Expanded Polytetrafluoroethylene Membrane-Based Humidification System for Aerosol Light Scattering Measurements

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***Abstract*—Atmospheric aerosols influence Earth's energy budget through scattering, absorption, and cloud condensation nuclei (CCN) activation, yet uncertainties persist in quantifying their effects. Hygroscopic growth in humid conditions alters aerosol scattering and CCN potential, making relative humidity (RH)-dependent scattering measurements essential for climate models and satellite validation. However, long-term datasets remain limited. This research improves the humidification system used to measure the aerosol light scattering humidity enhancement factor f(RH) at the Appalachian Atmospheric Interdisciplinary Research facility (AppalAIR) at Appalachian State University. Laboratory tests and modeling studies were conducted to enhance the control and reliability of expanded polytetrafluoroethylene (ePTFE) membranes which control the RH of the sample air stream. To my knowledge, such studies characterizing the RH response of ePTFE have not been performed before. A new membrane-based humidifier was designed and manufactured, and appropriate testing and control methods were developed. For the first time, the humidification capability of ePTFE was quantified by measuring RH changes across the membrane as a function of water temperature. Testing confirmed the functionality and effectiveness of the redesigned ePTFE humidifier. The new humidifier was deployed at AppalAIR, providing reliable f(RH) measurements during a two-month field campaign and remains in place for long-term monitoring.**

***Index Terms*—Aerosol measurements, Humidification, Relative Humidity, Control.**

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I. Introduction

ATMOSPHERIC aerosols, defined as liquid or solid particles suspended in a gas [1], play a critical role in the Earth's climate system and human health. These particles influence the Earth's radiation balance by scattering and absorbing solar radiation, which leads to direct radiative forcing [2], [3]. Aerosols can also act as CCN, altering cloud properties such as brightness, lifetime, and precipitation patterns [4], [5]. The net radiative effect of aerosols is primarily a cooling one, partially offsetting the warming caused by greenhouse gases, though significant uncertainties remain [3]. One of the main challenges in quantifying aerosol radiative forcing arises from the spatial, temporal, and compositional variability of aerosols [6]. Aerosols can change in size, shape, and chemical composition depending on ambient RH, making their optical properties highly variable [7]. To achieve consistency, many long-term aerosol measurements are performed under dry conditions, as recommended by the World Meteorological Organization [8]. However, models do not account for all physical affects and measurement in an international comparisons show inconsistencies [9], [10]. The scattering enhancement factor $f(RH, \lambda)$, defined as the ratio of the aerosol light scattering coefficient at a given RH to that at dry conditions, is crucial for accurate climate modeling and remote sensing validation [11], [12]. Aerosol types such as marine aerosols generally exhibit high f(RH) values, while biomass burning and mineral

dust aerosols typically show lower values [13], [14]. Accurate characterization of f(RH) is therefore essential for improving climate predictions and understanding aerosol-cloud interactions.
This study focuses on the development and implementation of an ePTFE membrane-based humidification system for aerosol light scattering measurements. This system aims to provide precise control of RH for aerosol samples, thereby enabling accurate determination of $f(RH)$ in laboratory and field settings. The following sections will outline the methodology, results, and implications of this work, contributing to the broader understanding of aerosol optical properties and their impact on climate.

II. Experimental Setup and Methodology

Multiple approaches for the humidification of aerosol sample streams are possible. Most established for aerosols are two different membrane-based methods. Firstly, Zhou et al. developed a two level humidifier system, which control RH in the sample stream with humidified purge air [15]. The concept consists of a supplementary humidifier for purge gas which uses a Humidifier FC-125 and two mass-flow controllers. Zero air gets mixed with humidified air to an arbitrary RH. A PermaPure® MD-700-24S-3 is used to transfer the moister into the sample stream. According to the authors, a full RH cycle lasted about 20 minutes. For the usage in Ecotech Aurora 3000 nephelometer, the air flow must be much higher than the achieved $1.35\,\mathrm{lpm}$. Additionally, the costs for the humidifier Nafion® tubes are high.
The second approach is based on a similar membrane with a significant difference, since it can be surrounded by water directly instead of humidified purge air. This is advantageous for large sample flows since the humidification ability is inexhaustible. Arbitrary RH can be achieved by controlling the water temperature. This inexpensive approach is capable of an extensive increase of RH throughout the membrane for short effective membrane lengths. The effective membrane length describes the length of the membrane that is directly exposed to the sample flow on one side and to water on the other side. All measurements are based on the FluoroFlex™ ePTFE Tubes 155-02 from International Polymer Engineering, one of only few ePTFE membrane manufactures.

A. Characteristics Expanded Polytetrafluoroethylene

This section aims to characterize the humidification ability of ePTFE membranes. The setup displayed in Figure 1 shows the method used to evaluate the humidification capability of ePTFE membrane. To keep the influence of humidified exhaust air low, room air is sampled at a distance $3\,\mathrm{m}$ and the RH and temperature of the air stream passing through the inlet tube were continuously measured. The purpose of the measurement is to quantify the difference in RH passing through the membrane, further referred to as ΔRH.
The sample stream then entered an ePTFE membrane with an effective length of $20\,\mathrm{cm}$. Most importantly, the water temperature of the water bath in this testing configuration can be adjusted to any temperature between $1\,^{\circ}\mathrm{C}$ and $40\,^{\circ}\mathrm{C}$, while the air sample temperature remains constant at $21\,^{\circ}\mathrm{C}$. This is a representative replication of a possible humidifier assembly. Even if it is not intended for the humidifier now, the measurements are extended to water temperatures below room temperature to gain a better understanding of the material. Downstream of the membrane, a second RH/temperature probe and a flow meter monitor these parameters. Finally, a vacuum pump provides constant air flow.

To observe hysteresis curves, different water temperature profiles were tested. The flow rate was initially set to the nephelometer sample flow rate of $10\,\mathrm{lpm}$. At high water temperatures, the RH_{meas} would exceed saturation, so the actual flow $\dot{V}$ is increased for these test points. All graphs show the ΔRH_{norm} for a normalized flow of $10\,\mathrm{lpm}$ (see Eq. 1).

$$\Delta RH_{norm} = \frac{\dot{V}}{10\,lpm} \cdot \Delta RH_{meas} \tag{1}$$

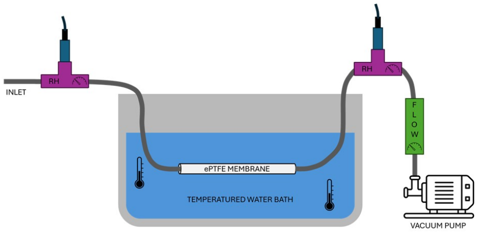

Figure 1: Test setup for testing of the humification ability of ePTFE with a temperatur-controlled water bath (1°C to 40°C). A vacuum pump pulls air though the tubing while measuring the RH before and after humidification. A flow meter measures the flow for each data point, which is set to 10 lpm for low water temperatures and elevated for higher temperatures in order to stay well-below saturation.

B. Hardware Design

Based on the ePTFE characterization test results, a new ePTFE membrane humidifier was designed and manufactured to humidify an aerosol sample stream. Goal of this humidifier is to ramp the RH from dry conditions ($RH = 40\%$) to $RH = 85\ldots90\%$ every hour, to gain a broad understanding of the hygroscopic behavior for atmospheric aerosols in the whole RH range.
AppalAIR is part of the larger NOAA measurement network that defines the boundary conditions for all sites. This includes the mentioned cycle time of 60 minutes for all measurements. It ensures relatively constant measurement conditions in each cycle. The hygroscopicity measurement is challenging for larger air flows since the change in humidification is slow for all known principles.
In order to design new humidifier hardware, an iterative approach is selected. Previous to this research, an ePTFE membrane-based humidifier was developed and used for many years. Due to a hardware change for the nephelometer (from TSI to Ecotech), the sample flow rate changed. The old concept is not capable of humidifying reliably, which resulted in catastrophic failures. Based on extensive analysis, points of weakness are identified and redesigned.

III. Results

A. Humidification Characteristic of Membrane

This section discusses the results gathered using the setup described in Section II-A. In the experiments, the change in RH (ΔRH) due to humidification through an ePTFE membrane was measured for different water temperatures. Based on the data shown in Figure 2, the ΔRH, increases as the water temperature rises. Specifically, at a water temperature of about $10\,^\circ$C, the ΔRH in the sample stream becomes positive, indicating humidification. Major humidification is achieved by water temperatures $\geq 20\,^\circ$C, which aligns with the phase transition described in Section II-A. At higher water temperatures, the RH would exceed saturation without the applied normalization above $35\,^\circ$C.

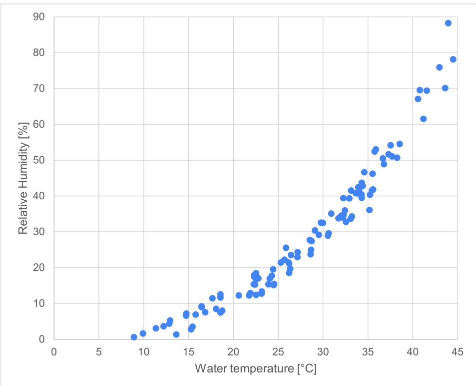

Figure 2: Measurement of the ability to humidify an aerosol sample stream with an ePTFE membrane in a temperature-controlled water bath. Measured change in relative humidity (ΔRH) for water temperatures $> 10\,^\circ$C with an exponential trend line for modeling purposes.

Interpreting the data presents several challenges. First, the plotted water temperature (x-axis of Figure

2) differs from the ePTFE membrane temperature. While the sample air stream temperature remains around $21\,^{\circ}\mathrm{C}$, the membrane surface temperature varies with the water temperature, creating a non-uniform temperature profile along the membrane. According to [16], the thermal conductivity of ePTFE is less than $0.1\,\frac{\mathrm{kCal}}{\mathrm{mh^{\circ}C}}$ $(0.12\,\frac{\mathrm{W}}{\mathrm{mK}})$. Second, RH variations occur due to factors like water stirring, with stirred water producing higher ΔRH values at elevated temperatures. Third, fluctuations in the inlet RH impact the humidification process. To account for non-constant inlet RH, the ΔRH rather than absolute values are analyzed. However, humidifying a dry sample stream by a $x\%$ might differ to a wet sample.

In Figure 3 the measured ΔRH at lower water temperatures is presented. Starting with a water temperature of $26\,^{\circ}\mathrm{C}$, the temperature was gradually decreased, with corresponding ΔRH values shown as blue dots. The data indicate a drying effect when the water temperature falls below 8 °C, with a maximum observed drying of 15% RH at $1\,^{\circ}\mathrm{C}$. Subsequent heating of the water (red dots) reveals a hysteresis effect: the ΔRH values during reheating exceed the initial cooling curve up to approximately $19\,^{\circ}\mathrm{C}$, at which point both curves converge.

These phenomena have not been previously documented for ePTFE membranes to my knowledge. The drying effect may result from condensation drying, where cooled membrane surfaces cause localized temperature drops, increasing RH until condensation occurs within the membrane structure. The fate of the condensed water remains unclear. The hysteresis behavior also lacks a definitive explanation, though the phase transition around $19\,^{\circ}\mathrm{C}$, as described by [16], may be responsible for the curve convergence.

While further investigation into these effects could yield valuable insights, the new humidifier design focuses on water temperatures at or above room temperature ($\geq 20\,^{\circ}\mathrm{C}$). Under these conditions, the drying and hysteresis effects do not significantly impact performance, ensuring reliable humidification in the target operational range.

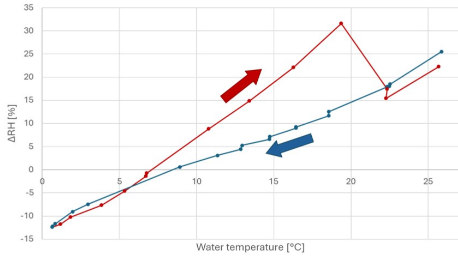

Figure 3: Hysteresis and drying behavior of an ePTFE membrane in a temperature-controlled water bath. In the experiment, an ePTFE membrane changes the RH of an aerosol sample stream depending on the water temperature surrounding the membrane.

B. New Hardware Design

Figure 4 shows the newly developed humidifier. The membrane (yellow) is surrounded by a water jacket and flows through a $16\,\mathrm{mm}$ inner diameter tubing with a $20\,\mathrm{cm}$ effective length, providing sufficient surface area for humidification. Stainless steel connectors (red) secure the membrane, with heat shrink tubing (green) ensuring water tightness. The water is contained in a $25.4\,\mathrm{mm}$ aluminum outer tube (grey), held together by Swagelok® fittings (light blue) with subsequently integrated water inlets (dark blue). An external $120\,\mathrm{W}$ heater is mounted on top of the aluminum water jacket to control the water temperature to adjust the RH. A solenoid pump achieves a continuous but very slow water transfer of about $4\,\frac{\mathrm{ml}}{\mathrm{min}}$.

To ensure reliable and efficient operation, several key design points were implemented in the following way:

- Port Design: The port attaches inside the membrane with machined grooves, ensuring a tight

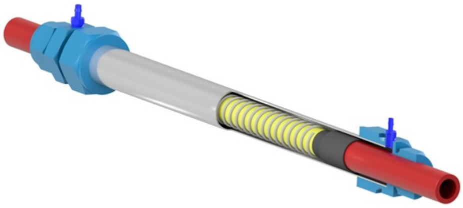

Figure 4: Membrane-based humidifier assembly for aerosol sample humidification. The sample air gets pulled through the port connectors (red) and the membrane (yellow). The connection point between membrane and stainless-steal connector is sealed by a double layer of heat shrink. Temperature-controlled water surrounds the membrane. For stabilization, a spring is holds the membrane in the center of an Aluminum jacket (grey). Stainless steel Swagelok® connectors hold the whole assembly in place and ensure the water in- and outlets (blue).

seal and high manufacturability.

- Enhanced Heat Shrink Sealing: A double-layered heat shrink was used to enhance water tightness. The inner layer has a low melting temperature to fill the porous ePTFE structure, while the outer layer provides structural integrity.
- Lightweight Aluminum Outer Tube: To keep the thermal mass small, an initial stainless steel water jacket was replaced by an aluminum one, improving system control response time while maintaining corrosion resistance.
- Spring Membrane Stabilization: An external spring was added around the membrane to prevent deformation, ensuring consistent airflow without obstructing the aerosol stream. Different approaches to stabilizing the membrane structure were evaluated and tested. For the applied pressure on the membrane used in our assembly, the external spring worked well. For higher stability, an internal spring was successfully tested.
- Water Inlet Size: The water inlet size is small ($ID = 2.6mm$) which limits the maximal water transfer provided by the solenoid pump. With a pump replacement and larger water tubing, the transfer of the water could be significantly increased.
- Closed-loop Controlled Heater: A proportional integral derivative (PID) controller was implemented to control the heater. Based on the outlet RH, the heater is turned on.

Figure 5: New humidifier assembly with attached heater module.

The new humidifier underwent rigorous testing, including a leak test, functional performance check, and particle loss assessment. The tests confirmed the reliability of the water-tight seal, effective humidification performance, and minimal impact on particle measurements. The resulting design provides a stable, efficient, and responsive humidification system for aerosol light scattering measurements. Figure 5 shows the actual humidifier, as it is in usage at

AppalAIR.

To better understand the humidification behavior of the ePTFE-based humidifier, an open-loop test was conducted focusing on its static response. The primary objective was to analyze the relationship between heat input and the resulting change in relative humidity (ΔRH) across the membrane. The test setup was similar to the ePTFE characterization experiment with a water bath. However, unlike the water bath setup, the humidifier's water temperature could not be actively cooled, meaning that some humidification occurred even when the heater was turned off.

6 presents the key findings of this test, plotting ΔRH on the y-axis against the heater's pulse width modulated (PWM) signal on the x-axis. Since the PWM signal directly influences the heat output, this visualization effectively demonstrates how the humidifier responds to different heating levels. The data points indicate a clear trend, confirming that equilibrium RH was reached during the experiment. A notable observation is that ΔRH tends to be slightly higher when PWM is decreasing compared to when it is increasing. This behavior is reflected in the dual data points for most PWM values, suggesting a possible hysteresis effect in the ePTFE membrane.

For modeling purposes, a linearization was applied to the collected data. While minor variations exist between increasing and decreasing PWM, the overall trend remains consistent, reinforcing the reliability of the measured humidification response.

C. Implementation

This section focuses on the results of the implemented humidification system with controller. Different controllers were tested and modified since the system is strongly non-linear. The control behavior of the best controller that could be found is displayed in Figure 7. The graph shows the setpoint RH for the controller and its corresponding measurements. At the beginning of the hour, the humidifier is turned off, since automated span checks were performed at this time. After a couple of minutes, the setpoint

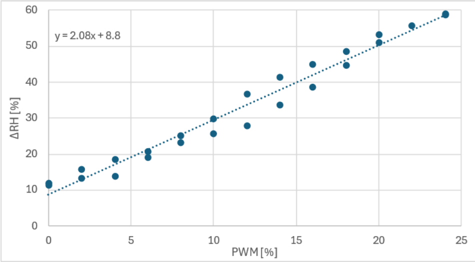

Figure 6: Humidification (in terms of ΔRH) of the new humidifier assembly for different power input in terms of PWM power. In a defined procedure, the PWM signal was successively increased to a maximum and lowered afterwards. Higher input power results in a higher water temperature, which increases humidification. However, if an input PWM was set for a second time, the ΔRH varied sometimes which showcases a non-linear membrane behavior.

increases step by step until it reaches it maximum 30 minutes after the hour, which is also the time, when the particle filter size changes from PM10 (particle matter $\leq 10\,\mu\text{m}$) to PM1. In the next $30\,\text{min}$, the setpoint RH lowers and the humidifier turns off eventually.

During peak humidification, when the setpoint RH is highest, the controller is unable to achieve the exact target RH. With a longer settling time at each setpoint, this could be improved, especially for higher RH levels. Overall, any arbitrary RH setpoint can be achieved; however, further improvements on the control strategy could improve response and settling time.

IV. Conclusion

This paper presents a comprehensive characterization of an ePTFE membrane as a humidification medium for aerosol sample streams. For the first time, the humidification performance of an ePTFE membrane has been systematically evaluated, demonstrating its ability to modify the RH of an aerosol

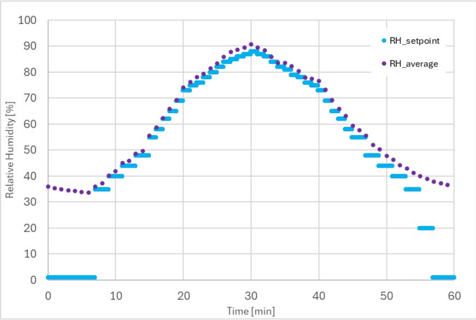

Figure 7: Minutely averaged relative humidity of aerosol sample stream at AppalAIR for each one hour. At the beginning and end of the hour, the humidifier is turned off and the RH falls slowly. At the peak of the hour, where the setpoint RH is highest, the controller cannot achieve the desired RH exactly.

sample stream. The results confirm a measurable RH increase across the membrane, as illustrated in Fig. 2, and highlight the presence of hysteresis effects at low water temperatures. These findings provide critical insights for future engineering applications utilizing ePTFE membranes in humidification systems.

Beyond the scientific characterization, this work also addresses the practical challenges of implementing an ePTFE-based humidifier in a real-world measurement system. A redesigned humidifier was developed to improve reliability and robustness, overcoming weaknesses identified in previous designs. Structural modifications, including an improved sealing mechanism, optimized heat shrink tubing, and a spring-supported membrane, have significantly reduced the risks of mechanical failure and water leakage. In addition, focusing on a small thermal mass improved the control response time of the assembly.

These modifications enabled more than two months of continuous operation in a field campaign without humidifier failures, demonstrating the effectiveness of the revised design.

This work lays the foundation for further refinement of ePTFE-based humidification systems. Future research should focus on improving system controllability and reducing oscillations while maintaining the balance between performance and complexity. The insights gained from this study provide a valuable basis for ongoing development, ensuring continued improvements in humidifier performance for aerosol measurement applications.

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References

[1] J. H. Seinfeld, *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change*, 1st ed., ser. New York Academy of Sciences Series. Newark: John Wiley & Sons, Incorporated, 2016.

[2] R. J. Charlson, J. Langner, H. Rodhe, C. B. Leovy, and S. G. Warren, "Perturbation of the northern hemisphere radiative balance by backscattering from anthropogenic sulfate aerosols*," *Tellus A: Dynamic Meteorology and Oceanography*, vol. 43, no. 4, p. 152, Jan. 1991.

[3] IPCC, *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1st ed. Cambridge University Press, Jul. 2023.

[4] U. Lohmann and J. Feichter, “Global indirect aerosol effects: A review,” *Atmospheric Chemistry and Physics*, vol. 5, no. 3, pp. 715–737, Mar. 2005.

[5] S. Twomey, “The Influence of Pollution on the Shortwave Albedo of Clouds,” *Journal of the Atmospheric Sciences*, vol. 34, no. 7, pp. 1149–1152, Jul. 1977.

[6] J. Haywood and O. Boucher, “Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review,” *Reviews of Geophysics*, vol. 38, no. 4, pp. 513–543, Nov. 2000.

[7] E. Swietlicki, H. C. Hansson, K. Hämeri, B. Svenningsson, A. Massling, G. McFiggans, P. H. McMurry, T. Petäjä, P. Tunved, M. Gysel, D. Topping, E. Weingartner, U. Baltensperger, J. Rissler, A. Wiedensohler, and M. Kulmala, “Hygroscopic properties of submicrometer atmospheric aerosol particles measured with H-TDMA instruments in various environments—a review,” *Tellus B: Chemical and Physical Meteorology*, vol. 60, no. 3, p. 432, Jan. 2008.

[8] World Meteorological Organization, *WMO/GAW Aerosol Measurement Procedures, Guidelines and Recommendations*, 2nd ed. World Meteorological Organization (WMO), 2016.

[9] M. A. Burgos, E. Andrews, G. Titos, A. Benedetti, H. Bian, V. Buchard, G. Curci, Z. Kipling, A. Kirkevåg, H. Kokkola, A. Laakso, J. Letertre-Danczak, M. T. Lund, H. Matsui, G. Myhre, C. Randles, M. Schulz, T. Van Noije, K. Zhang, L. Alados-Arboledas, U. Baltensperger, A. Jefferson, J. Sherman, J. Sun, E. Weingartner, and P. Zieger, “A global model–measurement evaluation of particle light scattering coefficients at elevated relative humidity,” *Atmospheric Chemistry and Physics*, vol. 20, no. 17, pp. 10 231–10 258, Sep. 2020.

[10] P. Zieger, R. Fierz-Schmidhauser, E. Weingartner, and U. Baltensperger, “Effects of relative humidity on aerosol light scattering: Results from different European sites,” *Atmospheric Chemistry and Physics*, vol. 13, no. 21, pp. 10 609–10 631, Nov. 2013.

[11] C. Pilinis, S. N. Pandis, and J. H. Seinfeld, “Sensitivity of direct climate forcing by atmospheric aerosols to aerosol size and composition,” *Journal of Geophysical Research: Atmospheres*, vol. 100, no. D9, pp. 18 739–18 754, Sep. 1995.

[12] P. Zieger, E. Kienast-Sjögren, M. Starace, J. Von Bismarck, N. Bukowiecki, U. Baltensperger, F. G. Wienhold, T. Peter, T. Ruhtz, M. Collaud Coen, L. Vuilleumier, O. Maier, E. Emili, C. Popp, and E. Weingartner, “Spatial variation of aerosol optical properties around the high-alpine site Jungfraujoch (3580 m a.s.l.),” *Atmospheric Chemistry and Physics*, vol. 12, no. 15, pp. 7231–7249, Aug. 2012.

[13] C. M. Carrico, P. Kus, M. J. Rood, P. K. Quinn, and T. S. Bates, “Mixtures of pollution, dust, sea salt, and volcanic aerosol during ACE-Asia: Radiative properties as a function of relative humidity,” *Journal of Geophysical Research: Atmospheres*, vol. 108, no. D23, p. 2003JD003405, Dec. 2003.

[14] R. Fierz-Schmidhauser, P. Zieger, G. Wehrle, A. Jefferson, J. A. Ogren, U. Baltensperger, and E. Weingartner, “Measurement of relative humidity dependent light scattering of aerosols,” *Atmospheric Measurement Techniques*, vol. 3, no. 1, pp. 39–50, Jan. 2010.

[15] J. Zhou, X. Xu, W. Zhao, B. Fang, Q. Liu, Y. Cai, W. Zhang, D. S. Venables, and W. Chen, “Simultaneous measurements of the relative-humidity-dependent aerosol light extinction, scattering, absorption, and single-scattering albedo with a humidified cavity-enhanced albedometer,” *Atmospheric Measurement Techniques*, vol. 13, no. 5, pp. 2623–2634, May 2020.

[16] S. Ebnesajjad, *Expanded PTFE Applications Handbook: Technology, Manufacturing and Applications*, ser. Plastics Design Library. Amsterdam: Elsevier, 2016.

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