Research Assessment Exercise 2020
Impact Case Study

University: The Hong Kong Polytechnic University (PolyU)
Unit of Assessment (UoA): 14 - Mechanical engineering, production engineering (incl. manufacturing & industrial engineering), textile technology and aerospace engineering
Title of case study: Clean Air Nanofiber Technologies

(1) Summary of the impact

Existing facemasks made of microfibers offer low protection against harmful 100-nanometer pollutants and viruses. Respirators with high-density fibers are hard-to-breath. A breakthrough technology using multi-layers of nanofibers separated by permeable substrate, has been developed by PolyU. A startup company - Avalon Nanofiber Ltd. Taipei - was created in 2014 with a total investment of HK$ 30 million, including new electrospinning equipment for producing large-scale nanofibers. The company employs 10 professionals to produce solvent-free facemasks/filters for public use and has sold over two million facemasks. People with respiratory diseases, compromised immune systems, and pollen allergies benefit from the facemask with low pressure drop and full protection.

(2) Underpinning research

Pollutants contain harmful nano-aerosols less than 100 nanometers. Given their tiny size, they can be easily inhaled into our lungs, and diffused across the alveoli to the capillaries. The blood carries the nano-aerosols to various organs of our body and the brain, causing acute respiratory problems, chronic cardiovascular diseases, and other serious damage **[1]**. The concentration of nano-aerosols can be very high, particularly in urban environments, 100 million count/m^3 indoor to over 200 million count/m^3 outdoor **[2]**. Nano-aerosols are also harmful because of their large specific surface, a potentially important interface through which to transmit toxic chemicals (from emission) that might be adsorbed. Airborne viruses are also in the nano-aerosol size range, they too can lead to acute sickness. Filters in filtration systems or individual facemasks can be used to trap nano-aerosols and research led by Professor Wallace Leung at the Hong Kong Polytechnic University (PolyU) since 2010 has created effective nano-aerosol facemasks and filters for the first time.
The primary capture mechanisms for nano-aerosols are diffusion and interception, which requires fibers with large specific surface-to-volume ratio. Conventional *microfiber* filters do not have such large specific surface, thus have poor protection from nano-aerosols. The only means by which respirators with microfibers can achieve this is by increasing the amount of fibers per unit filter area. However, this causes an extremely high pressure drop which makes breathing difficult when wearing the mask.

In contrast, *nanofibers* with diameter 100-300 nanometers (i.e. 1/10 smaller than microfiber) offer exactly the needed large specific surface area for diffusion and interception, resulting in excellent capture efficiency of nano-aerosols **[3, 4]**. The pores in between adjacent nanofibers are smaller, unfortunately, this results in high pressure drop. Our breakthrough technology is to rearrange the amounts of nanofiber that are necessary to achieve high capture efficiency into multiple thin layers, wherein each thin layer is supported by a permeable substrate. This resultant quasi-3D filter structure has low pressure drop due to micropores from the nanofiber layers interrupted by macropores from the permeable substrate. It is remarkable that both low pressure drop and high filtration efficiency are achievable at the same time as these two merits are always in opposing directions. The efficiency-to-pressure drop ratio is very high for our novel multilayer nanofiber technology **[4]**. We have tested four polymeric materials (polyethylene oxide, nylon, polyethylene alcohol, and polyvinylidene fluoride **[5]**) and one natural material (chitosan) and the multilayer nanofiber works in all cases with performance depending on the specific material.

For filtration over a prolonged period, the filter is eventually saturated with nano-aerosols and a cake grows over time on the nanofiber filter. The cake becomes the effective filter media. Unfortunately, the cake formed on the nanofiber filter surface is not too permeable because of the smaller pores between the nanofibers resulting in high pressure drop across the entire filter and cake. Our innovative solution is to place a microfiber layer upstream of the nanofiber layer. The cake forms on the microfiber layer which is much more permeable and provides a low pressure drop solution **[6]**. Although the initial pressure drop is slightly higher, over time the total pressure drop for the composite filter can be reduced by 1/3 or more when compared with the nanofiber filter alone **[6].**

(3) References to the research

5 outputs (2) – (6) published by author in top separation journal with journal impact factor: 5.107.

(1) S Ohlwein, R Kappeler, MK Joss, N Kunzli, B Hoffmann, Health effects of ultrafine particles: a systematic literature review update of epidemiological evidence, International Journal of Public Health 64:547–559, 2019.

(2) WWF Leung*, Yuen Ting Chau, "*Experiments on filtering nano-aerosols from vehicular and atmospheric pollutants under dominant diffusion using nanofiber filter*", Separation Purification Technology, 213, 186-198, 2019.

(3) CH Hung, WWF Leung*, *"Investigating the filtration of nano-aerosol using nanofiber filter under low Peclet number regime,"* Separation Purification Technology, Vol 79, Issue 1, 34-42, 2011.

(4) WWF Leung*, CH Hung, and PT Yuan, *"Effect of face velocity, nanofiber packing density and thickness on filtration performance of filters with nanofibers coated on a substrate,"* Separation and Purification Technology, Vol 71, 30-37, 2010.

(5) QQ Sun and WWF Leung*, "*Charged PVDF multi-layer filters with enhanced filtration performance for filtering nano-aerosols*", Separation Purification Technology, 212, pp854-876, 2019.

(6) WWF Leung*, WY Hau, HF Choy, *"Microfiber-nanofiber composite filter for high-efficiency and low pressure drop under nano-aerosol loading"*, Separation Purification Technology, Vol 206, 26-38, 2018

(4) Details of the impact

Introduction: Air contains a high concentration of pollutant particulates in form of nano-aerosols less than 100 nanometers both outdoors (from traffic, industrial/human activities, and power plant emissions) and indoors (70% from outdoor air plus indoor sources). This is a particular health hazard in urban areas, with many cities around the world frequently reaching 'unhealthy' levels of air pollution. Indoors, nano-aerosols can be removed by air filters equipped with effective filter media, while outdoor users need to wear high-efficiency, breathable facemasks. Two technologies using nanofiber filter media have been developed by PolyU to remove nano-aerosols, one for light aerosol loading using *multilayer technology* and the other for extended/heavy loading using a *composite filter*. Both technologies provide high protection against nano-aerosols with low pressure drop. People with respiratory diseases, compromised immune systems, and those who are allergic to pollens can benefit from the filters with low pressure drop and high protection. Below is a description of **various impacts** in details.

Creation of a new company and new jobs: In early 2014, the New York Times **[5a]** reported our newly developed facemask, which is highly breathable and has high efficiency against nano-aerosols. In late 2014, Avalon Biotechnology became interested in commercializing our facemask made from chitosan nanofibers which can provide disinfection in addition to offering protection against nano-aerosols. This was in alignment with their biotech interests. Consequently, a new start-up Avalon Nanofiber Ltd., based on our nanofiber technologies was established in October 2014 in Taipei with an investment of HK$ 30 million. The company has created jobs and now has 10 employees, consisting of technical, marketing and sales, IT, and accounting professionals.

Sharing our knowledge/knowhow for scale-up and benefiting R&D institutions overseas:
Under our guidance starting in 2015, Avalon used the Taiwan Textile Research Institute (TTRI) laboratory to carry out numerous tests, first confirming our research findings on chitosan nanofibers, and later extending the technology to an acid-free solvent for electrospinning using polyvinyl alcohol (PVA) in water, where water replaced acid solvent reducing emission to the environment. We started our testing using the TTRI 400-mm wide electrospinning machine to produce nanofibers, which is a scaleup compared to our smaller lab unit at PolyU. During our interactions with TTRI, we transferred knowledge and knowhow regarding air filtration with nanofiber filters to their technical engineers **[5b]**. TTRI was established by the Taiwan government to support textiles and related industry in Taiwan and can now better support the air filtration business and related activities in Taiwan/SE Asia.

Investment in production, R&D findings and benefits to facemask manufacturer:
In 2016, with our assistance Avalon scaled-up to full production and installed a brand new 750mm wide electrospinning machine with the upstream feeding roll and downstream collecting roll, and curing ovens in a new facility in New Taipei with an investment costs of approximately HK$ 15 million. Rolls of electrospun PVA nanofibers on a substrate were produced on a production scale by the end of the year. The nanofiber rolls were sent to TaoYou Toll Manufacturer, Taiwan, for producing facemasks using our proprietary multilayer arrangement to reduce pressure drop across the filter. TaoYou also benefits from the additional nanofiber facemask business. All along, we have provided close guidance and advice to Avalon and the test lab at TTRI.

Benefits to startup company and to consumers:
In early 2017, Avalon started to produce and sell PVA nanofiber facemasks using our multilayer nanofiber technologies. Over a thousand facemasks per month have been sold over the internet worldwide since the product launch in January 2017. To-date, over two million facemasks have been sold around the world through the internet **[5b, 5c]**. At a retail price of NT$ 230-330 per facemask (HK$ 60-85), this is an estimated NT$ 460-660 million (HK$ 120-170 million) in sales during the RAE period.

There are two different facemask designs available, a T-shape design and a 3D design. A consumer survey conducted by Avalon reveals "… *the T-shape design is comfortable and much breathable as compared to other brands. It does not trap heat, the feeling of wearing the mask is pretty good. The user can wear all day long unlike other 3D mask. Further, the eyeglass does not fog up. For the 3D nanofiber mask design, users felt that they are light and relatively thin, highly permeable and users can breathe freely through the mask. It is comfortable to wear the mask as it follows the face profile*…" **[5d]**. In addition to the benefit of highly breathable masks, test conducted on the street traffic emission using these nanofiber facemasks produced by Avalon reveals the protection efficiency of at least 70-80% against 'real' nano-aerosols **[Sec.3, Ref.2]**. This is a first on testing superior facemask in combating real pollutants!

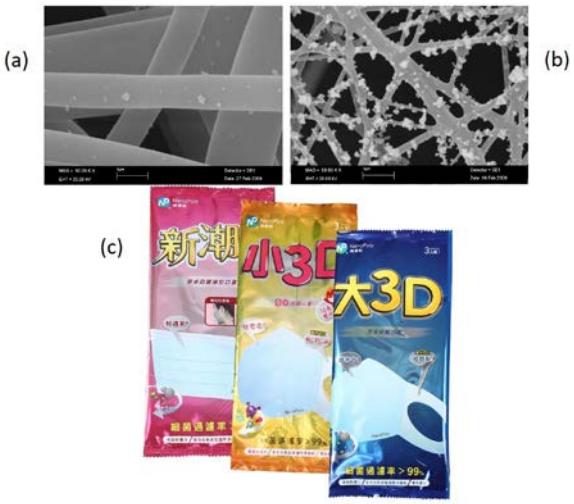
Additional IP generated, R&D, new technologies, and new markets:
Avalon has successfully secured 3 additional patents in China, Germany and USA, based on our two initial US patents resulting in a total of 5 patents/IPs covering the multilayer and composite filter technologies.

While Avalon has fully deployed the multilayer nanofiber technology for light aerosol loading as in facemask, Avalon has designed new facemask designs which have been awarded with three design patents on their T-shape and 3D designs. They have five unique characteristics **[5e]**. These design are all based on the multilayer nanofiber filter technology.

Avalon have also further carried out R&D on the composite nanofiber filter technology that was licensed from us. In the composite filter, a microfiber layer is positioned upstream of the nanofiber layer for heavy aerosol loading applications. The nanofiber provides high efficiency during initial filtration and once a cake layer forms on the microfiber layer, the cake becomes the effective filter media **[Sec. 3 Ref. 6]**. Avalon carried out extensive testing of using different materials for the microfiber layer, including media that carries electrostatic charges. This ongoing R&D is allowing Avalon to expand their business using the other licensed technology from PolyU for filter for use into transport and indoor filtration beyond the initial facemask applications.

Avalon are working with the Hong Kong MTR (mass transit railway) to improve air quality in their train stations, signing an MOU in March 2019. Nearly 6 million people in Hong Kong use the MTR daily. In September 2019, Avalon signed an MOU with MayAir, the largest supplier of indoor filters in Mainland China. Avalon is working with MayAir to install the improved composite filter technology in several key applications: HVAC/ventilation filter bags and pleated filters, specialized high-performance filters for clean rooms, and biomedical and pharmaceutical applications with disinfection. This further expands the original scope of the technology licensed from PolyU to important continuous filtration applications.

Reducing environmental emissions and waste:
Existing facemasks are primarily made of meltblown polypropylene (PP). Toxic vapors are emitted from the meltblown process as the molten PP is blown through nozzles under high temperature generating PP vapor that is ventilated to the environment. By using our technique of electrospinning PVA in water, there is no toxic gas emission and the process is environmentally friendly. Also, the volume of nanofibers produced is drastically reduced. It is typically 2% to 5% of what is needed for the meltblown method using molten PP. Therefore, there is no toxic gas emission from our process plus much reduced chemicals and materials usage, both of which benefit the environment.
The multilayer nanofiber filter and the composite filter technologies have key benefits of high efficiency and low pressure drop for light and heavy aerosols loading, respectively.



Legend:
(a) Left top – diesel emission captured by microfiber filter (very few nano-aerosols)
(b) Right top – same diesel emission nano-aerosols captured effectively by nanofiber media (a lot of aerosols capturing almost all emitted nano-aerosols)
(c) Bottom – 3 Products sold over 2 million by Avalon Nanofiber Ltd. using our multilayer technology and their new designs based on solvent-free PVA nanofibers

(5) Sources to corroborate the impact
[5a] The New York Times (Mar 2015): https://www.nytimes.com/2014/03/20/business/energy-environment/doctors-push-scrutiny-for-smog-masks.html
[5b] Letter from Dr. Henry Feng, CEO of Avalon Nanofiber, September 2019
[5c] https://www.nanopoly.com.tw/ecommerce/
[5d] Customers' Survey
[5e] https://www.avalon-nanofiber.com/2017/09/nanopoly-and-bank-of-taiwan-together-bring-the-nanofiber-mask-to-the-public-to-breath-healthly/