Measuring size-resolved particle penetration through face mask materials

Introduction

During the COVID-19 global pandemic, face coverings have been widely worn in public spaces under many countries' laws and guidelines. The intention is that coverings over the mouth and nose will protect others (rather than the wearer) against the spread of infection by capturing virus-laden droplets in exhaled air, coughs and sneezes. These face coverings commonly consist of layers of woven fabric.

Disposable surgical masks are intended for health care staff to protect patients during surgical procedures and in other medical settings. Respiratory filtering half masks are intended to protect the wearer and are regulated as personal protective equipment (PPE) for inhaled air only.

Numerous recent studies have emphasised the possibility of airborne coronavirus transmission (e.g. Zhang et al. (2020)). Both aerosols and droplets can be generated as a continuum of particle sizes during various normal respiratory activities including coughing, talking and singing.

It is therefore of interest to investigate the particle size-resolved filtration properties of various face mask materials across a wide particle size range.

A suitable instrument for achieving this is the Aerodynamic Aerosol Classifier (AAC; Fig. 1), which can select particle sizes between 25 nm and >5 µm.

The AAC transmits particles of a selected aerodynamic diameter by balancing opposing centrifugal and drag forces, (the centrifugal force being generated by a rotating cylinder) allowing the selected particles to be carried by the sheath flow to the outlet. This principle of aerosol selection or classification is independent of the charge state and produces a truly monodisperse aerosol, with a high transmission efficiency limited only by diffusion and impaction losses.

The AAC principle is described in further detail here: http://www.cambustion.com/products/aac/animation

Figure 1: The AAC

Size-resolved particle penetration

Various face covering samples were mounted and sealed in a 47mm filter holder and AAC-classified particle penetration was measured using the methodology reported by Payne et al (2018). As shown below (Fig. 2), the sample was placed downstream of the AAC which was run at a series of setpoints (automatically calculated rotational speeds and sheath flow pairs to select various aerodynamic diameters) from atomised dioctyl sebacate (DOS), chosen for its spherical morphology and size distribution that extends into the micro-scale.

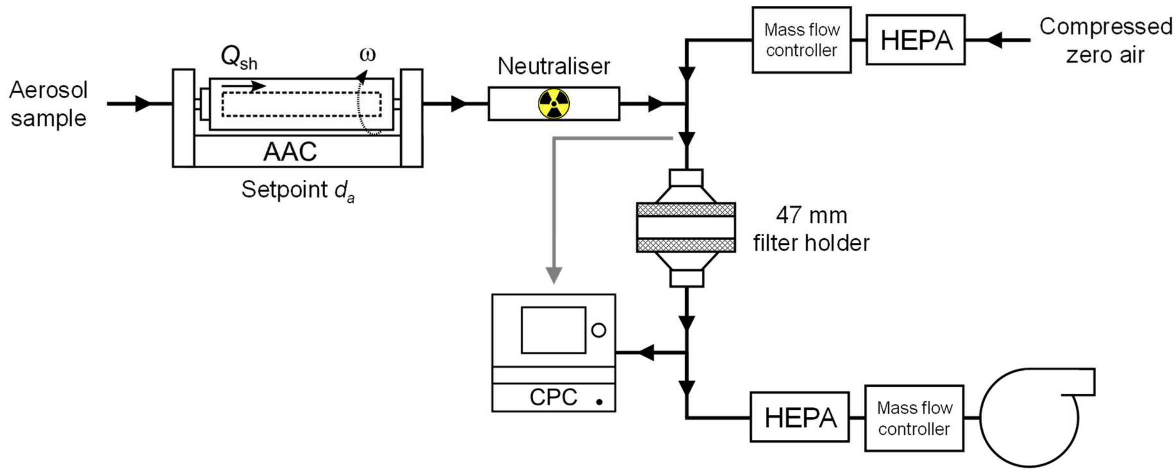

Figure 2: Schematic for measuring size-resolved particle penetration

Particle penetration tests were conducted for filter face velocities corresponding to 160 lpm flow through the entire mask, which is specified in EN 149 to represent **exhalation** flow in steady-state breathing resistance tests.

A constant 10:1 sheath:sample flow ratio was maintained for particle size selection. At reference classifier conditions (0°C and 1.013 bar(a)), the AAC can classify aerodynamic particle diameters from 32 nm to 3 μm at low flow (0.3/3.0 lpm sample/sheath flow) and from 202 nm to 6.8 μm at high flow (1.5/15 lpm sample/sheath flow).

The lower size limit of the AAC is sensitive to particle diffusion and the maximum obtainable rotational speed (this can be extended down to 25 nm if the sheath flow is reduced by approximately 25% at the maximum speed, which broadens the transfer function). The maximum selected aerodynamic diameter for these measurements was 2 μm, which is close to the upper size limit of the Condensation Particle Counter (CPC) model used to measure particle number concentration.

Measurements adhered to the short-term particle penetration test outlined in Clause 8.2 in ISO 16900-3 but for monodisperse aerosol. After a stabilisation time of 3 minutes, logging of filter penetration is initiated (at 1 concentration reading per second) and the short-term penetration value is the average taken over the following 30 seconds.

ISO 29463-3 requires that a neutraliser is installed downstream of the classifier (historically a Differential Mobility Analyser, DMA) so that an equilibrium charge distribution is prescribed on the aerosol incident on the filter sample. Therefore the AAC output was passed through a Krypton-85 neutraliser. The challenge aerosol then mixes with HEPA-filtered make-up air (to establish the correct filter face velocity), which is supplied by a compressed zero air cylinder. Particle number concentration upstream of the filter was recorded by bypassing the filter holder. The percent penetration at each particle size was calculated as the ratio of down- to upstream concentrations measured alternately with the same CPC. In all cases, the CPC was operating in single count mode; where necessary, dilution of DOS aerosol upstream of the AAC was provided by a modified version of the rotary disk diluter used in the Cambustion DMS500.

Results

Penetration measurements for AAC-classified DOS particles between 50 nm and 2 μm are plotted in Fig. 3 for samples cut from six commercially available face coverings.

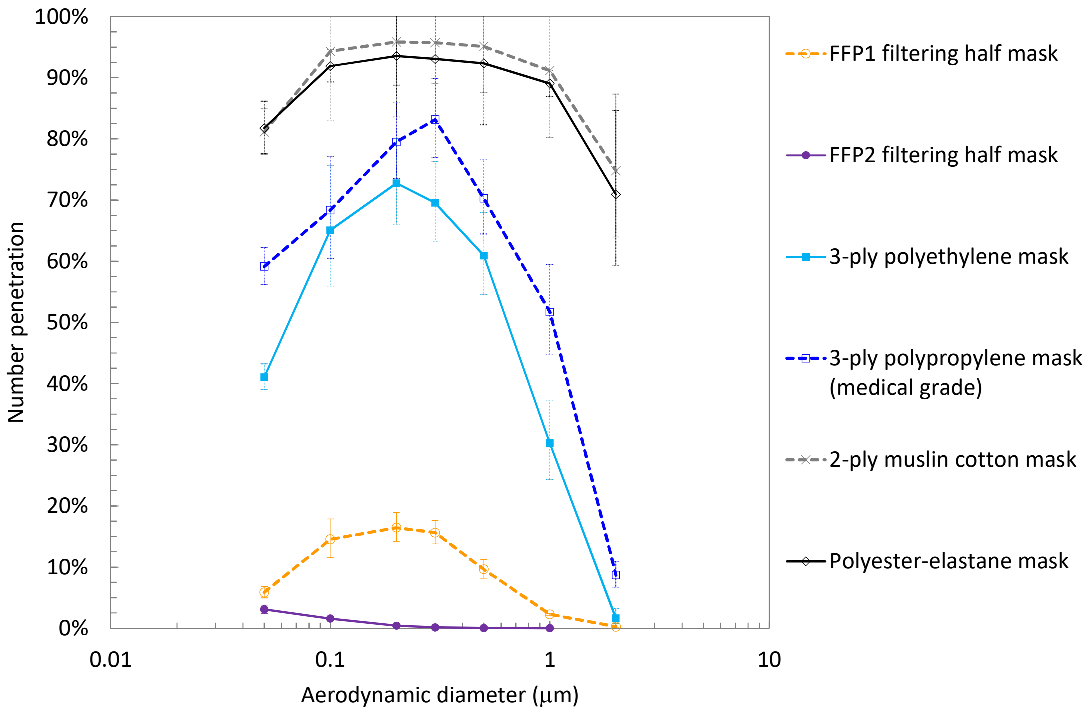

Figure 3: Number penetration of AAC-classified DOS particles through various face mask materials at 160 lpm equivalent through the entire mask

For each penetration value the error bars represent a two-sided 95% confidence interval, which was calculated in accordance with the specifications for particle counting statistics in Clause 7 of ISO 29463-2 (based on the Poisson distribution).

Filtration of the smallest particles is dominated by diffusion while the influences of interception and impaction are greatest for the largest particles, meaning a peak in penetration at intermediate sizes that generally falls around a few hundred nm for the flow rate and mask materials tested here.

The greater fibre spacing of the two woven fabric materials (muslin cotton and the polyester-elastane blend) mean significant particle penetration across the size range tested, in contrast to the regulated filtering respirators (which conform to the FFP1 and FFP2 classes in EN149). While there is also significant penetration on the nanoscale through the disposable polyethylene and polypropylene mask materials, filtration efficiency sharply improves as particle size approaches 1 µm, which suggests good protection against virus-laden droplets on the microscale.

Note: since these tests involve particle penetration of material samples sealed by an o-ring in a housing, the results are not representative of an entire face covering with air leakage around the edges.

Further Reading

AAC:	www.cambustion.com/products/aac
Publications:	http://www.cambustion.com/publications/pubinst/AAC

Note Regarding Standards

A variety of standards are used to measure and classify mask performance, with different challenge aerosols, test procedures and performance criteria. Manufacturers may select from the different standards for validation of their products, so packaging and availability in different geographical areas may vary.

FFP1/FFP2 categorises masks according to EN 149:2001+A1:2009 (European Union)

N95 categorises masks according to NIOSH-42CFR84 (United States of America)

KN95 categorises masks according to GB2626-2006 (People's Republic of China)

Publications referred to in the text

- CEN. (2009). EN 149:2001+A1:2009 Respiratory protective devices - Filtering half masks to protect against particles - Requirements, testing, marking.
- ISO. (2011). Part 2: Aerosol production, measuring equipment and particle-counting statistics. In ISO 29463:2011 High-efficiency filters and filter media for removing particles in air.
- ISO. (2011). Part 3: Testing flat sheet filter media. In ISO 29463:2011 - High-efficiency filters and filter media for removing particles in air.
- ISO. (2012). Part 3: Determination of particle filter penetration. In ISO 16900:2012 Respiratory protective devices - Methods of test and test equipment.
- Payne, S. D., Irwin, M., Johnson, T. J., & Symonds, J. P. (2018). A New Methodology for Measuring Filtration Efficiency as a Function of Particle Aerodynamic Diameter Using a Monodisperse Aerosol Source. FILTECH. Cologne, Germany. https://www.researchgate.net/publication/334896027_A_New_Methodology_for_Measuring_Filtration_Efficiency_as_a_Function_of_Particle_Aerodynamic_Diameter_Using_a_Monodisperse_Aerosol_Source
- Zhang, R., Li, Y., Zhang, A. L., Wang, Y., & Molina, M. J. (2020). Identifying airborne transmission as the dominant route for the spread of COVID-19. Proceedings of the National Academy of Sciences of the United States of America. https://www.pnas.org/content/117/26/14857