Supplemental information for “Filtration and breathability of nonwoven fabrics used in washable masks”

Thomas W. Bement1, David J. Downey1, Ania Mitros3, Rebecca Lau3, Timothy A. Sipkens1,2, Jocelyn Songer3, Heidi Alexander1, Devon Ostrom4, Hamed Nikookar1, Steven. N. Rogak1,*

1 Department of Mechanical Engineering, University of British Columbia, Vancouver BC Canada
2 Metrology Research Center, National Research Council of Canada, Ottawa ON Canada
3 MakerMask Group, https://makermask.org
4 Artist/researcher, Ostrom.ca, Toronto, ON, Canada

* Corresponding author. Tel: 1-604-822-4149; Fax: 1-604-822-2403
E-mail address: rogak@mech.ubc.ca
A. EFFECT OF PARTICLE CHARGE:

The DMA column used to test the effect of particle charge was the TSI 3081A Long with a rod charge of 6 kV and no sheath flow (Figure A1). This theoretically produces purely neutral particles, as the charged particles are precipitated out in the DMA column.

The method of charge neutralization specified in the NIOSH standard results in a bipolar quasi-neutral charge distribution. We followed this aspect of the standard but wanted to quantify the effect this had on the filtration efficiency. We repeated the multilayered tests with both neutralized and uncharged particles. The tests with neutral particles were done with the DMA column in line, with the sheath flow and voltage off. The tests with uncharged particles had the DMA column in line with the sheath flow and voltage at -6000 V. A two-tailed t-test, with an alpha of 0.1, showed no statistically significant pressure difference between neutralized and uncharged particles as expected.

A two-tailed t-test, comparing the means of the quasi-neutral charged vs. uncharged particles at 4.220 μm, showed no statistically significant difference in filtration efficiencies in all cases except 5 layers SmartFab Thick, 2 layers H100 and 5 layers Pellon 930. Additionally, at the smallest measured size of 0.498 μm, none of the materials show a statistically significant difference. These results suggest that the tested materials filter by mechanical modes, rather than electrostatic forces. This means the removal of charges on the filtering media from cleaning with isopropyl alcohol (IPA), likely shouldn't reduce the filtration efficiency of the materials tested.

Figure A1. TSI 3081A Long DMA column.
Table A1. Result summary of t-Test at 4.2 μm. α=0.1, t_{\text{reject}}= 2.132, CI = 95%.

| Mask    | T       | DOF | Condition       |
|---------|---------|-----|-----------------|
| SmFbx3  | -0.3244 | 4   | Fail to Reject  |
| SmFbx5  | 2.5661  | 4   | Reject          |
| SmFbx7  | 2.0468  | 4   | Fail to Reject  |
| OLFnx1  | -0.1596 | 4   | Fail to Reject  |
| OLFnx2  | 0.2507  | 4   | Fail to Reject  |
| OLFnx3  | -0.4101 | 4   | Fail to Reject  |
| Advnx1  | 1.4144  | 4   | Fail to Reject  |
| Advnx2  | 0.481   | 4   | Fail to Reject  |
| Advnx3  | -0.0052 | 4   | Fail to Reject  |
| H400x1  | 1.2247  | 4   | Fail to Reject  |
| H400x2  | -0.1459 | 4   | Fail to Reject  |
| H400x3  | 1.2247  | 4   | Fail to Reject  |
| H100x1  | -0.6072 | 4   | Fail to Reject  |
| H100x2  | -3.678  | 4   | Reject          |
| H100x3  | -1.2247 | 4   | Fail to Reject  |
| P930x5  | 4.7844  | 4   | Reject          |
| P930x10 | 1.8438  | 4   | Fail to Reject  |
| P930x15 | 0.4232  | 4   | Fail to Reject  |
| Flanx1  | 1.813   | 4   | Fail to Reject  |
| Flanx2  | -0.3536 | 4   | Fail to Reject  |
| Flanx3  | -0.1931 | 4   | Fail to Reject  |
B. OPS SIZE BIN AND AERODYNAMIC DIAMETER RELATION

The TSI3330 allows the user to introduce a refractive index, resulting in a corrected size for the size bin limits. In theory, this provides the physical diameter (as would be measured by microscopy). Taking the geometric mean (square root of the product) of the upper and lower bounds corresponding to a channel, we obtain the 4th column of Table B1. Finally, using a bulk density for solid sodium chloride of 1900 kg/m$^3$, the aerodynamic diameter associated with a particular OPS channel count is obtained. Thus we report the filtration efficiency for the smallest channel at 0.498 microns. Given uncertainties on the precise shape, refractive index and density of the sodium chloride particles, the uncertainty in the reporting size is substantial – perhaps 15%. This would translate the particle filtration data to the left or right but would have no influence on the comparisons between materials.

| OPS Channel | Nominal Bin Lower Limit | Refractive Index Corrected Lower Limit | Geometric Mean Diameter | Aerodynamic Diameter |
|-------------|-------------------------|--------------------------------------|-------------------------|----------------------|
| 1           | 0.300                   | 0.306                                | 0.340                   | 0.498                |
| 2           | 0.370                   | 0.381                                | 0.430                   | 0.620                |
| 3           | 0.460                   | 0.484                                | 0.540                   | 0.796                |
| 4           | 0.570                   | 0.596                                | 0.680                   | 0.962                |
| 5           | 0.710                   | 0.769                                | 0.840                   | 1.190                |
| 6           | 0.880                   | 0.932                                | 1.050                   | 1.480                |
| 7           | 1.090                   | 1.200                                | 1.360                   | 1.910                |
| 8           | 1.350                   | 1.550                                | 1.660                   | 2.320                |
| 9           | 1.680                   | 1.780                                | 1.980                   | 2.760                |
| 10          | 2.080                   | 2.200                                | 2.440                   | 3.400                |
| 11          | 2.580                   | 2.720                                | 3.040                   | 4.220                |
| 12          | 3.200                   | 3.400                                | 3.780                   | 5.250                |
| 13          | 3.960                   | 4.210                                | 4.690                   | 6.490                |
| 14          | 4.920                   | 5.220                                | 5.860                   | 8.120                |
| 15          | 6.100                   | 6.590                                | 7.230                   | 10.000               |
| 16          | 7.560                   | 7.950                                | 8.840                   | 12.200               |
C. FILTRATION EFFICIENCY AND PRESSURE DROP FOR INDIVIDUAL MATERIALS

Filtration efficiency was measured for all 16 OPS bins, but for compactness we present only results for 0.5 microns, 1 micron and 4.2 microns. Error bars on the following plots represent the range for (usually) 3 trials. Those without error bars were testing with only one sample. Layers are filtering independently when materials follow lines of constant $Q$ as the number of layers are changed (eg. P930x15 has 15 layers). For all materials, filtration efficiency increases with particle sizes. Thus, most of the non-woven fabrics have $Q$ ranging from 4-12 kPa$^{-1}$ at 0.5 microns, 6-15 at 1 micron, and 30-60 at 4.2 microns. Figure C4 shows the standard deviation ($Q$) / Average ($Q$) over the aerodynamic diameters 0.5 microns to 5.0 microns. This shows the relative variations of the material sample qualities.

Figure C1. Filtration at 0.5 micron aerodynamic diameter and pressure drop.
**Figure C2.** Filtration at 1.0 micron aerodynamic diameter and pressure drop. Legend for material types is given in Figure C1.
Figure C3. Filtration at 4.2 micron aerodynamic diameter and pressure drop. Legend for material types is given in Figure C1.
Figure C4. For each material the Standard Deviation (Q) / Average (Q) is from 9 or more samples, with at least 3 samples per layer count and 3 different numbers of layers, with the exception of Flti(2021) and Flti(2022) which both have 1 sample for the tests with 3 layers. The Average (Q) and Standard Deviation (Q) were calculated using the qualities of each sample.
D. MULTILAYER MATERIAL TESTING OF HOMOGENEOUS MATERIALS AND MASK ASSEMBLIES

SMS materials having high single layer filtration efficiencies have a much steeper slope because of the \( P_0 \) term (equation 4). Flannel also performs comparatively well with SMS materials. The Spunbond materials have slower sloped curves because of their lower single-layer filtration efficiencies.

The fitted efficiency curve (Figures D1b-D1c) doesn’t exactly line up with the measured single layer efficiency. Electrostatic effects are unlikely to be responsible for the discrepancy, since 5-layer tests of Pellon 930 with the DMA column indicated negligible charge effects. Sample inconsistency likely underlies both the discrepancy between model versus measurement as well as the large error bars for OlyFun and SmartFab.

Figure D1. Pressure drop (a), filtration efficiency at 0.498 μm (b) and 4.220 μm (c) based on number of layers for homogeneous multilayer material stacks. Circles represent average filtration measured from 3 samples. Curves are calculated by applying a non-linear least squares to a specified fit function (equation 4). Error bars represent one standard error based off the three samples.
Visual inspection shows qualitatively different regions in these materials (Figure D2).

![Image of material samples](image)

Figure D2. Photo of OlyFun (a) and SmartFab (b) materials with enhanced color balance. Visual variation in light levels passing through the sample is observable. Light green represents less dense areas while darker regions are more densely packed.

Applying the models acquired when fitting the homogeneous material tests and applying the equations used for predicting the pressure drop and penetration assuming each layer behaves independently a few potential mask stacks can be characterized based on their theoretical combined performance and their measured performance (Figures D3a-D3b).
Figure D3. Model predictions (closed symbols) at 0.5 μm (top) and 4.2 μm (bottom) versus experimental values (open symbols) for proposed mask stacks of Table 2.