

RESEARCH ARTICLES

Evaluation of Drying Methods for Humidity Control During Real-Time Respirator Fit Monitoring

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Respiratory protective devices are widely used to reduce occupational exposure to hazardous airborne particles. However, the protective performance of respirators can deteriorate during real-world use due to poor fit, even if they were initially well-fitted. The Exposure Protection Integrated Communicator (EPIC) is a recently developed portable system that is equipped with dual optical particle counters (OPCs) to measure aerosol concentrations inside and outside a respirator, enabling real-time fit monitoring in a real-world workplace. Since OPC performance is sensitive to humidity, this study evaluated two drying methods, Nafion tubing and a desiccant membrane (DM) dryer, for their effectiveness in reducing relative humidity and minimizing particle loss within the EPIC device. Experiments were conducted to characterize the efficiency of relative humidity (RH) reduction and particle transmission across a range of particle sizes (0.3–10 μm). Nafion tubing showed ~25% desiccant efficiency at ambient RH $\leq$ 40%, whereas the DM dryer achieved >50% efficiency at higher RH levels. However, both dryer units exhibited particle losses, particularly of larger micron-sized particles, with the DM dryer exhibiting >90% loss for particles >5 μm . These findings highlight the trade-offs between RH control and particle preservation in a field-deployable aerosol monitoring system. Nafion tubing has the potential for applications requiring real-time respirator monitoring under moderate RH environmental conditions. This study provides critical design insights for optimizing OPC-based systems like EPIC, where maintaining both sensor accuracy and particle transmission is essential.

Introduction

Occupational environments often contain hazardous airborne contaminants that pose health risks to workers, potentially leading to respiratory diseases such as asthma and bronchitis, as well as acute symptoms (Matheson et al., 2005; Ramachandran, 2005; Randem et al., 2004). Workers, particularly healthcare workers, rely on respiratory protective equipment to reduce exposure to hazardous aerosols. The recent COVID-19 pandemic has further highlighted the critical need for supply and proper usage of respirators. However, improper fitting may compromise the effectiveness of a respirator and gradually deteriorate over time of use. While both quantitative fit testing (QNFT) and qualitative fit testing (QLFT) can be performed

in accordance with protocols approved by the US Occupational Safety and Health Administration (OSHA) to ensure proper respirator protection, QNFT is preferred due to the numerical value outputs. Traditional QNFT relies on condensed nuclei counter (CNC) protocols described in OSHA 29 CFR 1910.134 Appendix A, such as the PortaCount® Fit Tester (TSI, Inc., Shoreview, MN, USA). PortaCount uses a CNC to measure aerosol concentrations inside and outside the respirator. While the CNC-based method is commonly used, the aerosol-based QNFT is not limited to CNC instrumentation (ISO 16975-3, 2017). Recent studies have demonstrated that optical particle counting (OPC) also performs well in quantifying respirator fit, achieving high sensitivity between 0.98-1.00 compared with CNC-based measurements (Wu et al., 2017).

A twin-tube sampling hose is utilized for QNFT: one tube is connected inside the respirator to monitor particle concentration, while the other one measures ambient concentrations in the breathing zone. Both CNC and OPC are effective in evaluating the performance of a respirator. The CNC works by exposing aerosol particles to supersaturated vapor, which causes them to grow to sizes detectable by optical methods (Baron & Willeke, 2001). An OPC detects and sizes particles by measuring the light scattered by individual particles as they pass through a light beam (Xu, 2001). However, humidity generated by human breathing within the sampling tube during the QNFT may affect particle count accuracy, particularly with OPC sensors, as water droplets/liquid can interfere with light scattering. A previous study also demonstrated that the performance of optical particle sensors is significantly affected by air humidity (Wang et al., 2015). In contrast, CNC is less affected by humidity due to its reliance on condensation-based detection.

Our preliminary data showed that relative humidity (RH) inside the tubing sharply increases after 45 minutes of respirator use, resulting in erroneous particle counts and a protection factor of zero – an implausible value indicative of sensor interference. Therefore, using dryer tubing instead of regular tubing with moisture-reducing additives is essential to reduce humidity interference and maintain measurement integrity.

Due to its hydrophilic properties, Nafion is a promising alternative for reducing RH within the tubing. It is a sulfonated tetrafluoroethylene-based fluoropolymer copolymer characterized by highly hydrophilic sulfonic acid ($-\text{SO}_3\text{H}$) groups. This composition enables Nafion to facilitate the transfer of water molecules across the membrane via first-order kinetics, ultimately establishing a water vapor partial pressure equilibrium on both sides of the membrane (Mauritz & Moore, 2004; Perma Pure Inc., 2023b). This unique property makes Nafion well-suited for various medical applications, including extracting water vapor from breath samples and introducing humidity into gas samples for therapeutic purposes (Perma Pure Inc., 2023b). Typically, water passes through the walls of the Nafion-based tubing and is

subsequently removed by a dry purge gas, thereby reducing the moisture content within the tube. The first objective of this study was to examine the desiccant effectiveness of Nafion-based dryer tubing in reducing RH.

Recently, a novel field-portable device, the Exposure Protection Integrated Communicator (EPIC), was prototyped for real-time respirator fit monitoring. It employed dual sensors with the OPC principle, allowing simultaneous monitoring of aerosol concentrations inside and outside the respirator and providing a quantitative evaluation of the respirator fit factor. The EPIC was designed to support QNFT and monitor respirator fit in real time while the wearer is working. The standard QNFT protocol typically includes eight exercises that take approximately eight minutes to complete (OSHA, 1998). A recent protocol modification reduced the number of exercises to four, shortening the test duration to less than 2.5 minutes (OSHA, 2004). The time length of either QNFT or modified QNFT is much shorter than a typical work shift, therefore, minimizing RH within the respirator sampling line is essential for prolonged real-time monitoring using EPIC or any similar devices.

However, no studies have yet examined the potential impact of Nafion-based dryer tubing/unit on particle counts during respirator monitoring. Therefore, the second objective of this study was to evaluate whether Nafion-based tubing/unit affects particle detection accuracy and, consequently, the respirator fit factor output when used in conjunction with OPC-based monitoring systems like EPIC.

Methods

Dryer units

Two commercially available dryer units: i) a Nafion tubing, with an outer layer of protective polypropylene braiding (*Perma Pure LLC, Lakewood, NJ, USA*) and ii) a desiccant membrane (DM) dryer (*Perma Pure LLC*), which is a portable Nafion tubing membrane dryer integrated with desiccant, were selected for this study. The DM dryer comprises a 24-inch-long Nafion tube coiled within a casing and surrounded by molecular sieve desiccants. This combination capitalizes on Nafion tubing dryers' selectivity and the simplicity of desiccant canister dryers (Perma Pure Inc., 2023a). As the gaseous sample flows through the dryer, it comes into contact solely with the Nafion tubing, which selectively absorbs water vapor while retaining the sample components quantitatively within the gas stream. The desiccant surrounding the tubing establishes a dry purge environment and enhances the efficiency of the drying process.

A straight Nafion tubing with a length of 10.6 inches and a DM dryer were tested in this study to analyze their desiccant efficiency and particle losses due to deposition on the tubing's internal surfaces. The selected straight Nafion tube and the Nafion tubing coiled within the DM dryer had identical dimensions, with an outer diameter of 0.108 inches and an inner diameter of 0.086 inches. A regular Tygon tube made of polyvinyl chloride (PVC), with

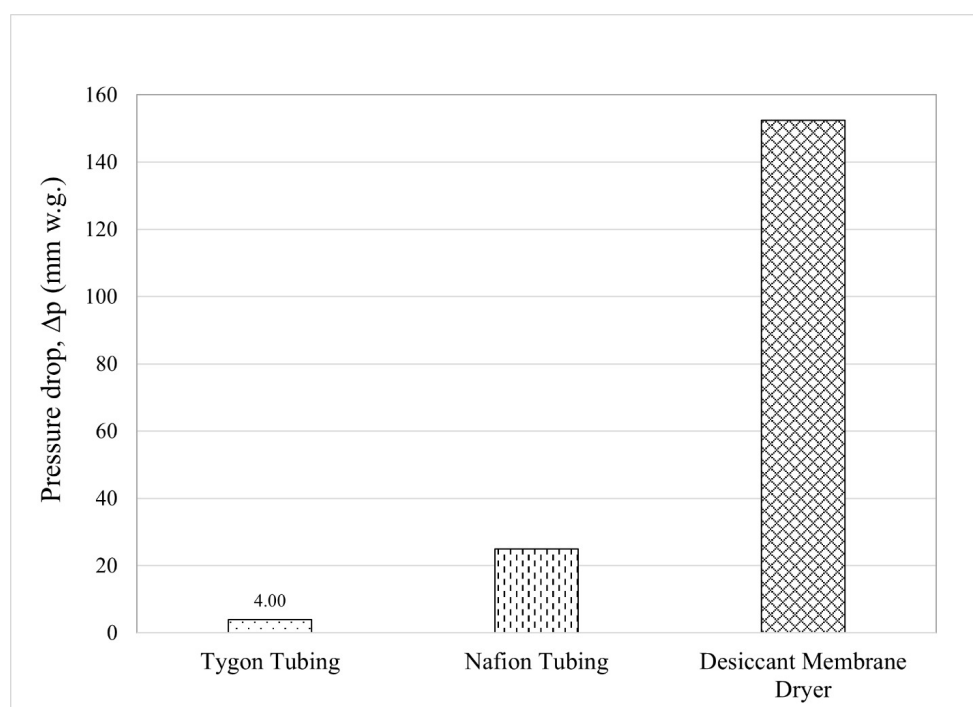


Figure 1. Pressure drop values of three tested units: Tygon tubing, Nafion tubing and Desiccant Membrane Dryer.

dimensions and length identical to those of the Nafion tubing, was used as a control group. The pressure drop across these three tubings was measured using the Magnehelic differential pressure gauge (*Dwyer Instruments Inc., Michigan City, IN, USA*). As shown in [Fig. 1](#), both Nafion dryer units exhibited much higher pressure drops than the Tygon unit. The DM dryer exhibited the highest pressure drop due to the coiled Nafion tubing within the dryer housing.

Desiccant efficiency evaluation

Two Nafion dryer units and one Tygon tube (control) were tested under varying RH conditions to evaluate their desiccant efficiency in reducing RH within units. The experiment was conducted in a 24 m³ controlled chamber, and its setup was illustrated in [Fig. 2](#). Each tested unit was separately connected to a pair of RH sensors (Sensor 1 and Sensor 2; *AC Infinity Inc., City of Industry, CA, USA*), positioned upstream and downstream of the tested unit to measure RH before (upstream) and after (downstream) air passed through the unit. A small pump was installed downstream of the unit to maintain a constant airflow of 1.15 L/min.

The first phase of testing evaluated the desiccant efficiency of Nafion tubing under different environmental RH conditions. The initial ambient RH in the chamber room was 30.0% and then elevated to 40.0% and 50.0% using a humidity generator to simulate varied ambient RH conditions. For each ambient RH level, the humidity generator introduced humid air to the upstream end of the Nafion tubing, reaching approximately 75.0% RH

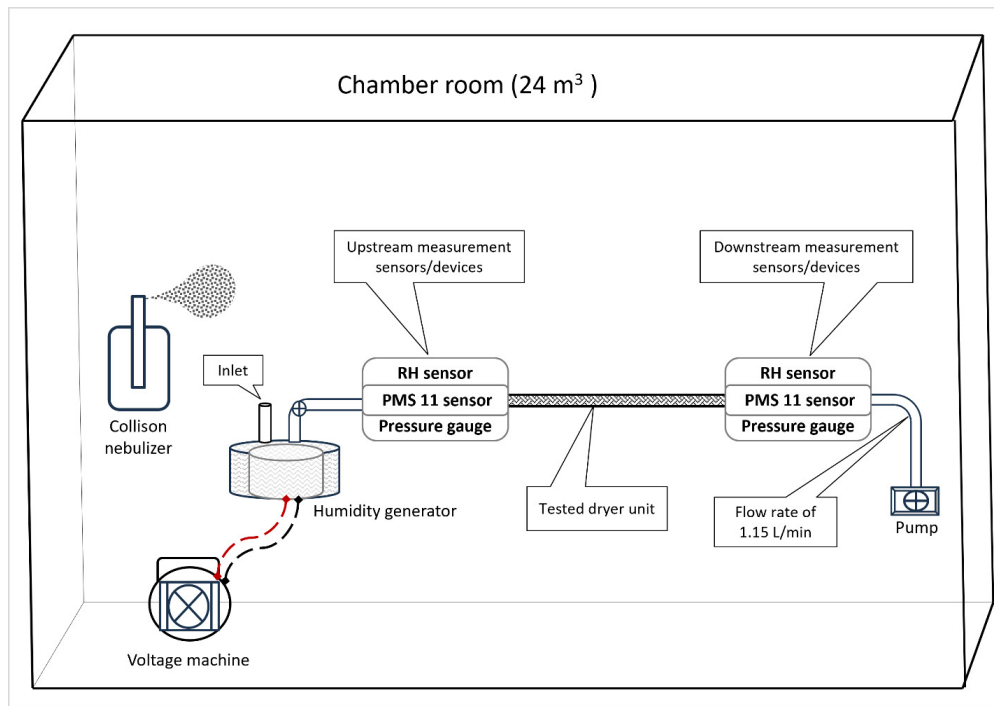


Figure 2. Schematic diagram of the experimental setup. The voltage machine was connected to a humidity generator to increase the humidity levels inside the tested unit. A pump was used to produce a continuous flow rate of 1.15 L/min.

(actual values of 74.37%, 75.81%, and 75.91%). The desiccant efficiency was quantified by comparing RH values measured at the upstream and downstream ends, using Equation 1:

$$\text{Desiccant efficiency} = \frac{RH_{\text{upstream}} - RH_{\text{downstream}}}{RH_{\text{upstream}}} \times 100\% \quad (1)$$

The second phase of testing compared the desiccant efficiency of all three tested units under the same chamber ambient RH level of 53.0%. The humidity generator introduced humid air to the upstream end of each unit, achieving RH values of 76.67%, 75.91%, and 76.60% for the Tygon tubing, Nafion tubing, and DM dryer, respectively. Downstream RH values were recorded to assess their desiccant efficiency using Equation 1. The upstream and downstream RH measurements of each testing group were repeated seven times to ensure accuracy and statistical reliability.

Particle loss evaluation

The particle loss evaluation of both dryer units was conducted in the same controlled chamber, as shown in [Fig. 2](#). Sodium chloride (NaCl), a common challenge aerosol used in standard respirator certification protocols, was generated by a 6 Jet Collison nebulizer (MRE, 6 Jet Vertical, *CH Technologies Inc., Westwood, NJ, USA*). The generated polydisperse aerosol had a size range from nanometers to micrometers. Particle counts were measured using the developed EPIC device equipped with two PMS 11 sensors (*Temtop Inc., San Jose, CA, USA*). The PMS 11 sensor employed

optical light-scattering technology to detect particulate matter larger than 0.3 μm , 0.5 μm , 0.7 μm , 1.0 μm , 2.5 μm , and 5 μm , providing measurements of both the mass and the number of airborne particles per unit volume.

To assess particle loss across the dryer units, two PMS 11 sensors (A and B) within the EPIC were connected to the upstream and downstream of the tested unit to monitor particle counts before (C_{Ambient}) and after (C~Drying unit~) the airflow passed through the dryer unit at a flow rate of 1.15 L/min. Each test ran for 1 minute, during which each PMS 11 sensor recorded 39 particle count measurements at a time resolution of 1.5 seconds. The connections of PMS 11 sensors A and B were alternated and repeated twice for each tested unit, resulting in a total of 76 particle count values per sensor. The particle loss efficiency was calculated using Equation 2 based on the averaged particle counts measured by PMS sensors A and B.

$$\text{Particle loss, \%} = \frac{C_{\text{Ambient}} - C_{\text{Drying tube}}}{C_{\text{Ambient}}} \times 100\% \quad (2)$$

Data analysis

Data analysis was performed using Microsoft Office Excel (Microsoft Corp., Redmond, WA). A paired t -test was performed to assess the statistical significance of differences between the reference tube and the dryer units, and among the dryer units under different conditions. Differences were considered statistically significant at p -values below 0.05.

Results and discussion

Desiccant efficiency evaluation

[Fig. 3](#) presents the RH values measured by upstream and downstream sensors, averaged over seven trials at three ambient RH levels (30.0%, 40.0%, and 50.0%). The results demonstrated that applying Nafion tubing significantly reduced ($p < 0.001$) RH inside the tubing across different ambient RH levels. The desiccant efficiency of Nafion tubing varied depending on ambient RH. Specifically, the desiccant efficiencies were 23.4%, 23.7%, and 19.5% at ambient RH levels of 30.0%, 40.0%, and 50.0%, respectively. This indicates that Nafion tubing has a high drying efficiency, consistent with the findings of Sundin et al. (1995), who demonstrated its effectiveness in removing water from wet carrier gas streams. Additionally, a paired t -test analysis revealed significant differences ($p < 0.001$) in desiccant efficiency between low ambient RH (30.0%) and high ambient RH (50.0%), as well as between medium ambient RH (40.0%) and high ambient RH (50.0%). However, no significant difference in desiccant efficiency ($p > 0.05$) was found between low (30.0%) and medium (40.0%) ambient RH. This variation can be attributed to the influence of ambient RH on the humidity within the Nafion tubing, where higher ambient RH levels can reduce the tubing's efficiency due to saturation effects (Zawodzinski et al., 1993; Gebel, 2000; Mauritz & Moore, 2004). As ambient RH increases, the Nafion

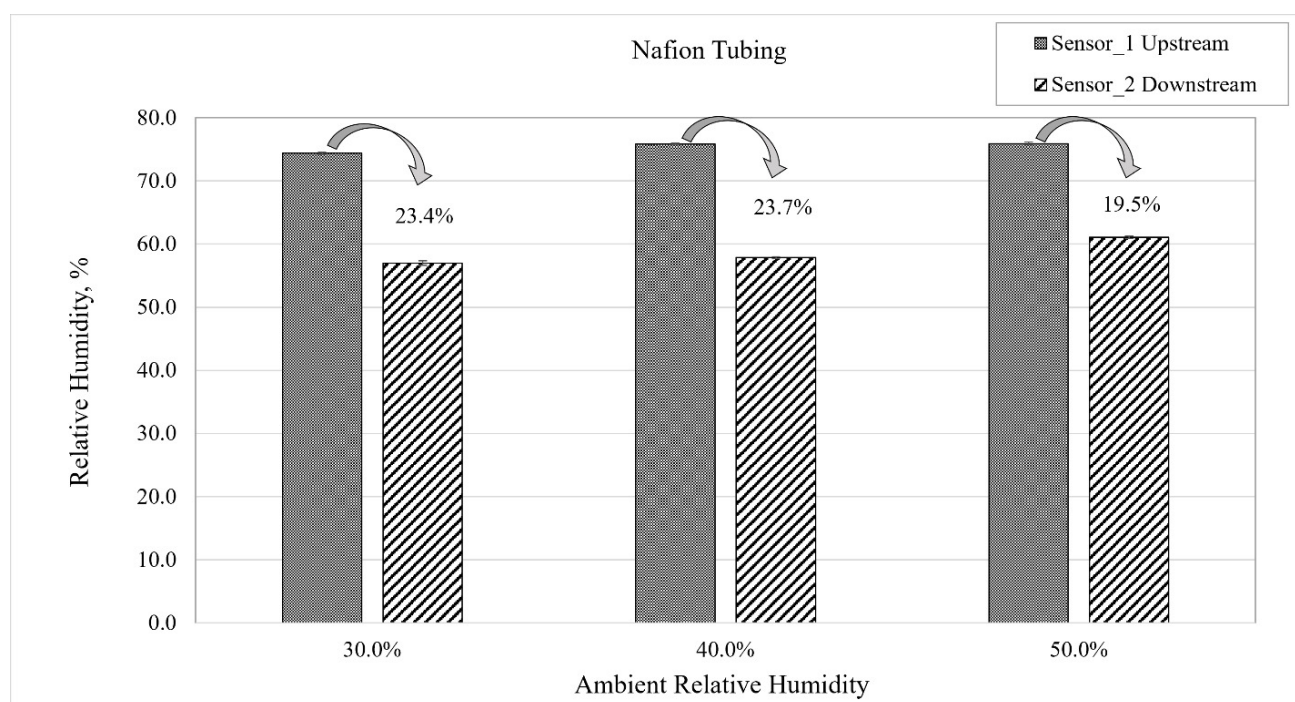


Figure 3. Relative humidity (RH) before and after the airflow passing through the Nafion tubing measured by upstream and downstream RH sensors at three ambient RH levels. The bars represent the RH values averaged over seven trials, and the error bars represent the standard deviation.

material approaches its maximum water-absorption capacity. When it becomes saturated, its ability to continue absorbing moisture decreases, reducing desiccant efficiency. At higher ambient RH levels, the Nafion tubing is less effective because it is closer to its saturation point, limiting its capacity to further reduce the humidity of the air passing through it (Gebel, 2000).

[Fig. 4](#) shows the RH values of the airflow before and after passing through the three different units at an ambient relative humidity of around 53.0%. It was observed that regular Tygon tubing achieved only 0.2% desiccant efficiency, which was significantly ($p < 0.01$) lower than the other two dryer units: Nafion produced 19.5% desiccant efficiency, while the DM dryer achieved 50.4% desiccant efficiency. Statistical analysis showed that both dryer units significantly reduced RH ($p < 0.01$) compared to the Tygon tube. Notably, the DM dryer reduced the RH below ambient, attributed to the high drying efficiency of the molecular sieve desiccants within it. Additionally, the findings revealed significant differences ($p < 0.001$) in desiccant efficiency between the dryer units and the Tygon tube (control). These findings suggest that Nafion dryers have considerable potential as an alternative to regular Tygon tubing in applications requiring humidity control within the tubing.

Particle loss evaluation

[Fig. 5](#) illustrates the average particle loss efficiency of Nafion tubing and a DM dryer across various particle size ranges. The results revealed particle count losses in both tested dryers, with the Nafion tubing showing a less pronounced reduction in particle counts than the DM dryer. The greater particle loss observed with the DM dryer can be attributed to its coiled-tubing

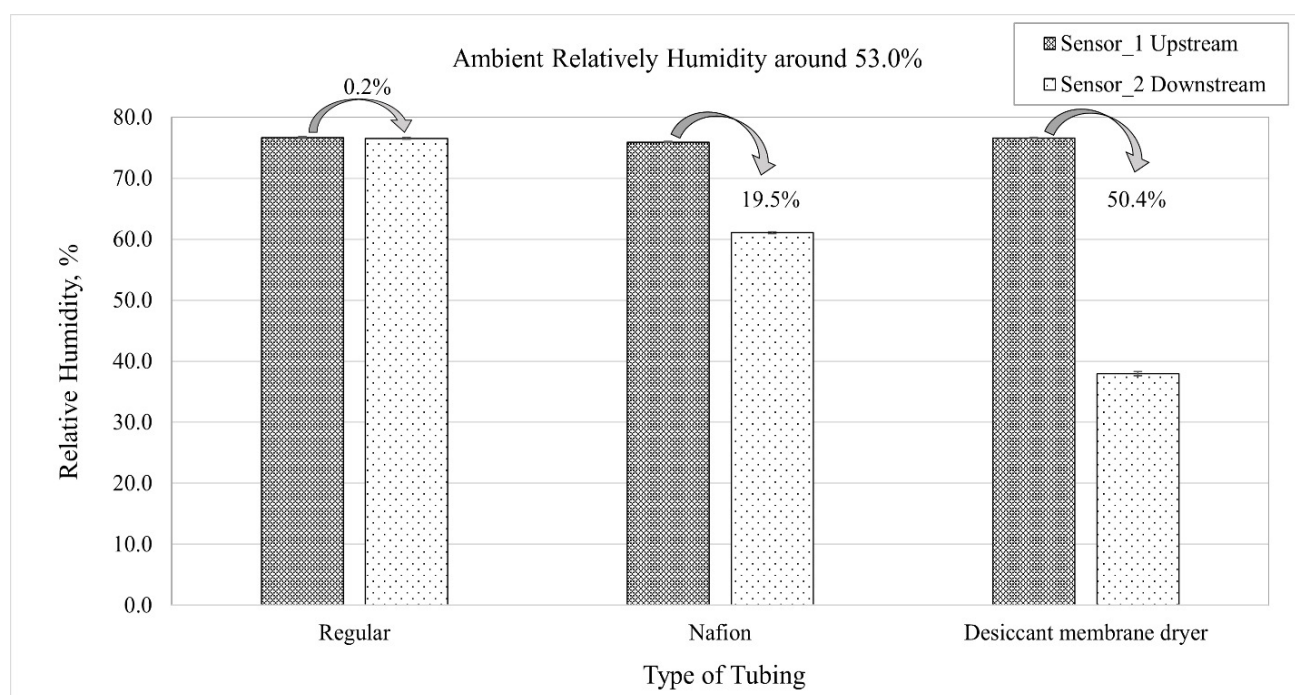


Figure 4. Relative humidity (RH) values of the airflow before and after passing through the three tested units measured by upstream and downstream RH sensors at an ambient relative humidity of around 53.0%. The bars represent the RH values averaged over seven trials, and the error bars represent the standard deviation.

design, which increases airflow resistance and, consequently, results in higher particle losses (Fsadni et al., 2016). Furthermore, as shown in [Fig. 1](#), the substantially higher pressure drops in the DM dryer and the Nafion tubing compared to the control tubing likely result from increased friction arising from their structural differences (Fsadni et al., 2016). The different lengths of the tested Nafion tubing and the DM dryer may also contribute to the difference in particle loss (Kumar et al., 2008; Tsai, 2015).

The results revealed that particle loss predominantly occurred in larger-sized particles. Nafion tubing exhibited a maximum particle loss of 25.5% for particles larger than $2.5\ \mu\text{m}$ across all six size ranges. It is attributed to the increased inertial impaction and sedimentation experienced by larger particles, whereas smaller particles ($> 0.3\ \mu\text{m}$) are more influenced by diffusion and electrostatic forces (Hinds & Zhu, 2022). The DM dryer exhibited particle loss of over 90% for particles larger than $5\ \mu\text{m}$, significantly ($p < 0.05$) exceeding the Nafion tubing, which showed 14.8% particle loss in the same range. This higher loss is due to several factors. The length of the tested tubing is a crucial factor, as longer tubing correlates with greater particle loss (Tsai, 2015). The DM dryer's coiled-tube design introduces a more complex airflow path, increasing the likelihood of particle impaction and deposition. This structural complexity results in a higher pressure drop and greater frictional losses, particularly affecting larger particles with higher inertia and a greater likelihood of being trapped within the tubing (Fsadni et al., 2016). Furthermore, the much higher pressure drop observed in the DM dryer (152.40 mm w.g.) compared to the Nafion tubing (25.00 mm w.g.) indicated more turbulent airflow and enhanced particle-wall interactions (Fsadni et

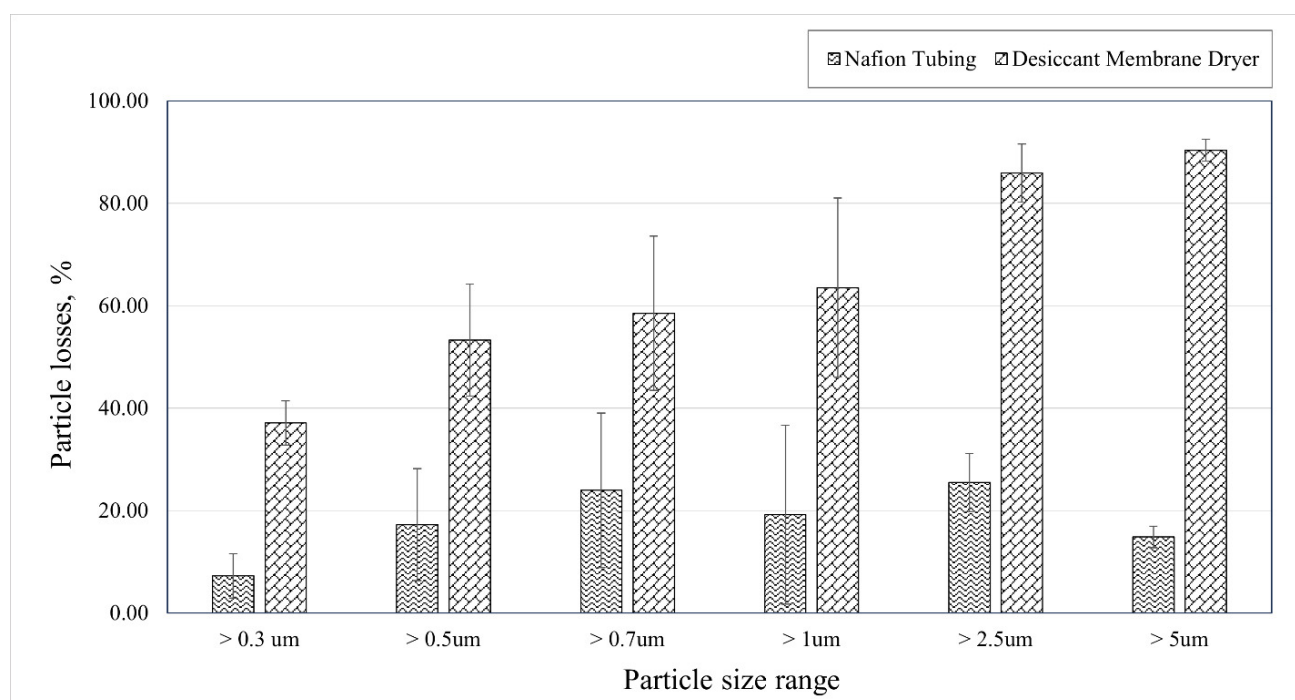


Figure 5. Particle loss efficiency of Nafion tubing and DM dryer across varying particle size ranges, measured by PMS 11 sensors A and B at a flow rate of 1.15 L/min. The bars represent the averaged particle loss values, and the error bars represent the standard deviation.

al., 2016). Due to their greater mass and inertia, larger particles are more susceptible to these interactions, resulting in increased particle loss (Fsadni et al., 2016; Hinds & Zhu, 2022).

A relatively lower count of small-sized microparticles ($>0.3 \mu\text{m}$) was lost compared to larger particles. Nafion tubing demonstrated an average particle loss of 7.3% for particles larger than $0.3 \mu\text{m}$, whereas the DM dryer exhibited a particle loss of 37.1% within the same size range. This finding contrasts with the behavior of nanosized particles, where the loss of smaller nanoparticles was greater than that of relatively larger nanoparticles, as observed by Kumar et al. (2008). A possible explanation for this discrepancy lies in the aerosol dynamics. For particles larger than $0.3 \mu\text{m}$, their inertia causes them to deviate from the streamlined airflow and collide with the tubing walls, resulting in higher losses (Hinds & Zhu, 2022). In contrast, Brownian motion primarily influences nanosized particles, leading to different behavior (Hinds & Zhu, 2022). Kumar et al. (2008) noted that smaller nanoparticles experienced greater losses than larger ones, likely due to higher diffusion rates that enhance deposition on tubing walls. Additionally, the different tube diameters used in Kumar et al. (2008) and our experiment may account for the contrasting results. Variations in tubing dimensions can significantly influence particle dynamics, contributing to the observed differences in particle loss efficiency.

These findings underscore a key trade-off in implementing OPC-based real-time respirator fit-monitoring systems such as EPIC: while effective RH control is essential for maintaining OPC performance and stability, it

may lead to substantial particle losses. Both Nafion tubing and DM dryer effectively reduced RH, supporting the operating requirements of OPC sensors. However, particle transmission was compromised in both systems, with the DM dryer exhibiting particularly high losses – over 90% for particles $>5\ \mu\text{m}$, compared to a maximum loss of 25.5% for particles $>2.5\ \mu\text{m}$ with Nafion tubing.

Such particle losses could affect fit-factor calculations, which depend on accurate measurements of aerosol concentrations both outside and inside the respirator. When particles are lost during transit through the sampling tubing, due to mechanisms such as inertial impaction, sedimentation, or diffusion, the concentrations reaching the OPCs no longer represent the true values. If particle loss is more pronounced in the ambient sampling tubing, the measured ambient concentration will be underestimated, leading to a lower apparent FF and an underestimation of the respirator's protective performance. Conversely, if greater loss occurs in the in-facepiece sampling tubing, the measured in-facepiece concentration will be artificially reduced, inflating the fit factor and potentially giving a false sense of adequate protection.

In this study, particle-monitoring configurations were symmetrically applied upstream and downstream of the sampling tubing, which helped maintain relative consistency in FF measurements. However, in practical field applications, asymmetries in tubing length, geometry, or flow dynamics may cause differential particle losses between the two sampling tubings, leading to systematic bias. Moreover, the observed particle losses were size-dependent, with larger particles ($>5\ \mu\text{m}$) experiencing disproportionately higher losses. If such size-selective losses are not accounted for, OPC-based systems such as EPIC may fail to represent the full particle-size distribution of the exposure environment accurately. For instance, when the DM dryer removes 90% of larger particles, the FF calculation would exclude this fraction entirely, potentially underestimating the exposure risk associated with those particles.

Given these trade-offs, Nafion tubing, while less efficient at high RH, preserved a greater proportion of particles across all size ranges and may be considered a more suitable option for EPIC-like systems when particle retention is critical. In contrast, the DM dryer, despite its superior RH reduction at elevated ambient humidity, imposes a substantially higher pressure drop and particle loss due to its coiled geometry and more complex internal flow path. Therefore, optimizing real-time respirator fit monitoring systems requires a careful balance between RH control and aerosol transmission fidelity, depending on the target particle size distribution and environmental conditions.

Conclusions

This study demonstrated that incorporating dryer units into real-time respirator fit-monitoring systems, such as EPIC, can effectively reduce RH within sampling tubing, thereby improving operating conditions for OPC sensors. Both Nafion tubing and the DM dryer lowered RH levels within

the tubing, with Nafion achieving ~25% desiccant efficiency at ambient $RH \leq 40\%$ and the DM dryer achieving >50% efficiency at higher RH environmental conditions. However, high particle losses were observed in both systems, with the DM dryer exhibiting much higher losses than Nafion tubing, particularly for particles >5 μm , due to its coiled configuration and higher pressure drop.

These findings underscore a critical trade-off in system design: while effective RH control is essential for OPC accuracy, excessive particle loss can compromise the reliability of aerosol concentration measurements. Nafion tubing, with its lower particle loss, may be considered as the candidate for integration into real-time respirator monitoring systems, particularly in environments with low to moderate RH. This study provides foundational data for optimizing the design and deployment of OPC-based systems like EPIC, advancing real-time in-use respirator performance evaluation.

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