Future trends in laboratory methods to predict HVAC in service filter performance

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From energy crisis to sustainable indoor climate – 40 years of AIVC

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The papers which have been peer reviewed are indicated in the table of contents.

Acknowledgments

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TightVent Europe has been initiated by INIVE EEIG (International Network for Information on Ventilation and Energy Performance) with at present the financial and/or technical support of the following partners: Lindab, MEZ-TECHNIK, Retrotec, BlowerDoor GmbH, Eurima, Soudal, Gonal, SIGA, Buildings Performance Institute Europe and the Covenant of Mayors for Climate & Energy.

venticool

The international ventilative cooling platform, venticool (venticool.eu) was launched in October 2012 to accelerate the uptake of ventilative cooling by raising awareness, sharing experience and steering research and development efforts in the field of ventilative cooling. The platform supports better guidance for the appropriate implementation of ventilative cooling strategies as well as adequate credit for such strategies in building regulations. The platform philosophy is pull resources together and to avoid duplicating efforts to maximize the impact of existing and new initiatives. venticool collaborates with organizations with significant experience and/or well identified in the field of ventilation and thermal comfort like AIVC (www.aivc.org) and REHVA (www.rehva.eu). venticool has been initiated by INIVE EEIG (International Network for Information on Ventilation and Energy Performance) with the financial and/or technical support of the following partners: Agoria-NAVENTA, Velux, WindowMaster, CIBSE nvg, the Covenant of Mayors for Climate & Energy and REHVA.

venticool
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INIVE EEIG (International Network for Information on Ventilation and Energy performance)

INIVE was founded in 2001. INIVE is a registered European Economic Interest Grouping (EEIG), whereby from a legal viewpoint its full members act together as a single organisation and bring together the best available knowledge from its member organisations. The present full members are all leading organisations in the building sector, with expertise in building technology, human sciences and dissemination/publishing of information. They also actively conduct research in this field - the development of new knowledge will always be important for INIVE members.

INIVE has multiple aims, including the collection and efficient storage of relevant information, providing guidance and identifying major trends, developing intelligent systems to provide the world of construction with useful knowledge in the area of energy efficiency, indoor climate and ventilation. Building energy-performance regulations are another major area of interest for the INIVE members, especially the implementation of the European Energy Performance of Buildings Directive.

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The following organisations are members of INIVE EEIG (www.inive.org):

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eERG - End-use Efficiency Research Group, Politecnico di Milano, Italy

IEQ-GA (Indoor Environmental Quality – Global Alliance)

The Indoor Environmental Quality – Global Alliance (IEQ-GA) was started by six (6) member organizations in 2014 with the signing of a Memorandum of Understanding (MOU). The member organizations include: AIHA; AIVC; ASHRAE; AWMA; IAQA; REHVA. In 2018, IISHRAE joined as the seventh member organization. The mission of IEQ-GA is to provide a scientific and technical basis for an acceptable indoor environmental quality (thermal environment; indoor air quality; lighting; acoustic; etc.) to occupants in buildings and places of work around the world, and to make sure the knowledge from research on IEQ is implemented in practice by engineers and practitioners.

The objective of the IEQ-GA is to get the member organizations to think together, work together and speak with the same voice. Our emphasis is on communications, coordination, cooperation and collaboration between the member organizations on indoor environmental quality issues. The alliance is formed as an interdisciplinary, international working group of member organizations interested in indoor air quality, thermal comfort, lighting and acoustic science, technology, and applications to stimulate activities that will help in a significant way to improve the actual delivered indoor environmental quality in buildings.

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REHVA, The Federation of European Heating, Ventilation and Air Conditioning associations founded in 1963, is an umbrella organization that represents over 120,000 HVAC designers, building services engineers, technicians and experts across 27 European Countries.
REHVA is dedicated to the improvement of the health, comfort and energy efficiency in all buildings and communities. The association provides its members with a strong platform for international professional networking, and knowledge exchange pursuing the vision of

improving health, comfort, safety and energy efficiency in all buildings and communities. It follows EU policy developments and represents the interests of its members in Europe and worldwide. This is achieved through the exchange of technical information, practical experience and research results by REHVA's working groups, seminars, publications and journal.

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Future trends in laboratory methods to predict HVAC in service filter performance

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ABSTRACT

Air filters installed in ventilation systems face various types of aerosols during their service life, both in residential and in commercial buildings. Their particle size is the most important characteristic and ranges from a few nanometers to a few micrometers. Different physicochemical properties, such as phase state, hygroscopicity, and morphology are also important to determine the impact of particulate matter on the behavior of air filters during their service life. Therefore, the performance of air filters installed in a Heating, Ventilation and Air-Conditioning (HVAC) system is strongly dependent on the properties of the particles captured during their service life and not only on the characteristics of the materials and technologies used to manufacture the air cleaning equipment.

Current laboratory test methods for evaluating HVAC filter performance include the determination of their fractional particle removal efficiency on a limited size range, typically between 300 nm and 10000 nm. Such information is useful and meaningful for clean filters. However, air filters performance (i.e. airflow resistance and removal efficiency) changes during their service life because of particle loading. For this reason, air filters are artificially clogged in laboratory with the intent to compare one product to another and to predict their behavior while they age in HVAC systems. Current standardized air filter loading procedures use synthetic dusts with particle size distributions very different from typical urban atmospheric aerosols. Consequently, the results obtained in this way differ from the air filter performance measured in real HVAC installations and the designers cannot use them to predict quantitatively the in-situ air filter performance. Standards writers are aware of the problem and this limitation is stated explicitly in EN ISO 16890 and ANSI/ASHRAE 52.2 standards. However, there is a need to perform the test in a short time. Moreover, the filtration industry consolidated this approach during the past decades and a lot of data is available with those dusts.

To improve the prediction of the size-resolved efficiency and the loading kinetics of HVAC filters we need improved test methodologies. ASHRAE is promoting the development of a new method to age air filters as part of ASHRAE Guideline Project 35 “Method for Determining the Energy Consumption Caused by Air- Cleaning and Filtration Devices”. Research teams in USA and Italy are attempting to improve the loading procedure to age HVAC filters using aerosols with more realistic particle size distributions. If successful, the new ageing procedure could provide a reliable prediction tool for evaluating the airflow resistance during the filter service life. In this way, we could optimize the performance of air cleaning equipment in realistic conditions.

In this paper, we summarize current laboratory ageing procedures. We compare the airflow resistance trend in an HVAC system monitored for more than one year, with the results from an ISO 16890 laboratory test on the same air filter. We discuss the difference between the mass increase values causing the same airflow resistance increase.

To reduce the difference between actual data and laboratory simulation results, we present an emerging technique with a preliminary evaluation of a new thermal flame generator for challenging HVAC filters with sub-micron potassium chloride aerosol at high mass concentrations. The thermal aerosol generator is able to reproduce the sub-micron urban atmospheric aerosol mass size distribution and it is a promising technique to solve some of the problems stated above.

KEYWORDS

Air filter test, urban aerosol size distribution, synthetic dust, nanoaerosol, air filter ageing.

1 INTRODUCTION

To assess properly the performance of air filters for general ventilation we need to evaluate their service life together with their initial airflow resistance and capability to capture particles. In fact, the behavior during their service life influences the required replacement interval and their average airflow resistance during operation. Both the duration of service and the particle removal performance of air filters installed in Heating, Ventilation and Air-Conditioning (HVAC) systems depend not only on the characteristics of the materials and technologies used to manufacture them, but also on the properties of the challenging aerosols. These properties include particle size, phase state, hygroscopicity, and morphology. An especially relevant property is the particle size distribution (PSD) of the challenging aerosol, which determines the loading kinetics of air filter media and the full-scale filter ageing process.

Current methods to evaluate the test dust capacity (also known as dust holding capacity) of an air filter provide a way to assess the performance in terms of duration in an abbreviated and cost-effective manner, by using synthetic dusts to simulate filter ageing. The characteristics of those dusts respond to the need for short-duration (hours) laboratory tests to simulate the behavior of an air filter over a much longer period (months). In addition to that, the test dusts must be relatively inexpensive and easily reproducible, so that different laboratories around the globe can use them and expect the same PSD of the test dust.

The new ISO 16890 standard series accomplishes such requirements by using a purely silica-based dust, with the intent of improving the repeatability and reproducibility of the measurements, compared to the carbon and vegetal fibers-based dusts used in ANSI/ASHRAE 52.2 standard. However, the PSD of the synthetic dusts is dramatically different from the PSD of the urban atmospheres challenging the filters during their operation. This is one of the reasons why we cannot use the results obtained ageing the filters with those synthetic dusts to predict quantitatively the in-situ air filter performance. EN ISO 16890 and ANSI/ASHRAE 52.2 standards state this limitation explicitly.

Most HVAC systems are in urban areas where approximately 80% of the population of the developed regions live and work (United Nations, Department of Economic and Social Affairs, Population Division, 2018). Filters cleaning the air in those HVAC systems are especially important when outdoor air is highly polluted. The PSD of particulate matter in polluted urban areas contains large amounts of nanoparticles generated by human activities. We should consider this as a key aspect when trying to reproduce in the laboratory the behavior of air filters cleaning outdoor polluted air.

2 URBAN ATMOSPHERIC AEROSOLS VS SYNTHETHIC DUSTS

Urban aerosols are mixtures of primary particulate emissions from industries, transportation, power generation, and natural sources; and secondary material generated by gas-to-particle conversion mechanisms. If we consider the number PSD for this kind of aerosols the major fraction is represented by particles smaller than 0.1 µm, while most of the surface PSD falls in the size range of 0.1 - 0.5 µm (Seinfeld & Pandis, 2012). On the other hand, the aerosol mass PSD usually has three distinct modes. The first two correspond to the sub-micrometer size range (nuclei and aggregation modes), while the third one is characterized by coarse particles of larger sizes.

The smaller particles form the nuclei or nucleation mode and are generated by primary particle formation processes of anthropogenic nature (mainly from combustion processes) and gas-to-particle transformations (nucleation), which create and emit the sub-micron particles in the atmosphere. These particles represent the greatest portion of the number PSD in an urban aerosol but give a rather small contribution to the mass or volume PSD and have a relatively short duration in the atmosphere. Moreover, because of the high concentrations of nuclei, especially at relatively short distances from the sources (in the order of few hundreds of meters), most of them coagulate quickly with each other, which determines an overlapping zone with the accumulation mode.

In the case of the accumulation mode, the particles are formed by photochemical reactions between volatile organic compounds (VOC) and nitrogen oxides present in the atmosphere under the effect of intense sunlight. Particles in the accumulation mode are also originated from the nucleation, condensation and aggregation processes of the smaller nuclei. The volume/mass distribution of this mode is centered mainly in the 0.1–2 µm size range (Seinfeld & Pandis, 2012). Together with the nuclei, the particles belonging to the accumulation mode constitute the so-called "fine" particles, which represent the relevant part of the number size distribution of an urban aerosol.

The coarse mode, instead, is characterized by particles generated from natural processes, such as wind erosion dusts and sea salt spray particles; and anthropogenic sources, like agriculture and mining activities. Due to their larger size, these particles have a short atmosphere lifetime (a few hours or days) and are rapidly captured in surfaces or deposited from gravity effect (Hinds, 1999).

Interestingly, the accumulation and coarse particle modes present comparable mass concentrations for most urban areas, despite of the high variability in the PSD within a given city (Seinfeld & Pandis, 2012). For this reason, it is important to distinguish the different modes, and analyze the urban aerosol PSD both in terms of particle mass and number distribution.

Previous works by Stephens (Stephens, 2018) and Azimi (Azimi, Zhao, & Stephens, 2014) studied the characteristics of 194 long-term PSD datasets from more than 10 different locations around Europe and North America, collected between 1996 and 2011. This information was compared with historical distributions that have been used as reference in widely recognized textbooks, such as the one by Seinfeld (Seinfeld & Pandis, 2012). While the latter constitutes the current basis for the definition of the assessment standards for air filter performance, the more recent PSD data analyzed in the aforementioned studies show lower concentration values for the number size distributions when compared to the historical data (Stephens, 2018).

Despite this slight discrepancy, the overall shape and parameters of the particle mass/volume distributions of the studied urban atmospheric aerosols can be regarded as similar to the historical representations. In particular, the presence of two distinct modes, one of which with high values of mass/volume in the sub-micrometer range, corresponding to the previously mentioned accumulation and nuclei modes. This supports the evidence of similar characteristics between different urban atmospheres around the world and provides a solid basis for taking a common urban atmospheric aerosol PSD as a reference for testing and assessing the performance of HVAC filters. To do this, it would be necessary to generate in the laboratory suitable test aerosols with particle size distribution similar to the reference one, at higher concentrations and within a defined tolerance.

On the contrary, the volume PSD of currently standardized test dusts, such as the ISO fine A2 dust used by ISO 16890, are completely different from the urban atmospheric aerosols. This difference is evident in Figure 1 below, in which we compare the cumulative size distribution plots of the ISO fine A2 dusts (previous and current version) and the reference urban atmospheric aerosol adopted by ISO 16890 series.

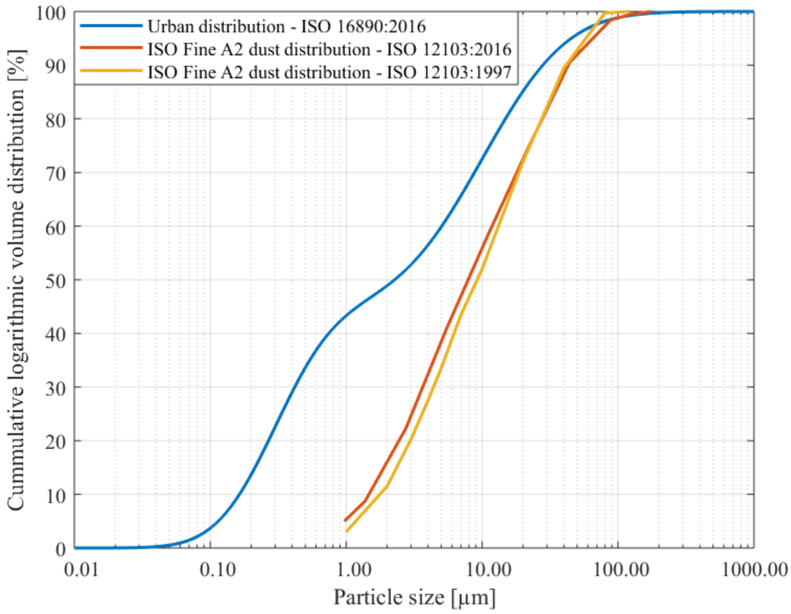

Figure 1 Cumulative PSD plots of A2 synthetic dust and typical urban aerosol adopted by ISO 16890

We highlight that about 50% of the particles in the urban atmospheric aerosol mass distribution adopted by ISO 16890 series are smaller than the smallest particles in ISO fine A2 dust.

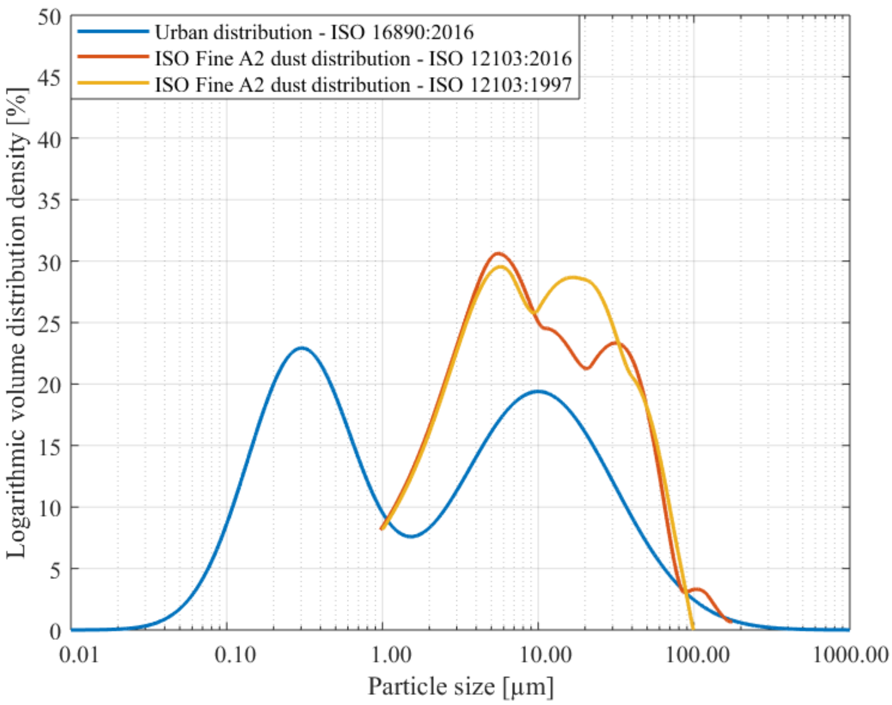

Figure 2 Volume PSD plots of A2 synthetic dust and urban aerosol

Figure 2 compares the logarithmic volume distribution densities of the typical urban atmospheric aerosol adopted by ISO 16890 and the ISO fine A2 dusts. This figure is even clearer in showing the huge difference between those particle size distributions. Those plots show that current synthetic test dusts cannot represent any urban environmental condition challenging the air filters used in HVAC systems during their operation. We cannot ignore such huge difference if we want to get data from laboratory tests that can predict reliably the in-situ performance. Previous analyses (Tronville & Rivers, 2005) have provided similar results, comparing an urban aerosol volume PSD with two different synthetic aerosols and two standard dusts.

3 COMPARISON BETWEEN IN-SITU AND ARTIFICIAL FILTER AGEING

As discussed in the previous sections, the differences in the PSDs of synthetic dusts and urban atmospheric aerosols yield significant discrepancies in the prediction of the air filters duration over time, and the performance change throughout their service life. In fact, current test methods provide a test dust capacity that is commonly used to predict the mass of particles causing a certain increase of airflow resistance. Many experts use this value to determine the expected filter duration in service.

However, long term data collected in-situ from air filters installed in HVAC systems for general ventilation purposes, demonstrated that filters working in real applications at the same airflow rate can reach the same airflow resistance values after capturing much lower amounts of particles.

We report and compare some performance data measured on three 4Vs compact filters (same model and manufacturer). The filter media of those filters was wetlaid fiberglass and their ISO 16890 ratings *e*$PM_{2.5}$ 90% (which could be reported also as *e*PM_1 86%, and *e*PM_{10} 97%). The pressure drop values were measured using a Siemens QBM65.1-10 differential manometer in the air-handling unit and an Aplisens APRE-2000G/N differential pressure sensor for the laboratory tests.

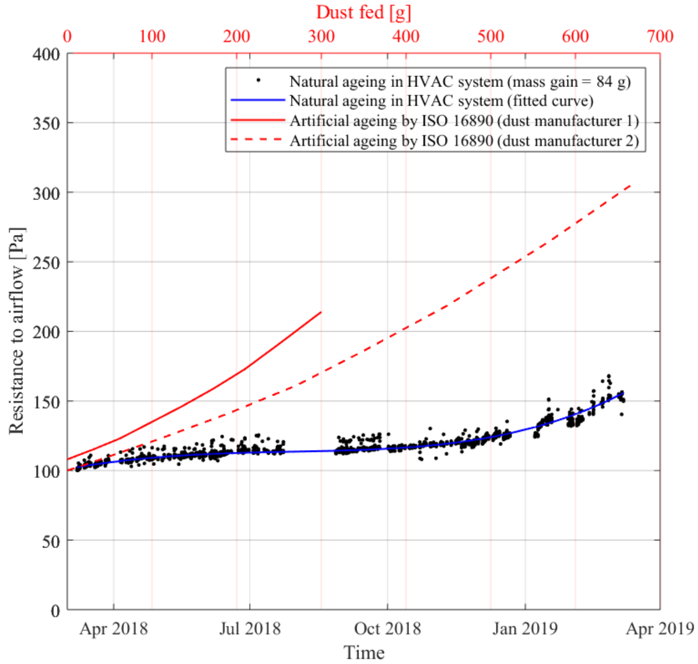

Figure 3 Comparison between in-situ airflow resistance data and laboratory assessment. The bottom abscissa (Time) is associated with the natural ageing data and fitting curve. The upper abscissa, in red color, corresponds to the artificial ageing data, represented by the red curves.

Figure 3 shows the airflow resistance data obtained during natural and artificial filter ageing with the same airflow rate. The data representing the natural ageing was measured as the pressure drop across the filter bank made up by two full size (592x592 mm) and two half size (592x287 mm) filters. We collected the data during several years of service even if we report the data for this filter set only. The artificial ageing results were obtained from two laboratory-clogging tests according to ISO 16890 performed on other two filter samples. We used ISO fine A2 dusts from different manufacturers to study the reproducibility of that dust. Both the laboratory and the in-situ ageing were performed at 3400 m^3/h.

The monitored HVAC system is serving a university classroom at Politecnico di Torino, Italy. Two separate time intervals where no data is available correspond to a one month pause in the operation during the summer break in August and another two weeks in December. After nearly one year of service, the filter increased its airflow resistance of about 50 Pa. This increment corresponded to about 84 grams of particles collected during its service life, as it was determined by weighting the 4 filters of the filter bank after dismounting and calculating the average of mass gain (comparing the final weight with the initial one before installation).

Figure 4 HVAC unit used for the natural ageing of the filters.

The curves representing the artificial ageing provide the mass of dust fed causing the corresponding increment of airflow resistance during the laboratory test. The curve obtained by using the synthetic dust from the manufacturer 1 (continuous line) shows that a pressure drop increase of 50 Pa is obtained after loading the filter with around 170 g of the ISO fine A2 dust. In contrast, about 225 g of the A2 dust made by the manufacturer 2 were needed to reach the same pressure drop on another sample of the same filter.

This comparison is a clear example of the different behavior caused by the different PSDs of the synthetic dusts and of the urban atmospheric aerosol. The discrepancy between laboratory results and field data is glaring. An air filter can reach the same pressure drop values as in the laboratory with lower amounts of mass of captured dust when challenged with aerosols having PSDs shifted towards smaller sizes, as in the case of urban atmospheric aerosols. We can clearly appreciate this difference here below in Figure 5, where we plot the filter mass gain against the airflow resistance values in the three cases.

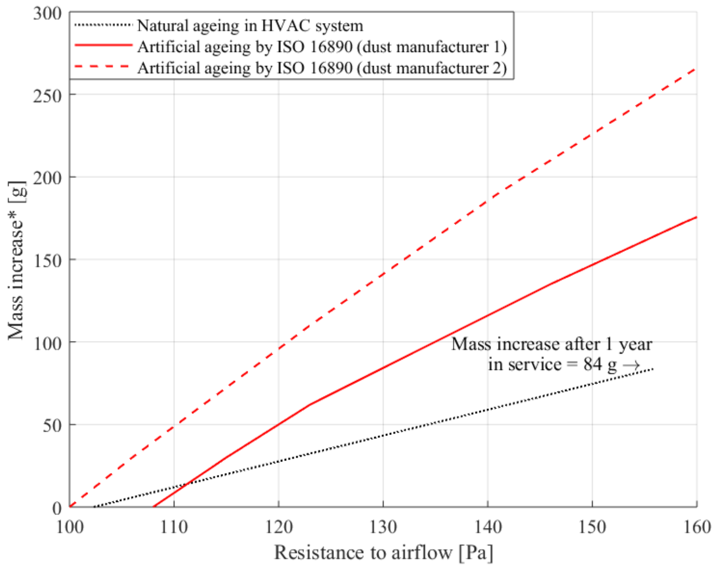

Figure 5 Air filter mass increase comparison between artificial and natural loading. (*) Assuming a gravimetric efficiency of 100% for the artificially clogged filters.

During the artificial loading process with current synthetic dusts, coarse particles stop on the surface of the filter medium and start forming a layer of granular material. This layer of synthetic dust covering the filter medium increases its efficiency and pressure drop by adding a layer of porous material, whose solid fraction is depending on the particles size distribution of the deposited particles. The increase of pressure drop is not linear because it does not depend only on the viscous resistance inside the filter media but also on the inertial resistance on the top of the filter medium. The higher the amount of dust covering the air filter medium, the higher the measured efficiency and the increase of pressure drop. This phenomenon is called "surface filtration".

When exposing air filters to ambient aerosol concentrations, a completely different phenomenon takes place. It is called "deep filtration" because the particles are small enough to get into the fibrous medium and do not stop on its surface. In this way, the particles deposited on the fibers decrease the filter permeability. However, the governing law remains the Darcy law, which accounts for viscous resistance only. In practice, the viscous resistance increase is directly proportional to the increase of solid fraction inside the filter medium.

The data provided by the monitored HVAC system show that a filter in actual operating conditions requires much less captured particle mass to reach the same pressure drop obtained in the laboratory. This is true even if the pressure drop increases in a linear way in a natural ageing process.

Current methods for determining air filter duration provide misleading information that is not coherent with the actual behavior of the filters when exposed to an urban atmosphere. This is a limitation making impossible for air filter and filtering media manufacturers to develop air filters minimizing the energy use and optimizing the replacement time when used in real applications.

4 NANOAEROSOL THERMAL GENERATOR

To generate a synthetic test aerosol having a PSD similar to that of an urban atmospheric aerosol, we investigated the performance of a thermal nanoaerosol generator (shown in Figure 6). This device burns a potassium chloride salt stick with an oxy-propane flame, generating large amounts of salt vapor, which condense in the air stream and form a mixture of ultrafine particles. The most relevant parameters impacting the nanoaersol obtained in this way are the salt stick feed rate into the oxy-propane flame, which can range between 1 and 25 mm/min and the diameter of the salt stick itself (10 or 12 mm).

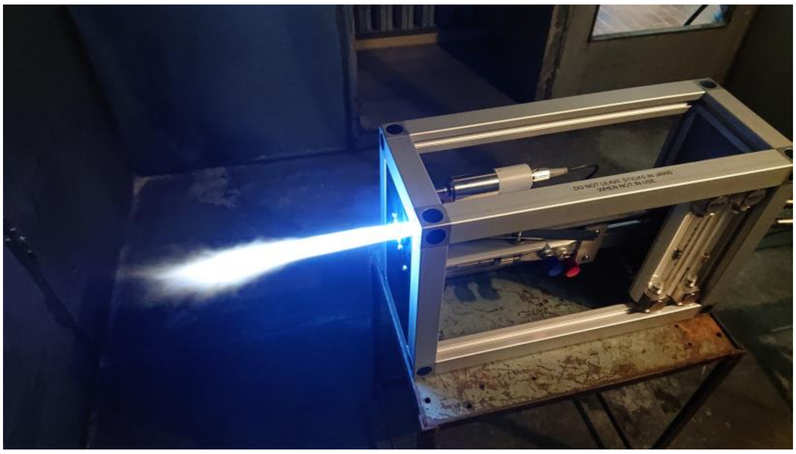

Figure 6 Picture of the nanoaerosol thermal generator in operation

Figure 7 contains a plot of some of the PSDs obtained with the thermal generator installed in a standardized ISO 16890 test duct operated at 3400 m^3/h. These are compared with the urban atmospheric aerosol from ISO 16890 standard.

The instrument used to measure the particle size distributions was a TSI 3910 nanoparticle sizer. The aerosol thermal generator injected the particles from the same point where the dust feeder is usually placed to age air filters with the standardized synthetic dusts. The temperature and relative humidity of the test air were between 20.6 - 34.6 °C and 33- 55%, respectively.

The results show that the nanoaerosol thermal generator produces a synthetic aerosol able to represent the accumulation mode of the typical urban aerosol. Following this positive preliminary evaluation, we will further investigate its use for the sake of achieving a much more realistic accelerated ageing of HVAC filters.

The concentration of the generated nanoaerosol was increasingly higher for faster salt stick feed rates, up to the maximum feed speed (25 mm/min). Higher feed rates could allow obtaining nuclei and accumulation modes even closer to the ISO 16890 reference urban aerosol PSD. As expected, the higher the salt stick feed speed rate, the higher the particle concentration in the test duct.

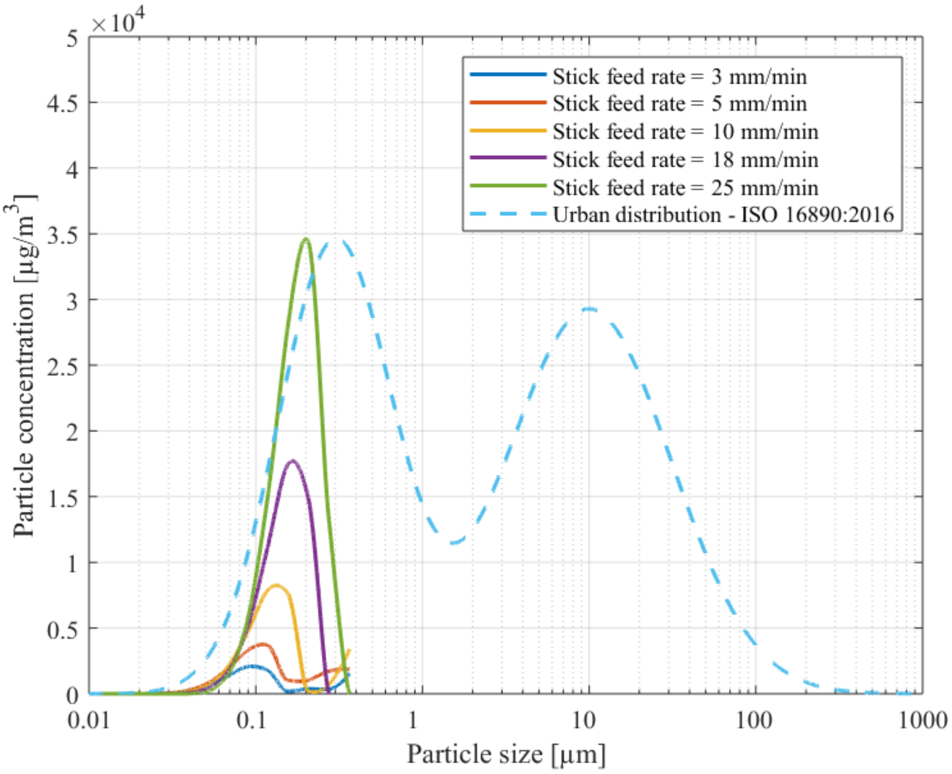

Figure 7 Comparison between the PSDs of the urban atmospheric aerosol according to ISO 16890 and nanoaerosol obtained using the thermal aerosol generator and a 10 mm diameter KCl stick with various feed rates.

5 CONCLUSIONS

The ageing behavior of air filters in HVAC systems is dramatically different from what current laboratory simulations provide. To reach a given pressure drop value, air filters clogged in a real environment require a much lower mass of captured particles, compared to the value provided by standardized laboratory tests with synthetic dusts.

The remarkable difference between the particle size distribution of the aerosol loading the filter during its operation in a real air conditioning or ventilation system and the one of the synthetic dusts can explain the limited value of current standardized tests. Current laboratory procedures prescribe a surface filtration process while in practice a deep filtration process occurs, at least during most of the filter service life. To bring the laboratory simulations closer to reality, it is essential to simulate the filter ageing with much smaller particles than those present in current normalized synthetic dusts.

To generate large amounts of ultrafine particles, a combustion process looks as the most obvious option. The thermal aerosol generator here presented and described is a promising solution for the aforementioned problem.

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