Experimental Study on the Leakage Characteristics of Filter Cassettes

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ABSTRACT

Hazardous aerosol particles harmful to human health can be found in various workplaces. Filter cassettes are often used for air sampling to measure dust concentration in the air. However, filter cassettes are prone to leakage if not correctly assembled, potentially causing exposure data to be underestimated. This study aims to examine all potential leak routes, mechanisms, and contributions to the leakage to find solutions to minimize the leaks.

The membrane filter and the support pad were held using 37-mm transparent styrene two-piece filter cassettes of two brands (A and B). They were assembled with a homemade manual presser, which can apply a controlled force onto the cassette from 40 to 350 N. To measure the direct force required to press on the top piece and tightly clamp both the filter and the backup pad, the top part of a typical cassette A was filed to prevent contact and friction with the bottom piece. The interface of the top and bottom pieces of the cassette was sealed from the outside with a sealing shrink band to prevent external leakage. Ambient aerosols were used as challenge agents. The aerosol number concentrations upstream and downstream of the filter cassette were measured using a condensation particle counter. The sampling time was set at one minute. The pressure drop across the filter cassette was measured using a pressure transducer calibrated using an inclined manometer.

The pressure drop across the filter cassette was measured using a pressure transducer calibrated using an inclined manometer. A sampling flow of 0.3 L min⁻¹ in the condensation particle counter (CPC) was chosen for low filter penetration. The results showed that the filed cassette A suffered from external leakage, regardless of whether it held the filter and/or the backup pad. For the normal cassette A, leakage was a function of the assembly press force. When the assembly force increased from 150 to 210 N, total aerosol penetration (through filter, pad, and other leaks) decreased sharply from 2.1% to 0.004%. Sealing with a shrink band could further reduce aerosol penetration to 0.001%, while the pressure drop rose to 17 mmH₂O. The re-assembling experiments showed that the service life decreased with increasing press force applied. For cassette A, the service life was 14 times when re-assembled with 210 N, while the service life dropped to 6 times when the force was 300 N.

In conclusion, sufficient press force is needed for cassette assembly to prevent both internal and external leakages. Despite the only subtle difference in cassette dimensions, the minimum assembly forces required for the two cassette brands differ, 210 N for brand A and 330 N for brand B. Use of a sealing shrink band is strongly recommended because it helps reduce external leakage, provides space for labeling, and prevents sample contamination during filter retrieval.

Keywords: Filter cassette, Sealing band, Press force, Cassette assembly, Leakage
1 INTRODUCTION

Hazardous aerosol particles harmful to human health are often produced in different workplaces. Most industrial hygienists commonly use filter cassettes for aerosol sampling to assess workers' exposure (Beaulieu et al., 1980; Buchan et al., 1986; Harper, 2006). They are popular because of superior portability, excellent overall value, and assumed defect-free reliability. The filter cassette data were used to determine whether the aerosol concentration exceeded the permissible exposure level regulated by the authorities (Soo et al., 2016). However, improper assembly of filter cassettes may cause leakage and underestimate aerosol concentrations in the workplace, thus affecting the accuracy of the exposure assessment (Frazee and Tironi, 1987).

Most of the original filter cassettes assembled by the manufacturers have good sealing performance in the first testing. However, inappropriately assembled cassettes, when reused, might not be firmly clamped between the filter and the support pad, resulting in a significant leakage (Baron et al., 2002; Van den Heever, 1994). Therefore, a leak test should be performed to ensure proper assembly of the filter cassette. The amount of leakage is a function of pressure drop across the filter cassette (Van den Heever and Tiernan, 1999). However, pressure drop might not be an ideal indicator due to the variability of the membrane filter.

A convenient test method uses ambient aerosols as test agents and uses a condensation particle counter to measure the filter cassette's upstream and downstream aerosol concentrations to estimate the leakage. Generally speaking, filter cassettes have two types of leakage, internal and external, as shown in Fig. 1. When the upper and lower parts of the filter cassette are not properly and tightly clamped, there might be a gap between the filter, the support pad, and the bottom piece of the cassette. Such a gap is defined as internal (bypass) leakage, which may cause aerosols to enter from the inlet of the top piece to pass through the edge of the filter and support pad. Internal leakage rate increases with the increase in gap height (Baron, 2002; Baron and Bennett, 2002).

The more times the filter cassette is re-assembled for use, the greater the wear in the interface between the upper and lower pieces of the cassette. Friction will cause the surface to become uneven and rough with irregular channel-like leaks, which are the source of external leakage (Baron, 2003). A common way to reduce external leakage is to seal the filter cassette with a shrink band from the outside. Apparently, the assembly press force is critical in cassette leakage, but the required minimum assembly force data is still limited. Therefore, the main objectives of this study are to identify factors affecting leakages and establish standard operating procedures for proper cassette assembly.

2 METHODS

This work used two brands (A and B) of 37-mm diameter transparent styrene two-piece filter...
The experimental setup is shown in the left plot of Fig. 2. The membrane filter (PTFE filter, 1.0 µm, 37 mm, Zefluor, Pall Corporation, Port Washington, NY) and the support pad (mixed cellulose ester, 37 mm) or silicone ring were assembled into the cassette. A homemade manual assembly presser, shown in the right plot of Fig. 2, was built to evaluate the effect of assembly force on the cassette leakage. The press consisted of a torque wrench, ram, and pressure sensor. It was designed in such a way that the ram and the bottom stage could hold the tape evenly. A wrench bar was used to amplify power through leverage. Note that this was a manual presser, and there was no control over how fast the force was applied. The pressure sensor was calibrated with standard weights from 5 to 35 kg in 5 kg increments. The regression analysis showed a high coefficient of determination ($r^2$) of 0.992. The presser was employed to apply 40–350 Newton (N) force evenly on the top piece of the cassette and then seal the cassette outside with a shrink band for external leakage prevention if the applied force was insufficient for fully sealing the filter.

In addition, the outer surface of the upper piece of cassette A is filed for some experiments so that the upper and lower pieces of the cassette do not come in contact with each other. Thus, no friction is generated during the assembly. This filed cassette is designed to identify and analyze external and internal leakages separately. This design can also determine the minimum assembly force required to minimize external leakage. The amount of friction that must be overcome is explored using regular cassettes to reduce the internal leakage rate. The internal leakage rate can be determined only when external leakage is prevented by sealing shrink bands. To obtain the leakage rate, aerosol number concentrations upstream and downstream of the filter cassette were measured using a condensation particle counter (CPC, Model 3776, TSI Inc., St. Paul, MN). The aerosol laboratory was constantly conditioned to maintain temperature from 24 to 26 degrees Celsius and relative humidity from 50 to 60%. Ambient aerosols in the laboratory were used as challenge aerosols, and the count median diameter measured using a scanning mobility particle sizer was 95 nm with a geometric standard deviation of 1.45. Indoor aerosol concentrations ranged from 4000 to 6000 # cm$^{-3}$. To complete a leak test, we did 3 minutes of upstream (room air) sampling, followed by 1 minute of purge, 3 minutes of downstream sampling, and another 3 minutes of upstream sampling. The leak rate was calculated as the ratio of the downstream concentration to the average of the two upstream concentrations. The pressure drop across the filter cassette was monitored with a pressure transducer, which was calibrated using an inclined manometer.
Table 1. List of operating parameters.

<table>
<thead>
<tr>
<th>Column (A)</th>
<th>Filter (F)</th>
<th>Pad (P)</th>
<th>Filter+O-ring (F+R)</th>
<th>Filter + Pad (F+P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Leakage (filed)</td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>Internal leakage (normal)</td>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
<td></td>
</tr>
</tbody>
</table>

The major operating parameters in the present study are listed in Table 1. Column (A) shows the filed top cassette piece used for simulating the potential leakage of different combinations of filter (F), support pad (P), filter and O-ring (F + R), and filter and pad (F + P). These combinations are with and without sealing shrink band (B) wrapping; that difference is indicative of external leakage. Column (B) shows the normal cassette used mainly to simulate internal leakage. The support pad was replaced by the silicone O ring to effectively prevent external leakage through the lateral side of the support pad (from the notch between the top and bottom cassette pieces), as shown in Table 1.

3 RESULTS AND DISCUSSION

Identifying the source of leakage requires knowledge of the filtration efficiency of the membrane filter and/or the support pad. It is because filter/foam penetration might become noise, thus undermining the accuracy of leakage rate measurements. When enough assembly force is applied to minimize leakage, the filtration efficiency is a function of the sampling flow, ranging from 0.3 to 3.0 L min⁻¹, as shown in the right plot of Fig. 3. Total aerosol penetration (aerosol penetration through filter/pad plus external leakage) is also a strong function of the applied assembly force ranging from 30 to 330 N, as shown in the left and right plots of Fig. 3. The right plot also indicates that the filter-O-ring combination is fully clamped at about 100 N; hence, the leakage rate will remain constant even with increasing press force. On the other hand, aerosol penetration increases with increasing flow rate because the submicron-sized ambient aerosols have a shorter retention time for deposition in the filter medium by diffusion. However, the low flow rate of 0.3 L min⁻¹ (left plot) shows a higher aerosol penetration than that of 0.6 L min⁻¹. This phenomenon is likely due to the effect of flow re-distribution. At an extremely low flow rate, air resistance through the leak pathways increases with increasing sampling flow. So, the sampling flow of 0.3 L min⁻¹ is used for the rest of the experiments to minimize the interference of the filter penetration.

Fig. 4 shows aerosol penetration through cassette A with a filed top (male) piece having no direct contact with the bottom (female) piece. This special cassette demonstrates the effect of direct press force on external leakage rate, as shown in the upper plot. The lower plot shows pressure drop across the filter cassette as a function of assembly force, a mirror image of the upper plot. As shown in Fig. 4, aerosol penetration of the support pad (P) is stable at 2.1% when the sampling flow is 0.3 L min⁻¹, and it is completely unaffected by the pressing force exerted on
Fig. 3. Total aerosol penetration (filter penetration plus all leakages) through cassettes under different flow rate and assembly force.

Fig. 4. Total aerosol penetration (external leakage and filter penetration) and pressure drop of the fielded cassette A. The top (male) piece is filed to make a gap in between the top and bottom pieces. With sealing shrink band (B) wrapping, aerosol penetration is not affected, indicating insignificant external leakage from the side edge of the support pad at low pressure drop, in this case, less than five mmH₂O. The airflow entering the cassette is mainly through the front face of the support pad. As for filter (F), when the applied force exceeds 150 N, total aerosol penetration is 0.008%, slightly lower than filter and pad (F + P). Theoretically speaking, F + P should have lower aerosol penetration than F because of more filter media. This mismatch indicates that external leakage through the side edge of the pad increases total aerosol penetration until the pressing
force reaches 230 N. Apparently, this high assembly force increases the packing density of the support pad and, therefore, reduces aerosol penetration from the side of the support pad. Total aerosol penetration remains stable at assembly force ranging from 230 to 350 N, indicating that the structural strength of the pad is sufficient to sustain the press.

When the pressing force exceeds 80 N, the total aerosol penetration of the cassette with filter and O-ring (F + R) reduces to 0.001%. The cassette with filter alone shows aerosol penetration of 0.008%, indicating that external leakage through the side of the support pad contributes 90% of aerosol penetration. All these phenomena shown in Fig. 4 agree well with the filtration theory that filtration efficiency is multiplicative while pressure drop across the filter media is additive. When a press force of 60 N or more is applied, all three combinations, including F-B, F-R-B, and F-P-B, have a total aerosol penetration rate close to 0.001%, which is less than the cases (P, F, F + P, F + R) that are without sealing band (B) wrapping. These results show that sealing shrink bands can effectively reduce external leakage.

A normal filter cassette requires a higher assembly force to tightly clamp the filter and support pad to minimize external and internal leakage compared with the filed cassette. The total aerosol penetration through a normal cassette and a filed cassette as a function of assembly press force from 40 to 350 N is shown in the upper plot of Fig. 5. In contrast, the lower plot displays a pressure drop across the cassettes. To overcome the side friction, the normal cassette A needs to apply 210 N press force on the filter and support pad, and its total aerosol penetration is reduced to 0.004%. Wrapping the cassette with a sealing shrink band (B) helps eliminate external leakage, thus further decreasing total aerosol penetration to 0.001%. In contrast to the normal cassette, the filed cassette has a low total aerosol penetration of about 0.1% when the pressing force starts at 40 N. The total aerosol penetration then gradually decreases with increasing pressing force, then reaches about the same level as the normal cassette (F + P) without sealing band. When wrapped with a sealing band, the filed cassette has an even lower total aerosol penetration. The F + P + B line shows that it takes only 70 N direct press force to clamp the filter and support pad tightly. In other words, 66.7% of the 210 N press force exerted on the normal cassette is for overcoming the friction between the top and bottom cassette pieces. The pressure drop across the cassette as a function of assembly force (bottom plot of Fig. 5) is a mirror image of the upper plot, as explained and shown in Fig. 4.

![Fig. 5. Total aerosol penetration (leakage and penetration) and pressure drop of a cassette A with a filed top piece and another one with a normal top piece.](image-url)
With the increasing number of reassembly times of the filter cassette, the frictional force between the top and bottom pieces will decrease due to wear, so the force required for assembly will also decrease. As shown in Fig. 5, cassette A generally requires at least 210 N to assemble the filter paper cassette to achieve the lowest penetration. The total aerosol penetration through cassette A, the pressure drop across the cassette, and the displacement (decrease in gap height between the top and bottom pieces) of the cassette is shown in the upper, middle, and lower plots of Fig. 6, respectively. When the cassette is re-assembled with 210 N for 1 to 14 times, the side friction decreases slightly with the increase in the number of reassemblies. The total aerosol penetration drops from 0.005% to 0.003%, apparently due to greater press force exerting directly on the filter and support pad. As a result, external leakage is reduced, as evidenced by the decreasing aerosol penetration shown in the upper plot and the increasing pressure drop shown in the middle plot. The displacement meter shows a decrease in the gap of 0.05 mm in the first five reassemblies, but it does not show any change afterward due to the sensitivity limit. The sealing band helps reduce external leakage, as shown by the lower aerosol penetration and higher pressure drop. After more than 15 times of re-assembling, aerosol penetration keeps increasing, and pressure drop keeps decreasing, indicating that the cassette eventually cannot generate a frictional force sufficient to hold the direct press force required to clamp the filter and the pad. Due to the detection limit of the displacement meter, the displacement information was not analyzed.

As shown in Fig. 7, when the number of reassembly times is between 1 and 6, and cassette A is re-assembled under 300 N, the total aerosol penetration remains stable at 0.003%. When the reassembly exceeds six times without a sealing band, the penetration rate of the cassette increases gradually, and the pressure drop decreases, indicating that the cassette is experiencing external leakage. After multiple reassemblies, it is postulated that the external leak passage is the channel-like structure between the top and bottom pieces. If leakage of 0.003% is set as the acceptance level, the sealing band can reduce external leakage and extend the service life to 13 times. After that, the cassette should be discarded. A lower assembly press force of 210 N leads to a service life of 14 times and can be extended to 17 times if a sealing band is employed, as shown in Fig. 6.
The difference in dimensions and surface roughness of cassette brands can affect the required minimum assembly force. Fig. 8 shows the total aerosol penetration and pressure drop of cassettes A and B as a function of assembly force. For cassette A, the application of 210 N for assembly can reach the lowest total penetration rate, indicating that the filter and pad have been properly clamped. In comparison, the cassette B assembly requires a minimum press force of 330 N to clamp the filter-pad combination. A decrease in aerosol penetration rate is accompanied by an increase in pressure drop, as shown in the lower plot of Fig. 8. Therefore, for a cassette of a specific brand, if the membrane filter production has good quality control, upon completion of assembly, the pressure drop can be measured to screen the acceptability of the cassette. Fig. 8 shows that to guarantee proper cassette assembly, the pressure drop across the cassette must be at least 15 mmH₂O under a flow rate of 0.3 L min⁻¹. However, the data of pressure drop across 10 PTFE membrane filters with 1 µm pore size shows high variation when tested as a function of flow rate from 0.3 to 2.5 L min⁻¹, as shown in Fig. 9. Therefore, in view of the present filter quality, a pressure check is not an ideal screening tool for judging whether the cassette is properly assembled or not.

4 CONCLUSIONS

The silicone O-ring is an ideal device for demonstrating external leakage from the side of the support pad. Using ambient aerosol particles and a condensation particle counter would serve the purpose of determining aerosol penetration through different components of the filter cassette. However, pressure drop across the cassette is not an ideal indicator for checking and screening whether the cassettes are properly assembled without a filter of stable quality.

The use of a sealing shrink band helps reduce external leakage. Without the band, aerosol deposits accumulated in the notch between the top and bottom pieces might fall onto the filter and contaminate the sample. Therefore, the sealing band should be a required item in the standard operating procedures of cassette assembly. In addition to preventing aerosol deposition in the notch, the sealing band also provides space for labeling, an essential step for occupational hygienists conducting air sampling.
Fig. 8. Total aerosol penetration (filter penetration and leakage) of cassettes A and B, as function of assembly force.

Fig. 9. The pressure drop variation of 1 µm PTFE filter.

It is important to apply enough press force when assembling filter cassettes in order to prevent both internal and external leakages. The required assembly force is different for different cassette brands. The required press forces for cassettes A and B are 210 and 330 N, respectively. The difference is due to the subtle dimensional variations. At present, most industrial hygienists use their fingers or palms to exert as much pressure as possible when assembling filter paper cassettes. Still, their strength is likely insufficient, i.e., less than 210 or 330 N.

The number of times that cassettes can be re-assembled decreases with increasing force. For cassette A, the service life is 14 times when the assembly press force is 210 N, but it drops to 6 times when the pressing force is 300 N. The application of the sealing band can extend the service life for just a few more reassemblies. The manufacturers might need to provide information regarding the assembly force and the number of cassette reassemblies. Otherwise, users have to work that out on their own.
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REFERENCES