on the outside wall of the bend. Furthermore, in the laminar flow regime, secondary recirculation may lead to deposition at the bend's inside wall. Crane and Evans (1977) empirically determined the transport efficiency of particles in laminar flow, while only considering inertial deposition effects in a bend with an angle φ in radians as:

$$\eta_{\text{bend, inert}} = 1 - Stk \varphi \quad (28)$$

Equation 28 implies that particles are lost at bends, except when $Stk = 0$. However, numerical calculations of deposition rates from Cheng and Wang (1981) and experimental data from Pui et al. (1987) reveal that no inertial deposition at bends for $Stk < 0.05 - 0.1$ takes place. Equation 29 presents the correlating fit of the experimental data from Pui et al. (1987) and is used to calculate the transport efficiency, while considering only inertial deposition and a laminar flow regime.

$$\eta_{\text{bend, inert}} = \left[1 + \left[\frac{Stk}{0.171} \right]^{0.452 \frac{Stk}{0.171} + 2.242} \right]^{-\frac{2}{\pi} \varphi} \quad (29)$$

The Stokes number can be calculated using Equation 17 while using d as the inner diameter of the tube instead of the diameter of the sampling tube d_s .

Inertial Deposition at Flow Constrictions

Generally, particle losses to any kind of constrictions to the flow should be characterized experimentally and should be avoided altogether. However, for a contraction with the contraction angle θ in degrees, from a large tube diameter d_i to a small tube diameter d_o the transport efficiency of particles with the Stokes number Stk can be calculated by the empirically determined Equation 30 for laminar flow conditions (Muyschondt et al., 1996).

$$\eta_{\text{cont, inert}} = 1 - \frac{1}{1 + \left[\frac{2Stk \left[1 - \left(\frac{d_o}{d_i} \right)^2 \right]}{3.14 \exp(-0.0185\theta)} \right]^{-1.24}} \quad (30)$$

3 Methods

When designing the sampling and vacuum system and specifying component dimensions and performance, pressure drops and particle losses must be minimized while adhering to constraints such as the target outcome, allowable lengths and sizes, cost, and performance limits. A practical guideline is to minimize the length of sampling and vacuum lines. In the sampling line, particle losses grow with increasing transport length. pressure losses in the vacuum line, which also increase with tube length, can lead to problems regarding the criticality of orifices. Unless otherwise noted, all figures and photographs are the author's own.

3.1 Design Requirements and Constraints

Numerous constraints must be considered when designing the flow system. Constraints differ for the sampling system and the vacuum system. The following few paragraphs will list constraints in the AerObs PM2.5 sampling and vacuum system that must be adhered to.

1. Inner Diameter of the Nafion Dryers

Two Permapure Nafion dryers with an inner diameter of 0.7 inch and length of 1.2 m each are installed in series to dry the air to a relative humidity below 40%. To minimize particle losses due to inertial deposition, it is important to not exceed this diameter, especially upstream of the dryers. Therefore, stainless steel tubing with an outer diameter of 3/4 inch was selected as the transport line, connected to the dryers.

2. Length and Diameter of Vacuum Line

The vacuum line with an inner diameter of approximately 1 inch is built into the walls of the AerObs and is roughly 10 m long. Because the vacuum line is partially inaccessible, the length of the line was estimated.

3. Length and Diameter of Sampling Line

The distance between the inlet head and the flow splitter is 5 m, of which 2.2 m are outside on the roof of the building and 2.8 m are inside the AerObs laboratory room. The upper flow splitter is at a height of 2 m above the laboratory floor.

4. Availability of Components and Their Dimensions

The flow system uses Swagelok components (stainless-steel pipes, connections, and valves for aerosol inlet lines and PFA tubing for exhaust lines) selected for their build quality and expected long-term supply continuity. All of the mentioned components are suitable for the operating pressures, and the stainless-steel parts are electrically conductive, which eliminates electrostatic particle losses. These components have fixed dimensions, which are listed in Table 1.

5. Laminar Flow Conditions in the Sampling Line

Laminar flow conditions are important to decrease the magnitude of particle losses within the sampling system. Since the inner diameters of the sampling system are known, the maximum flow rates were determined using Equation 1 and presented in Table 1. Note that not every component is currently incorporated into the system. In addition, laminar flow is not necessary in the exhaust and vacuum system, since filters installed upstream of the critical orifices remove the particles.

Table 1: Swagelok components that were considered for the PM2.5 transport system with standardized parameters inner diameters and maximum laminar flow rates.

Swagelok component	inner diameter d_i [mm]	maximum flow rate $Q_{max,lam}$ [Lmin ⁻¹]
1/4 inch stainless steel tube	4.57	6.5
3/8 inch stainless steel tube	7.75	11.0
1/2 inch stainless steel tube	10.21	14.5
3/4 inch stainless steel tube	15.75	22.3
1 inch stainless steel tube	22.10	31.3
1/4 inch PFA tube	3.18	4.5
1/2 inch PFA tube	9.55	13.5

6. Expected Pressure Ranges

The upper limit of the air pressure distribution is the ambient pressure at the inlet, while the lower limit of 40 hPa at the end of the vacuum line is provided by the vacuum pump. Furthermore, the criticality condition for the critical orifices described in Section 2.1.5 must be fulfilled.

7. Tube Material

The tube material is of particular interest, since material specific constants can affect frictional pressure losses and particle transport efficiencies. The sampling system consists of stainless steel tubing. The exhaust line material is made of PFA tubing and the vacuum pipes are made of steel. The stainless steel pipes in the sampling line are electro-polished to minimize particle losses.

8. Dimensions and Flow rates of Measurement Devices

The PM2.5 sampling line contains one TSI 3938 and four Grimm 5410 CPCs (Grimm CPCs) with 1/4 inch inlet and outlet connections. The CPCs have a critical orifice ensuring an inlet flow of 0.6 Lmin⁻¹ and 1 Lmin⁻¹ for the Grimm CPCs and the TSI CPCs, respectively.

3.2 Instrumentation

The data presented in this thesis were collected using CPCs and a Faraday Cup Electrometer (FCE), which directly or indirectly provide the particle concentration of the aerosol flow. Additionally, instruments such as a Catalytic Instruments Silver Particle Generator (SPG) (Catalytic Instruments GmbH & Co.KG., 2025), required for the generation of particles and the differential mobility analyzer (DMA), which is necessary for the selection of certain particle sizes and for the conversion of a polydisperse into a monodisperse size distribution were used within the scope of this thesis.

3.2.1 Condensation Particle Counter (CPC)

CPCs, also known as Condensation Nucleus Counters (CNCs) are commonly used for the measurement of ambient particle concentration. Accumulation (0.1 to 2 μm) and coarse mode particles (larger than 2 μm) can be detected and sized using light scattering, as is done with optical particle counters (OPCs) (Cheng, 2011; John, 2011). Under ideal conditions, the detection limit of OPCs is around 100 nm (Cheng, 2011). To detect Aitken mode (20 to 200 nm) and even nuclei mode particles (5 to 100 nm), CPCs are used instead (Cheng, 2011).

Working Principle

Aerosol particles are introduced into a chamber filled with supersaturated vapor, which condenses onto the particles, growing them to spheres of a few μm (Cheng, 2011). At these sizes, light scattering is applicable for the detection of the particles (Cheng, 2011). Figure 10 shows a schematic representation of the basic butanol-based CPCs working principle. Particles enter through the sample inlet into a heated saturator, which warms the stream and saturates the aerosol with vapor. The wall of this tube consists of a porous medium, which is fully wetted with an operating liquid (in this case butanol). In the cooled condenser, the temperature of the sample flow decreases, supersaturating the vapor, which leads to the condensation of the vapor onto the aerosol particles, growing them in size. The μm -sized particles travel into the optical cell, in which the focused laser light is scattered by the particle and detected by a photodetector. The flow rate of the aerosol is maintained by a critical orifice downstream of the optical cell (TSI Incorporated, 2016a). This process clearly changes the chemical composition, surface structure and size of the particle, making the CPC a particle count and number concentration measurement device, when used as a standalone device. The cutoff size is dependent on the solubility of a particle, the particle's ability to be wetted by a liquid and the particle's charge state.

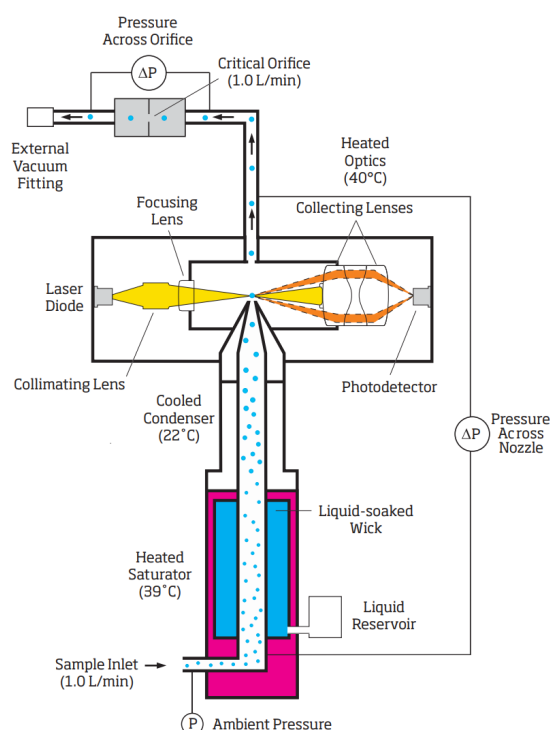


Figure 10: A flow schematic of the TSI CPC 3772, illustrating its working principle. Reprinted from TSI Incorporated (2016a).

Coincidence Error and Correction

If two or more particles pass the detector's sensing zone simultaneously or during the same processing time window, the CPC will only interpret the signal as one particle, which underestimates the particle number concentration. Typically, the maximum number concentration set by the manufacturer coincides with a concentration at which the CPC's coincidence rate reaches 10 % (Collins et al., 2013). Since the coincidence probability increases relative to the concentration and the statistical error is larger for small concentrations, the concentrations during measurements were targeted to remain between 1 000 and 10 000 pcm^{-3} .

TSI CPC Model 3772-CEN

The butanol-based CPC Model 3772-CEN from TSI (hereafter: TSI CPC) has a flow rate of 1.0 Lmin^{-1} with an uncertainty of $\pm 5\%$, a cutoff diameter d_{50} of $7 \text{ nm} \pm 0.7 \text{ nm}$ and a maximum concentration of $50\,000 \text{ pcm}^{-3}$ (TSI Incorporated, 2016a). This device was used for the experimental analysis of particle losses inside the three-way splitter.

TSI Universal-Scanning Mobility Particle Sizer (SMPS) 3938

The SMPS removes particles beyond the relevant size range with an impactor and combines an aerosol neutralizer, which charges the polydisperse aerosol, a DMA, which selects one particle size and a butanol-based CPC, which measures the particle concentration inside the sample flow (TSI Incorporated, 2016b). The TSI Electrostatic Classifier Model 3082, containing the aerosol neutralizer and a DMA, runs a scan of the particle number size distribution, by progressively increasing the DMA voltage. The particle size during that scan ranges from 10 to 1 000 nm with a sizing accuracy of $\pm 1\%$ at 100 nm, at a sheath/aerosol flow ratio of 10:1, and maximum concentration of 10^7 pcm^{-3} (TSI Incorporated, 2016b). The inlet flow rate of TSI CPC Model 3750 is 1 Lmin^{-1} , the cutoff diameter d_{50} is 7 nm, the concentration maximum is $100,000 \text{ pcm}^{-3}$ and the accuracy is $\pm 5\%$ (TSI Incorporated, 2018).

Grimm CPC 5410

The butanol-based Grimm CPC 5410 (hereafter: Grimm CPC) has a flow rate of 0.6 Lmin^{-1} and a maximum concentration of $100\,000 \text{ pcm}^{-3}$ with a particle concentration accuracy of $\geq 95\%$ (GRIMM Aerosol Technik, 2025). The four Grimm CPCs have different cutoff diameters. CPC 1 has a cutoff diameter d_{50} of 4.5 nm, CPC 2 has a $d_{50} = 7 \text{ nm}$ and CPC 3 and 4 have a $d_{50} = 10 \text{ nm}$. The cutoff diameter of a CPC can be changed, by adjusting the saturator and/or the condenser temperature. To decrease the cutoff diameter, the supersaturation is increased, which is done by either increasing the saturator temperature or by decreasing the condenser temperature (GRIMM Aerosol Technik, 2025). Table 2 summarizes all the measurement devices used for the experimental setup, their inlet flow rates, cutoff diameters and maximum concentrations.

3.2.2 Faraday Cup Electrometer (FCE)

FCEs are used primarily for the calibration of aerosol measurement instruments, such as CPCs and for the characterization of any type of aerosol transport systems. They provide highly sensitive measurements of the net charge on aerosol particles, which can be converted into particle concentration, if the charge distribution of particles is known. Figure 11 shows a flow schematic of the principle behind TSI Aerosol Electrometer Model 3068B (TSI Incorporated, 2006).

Working Principle

Before entering the FCE, the polydisperse aerosol sample is electrically charged inside the aerosol neutralizer. Charged particles travel into the aerosol electrometer with an embedded Faraday cup. Figure 11 schematically illustrates the interior of an aerosol electrometer. The charged particles collide with a conductive filter, which captures the charge. This signal is processed by the electrometer into a current. When a size-dependent charge distribution of the aerosol particles is known, the amplitude of the current can be transformed into particle count or concentration (TSI Incorporated, 2006).

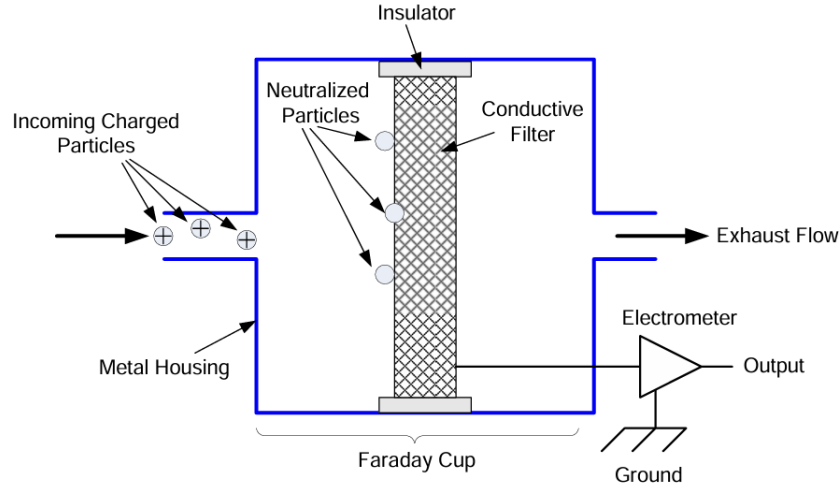


Figure 11: Working principle of an aerosol electrometer, which has an integrated Faraday cup. Reprinted from TSI Incorporated (2006).

TSI Aerosol Electrometer Model 3068B

In this thesis, the TSI Aerosol Electrometer Model 3068B (hereafter: FCE) is used for the characterization of the PM_{2.5} transport system. The inlet flow rate of this FCE is adjustable between 0.3 and 10 Lmin⁻¹ with a flow control accuracy of $\pm 5\%$ at 10 Lmin⁻¹. The particle size range at which the FCE detects particles lies between 2 and 5000 nm, with a measurement range of ± 12 pA and a current accuracy of $\pm 2\%$ or ± 5 fA. The FCE measurements also contain noise, which is < 1 fA root mean square at an average of one second for this model.

Table 2: Instrument Specifications

Instrument	Q (Lmin ⁻¹)	d ₅₀ (nm)	C _{max} (cm ⁻³)	Accuracy (%)
Grimm 5410 CPC 1	0.6	4.5	100 000	± 5
Grimm 5410 CPC 2	0.6	7	100 000	± 5
Grimm 5410 CPC 3	0.6	10	100 000	± 5
Grimm 5410 CPC 4	0.6	10	100 000	± 5
TSI CPC 3772-CEN 1	1	7	50 000	± 5
TSI CPC 3772-CEN 2	1	7	50 000	± 5
TSI CPC 3750	1	7	100 000	± 5
TSI Aerosol Electrometer 3068B	0.3 - 10	2	468 000 at 10 Lmin ⁻¹	± 2
TSI Aerosol Electrometer 3068B	0.3 - 10	2	15 600 000 at 0.3 Lmin ⁻¹	± 2

3.2.3 Differential Mobility Analyzer (DMA)

A DMA acts as a filter, selecting only particles of a certain electrical mobility Z_p . Electrical mobility Z_p in m²V⁻¹s⁻¹ is inversely dependent on the particle diameter (Equation 31)

$$Z_p = \frac{n \cdot e \cdot C_c}{3\pi\mu d_p} \quad (31)$$

where n is the number of elementary charges on the particle, e in C is the electron charge, C_c is the Cunningham slip correction factor, μ in kgm⁻¹s⁻¹ is the dynamic viscosity of the gas and d_p in m is the particle diameter (Flagan, 2011).

Figure 12 shows the working principle of a cylindrical DMA. Charged particles are introduced into the annular aerosol entrance channel, which distributes the aerosol uniformly around the circumference of the cylinder and simultaneously confines the aerosol to a narrow radial band. A particle-free sheath air flow establishes a laminar flow profile in which the charged particles are carried towards the outlet. The inner electrode is maintained at a high voltage, attracting the charged particles. This process results in particles with the desired electrical mobility passing through the classified aerosol outlet port, while particles with higher electrical mobility deposit on the inner electrode and particles with lower electrical mobility are extracted via the excess air outlet or impact further down (Flagan, 2011).

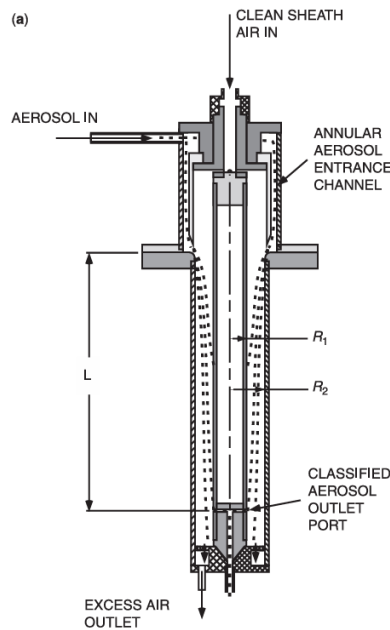


Figure 12: Schematic illustration of the working principle of a cylindrical DMA, designed by Knutson and Whitby (1975). Adapted from Flagan (2011) with permission.

University of Vienna's DMA

The University of Vienna operates multiple different DMAs. In this thesis, measurements were performed using a DMA referred to by our group as the "RAX-DMA". It is a cylindrical DMA, with a voltage range between 0.0002 and 10 kV, which classifies charged particles based on their electrical mobility, corresponding to a particle electrical mobility diameter range of 6 to 817 nm. Particles are electrically charged by a soft X-ray source inside the TSI Advanced Aerosol Neutralizer Model 3087 (hereafter: neutralizer). The DMA voltage tends to fluctuate by ± 0.0004 kV. This changes the selected particle size by only a fraction of a nm for particles larger than 7 nm. These fluctuations, and the delicacy of the DMA's adjustment wheel, make the precise selection of particle sizes, particularly below 7 nm, considerably difficult.

3.2.4 Silver Particle Generator (SPG)

The SPG made by Catalytic Instruments GmbH & Co.KG continuously produces silver particles by vaporizing liquid silver into a silver gas, which then homogeneously nucleates into nanoparticles. It provides silver particles with a stable concentration and size distribution between 2 and 300 nm. Particles smaller than 20 nm are usually spherical, while bigger particles often display an agglomerate shape (Catalytic Instruments GmbH & Co.KG., 2025). By adjusting the temperature, aerosol flow rate, dilution flow rate and including the residence

chamber and the P1000 PCRF Accessory Kit, particle size and concentration can be controlled. Furthermore, the agglomerate particles can be sintered in the S8000 Particle Sintering Device, which shapes the particles spherically. This process also decreases the particle diameter and concentration and narrows the particle size distribution (Catalytic Instruments GmbH & Co.KG., 2025).

3.2.5 Catalytic Vapor Filter (CVF-400)

The CVF-400 uses a heated catalytic element to convert butanol and isopropyl alcohol vapor into water vapor and carbon dioxide. It heats air with a maximum flow rate of 4 Lmin^{-1} to 450°C . This requires the dilution with room-temperature air, through a critical orifice with a flow rate of 7 Lmin^{-1} . Figure 13 shows the working principle and the interior design of the CVF-400. The valve controls the flow direction. The gas only flows through the catalyst if it is sufficiently heated, otherwise the fluid is directed straight to the outlet of the CVF-400.

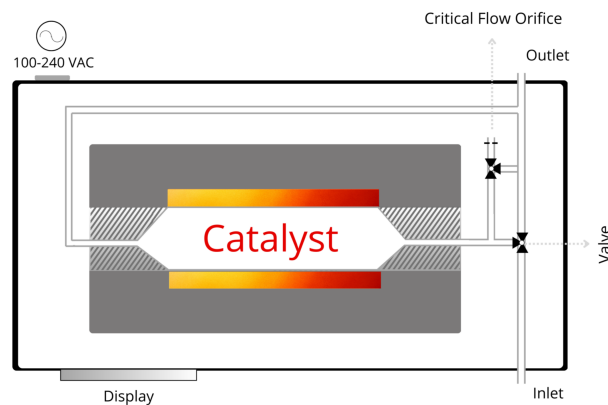


Figure 13: Schematic representation of the working process and interior design of the CVF-400 by Catalytic Instruments GmbH & Co.KG. Reprinted from Catalytic Instruments GmbH & Co.KG. (2024).

3.2.6 Other Instruments

In addition, devices were used to measure pressure and flow rate. Flow rate measurements up to 20 Lmin^{-1} were performed using the TSI Mass Flowmeter 4140 (hereafter: TSI MFM), which has a flow measurement uncertainty of $\pm 2\%$ of the reading or $\pm 0.005 \text{ Lmin}^{-1}$, whichever is greater for air at standard conditions. The uncertainty increases for non-standard conditions and for other gases (TSI Incorporated, 2022). For more accurate measurements of the flow rate, the Sensidyne's Gilian Gilibrator-2 System (hereafter: Gilibrator) was used. A soap film is detected as it passes through the measuring tube (Sensidyne, LP, 2020). The Gilibrator measures flow rates between 1 mlmin^{-1} and 30 Lmin^{-1} by this process with an accuracy of 1% (Sensidyne, LP, 2020).

The pressure measurement, especially within the vacuum system was performed with Jumo Delos SI 488 - absolute pressure sensors (hereafter: Jumo pressure sensors), which have an measurement accuracy of $\pm 0.3\%$ of the output value at 20°C and a range between 0 and 1 bar absolute. This uncertainty accounts for multiple contributing effects, including linearity, hysteresis, repeatability, and deviations from the initial and final values of the measuring range (JUMO GmbH & Co. KG, 2012). The pressure resolution is 1 hPa.

3.3 Pressure Analysis of the AerObs Flow System

For the theoretical assessment of the pressure distribution within the sampling and vacuum system, an algorithm was created that uses the Darcy-Weisbach equation (Equation 7) and the Haaland approximation (Equation 10) for the Darcy friction factor f . The algorithm computes the pressure differential within the pipe and the resulting change in flow rate for steps of one centimeter within the system. Different sections of the flow system may vary in inner diameter or flow rate. Therefore, the frictional pressure losses of every section of the sampling and vacuum line were calculated separately. The resulting pressure distributions of multiple sections were subsequently merged, which resulted in the pressure distribution within the entire sampling and vacuum system.

3.3.1 Vacuum Pump Performance

An experimental setup to test the pressure capabilities of the new Busch MINK MV 0060 D Synchro Dry claw vacuum pump (hereafter: vacuum pump), using six needle valves, each adjusted to $1 \text{ m}^3\text{h}^{-1}$ and one Jumo pressure sensor, was assembled. The needle valves represent the six inlets for which the pump is supposed to provide sufficient vacuum. The Jumo pressure sensor was positioned downstream of the needle valves and measured the absolute pressure within the vacuum system, and thus the capabilities of the pump, while the inlets were opened one by one.

Figure 14 shows the experimental setup of the pressure measurement configuration. The vacuum line tubes, which were directly connected to the pump, have an inner diameter of 25 mm and an estimated length of 10 m. This length had to be estimated since the tube is integrated into the wall of the AerObs laboratory and is thus not visible. Several thinner tubes with an inner diameter of 12 mm and a length of 0.8 m, protrude from the wall into the laboratory. Because pressure losses inside the 25 mm thick tube are relatively small, the additional few meters between the protruding tubes were neglected. The distance between each protruding tube and the pump was assumed to be 10 m for determining the performance of the vacuum pump.

At the end of these protruding tubes, ball valves are installed to enable quick access to the vacuum line. 8 mm PVC tubes, which have an inner diameter of 5 mm were cut to length of approximately 50 mm and were connected to the vacuum line. Needle valves were set to a flow rate of $1 \text{ m}^3\text{h}^{-1}$, which was measured with a TSI MFM. The adjusted needle valves were connected to the six protruding vacuum lines, acting as inlets.

Thus, by opening and closing the ball valves, the flow into the vacuum system varied between 0 and $6 \text{ m}^3\text{h}^{-1}$ in steps of $1 \text{ m}^3\text{h}^{-1}$. In Figure 14, the box with the letter "P" indicates the pressure sensor. The protruding tube on which the pressure sensor in Figure 14 is positioned is arbitrarily selected.

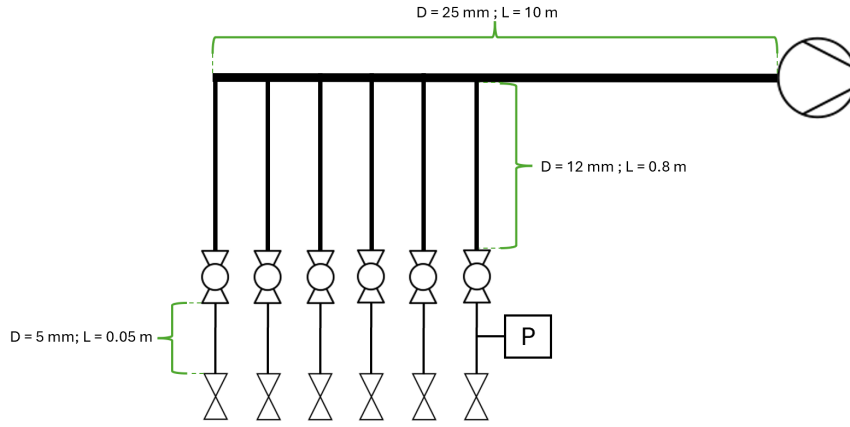


Figure 14: Schematic of the experimental setup for determining the performance of the vacuum pump and the AerObs vacuum system. The needle valves were each set to a flow rate of $1 \text{ m}^3\text{h}^{-1}$.

3.3.2 Calculation of the Pressure Distribution in the Sampling and Vacuum Lines

For the calculation of the pressure distribution of the sampling-, exhaust- and vacuum lines a self-developed algorithm determining frictional pressure losses was created.

Algorithm for Calculating the Pressure Distribution and Frictional Pressure Losses

The calculation of the pressure distribution inside a cylindrical tube was performed with two self-developed algorithms, which work in opposing directions. The first algorithm requires the input of the highest pressure and flow rate of the segment of interest and calculates the gradual drop in pressure and flow rate. The second algorithm requires the input of the target pressure and flow rate of a segment, and calculates the gradual increase in pressure and flow rate. Both algorithms work using Equations 7 and 10 and initial values such as diameter d , length L , step size dx , viscosity of the medium μ at standard conditions, temperature T , the initial pressure P_i and flow rate Q . The algorithm calculates the frictional pressure losses for each step of length dx and subtracts or adds that value to the former pressure.

The first algorithm was used in cases where the pressure distribution of interest was downstream of a known pressure and flow rate. The second algorithm was used for the opposite case, where the pressure distribution of interest lied upstream of a known pressure and flow rate. However, these algorithms work only for flow segments, in which none of the initial parameters changes. As soon as there is a branching of the flow system, which would affect the volumetric flow rate, or the diameter of the tube changes, the calculation becomes more nuanced. For a change in diameter, the pressure and flow rate arising as a result of the previous calculation were taken as the initial parameters of the new segment of interest. Similarly, when the flow system split into multiple flows, the distribution of pressure and flow rate was calculated for every individual branch. As soon as the pressure and flow rate for every step in every segment were determined, the pressure distributions of all the segments were connected, providing a gradual decrease in pressure, following the flow direction.

Because the mass flow rate $\dot{m}$ in the AerObs flow system is constrained by critical orifices, the initial value for the volumetric flow rate Q was calculated using Equations 12 and 4. The discharge coefficient, which is the ratio of actual to ideal flow rate, was set to 0.732 based on typical values for orifices with conical entrance plates ranging from 0.73 to 0.734 (Miller, 1996).

Setup of Sampling and Vacuum System

In December 2025, a preliminary PM_{2.5} sampling setup was constructed to measure the concentration of particles released by fireworks during New Year's Eve. Figure 15 shows a schematic of the preliminary PM_{2.5} sampling and vacuum system of the AerObs, which was used to measure particles from 24.12.2025 to 07.01.2026. The parameters for the inner diameter D and the length L of a segment are indicated in green, while parameters of replaced components are indicated in blue. The theoretical calculations of pressure losses were performed with the algorithm introduced in Section 3.3.2 for this sampling and vacuum system, with the parameters given in Figure 15. The setup is considered preliminary because the inlet flow rate of this setup is 3.4 Lmin^{-1} , while the inlet itself was characterized for a flow rate of 16.6 Lmin^{-1} . Furthermore, the low flow rate increases the residence time of particles in the transport system, increasing the magnitude of diffusional and sedimentary particle losses. The optimal configuration resulting in a higher flow rate would be obtained with an isokinetic flow splitter, with outlets for the excess flow. This isokinetic flow splitter for the PM_{2.5} sampling line is planned and designed, but has not yet been produced. Instead, the aerosol flow is split with two three-way splitters. The five branches directly lead to the particle counters, where the particle concentration is measured, followed by the particles being filtered out. The particle-free air flows out of the devices, into the exhaust line. The pressure sensor indicated as "P" in Figure 15 was installed downstream of the point where all the exhaust lines united into one.

Since the PM_{2.5} line incorporates five butanol-based CPCs, a Catalytic Vapor Filter (CVF-400) is installed in the exhaust line to chemically break down the butanol into H_2O and CO_2 before the air flows into the vacuum pump (Catalytic Instruments GmbH & Co.KG., 2024). Because the interior design of the CVF-400 is unknown, the dimensions and parameters of the components were estimated. A schematic representation of the CVF-400 is shown in Figure 13 in Section 3.2.5.

Due to the installation of sensors into the sampling and vacuum system, environmental parameters including average pressure and temperature, as well as dew point temperature were assessed and incorporated into the analysis. This enabled the determination of the performance of certain components within the flow system.

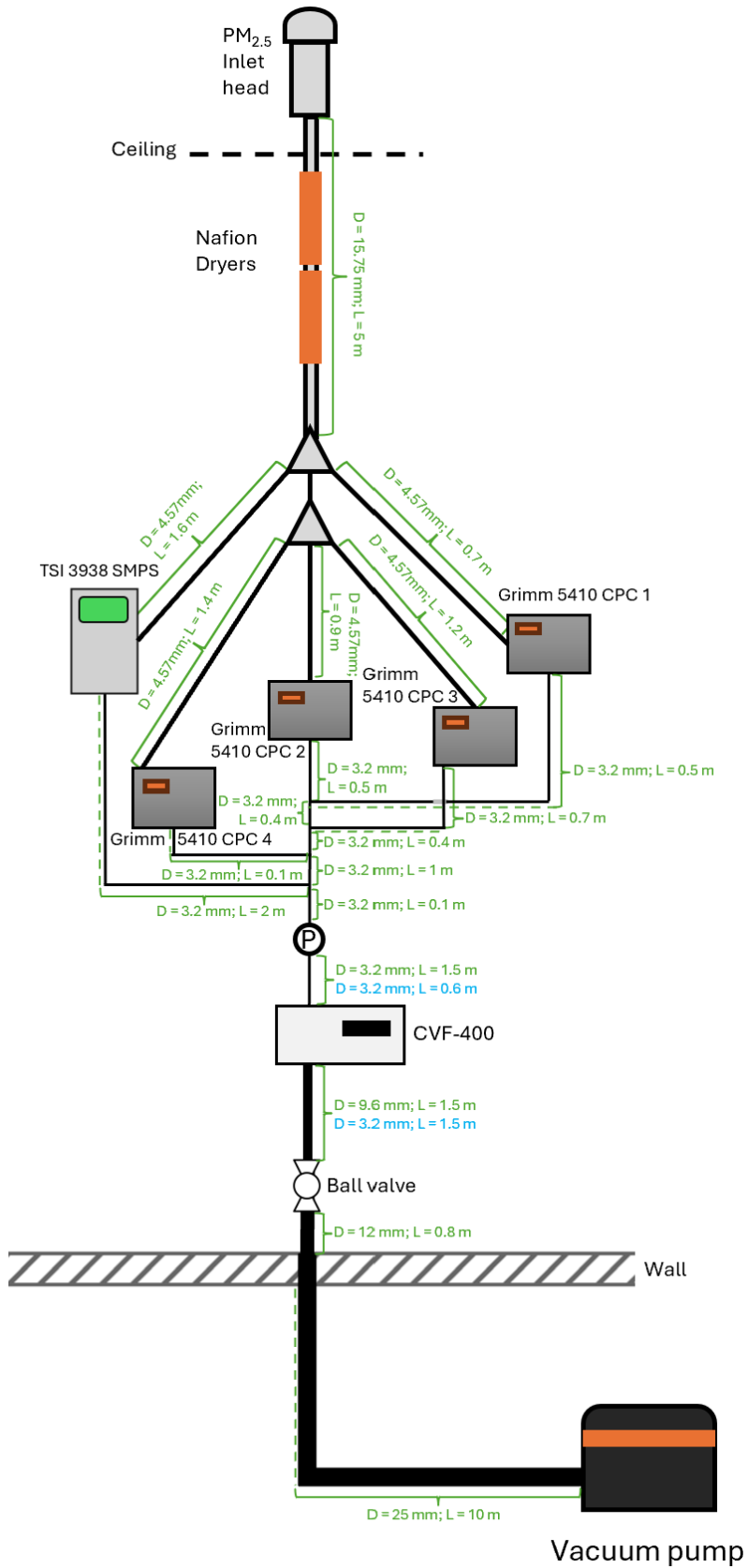


Figure 15: Schematic representation of the PM_{2.5} sampling and vacuum system built in December 2025 and used for the analysis of the pressure distribution. The thickness of lines indicates the inner diameter.

3.4 Theoretical Characterization of Particle Losses in the PM_{2.5} Transport System

The theoretical assessment of particle losses and the thus resulting transport efficiency of the transport system of interest was performed using the Particle Loss Calculator (PLC) (Weiden et al., 2009). This includes components, such as the three-way splitter, shown in Figures 17a and 17b, as well as the entire PM_{2.5} transport line shown in Figure 16. Weiden et al. (2009) show that the PLC provides satisfactory results, especially for more trivial sampling system geometries and small Reynolds numbers. Despite the added complexity of flow splitters in the AerObs PM_{2.5} transport system, the theoretical characterization of particle losses and the resulting transport efficiency was also determined using the PLC.

3.4.1 Particle Loss Calculator

For the theoretical analysis of particle losses within the transport system of the AerObs, the Particle Loss Calculator (PLC) software was used (Weiden et al., 2009). The software calculates the particle size-dependent transmission and transport efficiency of a sampling line by employing theoretical and empirical equations, including equations mentioned in Section 2.2.2 and 2.2.3. Various loss mechanisms can be evaluated separately. Transport line parameters, such as flow rate, tube length, first and second inner diameter, inclination angle and bend angle can be specified. Ambient and particle parameters, such as the density and shape factor can be adjusted and there is an additional possibility to consider sampling effects.

However, some effects, such as electrostatic deposition, thermophoresis, diffusiophoresis, interception, coagulation and re-entrainment are not considered in the PLC. Furthermore, only non-isoaxial and non-isokinetic aerosol sampling effects are accounted for (Weiden et al., 2009).

3.4.2 Sampling and Vacuum Line of Interest

Figure 16 shows a schematic of the PM_{2.5} system, including the vacuum system, as of April 2026, to be characterized theoretically and experimentally. Particles with aerodynamic diameters smaller than 2.5 μm are selected by the PM_{2.5} inlet head DIN EN 12341 and transported to the rest of the sampling system, which includes the four Grimm CPCs with different d_{50} cutoff diameters, the TSI 3750 CPC, installed with a TSI Electrostatic Classifier Model 3082 as a TSI SMPS Model 3938 arrangement and a custom-modified Compact Catalytic Stripper CCS004 by Catalytic Instruments GmbH & Co.KG (hereafter: Catalytic Stripper), which removes the particle and gas-phase semi-volatile fraction of an aerosol. The Catalytic Stripper is installed upstream of the Grimm CPC 4. The fraction of particles entirely comprised of volatile organic compounds (VOCs) is thus lost before reaching Grimm CPC 4. Additionally, the PM_{2.5} sampling system incorporates a Picarro G2401 greenhouse gas concentration analyzer (hereafter: Picarro) that measures the ambient gas concentration of H₂O, CH₄, CO and CO₂.

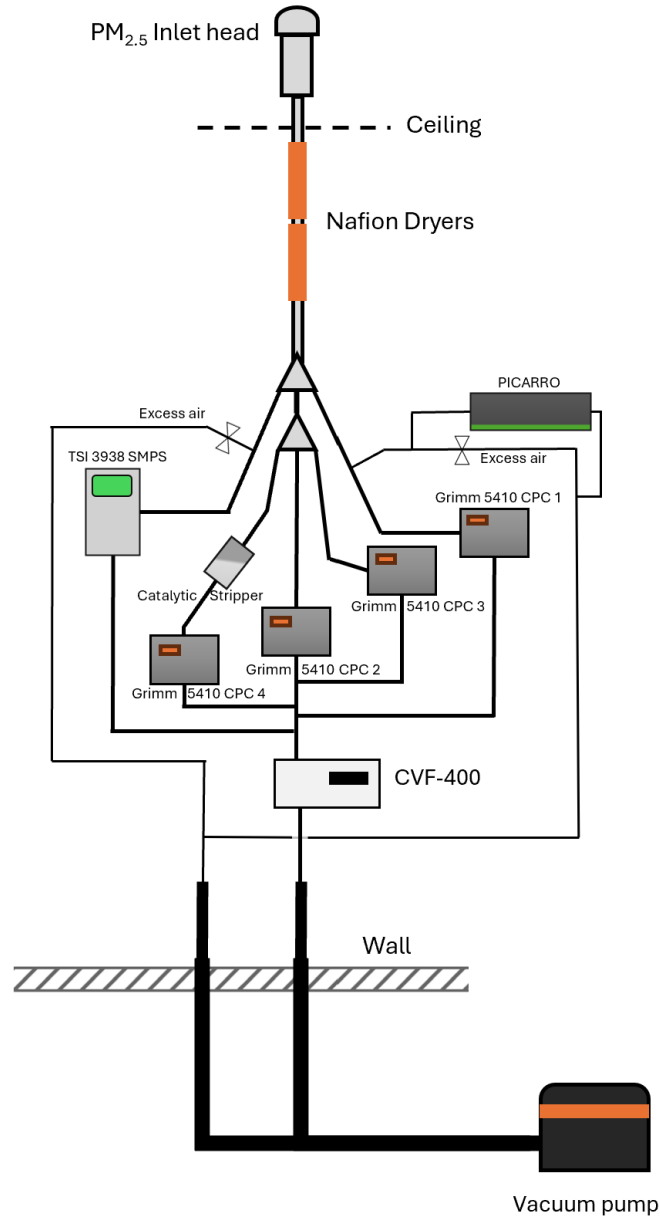
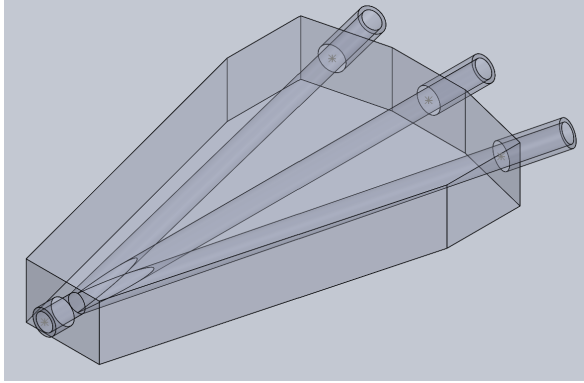


Figure 16: Schematic of the PM_{2.5} sampling and vacuum system (as of April 2026) including measurement devices. Line thickness indicates inner diameter. The grey triangles represent the two installed three-way splitters.

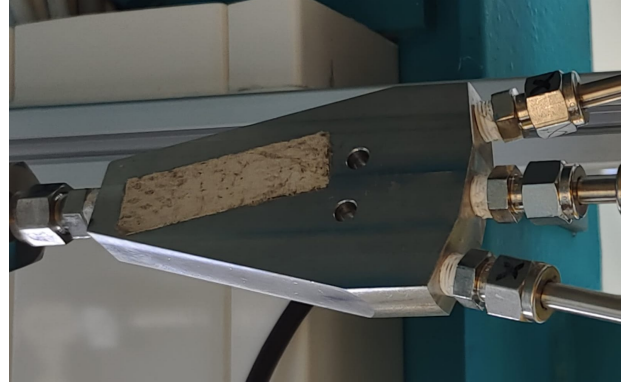
3.5 Experimental Characterization

When measuring the particle number concentration in ambient air, particle losses during aspiration, transport and splitting must be accounted for. Otherwise, the measurements would underrepresent the ambient concentration. Therefore, the characterization of the transport system is of great importance for correctly determining ambient aerosol concentrations. Commercially available components in the PM_{2.5} sampling line, such as the DIN EN 12341-compliant inlet head, are characterized and calibrated with specified cut-off curves (Patel and Aggarwal, 2022), thereby rendering further investigation of particle losses within the inlet head (at a flow rate of $1 \text{ m}^3 \text{ h}^{-1}$) unnecessary.

Trivial components, such as the vertically aligned 3/4 inch transport tubing, connecting the inlet head to the Nafion dryers, also need no experimental characterization, since the particle losses attributed to them can simply be calculated with the PLC. Experimental characterization is necessary if the component or the combination of multiple components is more complex and not yet characterized, such as the three-way splitters from the German Aerospace Center (DLR). Figure 17a shows a 3D technical drawing of the three-way splitter, with transparent walls. Figure 17b shows a picture of the three-way splitter installed into the flow system. The splitting distribution of aerosols through the three-way splitters and the particle losses attributed to this component were characterized using setups introduced in Section 3.6.1.



(a) Technical drawing of the three-way splitter



(b) Photo of the three-way splitter

Figure 17: (a) 3D technical drawing of the three-way splitter with transparent walls to visualize the interior of the three-way splitter. The inner diameter of the branches is 4.57 mm. (b) Photo taken of the three-way splitter installed in the PM2.5 sampling system of the University of Vienna AerObs.

3.6 Experimental Characterization of Particle Losses and Splitting Performance of the Three-Way Splitter

Characterizing the three-way splitter requires determining the particle loss fraction, as well as the particle flow distribution uniformity. Size-dependent particle losses in a transport component are quantified by comparing the particle concentration before and after the sample aerosol passes through it, either by direct measurement or calculation. Characterizing the splitting performance reveals whether particles are preferentially directed through one branch of the three-way splitter over the other. Both behaviors may be particle-size-dependent and were analyzed using monodisperse particles of different sizes. Subsequently, for each selected size, the acquired data of the concentration was plotted and the mean was calculated. The relative difference of the mean concentrations $\Delta\bar{C}_{rel, CPCs}$ and $\Delta\bar{C}_{rel, FCE}$ measured with different devices was calculated with Equation 32. The left equation is relevant for measurements with the TSI CPCs, while the right equation is used for the data analysis of measurements including the FCE.

$$\Delta\bar{C}_{rel, CPCs} = \left(\frac{\bar{C}_{CPC2}}{\bar{C}_{CPC1}} - 1 \right) \cdot 100 \quad \Delta\bar{C}_{rel, FCE} = \left(\frac{\bar{C}_{CPC}}{\bar{C}_{FCE}} - 1 \right) \cdot 100 \quad (32)$$

To account for CPC cutoff-effects, the counting efficiency of the last calibration was applied. For the counting efficiency of y for particle size x , the mean concentration was multiplied by a factor $\frac{1}{y}$. Furthermore, the ratio between the mean CPC concentration $\bar{C}_{CPC}$ and mean FCE concentration $\bar{C}_{FCE}$ gives the transport efficiency of the component of interest.

3.6.1 Measurement Setups

As mentioned, the characterization was performed with monodisperse aerosol. Since only one particle size was selected, the generated sample aerosol should have a high particle number concentration to ensure adequate counts. Depending on the required flow rate of the measurement devices, the aerosol had to be diluted and mixed thoroughly to ensure a homogeneous distribution of particles across the cross section of the transport line. The generation of particles was carried out by either using an SPG, which provided a wide distribution of particle sizes with a high and constant concentration or an atomizer which aerosolized monodisperse polystyrene latex (PSL) particles mixed into pure distilled water. The polydisperse aerosol provided by the SPG was charged and classified by the RAX-DMA to obtain monodisperse particles with electrical mobility diameters between 7 and 800 nm. The sample aerosol was diluted with particle-free air and evenly mixed with an annular gap mixer. The mixed aerosol passed through a relaxation volume, which homogeneously distributed the particles across the cross section of the transport tube and removed any turbulence.

Splitting Performance of the Three-Way Splitter

To determine how evenly the three-way splitter splits the aerosol flow, comparable setups to the ones shown in Figure 19 were arranged. This setup is shown in Figure 18. In the setups shown in Figures 18a and 18b a monodisperse aerosol with sizes between 7 and 200 nm and a sample flow rate of 1 Lmin^{-1} was produced with the SPG and the RAX-DMA. In the schematic representations of the setups the aerosol neutralizer is not shown as an individual component, but incorporated into the setup of the RAX-DMA. Subsequently, the aerosol flow was diluted with particle-free air via an annular gap mixer, reaching an aerosol flow rate of 3 Lmin^{-1} . The aerosol was then distributed evenly inside the relaxation volume and flowed into the three-way splitter, where it was divided into three branches, each with a flow rate of around 1 Lmin^{-1} , labeled branch 1, 2 and 3 from top to bottom. Subsequently, the aerosol entered either the TSI CPC 1, TSI CPC 2 or a critical orifice of 1 Lmin^{-1} . Arrows indicate the flow direction in Figures 18a and 18b. The critical orifice was installed to provide a symmetrical flow through the three-way splitter. Ideally, a third CPC with the same flow rate and cutoff diameter would be installed instead of the critical orifice. However, at that time, a third device was not available.

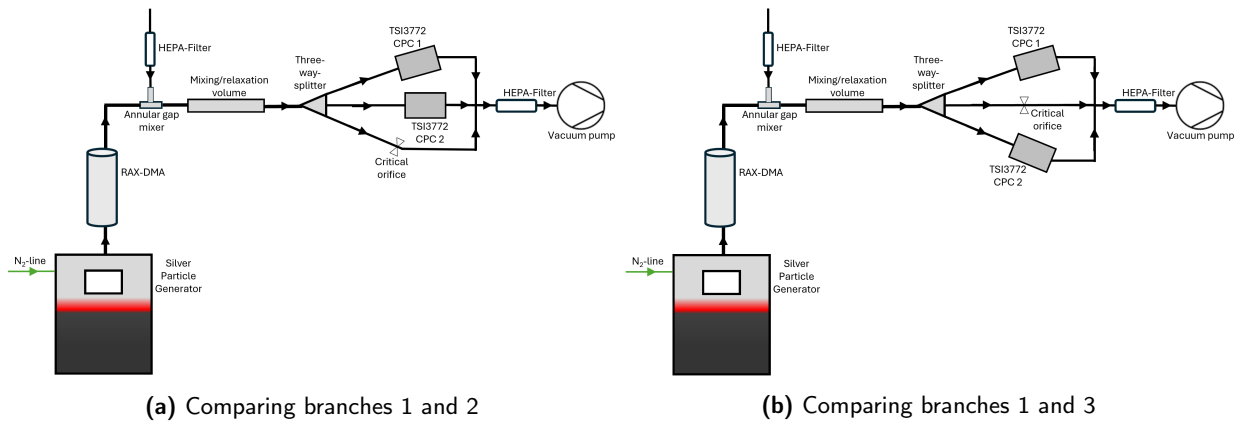


Figure 18: Schematic representation of the measurement setup. (a) shows the experimental setup to determine the splitting performance of generated silver particles through the three-way splitter, comparing outer branch 1 or 3 to the middle branch 2. A critical orifice with the same flow rate as the CPCs is built into the branch, where no CPC is connected. (b) shows the experimental setup to determine the splitting performance of the three-way splitter, comparing the outer branch 1 to branch 3. A critical orifice with the same flow rate as the CPCs is built into the middle branch. Arrows indicate the flow direction.

Particle Losses in the Three-Way Splitter

To characterize the particle losses attributable to the three-way splitter, the monodisperse sample aerosol was evenly split via a T-piece. One path led to the FCE, where the particles gave off the charge they acquired in the aerosol neutralizer, by which they were counted and their concentration was calculated. The other path directed the flow towards the three-way splitter, where the aerosol was split into three branches with the same diameter and flow rate. Afterward, the aerosol flowed into either TSI CPC 1, TSI CPC 2 or a critical orifice. The positions of these were interchanged alternately. After passing through CPCs, the critical orifice or the FCE, the sample aerosol flowed through a HEPA-filter, which filtered out the particles and the particle-free air passed through a vacuum pump.

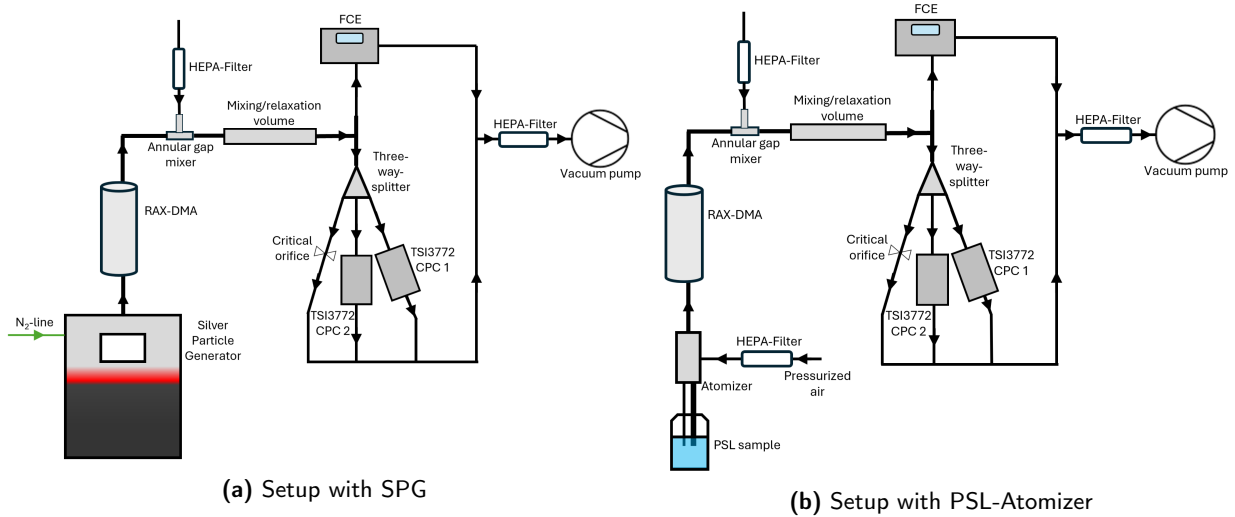


Figure 19: (a) shows the experimental setup to characterize the losses of monodisperse silver particles inside the three-way splitter, generated by the SPG. (b) shows the experimental setup to characterize the losses of monodisperse PSL particles inside the three-way splitter. Arrows indicate the flow direction.

Figures 19a and 19b illustrate the experimental setups employing the SPG and aerosolized PSL particles for particle generation, respectively. The arrows indicate the flow direction. Note that the SPG suspends the silver particles in nitrogen gas instead of air, which is indicated in Figure 19a in green.

3.7 Experimental Characterization of Particle Losses and Flow Splitting in the PM2.5 Transport System

For reasons described in Section 1, the direct experimental characterization of the PM2.5 transport system is crucial for measuring urban aerosol concentration and a reliable method to account for particle losses. Therefore, the following experiments were performed, characterizing silver particle losses inside the PM2.5 transport system.

3.7.1 Measurement Setup

Figure 20 shows the schematic measurement setup of the PM2.5 particle-loss characterization experiment for the transport system, excluding the 3/4 inch wide vertical tubes and Nafion dryers. This includes every part of the transport line below the second Nafion dryer, visible in Figure 16.

The particle generation was performed by the SPG, which produced a high concentration ($>10^6$) of poly-disperse aerosol with a wide size distribution (2 to 300 nm). The silver particles were pushed out of the SPG with 1 bar overpressure and a flow rate of 2 Lmin^{-1} into the aerosol neutralizer, which charged the particles in an X-ray source. The negatively charged silver particles were then selected in the RAX-DMA, based on their electrical mobility, as described in Section 3.2.3. The monodisperse aerosol sample flowed into an annular gap mixer, where the aerosol was diluted with a ratio of 1:6 with particle-free air and mixed by turbulence. In the subsequent mixing volume, the particles were homogeneously distributed after being turbulently mixed in the annular gap mixer. The particle stream was split into two streams via a T-piece. One stream flowed into the FCE, which had a flow rate set to 5.61 Lmin^{-1} to match the flow rate of the transport system (approximately 5.6 Lmin^{-1}), through which the other stream flowed. The current, representative of the charged particle concentration was measured inside the FCE. The aerosol particles that were not deposited on the walls of the transport system leading to the CPCs were measured by CPCs, which also determined the particle concentration of the aerosol flow. Devices such as the Picarro and the CVF-400 were of no importance to the characterization experiment, but were incorporated into the setup and are therefore also marked in Figure 20. The flow was provided by the vacuum system and the vacuum pumps of the AerObs.

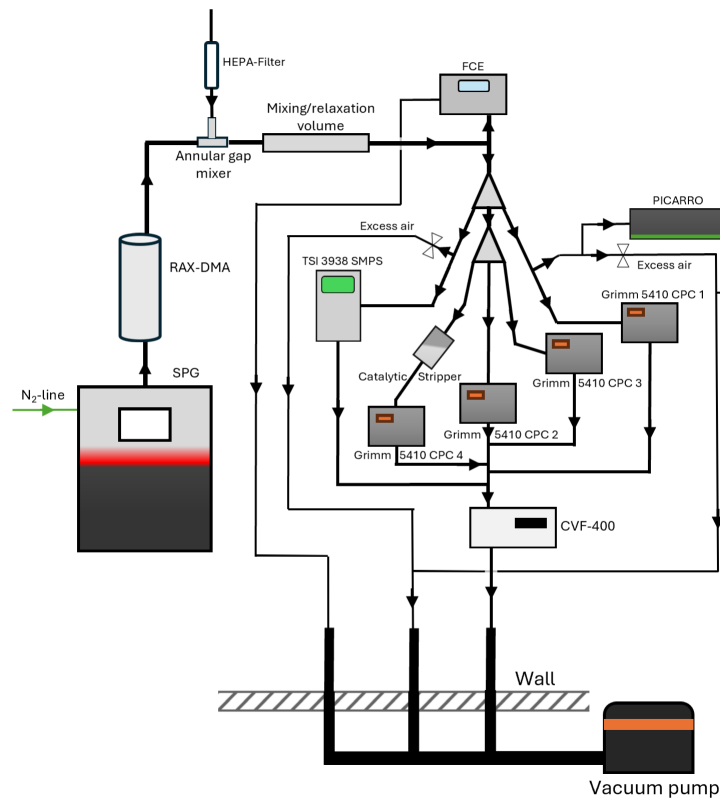


Figure 20: Schematic of the experimental setup characterizing the particle losses in the PM_{2.5} transport system. Arrows indicate the flow direction.

Due to an unexpected laser error in Grimm CPC 3 just before the start of the experiment, the device was excluded from the setup and replaced by a critical orifice with a flow rate of 0.6 Lmin^{-1} . To still characterize the transport system of the CPC 3, one measurement was conducted following the setup shown in Figure 20, while CPC 3 was replaced by a critical orifice, followed by another measurement in which the position of CPC 4 and the critical orifice were exchanged. Thus, the entire transport system shown in Figure 20 was characterized.

4 Results

The results section is split into findings regarding the pressure distribution and characterization of particle losses. Initially, the results of the performance experiment of the pump will be presented, followed by the presentation of the pressure distribution inside various setups of the AerObs PM2.5 sampling and vacuum system. Subsequently, the findings of the theoretical characterization of the PM2.5 transport system are reported. For the experimental characterization, the splitting distribution and transport efficiency of the three-way splitter is shown. Finally, the results of the characterization of the PM2.5 transport system are reported and compared to the theoretical transport efficiency.

4.1 Pressure Distribution in the AerObs Flow System

In this section, the results of the performance experiment of the pump, as well as the general pressure distribution inside different setups of the PM2.5 sampling and vacuum system will be discussed and illustrated.

4.1.1 Vacuum Pump Performance

This experiment evaluates the performance characteristics of the vacuum pump, but also the AerObs vacuum system, under different flow rates, representative of the aimed objectives discussed in Section 1.2. The experimental setup is shown in Figure 14. Figures 21a and 21b show the pressure measurement within the vacuum system, as well as the calculated pressure distribution along the vacuum line, represented by the colored lines, for six different flow rates. As mentioned in Section 3.3.2, the calculation of the pressure distribution in the vacuum line starts upstream of a component, which has constant pressure or flow rate values, such as the constant pressure upstream of a pump, or the constant mass flow rate through a critical orifice. Therefore, the calculation begins upstream of the pump, with an initial pressure (given by the parameters of the vacuum pump) and mass flow rate (given by the critical orifice parameters). For Figure 21b the initial pressure is taken directly from the pressure measurement in front of the pump. This pressure can also be calculated using the mass flow rate and the vacuum pump's pumping speed curve shown in Figure 22. This calculated pressure distribution is shown in Figure 21a.

The uncertainty of the flow rates takes into account the poor adjustment of the needle valves (small adjustment of the needle valve may cause a big change in flow rate) that determine the flow rate, the accuracy of the TSI Flowmeter and ambient pressure fluctuations. Since the adjustment of the needle valves is not as quantifiable, the overall uncertainty of the flow rate is estimated. For the pressure measurement, one Jumo pressure sensor is positioned near the ball valve of the vacuum line, designated as length zero (1 cm) and another is installed just in front of the vacuum pump, which is at the end of the line. The measurement points show the measured pressure value. The uncertainty of the calculated pressure distribution is determined using Gaussian error propagation, with a 10 % wall thickness uncertainty, 1 hPa uncertainty of the initial pressure as well as the uncertainty of the volumetric flow rate. The uncertainties of the pressure measurement are shown as error bars.

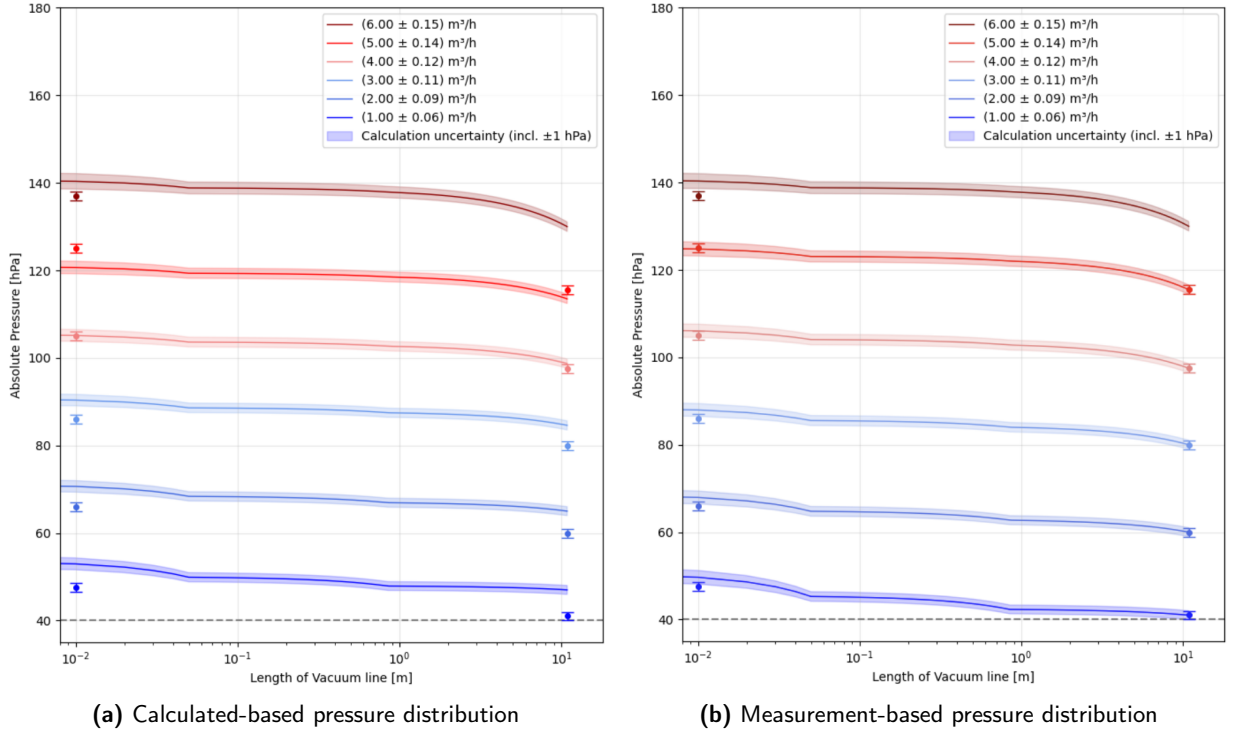


Figure 21: The calculated pressure distribution inside the AerObs vacuum line and the measured pressure at one inlet ($x = 0.01$ m) and directly in front of the vacuum pump ($x = 10.86$ m). For (a) the initial pressure value is calculated using Equation 12 and the pumping speed curve, while for (b) the measured pressure in front of the vacuum pump is taken as the initial pressure values. The data points show the measured pressure values with uncertainties shown as error bars.

Table 3 shows the pressure values that were measured and calculated, also shown in Figure 21, for different inlet flow rates. The measurement-based calculated pressure at the inlet P_{inlet} uses the pressure measured at the pump (P_{pump} measured) as an initial pressure value for the calculation, while the calculation-based P_{inlet} uses the calculated pressure at the pump (P_{pump} calculated) as its initial value instead. " P_{inlet} measured" and " P_{pump} measured" denote the pressures measured directly at the inlet and the pump, respectively. For a flow rate of $6 \text{ m}^3\text{h}^{-1}$, the pressure at the pump was not measured, because a second pressure sensor was not yet available, so the corresponding two values are missing from Table 3.

Table 3: Measured and calculated pressures at sensor locations for various flow rates in (m^3h^{-1}). "measurement-based" denotes that the initial pressure value used for the calculation was measured while "calculation-based" denotes that the initial pressure value was calculated. The pressure values are presented in hPa.

Flow rate (m^3h^{-1})	P_{inlet} (hPa) measurement-based	P_{inlet} (hPa) calculation-based	P_{pump} (hPa) calculated	P_{inlet} (hPa) measured	P_{pump} (hPa) measured
1.00 ± 0.06	51 ± 1.7	56.8 ± 1.9	47.0 ± 1.0	48 ± 1	41 ± 1
2.00 ± 0.09	69 ± 1.6	73.6 ± 1.7	65.0 ± 1.1	66 ± 1	60 ± 1
3.00 ± 0.11	89 ± 1.6	92.7 ± 1.6	84.6 ± 1.1	86 ± 1	80 ± 1
4.00 ± 0.12	107 ± 1.7	107.2 ± 1.7	98.7 ± 1.1	105 ± 1	98 ± 1
5.00 ± 0.14	125 ± 1.7	122.4 ± 1.7	113.5 ± 1.1	125 ± 1	116 ± 1
6.00 ± 0.15	-	139.4 ± 1.8	130.0 ± 1.1	137 ± 1	-

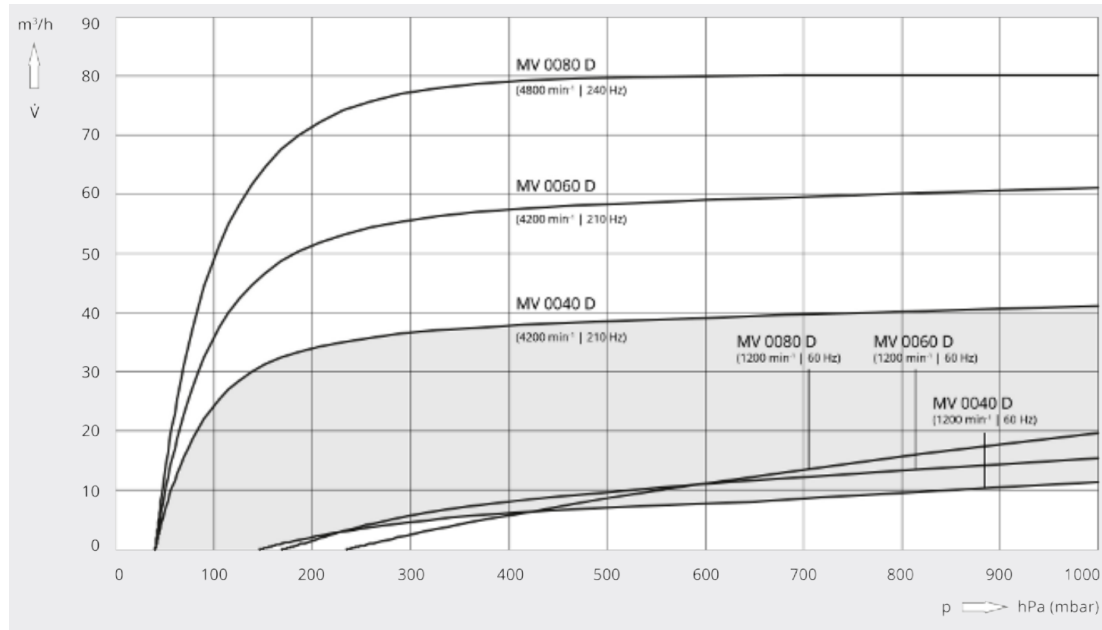


Figure 22: Pumping speed curve of the Busch MINK MV 0040-0080 D Synchro vacuum pumps operated with air at 20 °C and a tolerance of $\pm 10\%$. Reprinted from the product leaflet of MINK MV 0040-0080 D Synchro vacuum pumps by (Busch Vacuum Solutions, 2025).

To test the vacuum system for hermeticity, the vacuum pressure was measured without any air flowing inside the vacuum system. Here, the measured end pressure is lower than expected at an average of 23.6 ± 2.1 hPa, where the uncertainty is the combination of the instrument uncertainty, instrument resolution and standard deviation of five measurements. According to the manual of the vacuum pumps, the minimal end pressure is 40 hPa, with a tolerance of $\pm 10\%$. It was deemed appropriate to accept a minimal pressure of 24 hPa and extrapolate the pumping speed curve for the MINK MV 0060 D Synchro, starting at 24 hPa instead of 40 hPa, while assuming that the shape of the pumping speed curve stays consistent. This extrapolated pumping speed curve was used to determine the calculation-based pressure distribution shown in Figure 21a.

4.1.2 Pressure Distribution in the Sampling and Vacuum System

Because the pressure is only measured at one position of the vacuum system during these measurements, the pressure distribution inside the sampling and vacuum system shown in Figure 15 is calculated with the algorithm introduced in chapter 3.3.2. The dimensions of the transport line (shown in Figure 15) are constant for every calculation. The only parameters that are varied, are the ones indicated in blue. Furthermore, it was noticed that the CVF-400 itself increases the pressure upstream of the device. To determine the root of this pressure increase, the CVF-400 was excluded in one setup and replaced with two critical orifices (3 Lmin^{-1} and 4 Lmin^{-1}), with a sum flow rate of 7 Lmin^{-1} , equal to the one incorporated in the CVF-400. This leads to a total of five setups, described in Table 4, which are analyzed. The description indicates the characteristics of the setup, while the setup name combines the description and the values of the measured pressure. In front of the vacuum pump 40 hPa is assumed as the initial pressure.

Table 4: The five configurations of the PM2.5 vacuum line for which the pressure distribution is analyzed by the algorithm. Green and blue describe the parameters mentioned in Figure 15.

Setup Name	Description	Meas. Pressure
P Jumo = 283hPa 1/2in PFA-tube	CVF-400, 1/2inch PFA-tube (green)	283 hPa
P Jumo = 447hPa 1/4in PFA-tube	CVF-400, 1/4inch PFA-tube (blue)	447 hPa
P Jumo = 156hPa 1/2in PFA-tube	no CVF-400, + CO, 1/2inch PFA-tube (green)	156 hPa
P Jumo = 154hPa 1/2in PFA-tube	no CVF-400, 1/2inch PFA-tube (green)	154 hPa
P Jumo = 176hPa 1/4in PFA-tube	no CVF-400, 1/4inch PFA-tube (blue)	176 hPa

Furthermore, the measured pressure upstream of the CVF-400 decreases after the device is turned off. At first, the pressure dropped within a few seconds by almost 10 hPa. Afterward, the pressure gradually decreases by another 15 hPa when the device fully cools down after a few hours. These effects suggest that the route that bypasses the catalyst causes less frictional pressure losses and the increased temperature and thus the increased volumetric flow rate also leads to higher frictional pressure losses. Since the exact dimensions of the interior components of the CVF-400, such as the lines, valves and the catalyst itself, are unknown, the dimensions are estimated and adjusted to equate to the measured pressure losses experienced in one of the five setups. These tailored dimensions are used for all five configurations and are not adjusted further. Table 5 shows the estimated dimensions of both paths of the CVF-400, shown in Figure 13.

Table 5: The estimated dimensions of both paths of the CVF-400. When the device is turned off, air coming from the exhaust of the measurement devices, flows straight to the outlet of the device. When turned on, the exhausted air flows through the catalyst, thus increasing the traveled distance.

Component	CVF on	CVF off
Tube	D = 4.2 mm; L = 80 cm	D = 4.2 mm; L = 25 cm
First valve	D = 1 mm; L = 2 cm	D = 1 mm; L = 2 cm

Figures 23 and 24 show the calculated pressure distributions of the setup shown in Figure 15, plotted against the length of the flow line. The plot lines represent the pressure dependent on the length of the flow line, for different devices: Grimm CPC 1 and 2, critical orifices (COs) 1 and 2 replacing the other two Grimm CPCs and the TSI SMPS. Figure 23 shows the first two configurations described in Table 4. The figure shows the calculated pressure inside the sampling and vacuum system for the case where the CVF-400 is connected but turned off, meaning the catalyst is at room temperature and is bypassed. The direction of the calculation of the pressure distribution follows the flow direction in the sampling system, using the first algorithm. In contrast, the pressure distribution in the vacuum system is calculated with the second algorithm opposing the flow direction. The x-axis describes the length of the tube from the opening of the inlet (designated as length zero). Since the magnitude of the pressure drop varies significantly between components, the y-axis is divided into three segments to improve visibility. The two plots in Figure 23 differ by the configuration of the two components, indicated in green and blue in Figure 15. The left plot has the segment with parameters marked in green (1/2 inch PFA-tube), while the right plot uses the component parameters marked in blue (1/4 inch PFA-tube). The horizontal lime-green dotted line indicates the pressure measured with the Jumo pressure sensor, while the purple dotted line represents the calculated pressure at the position of the pressure sensor in the vacuum line. In Figure 23 no lime-green line is indicated in the right plot, because in this setup the CVF-400 was not turned off and the temperature dependence of the pressure drop inside the CVF-400 was noticed when the setup was no longer standing.

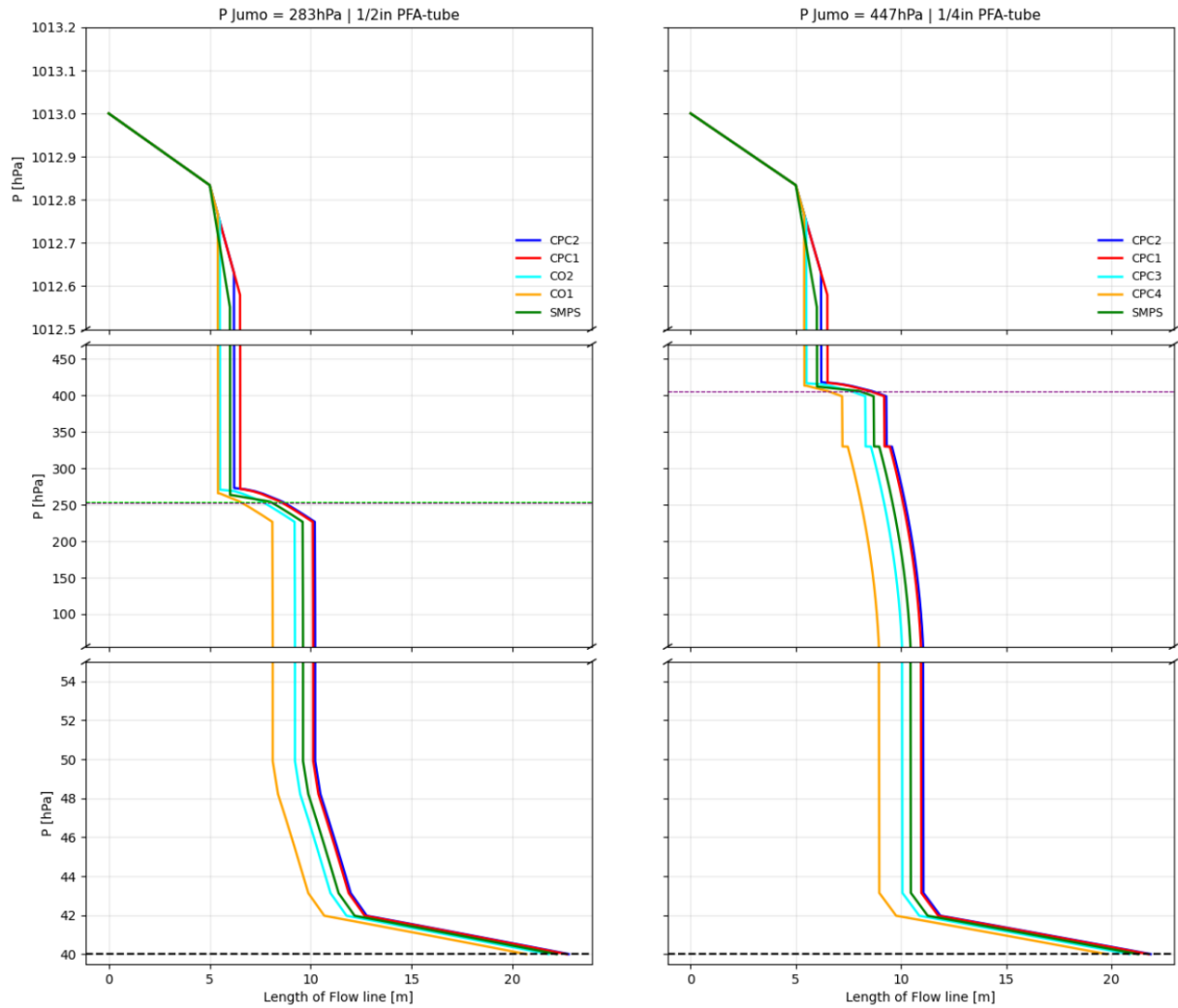


Figure 23: The absolute pressure distribution of two different setups of the PM2.5 sampling and vacuum line (shown in Figure 15), while including a switched off and cooled down CVF-400. The purple dashed line indicates the calculated pressure value at the position of the pressure sensor in the setup, while the lime green dashed line shows the measured pressure value. The left column of plots shows the pressure distribution with an 1/2 inch thick exhaust tube after the CVF-400, while the right column of plots shows the case with an 1/4 inch thick exhaust tube.

Even though the differently colored lines representing the exhaust lines of the devices do not overlap in Figure 23, they are all united to one tube below the purple horizontal dotted line. The exhaust lines do not overlap due to differences in their respective lengths. The air flow starts at the inlet and is then divided by the three-way splitters. In Figures 23, 24 and 25 the vertical drop of pressure between 1012 hPa and a few hundred hPa is due to the installed COs and the integrated COs of the CPCs. After passing through the devices, the individual exhaust lines unite one by one until the air flows through a single tube once more. The last 10 m are the one inch thick tubing inside the walls of the AerObs, leading to the vacuum pump.

Figure 24 shows the pressure dependent on the line length for the same setup as in the results shown in Figure 23. However, the CVF-400 is fully operational, which implies that the air coming from the devices flows through the catalyst, covering a longer distance. Furthermore, the temperature is higher. This increases the volumetric flow rate downstream of the CVF-400 by the same factor as the increase of temperature in the vacuum system, as can be seen in Equation 4. The mass flow rate is constant due to the critical orifices and the downstream pressure, provided by the vacuum pump, is also constant for a constant mass flow rate. Therefore, the velocity of the fluid and thus the volumetric flow rate must increase, which increases the frictional pressure losses.

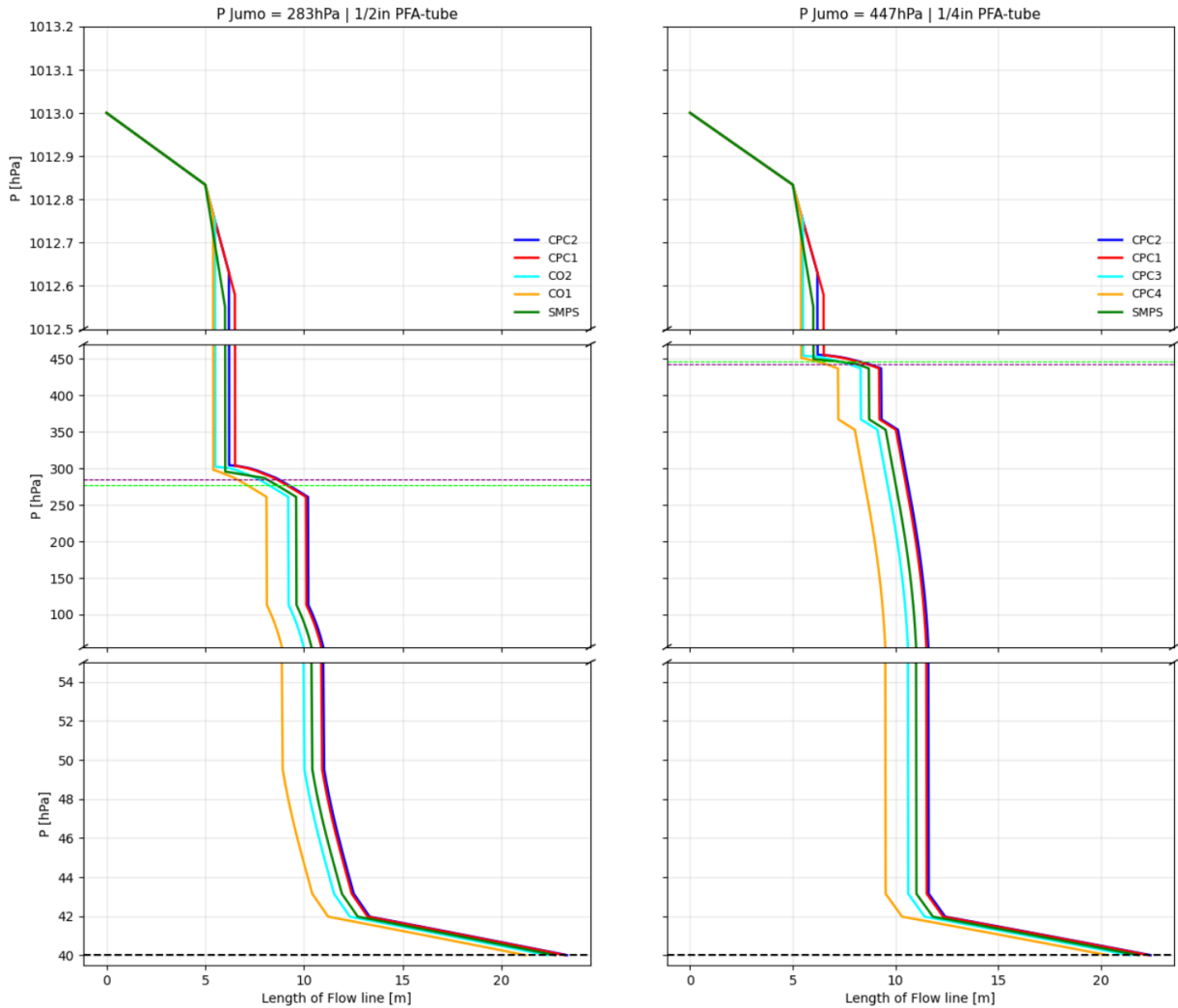


Figure 24: The absolute pressure distribution of two different setups of the PM_{2.5} sampling and vacuum line (shown in Figure 15), while including the CVF-400 at 450 °C. The purple dashed line indicates the calculated pressure value at the position of the pressure sensor in the setup, while the lime green dashed line shows the measured pressure value. The left column of plots shows the pressure distribution with an 1/2 inch thick exhaust tube after the CVF-400, while the right column of plots shows the case with an 1/4 inch thick exhaust tube.

Figure 25 shows the calculated pressure distribution of the PM_{2.5} sampling and vacuum line without the CVF-400. The difference between the values of the measured pressure and the calculated pressure at the same position does not exceed 10 %.

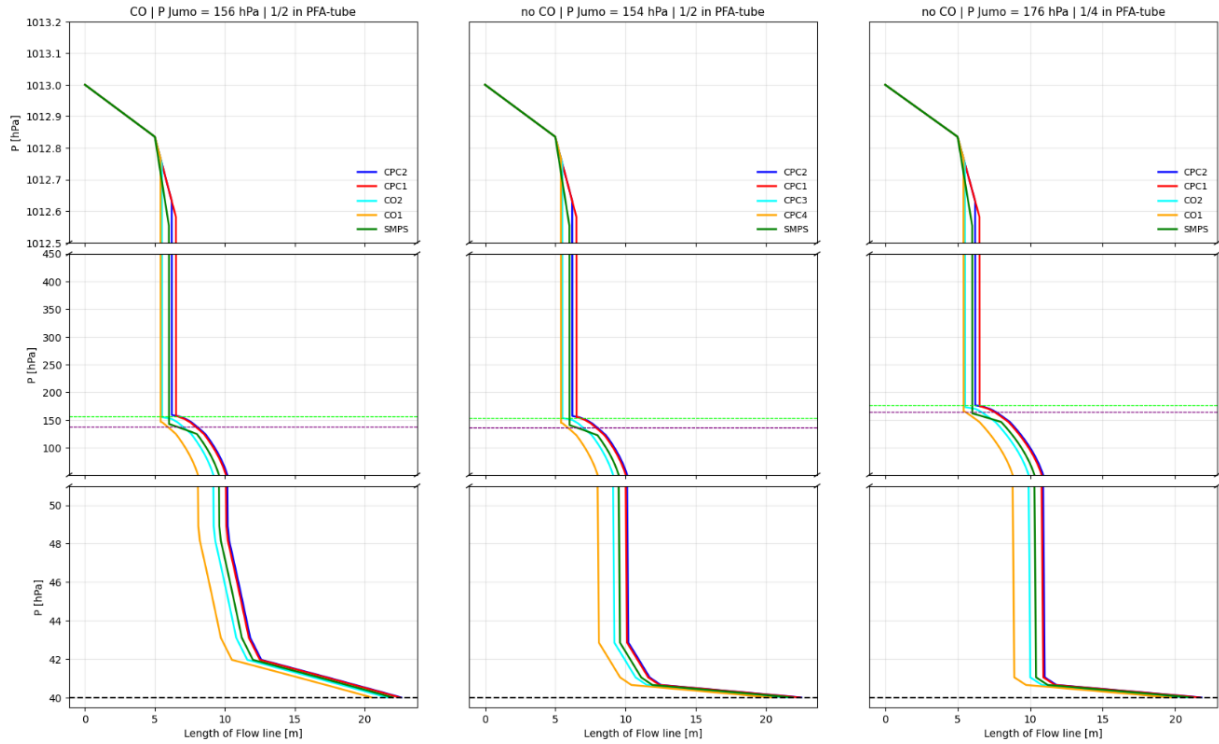


Figure 25: Absolute pressure distribution inside the entire PM_{2.5} sampling and vacuum line, while bypassing the CVF-400 in three different ways. Each column of plots represents one setup, where the absolute pressure was measured. The purple dashed line indicates the calculated pressure value at the position of the pressure sensor in the setup, while the lime green dashed line shows the measured pressure value. The left column of plots displays the absolute pressure, when excluding the CVF-400, but introducing a critical orifice with a flow rate of 7 Lmin⁻¹, imitating that component of the CVF-400. The middle column represents the case where the CVF-400 is excluded and no critical orifice is installed and the right column shows the same case as the middle column, but with 1/4 inch PFA-tubing installed after the CVF-400, instead of a 1/2 inch PFA-tube.

4.2 Theoretically Characterized Particle Losses in the PM_{2.5} Transport System

This section presents the results of the theoretical characterization, beginning with those obtained using the Particle Loss Calculator (PLC) (Weiden et al., 2009). Figure 26 shows the calculated size-dependent transport efficiency of the three-way splitter, using the PLC. 40 % of particles with a diameter of 10 nm are lost, due to diffusion. Apparent from the slight drop in transport efficiency for larger particles, the calculation is conducted for a horizontally aligned three-way splitter, imitating the setup presented in Section 3.6.1 and uses a particle density of 10 gcm⁻³. This calculation assumes equal selection probability for all three-way splitter branches.

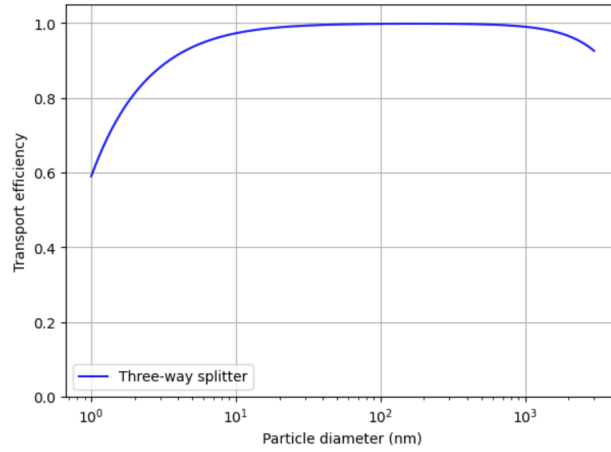
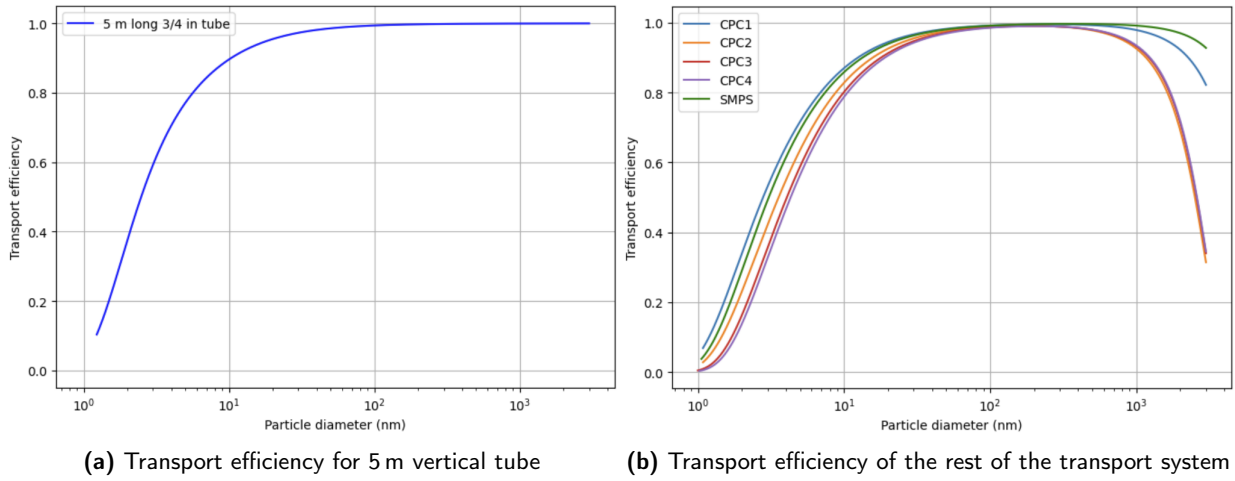


Figure 26: The size-dependent transport efficiency of a horizontally aligned three-way splitter, calculated with the PLC for particles with a density of 10 gcm^{-3} .

The transport efficiency of the 3/4 inch vertical transport system, directly downstream of the inlet, which is calculated with the PLC, is shown in Figure 27a. Additionally, the transport system of the individual transport lines to the Grimm CPCs 1 to 4 and the TSI SMPS is shown in Figure 27b. The setup is shown in Figure 16. The specified particle density is 10 gcm^{-3} , which is the maximum density the PLC allows, approximately representing the density of silver (10.50 gcm^{-3} (Weast et al., 1988)), which will be used for the experimental characterization of the transport efficiency.



(a) Transport efficiency for 5 m vertical tube

(b) Transport efficiency of the rest of the transport system

Figure 27: (a) Transport efficiency of the 3/4 inch tubing connecting the inlet to the rest of the PM2.5 transport system. (b) Transport efficiency of the 1/4 inch transport line leading to the devices. The efficiencies are calculated with the PLC.

Since the segment shown in Figure 27a is a straight vertical tube, there are no particle loss mechanisms affecting larger particles. Figure 27b presents the sedimentary and inertial loss effects for larger particles. Figure 28 shows the product of the transport efficiencies presented in Figures 27a and 27b for particles with a density of 10 gcm^{-3} . It illustrates the size-dependent transport efficiency of the lines leading to each device, which theoretically characterizes the entire PM2.5 transport system presented in Figure 16 for silver particles, or particles of the same density.

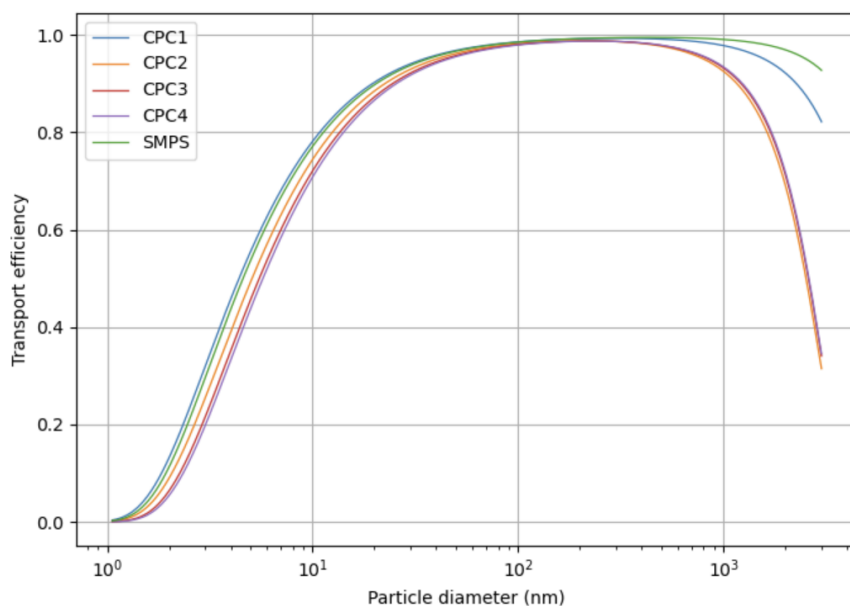


Figure 28: Transport efficiency of the entire PM_{2.5} transport system for silver particles, assuming particle losses inside the Nafion dryers are comparable to those of typical tubes.

4.3 Experimental Characterization of Components in the Transport System

This section presents the results of the characterization of the splitting performance of the three-way splitters and the particle losses in both the three-way splitters and the entire AerObs PM_{2.5} transport system. The experimental setups are presented in Section 3.5.

4.3.1 Three-Way Splitter Characterization

Splitting Performance Results

The results of the characterization of the splitting distribution and the particle losses of the three-way splitter performed as described in Section 3.6.1 are presented in this section. Before the experiment is conducted, the average flow rates of the relevant devices are measured with a Gilibrator. The average inlet flow rates of the two TSI CPCs and the critical orifice, installed into the setups described in Section 3.6.1 are shown in Table 6.

Table 6: Average flow rates, measured at the inlet of the TSI CPCs and the critical orifice with the Gilibrator.

Device/Component	Flow rate Q (Lmin ⁻¹)
TSI CPC 1	0.976 ± 0.010
TSI CPC 2	1.034 ± 0.011
Critical Orifice	1.074 ± 0.011

In addition, the ratio between the flow rate of the sample and sheath flow of the RAX-DMA is kept at between 1:10 and 1:6 to ensure the DMA selects the right particle sizes. After the measurements are completed, the concentration difference between TSI CPC 1 and 2 for laboratory air is evaluated. Figure 29 shows the raw concentration data plotted against the time in seconds. Figure 29a shows measurements of the same laboratory air sample split by a T-piece, while Figure 29b shows measurements with the two CPCs side by side, each with its own open inlet. The mean difference in concentration is 7.8 % for 29a and 9.4 % for 29b, indicating that CPC 2 measures a higher concentration.

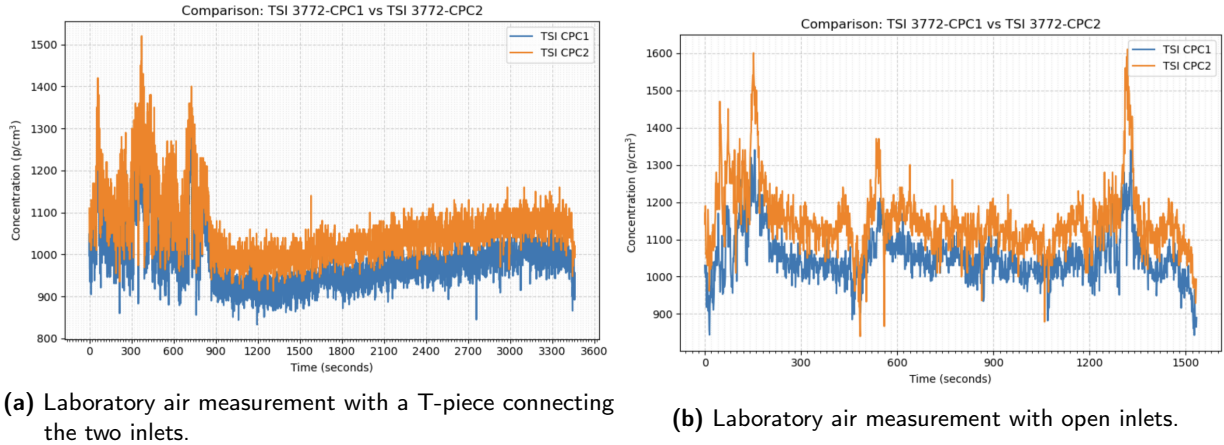


Figure 29: Particle concentration of laboratory air measurements with TSI CPC 1 (blue) and TSI CPC 2 (orange) with the CPC inlets connected with a T-piece in (a) and with two open inlets in (b).

The measurements are performed, the concentrations and relative difference of the mean concentration between TSI CPC 1 and CPC 2 are calculated with Equation 32 and plotted for each measurement. The relative difference of the mean concentration between TSI CPC 1 and CPC 2 depending on the selected electrical mobility diameter is shown in Figure 30. The uncertainty of the relative difference is calculated with Gaussian error propagation, considering the $\pm 5\%$ uncertainty of the CPCs and the statistical error of the measurement calculated with the standard error of the mean (SEM). The error bars of the electrical mobility diameter arise from the voltage fluctuations of the RAX-DMA. The effect of these fluctuations is only relevant for sizes below 10 nm.

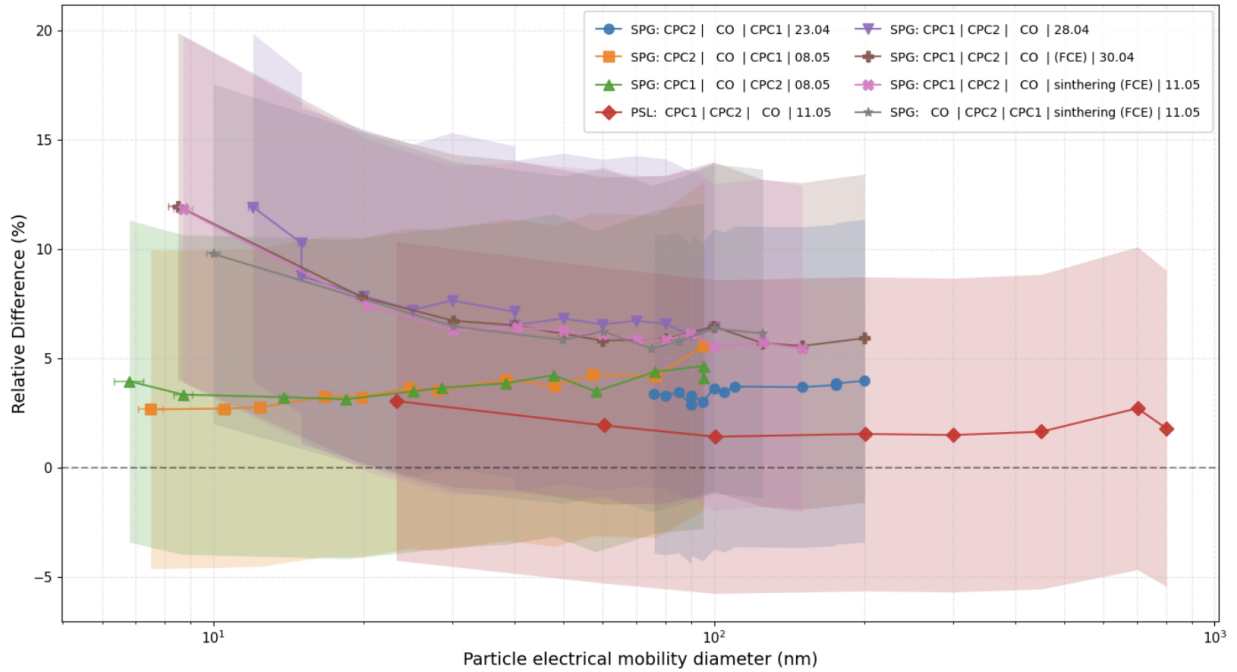


Figure 30: Relative difference of the mean concentration, depending on the branch of the three-way splitter measured with the TSI CPC 1 and 2, plotted against the logarithmic particle electrical mobility diameter. The setup is shown in Figures 18 and 19. The legend describes the aerosol generation, followed by the arrangement of CPCs and CO and then the date of measurement. This figure shows the collection of multiple measurements and setups.

The legend in Figure 30 shows the different setups used for the characterization of the three-way splitter. The labeling starts with the source of the aerosol particles (SPG or PSL), and is then followed by the positioning of the CPCs and the CO relative to the three-way splitter. "(FCE)" indicates that the setup shown in Figure 19 is used, followed by the date of the measurement. Starting at the top left of the legend and proceeding downward, the first three entries compare the outer branches of the flow splitter.

The rest of the measurements compare the middle branch to one of the outside branches. Excluding the measurement with PSL, the concentration difference between CPC 1 and CPC 2 has increased and is size-dependent, decreasing with increasing diameter.

Results of the Particle Loss Characterization

As described in Section 3.6.1, the particle losses of the three-way splitter are characterized and shown in this section. Figure 31 shows the relative difference of the mean concentration measured by the TSI CPC 1 or 2 and the FCE, with the setup of this experiment shown in Figure 19. The labeling of the measurement follows the legend in Figure 30. The uncertainties are calculated using Gaussian error propagation, taking into account the $\pm 5\%$ uncertainty of the CPCs, the FCE's $\pm 2\%$ uncertainty and the SEM.

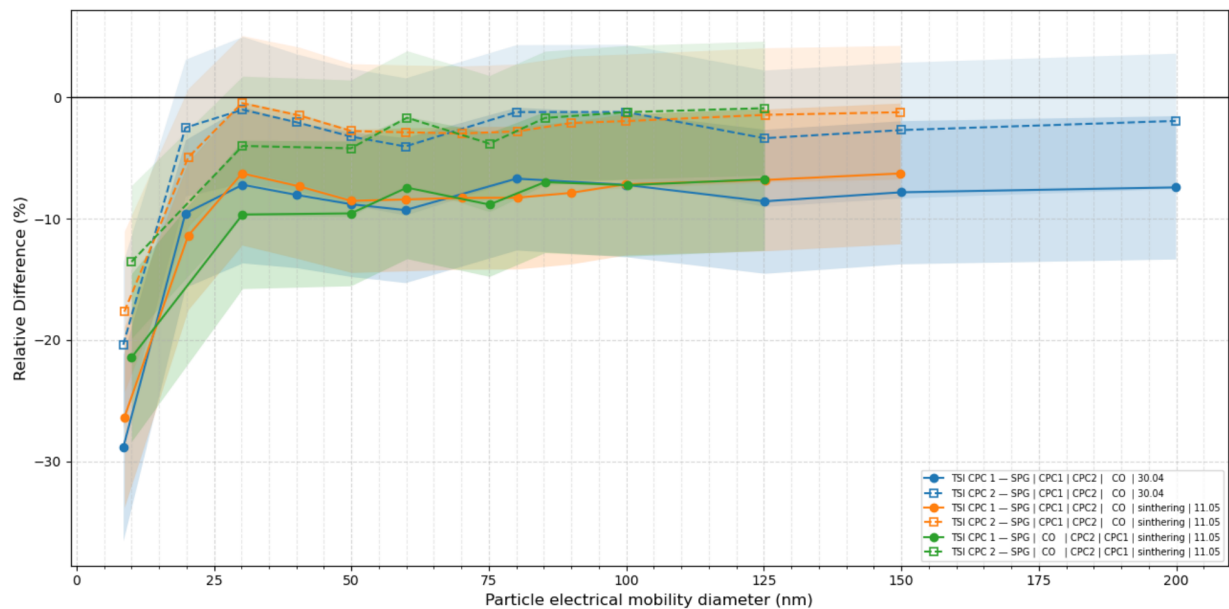


Figure 31: Relative difference of the mean concentration, of three measurement series, measured with the FCE vs with the TSI CPC 1 and 2, plotted against the particle electrical mobility diameter. Filled circles and open squares represent the relative difference between the mean FCE concentration and the mean concentration measured by TSI CPC 1 and TSI CPC 2, respectively. Different colors indicate different measurement series. The setup of this experiment is shown in Figures 19a.

An 8% relative difference between the concentrations of TSI CPC 1 and 2 is observable in Figure 31, as the curves have similar shapes but are offset. For this reason, the concentration measured by TSI CPC 1 is adjusted to match TSI CPC 2's concentration. Because an 8% loss across this size range is not expected for a flow splitter of these dimensions, this supports the chosen adjustment direction. Possible reasons for this concentration-difference are mentioned in section 5.2. The offset-adjusted plot is shown in Figure 32.

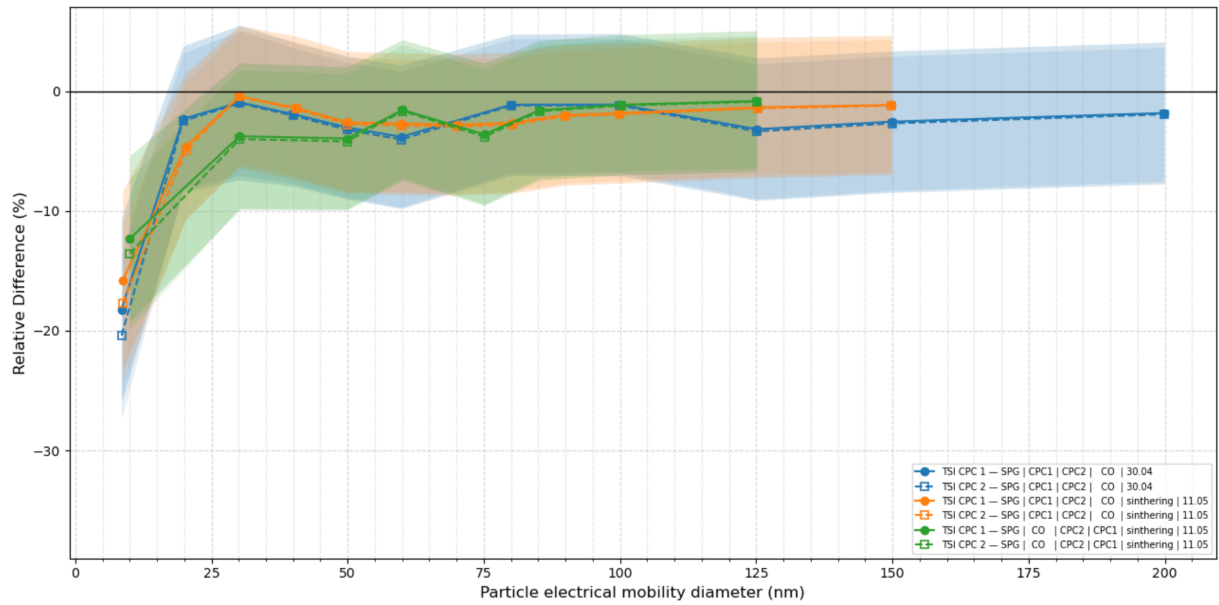


Figure 32: Offset-adjusted relative difference of the mean concentration of three measurements with the setup shown in Figure 19a depending on the particle electrical diameter. The concentration of TSI CPC 1 was adjusted by 8 % to attribute for the concentration difference between TSI CPC 1 and 2.

The relative difference between the FCE and the TSI CPCs, for particle sizes above 25 nm, is not significant and within the uncertainty of the measurement. However, the detection of particles with sizes smaller than 25 nm is affected by the TSI CPC's counting efficiency. Therefore, the TSI CPC concentrations are adjusted by the inverse value of the counting efficiency, as described in Section 3.6.1. Figure 33 shows the size-dependent transport efficiency, calculated as the ratio between the TSI CPC and the FCE concentration, corrected for the TSI CPC's counting efficiency.

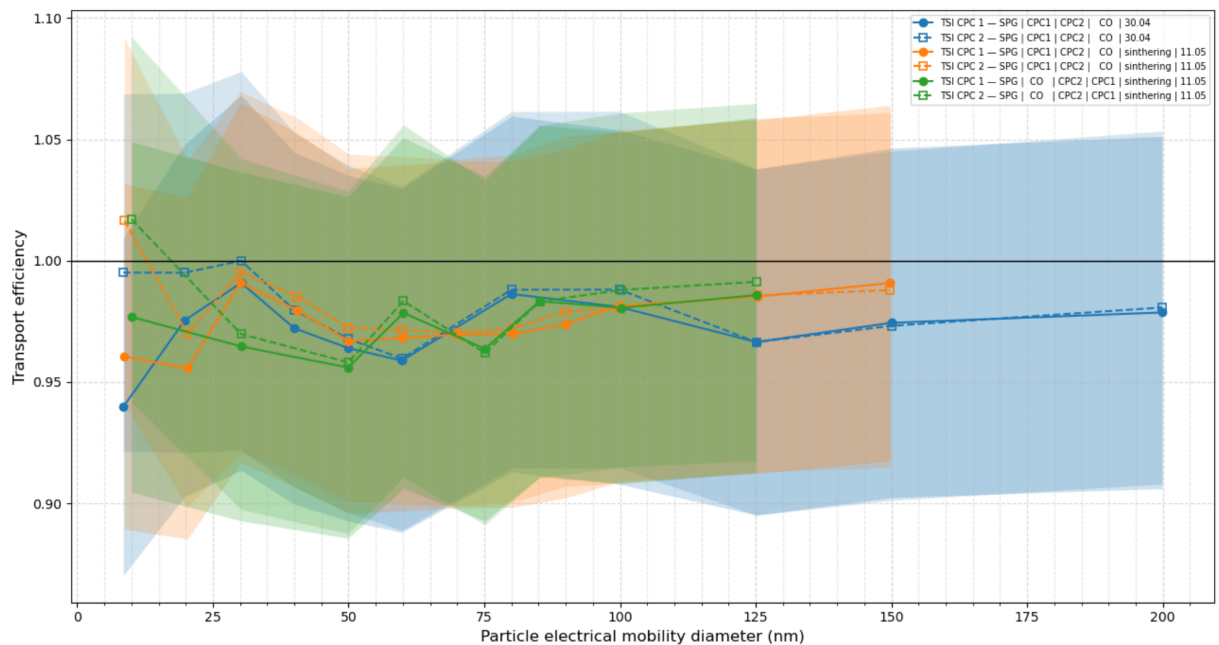


Figure 33: Transport efficiency of the three-way splitter for silver particles, calculated as the concentration ratio between TSI CPCs and the FCE, with concentrations corrected for offsets and counting efficiency.

4.3.2 Characterization of the PM2.5 Transport System

As mentioned in Section 3.7, the Grimm CPC 3 was excluded and replaced with a critical orifice of the same flow rate due to an unexpected laser error. To characterize the transport line without the Catalytic Stripper that led to the excluded Grimm CPC 3, the positions of the critical orifice and Grimm CPC 4 were swapped for the first measurement. The particles generation is performed with the SPG at a main flow rate of 2 Lmin^{-1} . The flow rate at the inlet of the transport system, measured with a TSI MFM, fluctuates between 5.58 and 5.65 Lmin^{-1} . To ensure symmetric splitting at the T-piece connecting the RAX-DMA, the FCE and the transport system, the FCE flow rate was set to 5.61 Lmin^{-1} . Before each measurement, a zero-filter test was conducted to ensure the absence of leaks, during which the zero offset - i.e., the background current - of the FCE was reset.

Figure 34 shows the concentration data collected by the Grimm CPCs 1, 2 and 4 and the FCE plotted against elapsed time. The relative difference of the mean concentration between CPCs and FCE is also plotted for the electrical mobility sizes selected by the RAX-DMA. The uncertainties for Figures in this section are computed with Gaussian error propagation, using $\pm 5\%$ CPC uncertainty, $\pm 2\%$ FCE uncertainty, the calculated SEM and $\pm 5\%$ uncertainty of the particle-size-dependent counting efficiency values provided by the last CPC calibration by the manufacturer. The counting efficiency factors are shown in Table 7.

Table 7: Counting efficiencies provided by the manufacturer, during the last calibration of the four Grimm CPCs for different particle diameters used for the correction of the transport efficiency. The uncertainty of the measurement is $\pm 5\%$

d_p (nm)	Grimm 1	Grimm 2	Grimm 3	Grimm 4
2	0.03	—	—	—
3	0.18	—	—	—
4	0.40	—	—	—
5	0.59	0.18	—	—
6	0.70	0.36	—	—
7	0.77	0.52	0.05	0.04
9	—	0.73	0.40	0.36
10	0.89	—	0.54	0.51
11	—	—	0.64	0.61
12	—	0.91	—	—
14	—	0.96	0.84	0.81
15	—	0.98	—	—
20	1.00	1.01	0.96	0.96
30	1.02	1.03	0.99	0.99
40	1.03	1.04	1.00	1.00

The background concentration of the FCE is subtracted before determining the relative difference between Grimm CPCs and FCE. The measured Grimm CPC concentrations at the plateau of the Grimm CPC's counting-efficiency curves are higher than the measured FCE concentration. Since this behavior has no physical explanation, is not expected from the measurements, and most likely arises from a problem with the FCE, the FCE concentration is adjusted by a factor of 11% to match the concentration of the Grimm CPC at particle diameters much larger than the Grimm CPC's cutoff diameter. The value of the factor is chosen because it best aligns the Grimm CPC concentration with the FCE concentration at the plateau of the Grimm CPC's counting efficiency. Possible reasons and the validity of this adjustment are discussed in Section 5.2. Figures 35 and 36 use the adjusted concentration data.

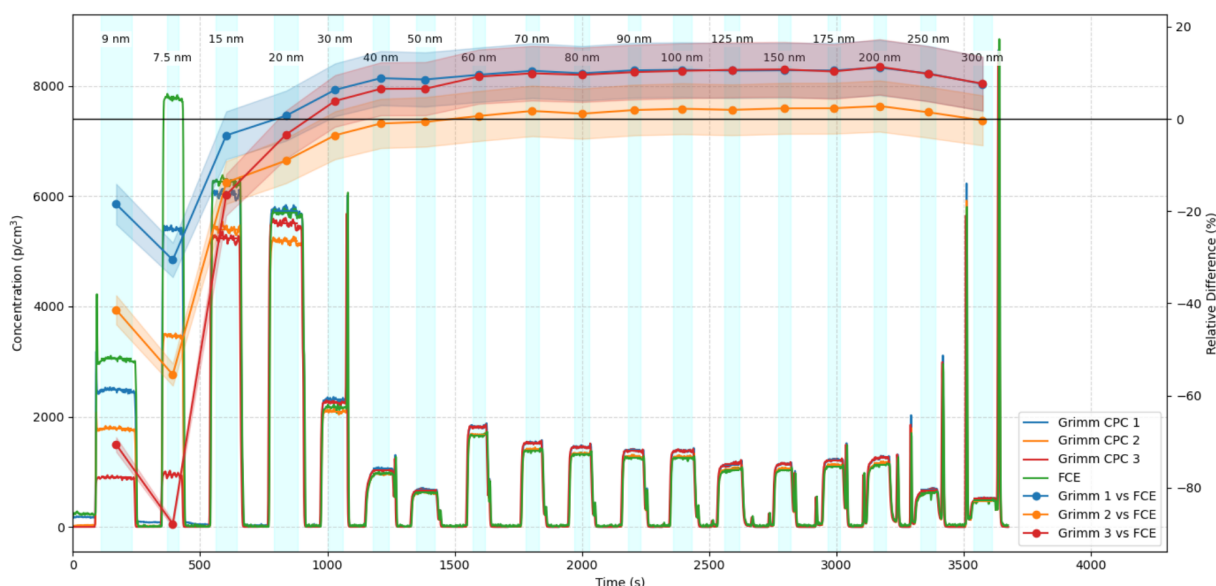


Figure 34: Uncorrected silver particle concentration measured by the Grimm CPCs 1, 2 and 4 and the TSI FCE, as well as the relative difference of the mean concentration of Grimm CPCs vs FCE, plotted against elapsed time with different selected particle sizes. The time window chosen for the mean calculation is highlighted in cyan. Grimm CPC 4 replaces the missing Grimm CPC 3 to characterize CPC 3's transport line. Since Grimm CPC 4 simply substitutes for Grimm CPC 3 and both have the same cutoff, the concentrations measured by Grimm CPC 4 are labeled "Grimm-3" in Figure 34.

It was observed that Grimm CPC 2 measures approximately 7 % lower concentrations than the other Grimm CPCs across all sizes of the plateau of the Grimm CPC's counting efficiency, even when their positions are swapped, which rules out line effects. Therefore, in subsequent Figures the concentration measured by Grimm CPC 2 is adjusted to match the others.

With the data, shown in Figure 34, the transport efficiency can be calculated as the concentration ratio of Grimm CPCs and FCE, depending on the particle size. This is shown in Figure 35. On the right-hand side of Figure 35, the efficiency parameters of the Grimm CPCs are taken into account in the calculation of the transport efficiency, using the counting-efficiency curves provided by the manufacturer. This isolates the particle diameter dependent losses attributable to the transport system. For particle sizes between 50 and 300 nm, the particle transport efficiencies for all three lines overlap or fall within the uncertainty of the measurement. Figure 36 shows the experimentally determined, counting-efficiency-corrected transport efficiency of the PM_{2.5} transport system for silver particles, compared to the theoretical transport efficiency, calculated with the PLC.

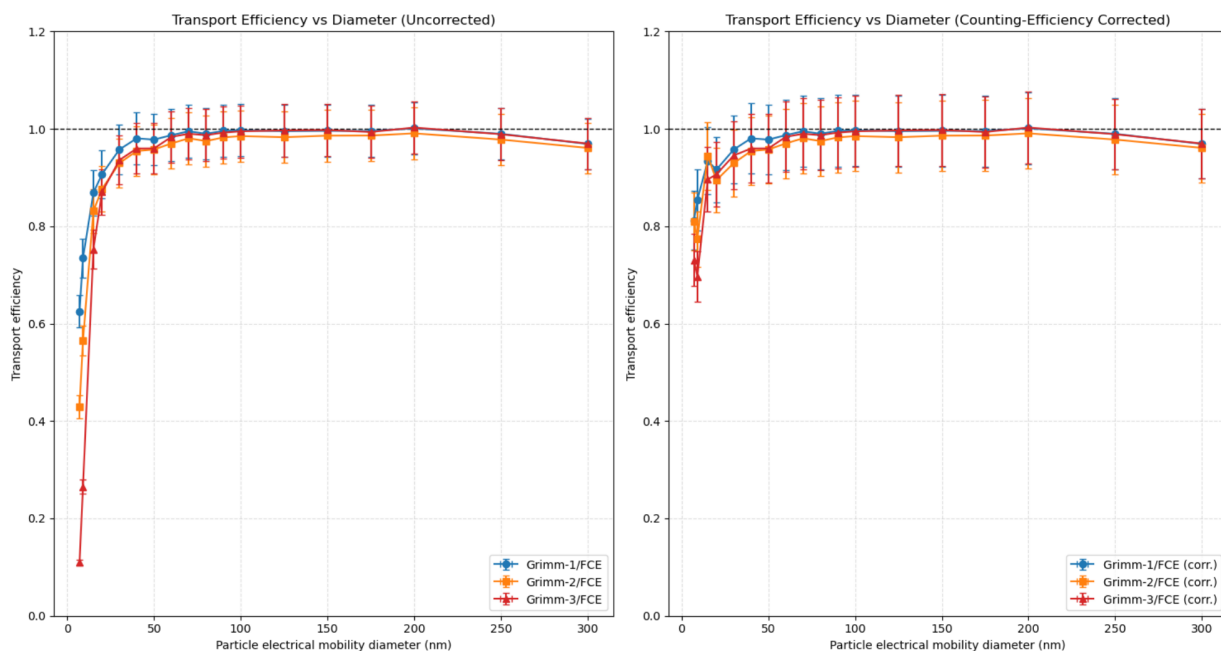


Figure 35: The left panel shows the particle-size-dependent concentration ratio between Grimm CPCs and the FCE, while on the right the transport efficiency of the PM_{2.5} transport system of the AerObs, characterized with silver particles is shown.

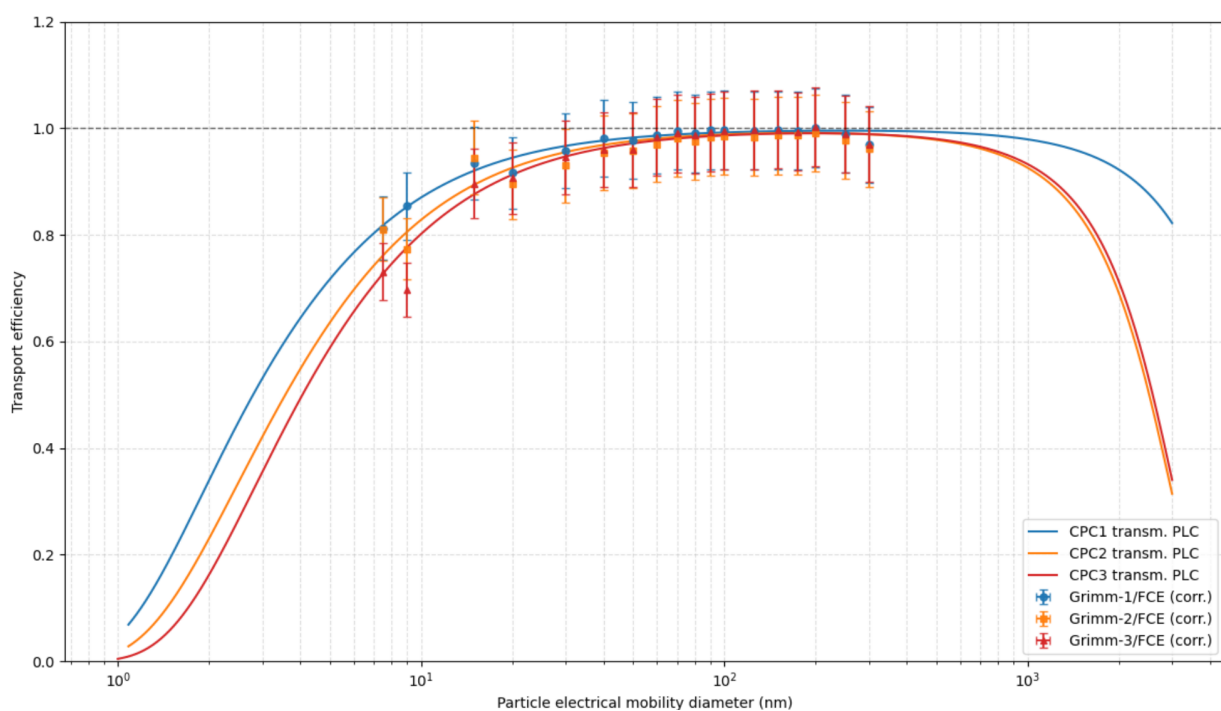


Figure 36: The experimentally determined transport efficiency of the PM_{2.5} transport line leading to the Grimm CPCs 1, 2 and 3 depending on particle electrical mobility diameter illustrated as data points, and the theoretically calculated size-dependent transmission efficiency of the same line indicated as curves. For this figure, the particle electrical mobility diameter is assumed to be equivalent to the particle diameter used in the PLC calculations.

Figure 37 shows the concentration data from Grimm CPCs 1, 2, and 4 and for the FCE, along with the relative difference between the Grimm CPC and FCE mean concentrations, plotted against elapsed time. Between the measurements of Figures 34 and 37, the Grimm CPC 4 was installed in its original position. The transport line leading to Grimm CPC 4 incorporates a Catalytic Stripper at 350 °C. Also indicated in cyan are the time intervals of size selection, as well as the corresponding particle electrical mobility diameters selected by the RAX-DMA. This presents the data used to characterize particle losses in the PM_{2.5} transport line, excluding the Grimm CPC 3 line.

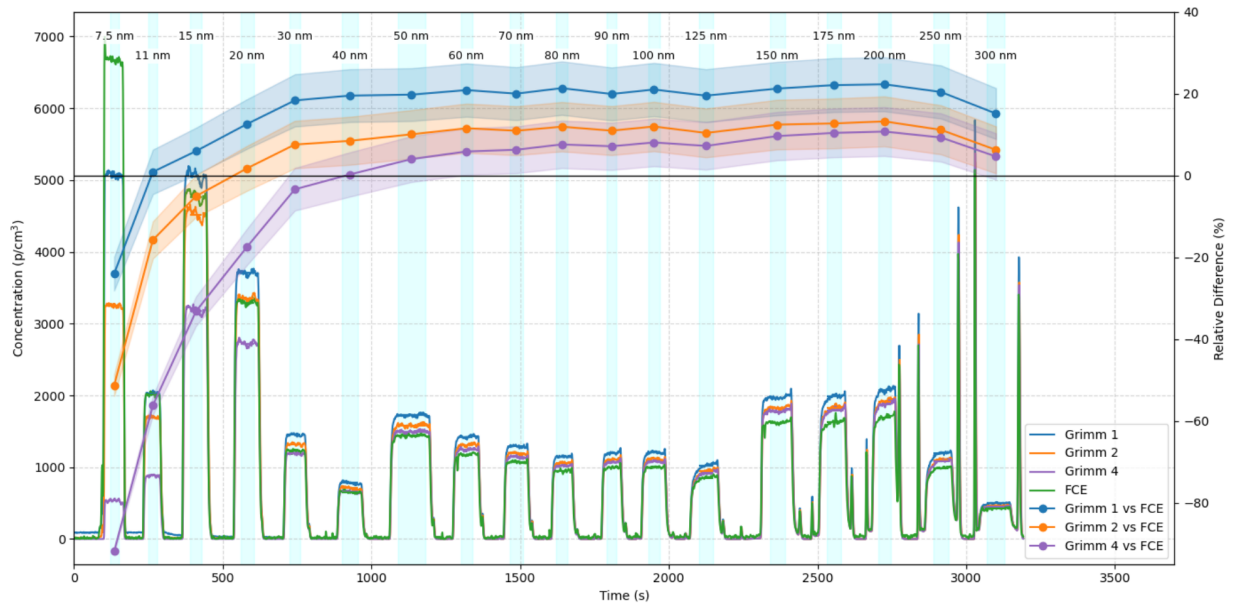


Figure 37: Silver particle concentration measured by the Grimm CPCs 1, 2 and 4 and the FCE, as well as the relative difference of the mean concentration measured by Grimm CPCs vs FCE, plotted against elapsed time with different selected particle electrical mobility diameters.

The relative difference between Grimm CPC 1 and 2 and the FCE is positive, indicating the FCE reported lower concentrations. Yet, the concentration offset between Grimm CPC 1 and 2 remains constant, suggesting the issue likely lies with the FCE. Therefore, it was deemed appropriate to adjust the FCE concentration to match the concentration of Grimm CPCs at the plateau of the counting-efficiency curves of the Grimm CPCs, which is approximately 21 %. Since the concentrations are similar between the measurements shown in Figures 34 and 37, the change in the relative difference between measurement series is unlikely to be concentration-dependent, and is more likely attributable to drift over time. On the left-hand side of Figure 38 the size-dependent transport efficiency of the transport line to Grimm CPCs 1, 2 and 4, is plotted, using the 21 % adjusted FCE concentration. As done for Figure 35, the concentration measured by Grimm CPC 2 is adjusted by 7 %. On the right-hand side of Figure 38, the CPC concentrations corrected for counting efficiency are used to determine the transport efficiency. The experimentally determined transport efficiency, shown on the right-hand side of Figure 38, and theoretical calculations of the transport efficiency of the AerObs PM_{2.5} transport system, shown in Figure 27b, are collectively illustrated in Figure 39. The experimental data is shown as data points, while the theoretical calculations are indicated as lines.

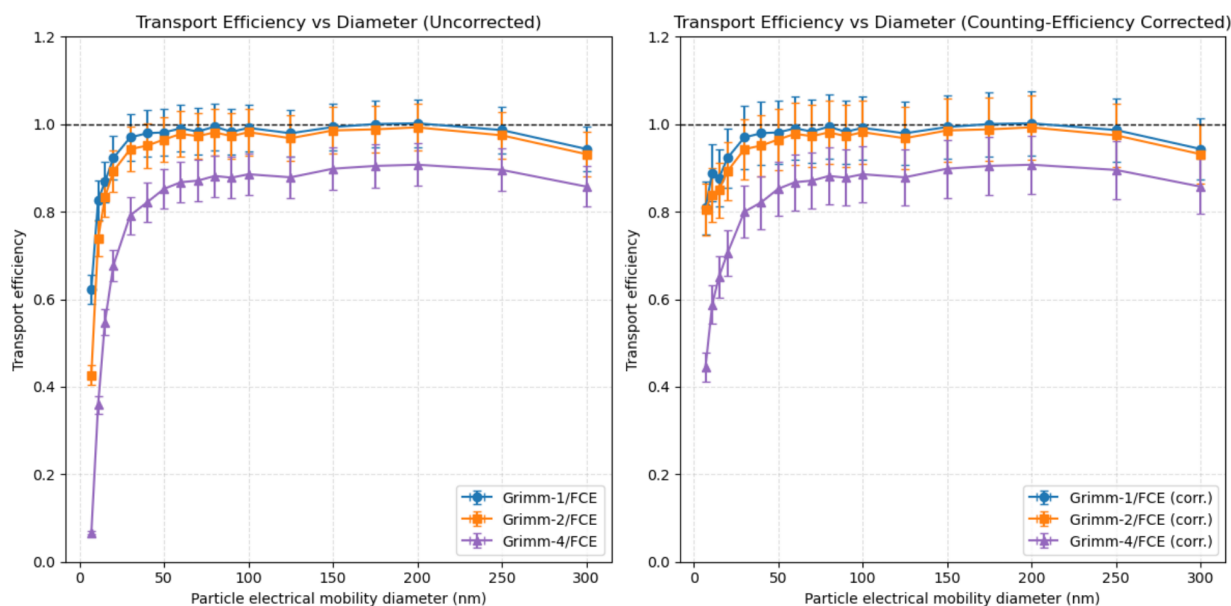


Figure 38: The size-dependent transport efficiency calculated as the concentration ratio between CPCs and FCE. On the left-hand side the counting efficiency of the CPCs is not considered, on the right-hand side the CPC concentration is counting efficiency corrected.

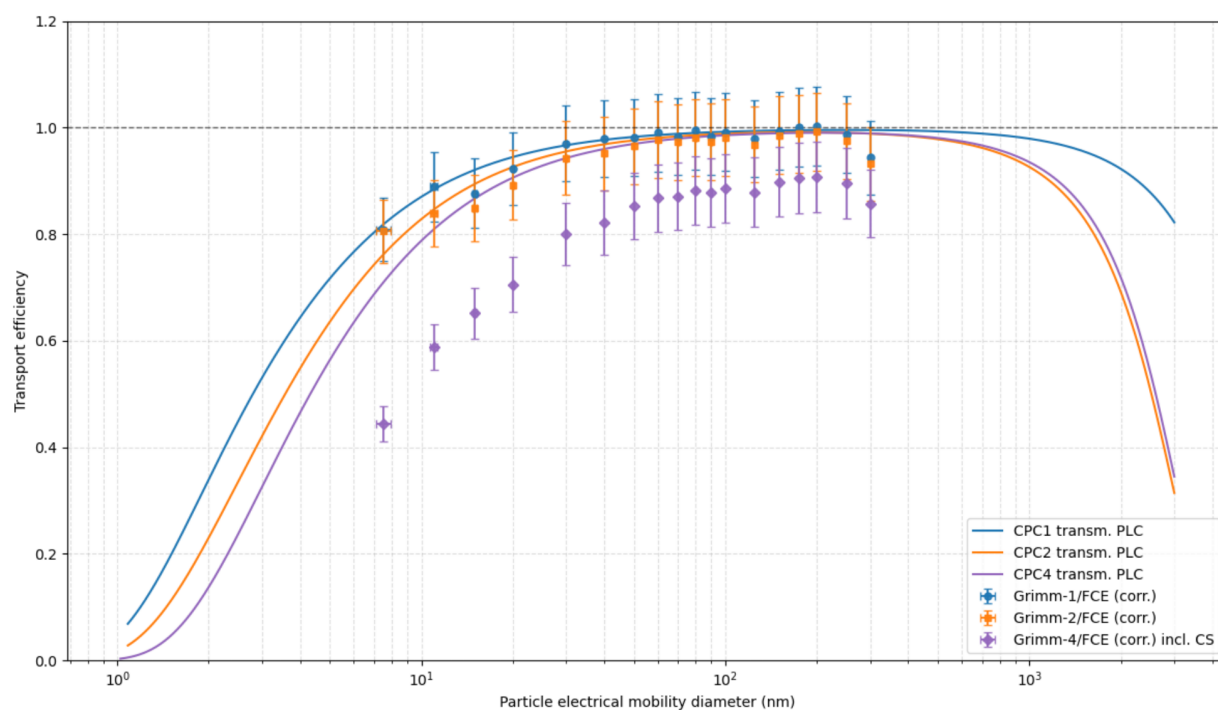


Figure 39: The experimentally determined transport efficiency of the PM_{2.5} transport line leading to the Grimm CPCs 1, 2 and 4 depending on particle electrical mobility diameter illustrated as dots, and the theoretically calculated size-dependent transmission efficiency of the same line indicated as curves. The transport line of Grimm CPC 4 includes a Catalytic Stripper. For this figure, the particle electrical mobility diameter is assumed to be equivalent to the particle diameter used in the PLC calculations.

Finally, the theoretical and experimental transport efficiency of the entire PM_{2.5} transport line, for silver particles, while excluding the vertical 3/4 inch tube and the SMPS line, is shown in Figure 40. The transport line leading to Grimm CPC 4 is equipped with a Catalytic Stripper, which amplifies particle losses.

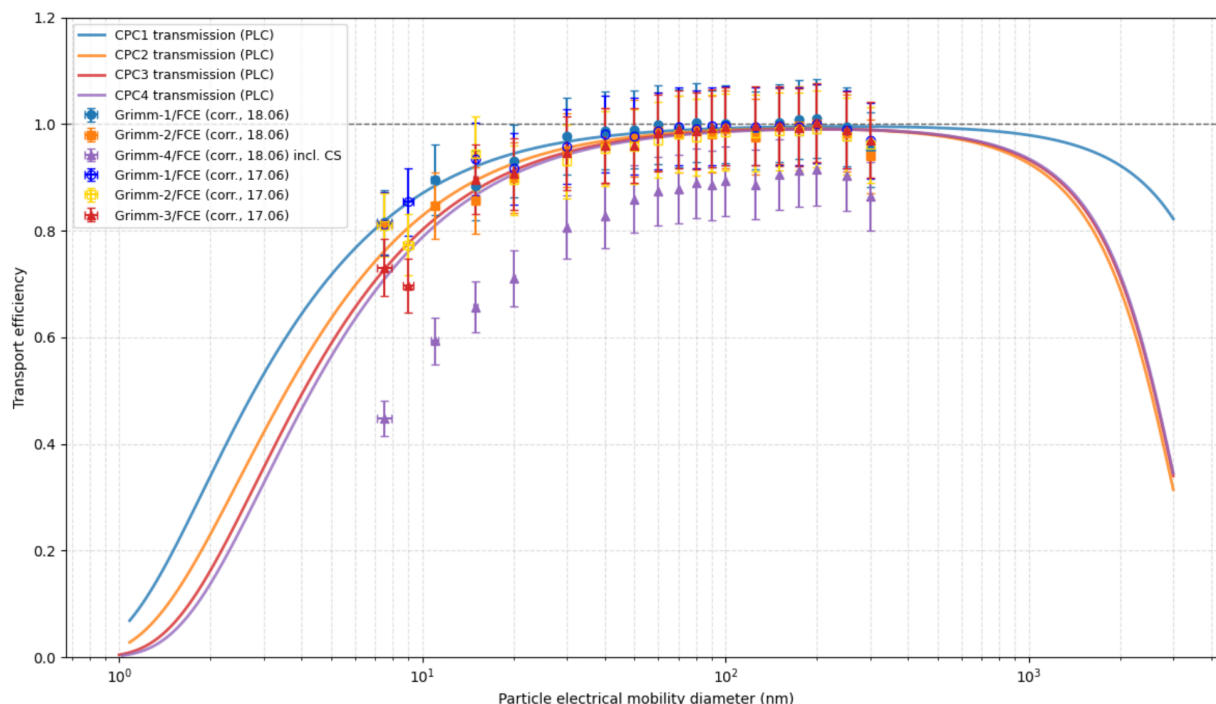


Figure 40: The experimentally and theoretically determined, particle-size-dependent transport efficiency of the PM_{2.5} transport system, for monodisperse silver particles. The CPC 4 line includes a Catalytic Stripper. For this figure, the particle electrical mobility diameter is assumed to be equivalent to the particle diameter used in the PLC calculations.

5 Discussion

5.1 Pressure Calculations and Measurements

The results shown in section 4.1 indicate that the algorithm, which uses the Darcy–Weisbach Equation 7, combined with the Colebrook relation 9 and, in particular, the Haaland approximation 10 for the Darcy friction factor f , predicts the pressure losses within the vacuum system sufficiently well, meaning calculated values lie within the uncertainties of the measurements. This is evident by the insignificant difference between the calculated and measured pressure values, shown in Figure 21b. Furthermore, an approximate calculation of the end pressure and flow rate, using Equations 4 and 12 is possible, if the correct parameters, such as the critical orifice diameter or flow rate and the pumping speed of the vacuum pump, are known. It also shows that using a measured end pressure near the vacuum pump, results in better alignments between pressure measurement and calculation than estimating the initial parameters. However, this may be attributable to the pump's unexpectedly high performance. Since the performance curve of the vacuum pump, shown in Figure 22, does not match the measured performance, correctly estimating the initial pressure became challenging. Other possible explanations, are a malfunction of the pressure sensor or lower air temperatures during the pressure measurement, compared to the 20 °C shown in the pumping speed curve. However, the final pressure of both vacuum pumps were measured. The vacuum pump, which was not in operation during the experiments, reaches a final pressure between 38 and 39 hPa, which is to be expected from Figure 22. This supports the claim that the final pressure of the vacuum pump used during the pressure measurements, is truly lower, than expected, and thus indicates that the pump creates a vacuum that exceeds expectations.

Figure 21 also shows that the vacuum pump is adequate for achieving the required vacuum at a flow rate of $6 \text{ m}^3\text{h}^{-1}$, since the measured pressure at the inlet of the vacuum line is 137 hPa (at $6 \text{ m}^3\text{h}^{-1}$). This indicates that the planned number of inlets for the AerObs extension is feasible with the vacuum pump, assuming the measurement devices and the vacuum inlets are connected with tubing with sufficiently large inner diameters.

The measurements discussed in Section 4.1 show that the CVF-400 attributes to a substantial pressure loss, which is most probably caused by the small diameter of valves inside the device. In addition, the magnitude of the pressure loss drops rapidly when the device is switched off and then continues to decrease until the catalyst cools to room temperature, suggesting a temperature dependence. The results presented in Figures 23 and 24 also show that the assumed dimensions of the CVF-400, as illustrated in Figure 13 and the consideration of the volumetric flow rate increase, due to higher temperatures, are satisfactory and are supported by pressure measurements and calculations. This does not imply that these are the actual dimensions and temperatures inside the CVF-400. Rather, the assumed parameters yield the same pressure drops as the actual ones. Figures 23 and 24 further show that the pressure criticality conditions are fulfilled for all setups discussed because the upstream to downstream pressure ratio is below the value in Equation 11 (1.8929). However, it is evident that replacing thin tubes in the exhaust line, such as 1/4 inch PFA-tubes with thicker tubes (1/2 inch PFA-tubes) results in significantly lower pressures, downstream of the critical orifices. This is especially important, if a CVF-400 is installed in the exhaust line. If possible, decreasing the length of the exhaust line further decreases pressure losses. However, the impact of the inner diameter outweighs the length effect, which can also be seen in the Darcy-Weisbach Equation 7 (U_{avg} is inversely dependent on d^2). Adjusting the length of the flow line L by a factor of two changes ΔP by a factor of two, while adjusting the inner diameter d by a factor of two changes the pressure difference by a factor of 2^4 .

At last, it is worth mentioning that pressure losses within the sampling system are approximately 0.2 Pa and thus have a negligible impact for the measurements of particle concentrations.

5.2 Analysis and Discussion of Particle Losses

The characterization of the three-way splitter has shown that silver particles of sizes between 7 and 800 nm, do not significantly prefer a certain branch over the others, which is shown in Figure 30. The agreement between the green and orange measurements, taken before and after flipping the three-way splitter, implies that it splits symmetrically. The TSI CPC connected to the central branch tends to measure a higher concentration than the other CPC (4 to 9% relative difference between 8.5 and 20 nm), especially for particles sizes smaller than 20 nm. Although this effect, as well as the particle losses within the three-way splitter, shown in Figures 31, 32 and 33, are reproducible, the high uncertainty of the measurements renders the observed difference in transport efficiency and splitting distribution insignificant but noteworthy. The difference in flow rate between TSI CPC 1 and TSI CPC 2 of approximately 6 % may have an effect on the concentration difference, because the flow rate and concentration of TSI CPC 2 are higher than those of TSI CPC 1. However, because the TSI CPC flow rates were measured only once at the beginning of the first measurement, it is difficult to determine whether the increase in relative difference stems from a further decrease in TSI CPC 2's flow rate. Furthermore, an increased difference in flow rate appears as an unlikely explanation, as these measurements comparing the middle branch to the side branches were performed before and after the green and orange sets, which show that the difference between the TSI CPCs remains approximately 4 % across all sizes. This leaves the three-way splitter itself as the most likely cause for the increased relative difference. The reason for the decreased relative difference of the mean concentration of the PSL measurement, shown in red in Figure 30, is unknown. However, the shape of the PSL measurement curve still matches the shape of the other measurements.

Since the counting-efficiency-corrected transport efficiency of the three-way splitter shown in Figure 33 is approximately 0.975 across the entire size range, no significant particle losses attributable to the three-way splitter, are observed. This is also expected, due to the small size of the three-way splitter.

As can be seen in Figure 40 the theoretical transport efficiency and the experimentally determined transport efficiency are similar for the selected silver particle size range. The theoretical transport efficiency curve almost always falls within the uncertainty of the experimental data. The few data points, where the theoretical transport efficiency does not lie within the measurement uncertainty, could be explained by the counting-efficiency-correction. The counting-efficiency curve of the Grimm CPCs is steep for small diameters (see Table 7). For example, at 7 nm the counting efficiency of Grimm CPC 4 is 0.05 and 0.15 at 7.5 nm, which means a relatively small increase in particle size (for a DMA), changes the correction factor by a magnitude of 3. Note also that the uncertainty bars shown in Figures 36, 39 and 40 of the electrical mobility diameters selected by the RAX-DMA, only consider the fluctuation of the DMA voltage. Whether the RAX-DMA actually selects the electrical mobility corresponding to the applied DMA voltage is uncertain and an uncertainty arising from the thickness of the classified aerosol outlet of the RAX-DMA is unknown.

The concentration drop in Grimm CPC 4 (Figure 37) is likely due to the added particle losses from the Catalytic Stripper, which even introduces thermophoretic losses. Thermophoretic particle losses are independent of particle size for particles much smaller and much larger than the mean free path of the gas molecules (Brockmann, 2011). This behavior can be observed from Figures 37, 38, 39 and 40.

It is worth noting that Equation 14, which the PLC employs to calculate the transport efficiency, contains a flaw. Equation 14 implies that transport efficiencies of multiple segments can simply be multiplied, resulting in the combined transport efficiency. However, the particle loss mechanisms, assume a homogeneous distribution of particles at the start of every calculation (Brockmann, 2011). This implies that for every segment, the initial distribution of particles is homogeneous, which is not true. Consequently, transport lines with the same parameters but different numbers of divisions exhibit discrepant efficiencies. Put differently, Equation 14 implies that a single line of length x does not have the same transport efficiency as two lines of lengths $x/2$ each, connected in series (assuming all other parameters are the same for both cases). This effect increases diffusional particle losses, since the homogeneous re-distribution, artificially pushes particles towards the walls, which wrongfully lowers the theoretical transport efficiency for smaller particles. On the other hand, the re-distribution of particles into homogeneity decreases sedimentary particle losses, since the particles are artificially pushed upwards at every division. This increases the theoretical transport efficiency of particles with higher mass. This effect can be avoided to an extent, by minimizing the number of segments as much as possible. However, whenever other parameters, such as flow rate, inner diameter, inclination angle or bend angle change, a new segment has to be introduced. Thus, avoiding this flaw entirely is unrealistic for a transport line, such as the PM_{2.5} transport system. This means, the theoretical transport efficiency results should be viewed with considerable uncertainty (especially for particles of sizes up to 30 nm). Therefore, the agreement between theory and experiment, despite the limitations of the calculations using Equation 14 and the PLC, may be the result of two counteracting effects.

Additionally, it is important to note that any losses attributed to the inlet head and the Nafion dryers were not determined in this thesis. The inlet head upper cutoff curve from Patel and Aggarwal (2022) is accepted as provided. Nafion dryers are assumed to exhibit particle losses similar to typical tubes. Nevertheless, to characterize the sampling system completely, a check of the validity of these assumptions ought to be made. Furthermore, the transport line leading to the TSI SMPS was not determined experimentally. However, since theory and experiment seem to compare rather well (calculated transport efficiency lies within uncertainties of measured transport efficiency), the theoretically determined transport efficiency for sizes between 7.5 and 300 nm can be used, instead.

Furthermore, for the data evaluation the concentration of Grimm CPC 2 was adjusted by 7 %, to match the concentration levels measured by Grimm CPC 1. This was deemed appropriate, since after changing transport lines, CPC 2 still measured a 7 % lower concentration than Grimm CPC 1 and 4, therefore discarding line effects as the reason for the concentration difference. This behavior is likely due to an issue within Grimm CPC 2, since the concentrations of Grimm CPC 1 and 4 (installed in Grimm CPC line 3), shown in Figure 34 overlap for particle sizes at the plateau of their respective counting-efficiency curves. Additionally, for the measurements shown in Figures 34 and 37, the particle concentration of the FCE was adjusted by 11 % and 21 %, respectively, to match the concentration of the Grimm CPCs at sizes where the Grimm CPCs are not affected by the counting efficiency. Furthermore, between measurements shown in Figures 34 and 37, only the position of Grimm CPC 4 was swapped with the critical orifice replacing the Grimm CPC 3. The setup was not changed otherwise. No explanation for the sudden drop in FCE concentration, compared to the concentration measured with Grimm CPC 1 and 2, was found, which indicates an issue within the FCE. This behavior was also observed by a colleague during attempts at calibrating the Grimm CPCs. During multiple calibration experiments, the FCE concentration was significantly lower than the Grimm CPC concentration.

In addition, the FCE's background current (which is converted into a concentration) was very high, sometimes making measurements of concentrations below 500 pcm^{-3} impossible. The FCE has also had multiple engine errors in the past months. For these reasons we sent the FCE back to the manufacturer for maintenance. Since the FCE has had multiple issues, adjusting its concentrations to match the Grimm CPC's concentration was a reasonable approach.

In Figure 40 a drop in the experimental transport efficiency, for all Grimm CPCs, can be observed, for particle sizes of 250 and 300 nm. This decrease is not supported by the theoretical calculation of the transport efficiency, as can be seen in Figure 40. Although the curves lie within the measurement uncertainties, the effect was observed in two independent series, which argues for a physical cause. One possible explanation is the theoretical model, which predicts decreasing transport efficiency for particles with higher mass, as discussed above. However, the density is constant and the size dependence is already considered in the calculation of the theoretical transport efficiency. Alternatively, the presence of multiply charged particles could account for the observation. The fraction of multiply charged particles increases with particle size (Flagan, 2011). For a particle size of 200 nm, approximately 20 % of particles are singly charged, 13 % are doubly charged and 6 % are triply charged (Flagan, 2011). Since multiple charges on a single particle would be counted as multiple particles in the FCE, but as a single particle in the CPC, the difference in concentration between Grimm CPCs and FCE would increase, which would decrease the transport efficiency. This effect could theoretically explain the drop in transport efficiency for the largest selected particle sizes, since the probability to attain multiple charges increases with increasing particle size. However, to be selected by the DMA the doubly charged particles would have to have twice the diameter to have the same electrical mobility diameter as a singly charged particle of that given size. Therefore, particles with diameters of 500 and 600 nm would need to be present in the aerosol flow of the SPG for this effect to play a role. Since during experiments using the SPG we select sizes on the right arm of the size distribution generated by the SPG, this effect should be almost negligible since the concentration of particles with double the diameter is marginal.

The difference in transport efficiency between the transport lines leading to Grimm CPC 3 and Grimm CPC 4, are likely attributable to the Catalytic Stripper. In that device, particles have to pass through a catalyst, which increases particle losses. Furthermore, since the Catalytic Stripper has a temperature of 350°C , thermophoretic particle deposition may lead to particle losses. However, additional losses within the Catalytic Stripper, are not discussed in this thesis.

Overall, the combination of theoretical and experimental characterization presented in this thesis demonstrates that the AerObs vacuum and PM_{2.5} transport systems perform largely as expected, with identified discrepancies pointing toward specific areas for future assessment.

6 Conclusion

This thesis investigated the pressure distribution within the University of Vienna's AerObs vacuum system and PM2.5 sampling system, as well as the particle deposition and transport efficiency within the PM2.5 transport system. The pressure distribution was determined by combining measured pressure values within the vacuum system and theoretical calculations of the pressure difference, using the Darcy-Weisbach Equation 7. Likewise, the analysis of the particle deposition and thus the transport efficiency within the PM2.5 transport system was performed by combining experimental findings with theoretical results using the PLC. The splitting distribution and particle deposition within a small three-way splitter was performed first to check whether the three-way splitter is suitable for the transport system, followed by the analysis of the transport efficiency of the PM2.5 transport system, as shown in Figure 40.

The results of the pressure analysis of the AerObs vacuum system show that the vacuum pumps provide sufficient vacuum and flow for the planned number of inlets that would require a volumetric flow rate of $6 \text{ m}^3\text{h}^{-1}$. Additionally, the results of the pressure calculation suggest that an exhaust line that primarily uses 1/2 inch PFA-tubing will most likely maintain the required critical pressure downstream of the orifices, even with the CVF-400 included in the setup. Depending on the setup of the exhaust line, the CVF-400 can introduce significant frictional pressure losses. In the setups analyzed in Section 4.1 the pressure drop attributable to the CVF-400 ranges from 130 to 300 hPa. By contrast, pressure losses in the sampling system, as well as in the larger diameter vacuum tubes are negligible compared to those of the exhaust line. Given the initial parameters and the exhaust line dimensions, using the pressure distribution algorithms would suffice to verify the operability of the setup of interest.

The results of the three-way splitter characterization show that for the employed size range, particle losses, as well as branch-dependent splitting preferences are insignificant and lie within the uncertainty of the measurement. Therefore, the three-way splitters are suited for splitting a flow of silver aerosol with diameters between 7 and 800 nm. The theoretical analysis of particle losses within the three-way splitter, calculated with the PLC, further support this claim. However, the TSI CPC connected to the middle branch measured an approximately 4 to 9 % higher concentration of particles compared to both other branches, for silver particles smaller than 20 nm. It is unclear whether this effect is attributable to the three-way splitter or to other factors, such as different counting efficiencies or the different flow rates of the TSI CPCs. Despite the large measurement uncertainty (approximately $\pm 8 \%$), the effect appears reproducible and therefore warrants further investigation to isolate its cause.

The analysis of the size-dependent transport efficiency of the PM2.5 transport system, performed with four Grimm CPCs and the FCE shows that particles between 7.5 and 300 nm behave as predicted by theory, although this agreement may partly reflect counteracting biases in the theoretical calculation rather than a fully independent validation (see Section 5.2). While particle losses are negligible for sizes between 30 and 300 nm, smaller particles are lost due to diffusion, decreasing the transport efficiency to the Grimm CPC 1 ($d_{50} = 4.5 \text{ nm}$) by up to 18 %, to the Grimm CPC 2 ($d_{50} = 7 \text{ nm}$) by up to 19 %, and to the Grimm CPC 3 ($d_{50} = 10 \text{ nm}$) by up to 30 %. Due to a Catalytic Stripper incorporated into the Grimm CPC 4 ($d_{50} = 10 \text{ nm}$) line, up to 55 % of silver particles are lost before reaching Grimm CPC 4. When using the PM2.5 sampling system to monitor ambient particle number concentration, it is recommended to account for particle losses within the transport system (especially for particles smaller than 20 nm) in order to determine the "true" ambient particle number concentration. Since experimental and theoretical results agree, the transport efficiency of the PM2.5 system could be estimated with the PLC for particles of lower, more realistic density (while considering the limitations explained in Section 5.2).

7 Outlook

The results of the characterization of particle losses in the PM_{2.5} sampling system provide valuable insights into the transport efficiency for silver particles between 7.5 and 300 nm. However, to fully characterize the entire PM_{2.5} sampling system of the AerObs, some further steps are necessary. Although the findings suggest that the experiment and theory agree, and thus the remaining transport efficiency of the transport system, could be calculated with the PLC, experimental characterization is recommended. Especially selecting other sizes outside the range of 7.5 to 300 nm would characterize the size-dependent transport efficiency for all particles aspirated by the PM_{2.5} inlet. Furthermore, the experiments presented in this thesis mostly utilize silver particles which have a density of 10.50 g cm^{-3} . Therefore, the transport system is specifically characterized for silver particles and particles of the same density. Particles with smaller densities have less inertia and thus behave differently. Since most atmospheric aerosol particles, such as ammonium sulfate, sea salt, mineral dust and black carbon do not have densities greater than 3 g cm^{-3} , the transport efficiency of the PM_{2.5} transport system ought to be characterized for these particles as well (Hinds and Zhu, 2022). Additionally, using well-calibrated, low-uncertainty CPCs, FCEs and DMAs would strengthen the characterization.

Verifying the validity of the assumption that particle losses within Nafion dryers compare to those in regular tubes, is also recommended. Zoller et al. (2020) show that more singly charged particles are lost in the Nafion dryers than uncharged particles, indicating possible particle losses due to electrostatic deposition. In addition, Zoller et al. (2020) found that their Nafion dryer (operated at 0.9 L min^{-1}) had the highest share of diffusional losses among the components of their sampling system, for particles with a diameter of 10 nm. Furthermore, characterizing the inlet efficiency of the DIN EN 12341 inlet head to check whether the upper cutoff of $2.5 \mu\text{m}$ is accurate, is advised. Since the sampler effectiveness of the PM_{2.5} inlet head is characterized for $1 \text{ m}^3 \text{ h}^{-1}$, either increasing the flow rate or characterizing it for the lower flow rate is recommended if the inlet head continues to be operated at a different volumetric flow rate than $1 \text{ m}^3 \text{ h}^{-1}$ in the future.

To improve the transport efficiency, implementing isokinetic flow splitters to ensure an increased flow rate at the inlet, is recommended. A possible design for a PM_{2.5} isokinetic flow splitter is provided in the Appendix 9.1. Ideally, after incorporating a suitable isokinetic splitter into the PM_{2.5} transport system, adjusting the inlet flow rate to the required $1 \text{ m}^3 \text{ h}^{-1}$ and finalizing the setup, the transport efficiency of that system should be characterized again using particles that are represented in the atmosphere.

Furthermore, the transport efficiency should then be considered in the measurement of ambient particle concentration. Since the SMPS acquires the number size distribution of a five minute time interval, the size distribution could be used to correct the concentrations for the size-dependent particle losses within the PM_{2.5} transport system. This would result in more accurate estimates of ambient aerosol particle concentrations.

8 AI Disclosure

I used AI-based tools, such as ChatGPT and claude.ai to assist with code refactoring, grammar and style editing, and translation, finding synonyms as well as to help locate and format citations. All AI outputs were critically reviewed and verified by me. I checked and corrected refactored code, validated translations for accuracy and meaning, and ensured that all references and citations correspond to real sources. No AI-generated content is presented as my own without substantial review and revision, and the intellectual contribution, scientific content, data analysis, interpretations and conclusions presented in this thesis are my own. The use of AI complied with my institution's guidelines and applicable ethical standards.

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9 Appendix

9.1 Re-design of the PM2.5 Isokinetic Flow Splitter

Due to a design flaw of the previous isokinetic flow splitters, the emergence of leaks, was inevitable. Numerous attempts of resealing the leaks were made, mostly with ceramic glue. Welding the leaks shut was not possible, due to their inaccessibility.

For this reason, the isokinetic flow splitters were re-designed. The designs main objectives are minimizing particle losses, ensuring hermeticity and splitting the particle flow evenly among the five flow-paths. The new design of the PM2.5 isokinetic flow splitter has a conical body and five 1/4 inch sampling probes, which are bent to enable isoaxial sampling. Figure 41 shows a sketch of the PM2.5 isokinetic flow splitter in SolidWorks (Dassault Systèmes SolidWorks Corp., 2024). The sampling probe in the center, is connected to the TSI SMPS 3938. Thus, the sampling flow rate is 1 Lmin^{-1} , resulting in a mean fluid velocity of 1.02 ms^{-1} inside the sampling probe. The remaining four sampling probes are equally spaced around the central probe at a fixed radius, providing the most symmetric geometry. The sampling flow rate is 0.6 Lmin^{-1} for each 1/4 inch probe, equating to a mean fluid velocity of 0.610 ms^{-1} . The cylindrical body in which the five sampling probes are placed, has an inner diameter of 22 mm, which, considering the initial flow rate of 16.7 Lmin^{-1} , equals to a mean flow velocity of 0.614 ms^{-1} .

Additionally, the base plate of the isokinetic flow splitter body, contains four excess flows, with 3.31 Lmin^{-1} each. The four tubes mirror the sampling probe layout but are rotated by 45° relative to the other sampling probe tubes. This is better visible in Figure 42, which shows the top view of the isokinetic flow splitter. The excess flow enables isokinetic sampling as a result of an increased velocity and reduces the residence time of aerosol particles between the inlet and the isokinetic flow splitter.

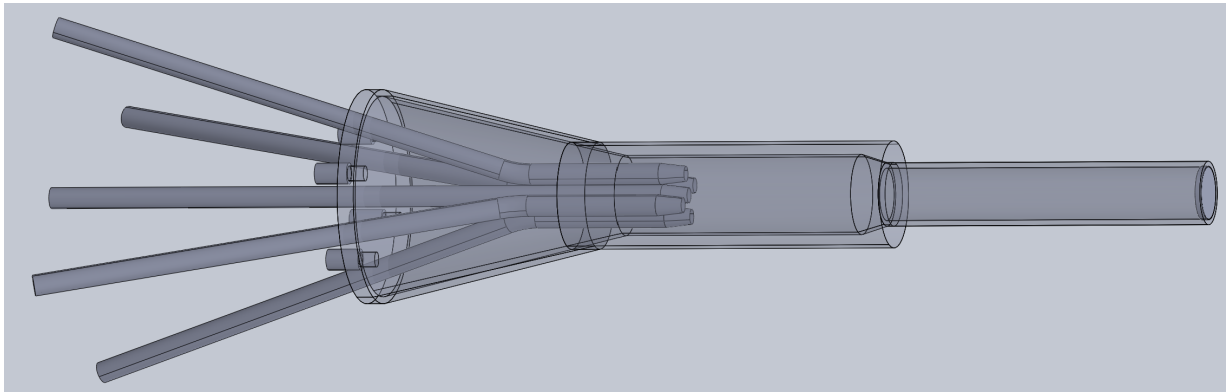


Figure 41: New design of the PM2.5 isokinetic flow splitter demonstrated in SolidWorks (Dassault Systèmes SolidWorks Corp., 2024). The isokinetic flow splitter will be installed vertically.

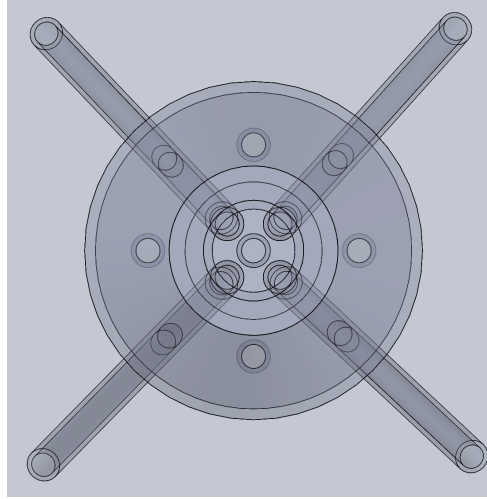


Figure 42: The top view of the new design of the PM2.5 isokinetic flow splitter demonstrated in SolidWorks (Dassault Systèmes SolidWorks Corp., 2024). The 1 Lmin^{-1} sampling tube is in the center, while the four 0.6 Lmin^{-1} sampling tubes are forming a cross. The four excess flow outlets are aligned in a plus-shaped arrangement.

Using Equations 17 and 18 the flow rate parameters and dimensions of the isokinetic flow splitter presented in Figure 41, the particle concentration ratio between the flow inside and outside the sampling probe is calculated. A size-dependent plot of the concentration ratio of particles with a density of 2.7 gcm^{-3} is shown in Figure 43. Figure 43a shows the case for the outer sampling tubes that have a flow rate of 0.6 Lmin^{-1} , while Figure 43b shows the case for the central sampling tube that has a flow rate of 1 Lmin^{-1} .

The outer sampling probes provide near isokinetic sampling, yielding negligible bias for particle sizes up to $2.5 \mu\text{m}$, whereas the central probe shows a 7 % reduction in concentration at $2.5 \mu\text{m}$ due to an imbalance in the velocity ratio.

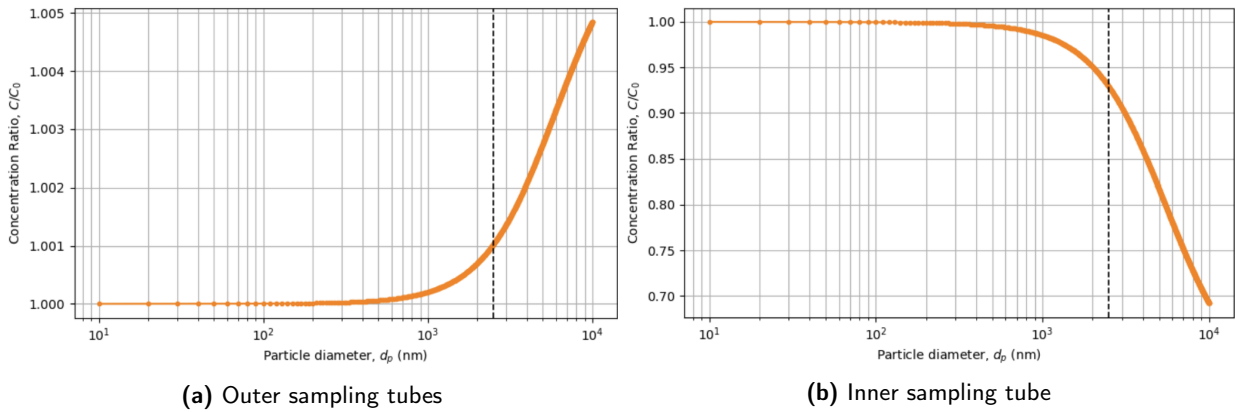


Figure 43: Concentration ratio depending on particle diameter for the sampling tubes of the newly designed isokinetic flow splitter. A particle density of 2.7 gcm^{-3} is selected. The vertical dashed line indicates the $2.5 \mu\text{m}$ cutoff of the inlet. (a) shows the concentration ratio depending on particle sizes for the four outer sampling tubes with a flow rate of 0.6 Lmin^{-1} (b) shows the size-dependent concentration ratio for the inner sampling tube, with a flow rate of 1 Lmin^{-1} .

In Figure 44 the calculation of the pressure distribution is performed for a switched off but not fully cooled

down CVF-400, where the temperature has reached approximately 250 °C.

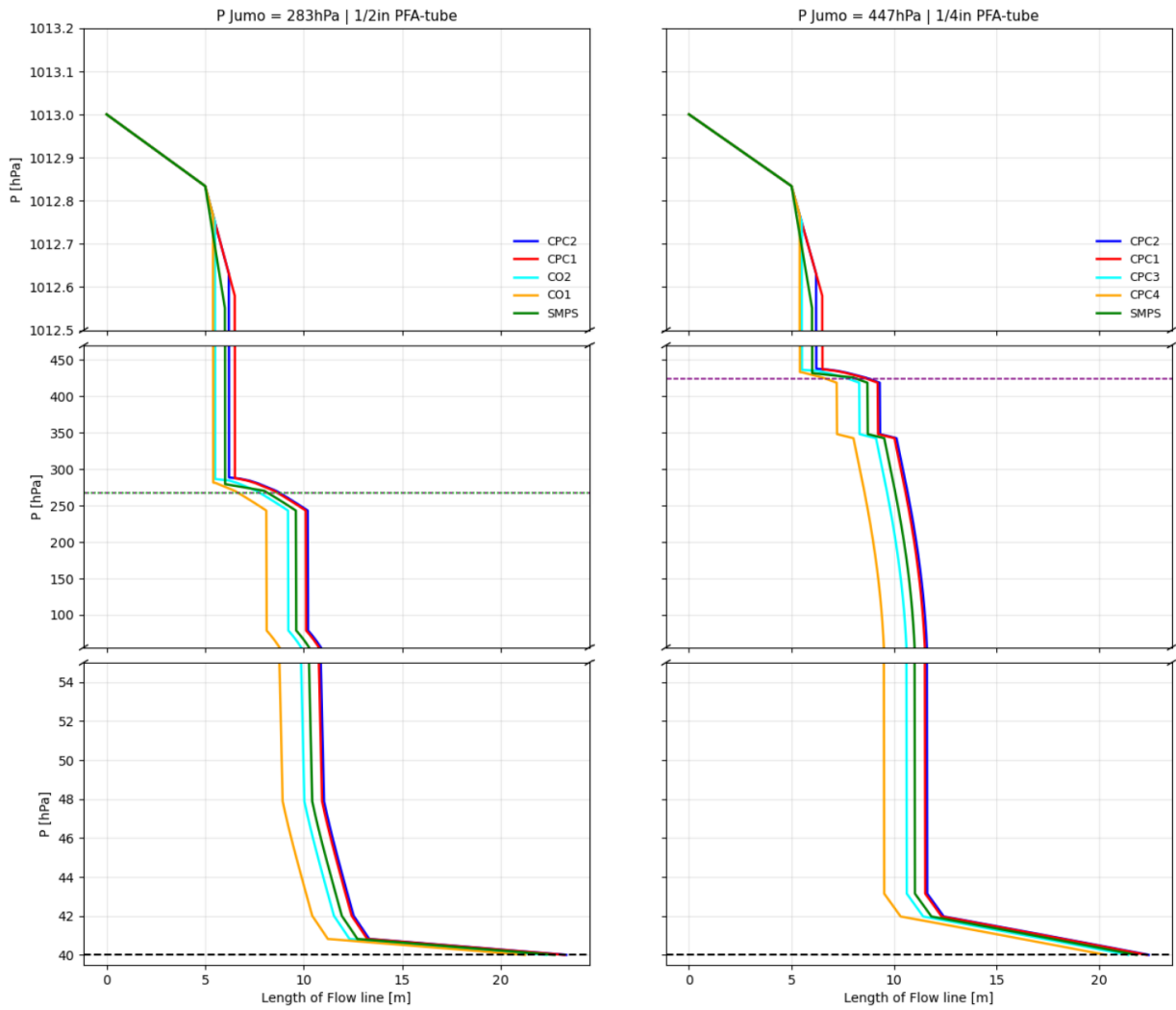


Figure 44: The absolute pressure distribution of two different setups of the PM2.5 sampling and vacuum line, while including the CVF-400 at roughly 250 °C. The purple dashed line indicates the calculated pressure value at the position of the pressure sensor in the setup, while the lime green dashed line shows the measured pressure value. The left column of plots shows the pressure distribution with an 1/2 inch thick exhaust tube after the CVF-400, while the right column of plots shows the case with an 1/4 inch thick exhaust tube.

The following Figures 45 to 51 show a collection of measurement series of the three-way splitter particle-loss and splitting-performance characterization.

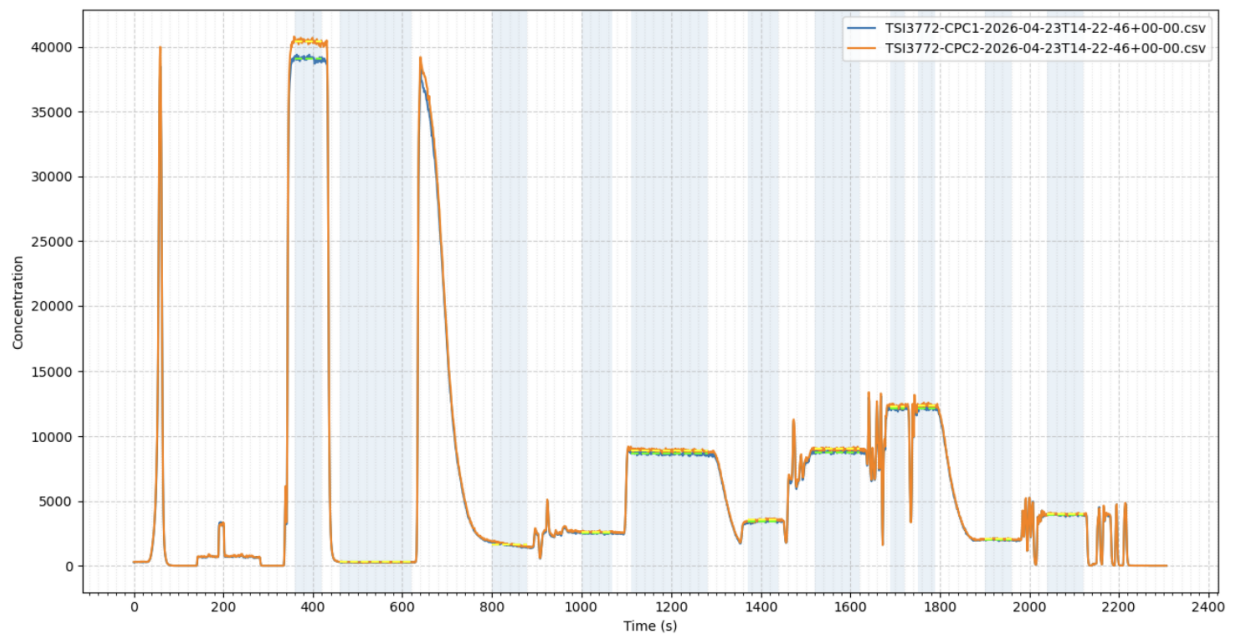


Figure 46: Second part of the raw concentration data of the three-way splitter characterization experiment, performed on 23.04.2026.

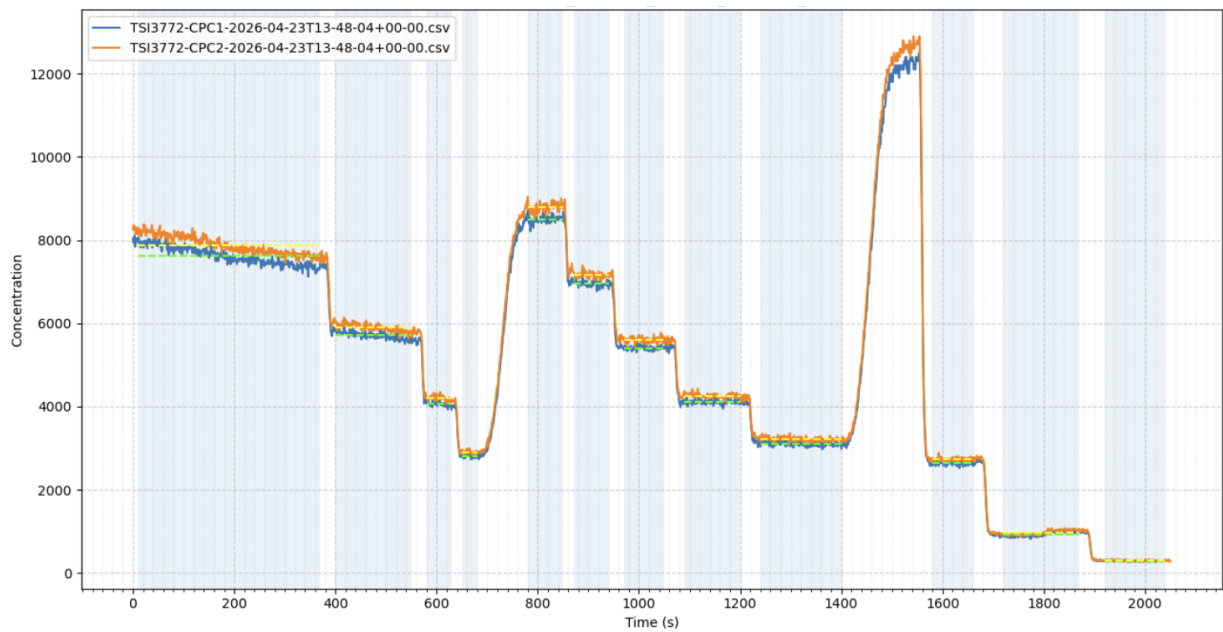


Figure 45: First part of the raw concentration data of the three-way splitter characterization experiment, performed on 23.04.2026.

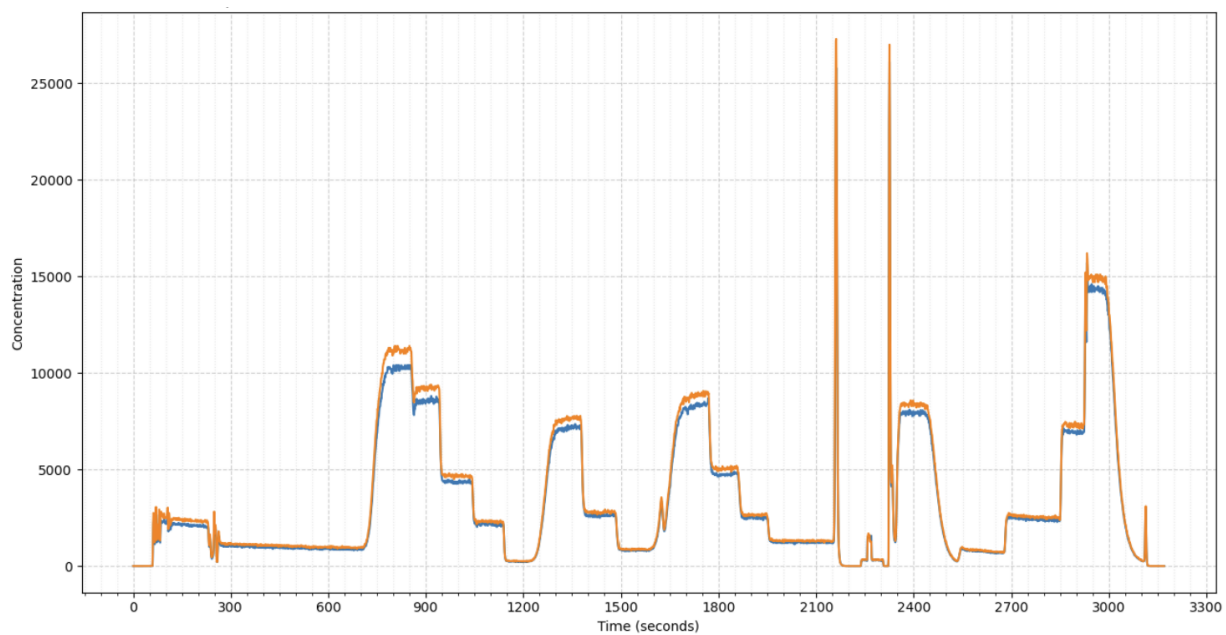


Figure 47: Raw concentration data of the three-way splitter characterization experiment, performed on 28.04.2026.

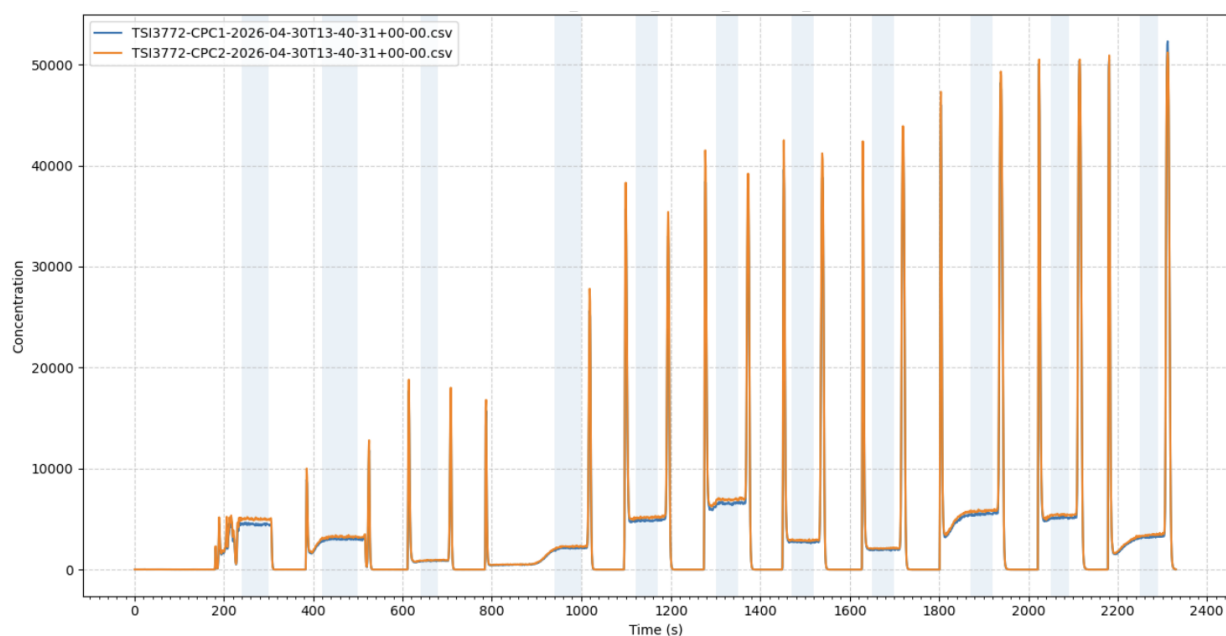


Figure 48: Raw concentration data of the three-way splitter characterization experiment, performed on 30.04.2026.

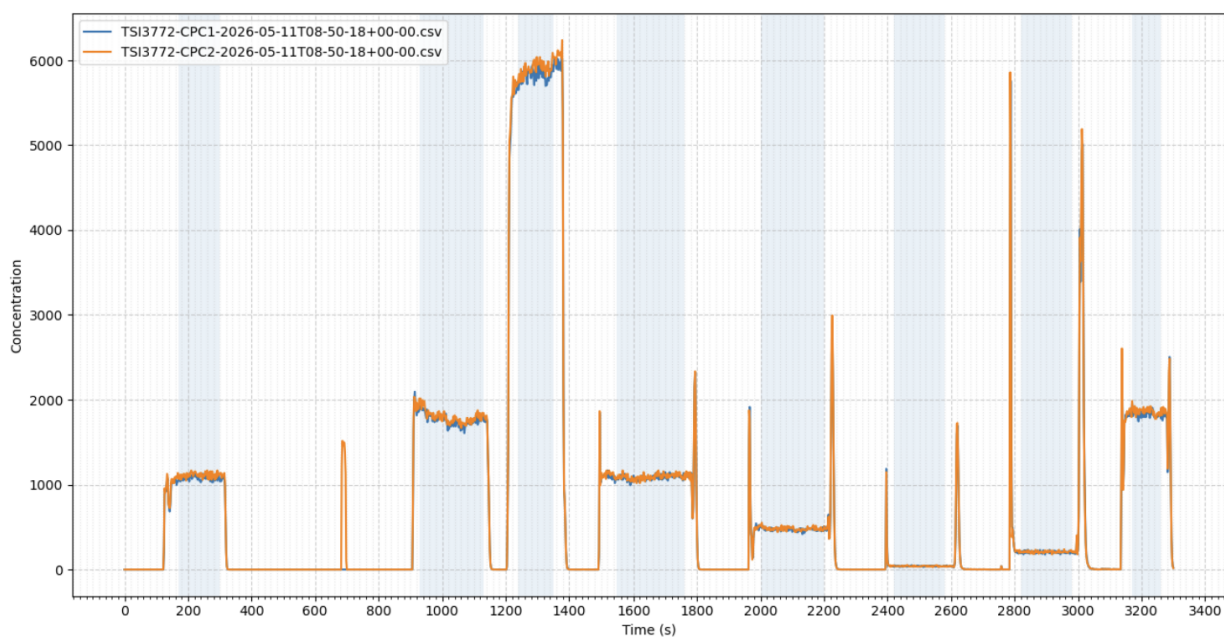


Figure 49: Raw concentration data of the three-way splitter characterization experiment with PSL, performed on 11.05.2026.

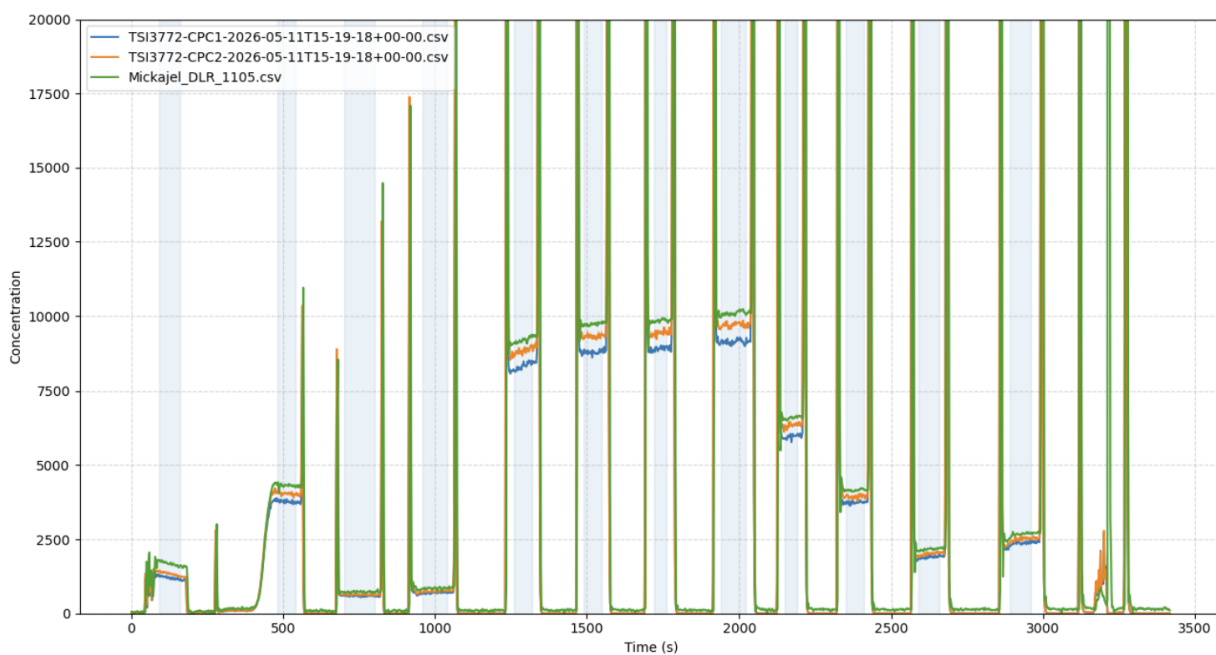


Figure 50: First part of the raw concentration data of the three-way splitter characterization experiment, performed on 11.05.2026. The FCE data is shown in green.

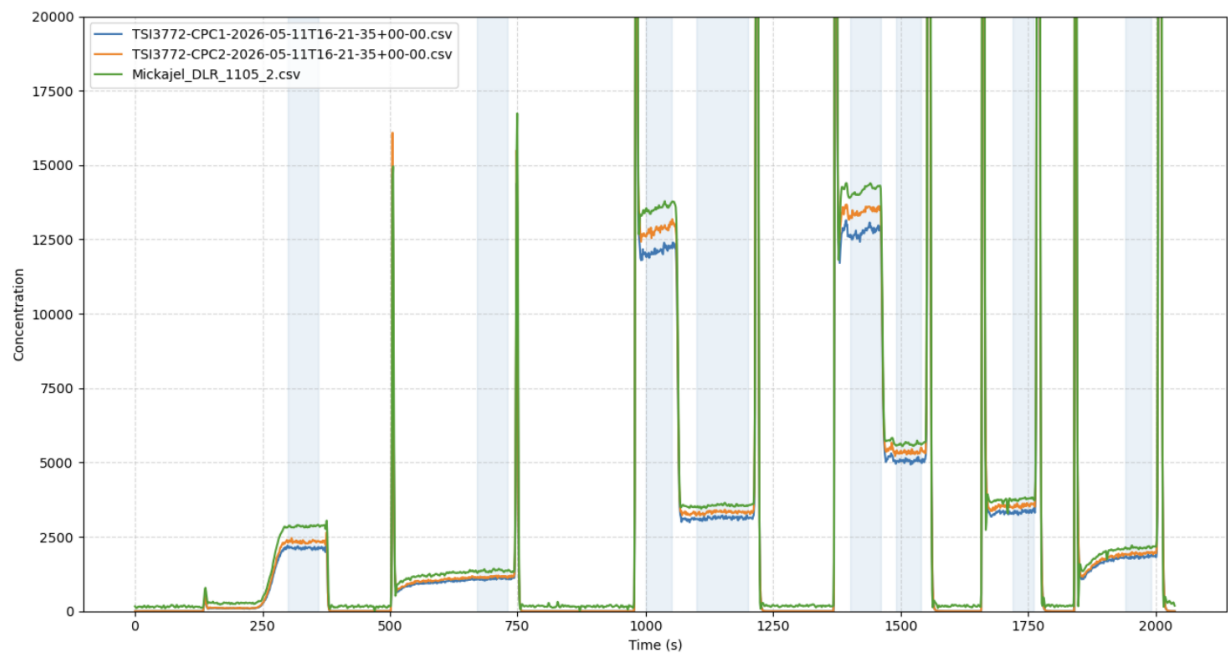


Figure 51: Second part of the raw concentration data of the three-way splitter characterization experiment, performed on 11.05.2026. The FCE data is shown in green.