NUMERICAL STUDIES OF INTERNAL FLOW IN DIFFERENT TYPES OF FILTERS

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Abstract: The quality of ambient air attracts considerable, widespread interest. Over the last decades, air purification has become an integral part of HVAC systems, process engineering, automotive and respiratory protection. Efficient separation of micro- and nano- particles is solidly linked with the development of new, sophisticated filtrating materials, as well as generating and validating mathematical models of such porous structures. The paper regards the numerical modeling of various filters. The presented work aims to validate four virtual filtrating materials –the fiberglass HEPA filter, the paper filter used in the automotive industry, knitted wire mesh and polyurethane foam. The pressure drop obtained for the filters under investigation was examined. The CFD results were validated against the data available in the literature. The agreement of the results of numerical and experimental studies proves the suitability of the proposed methods. At the same time, the simplifications employed in the simulations leave room for further improvement in future works.

Keywords: HEPA, paper, knitted wire, foam, porous media, computational fluid dynamics

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1. Introduction

Air pollution attracts attention due to the consistently shown associations between negative health effects and air quality [1–3]. Epidemiology studies show that one out of nine deaths is a result of the low quality of air [2]. High particulate matter concentration in association with gaseous pollution of both indoor and outdoor air is strongly linked with the exposure-risk relationship of adverse health effects such as acute lower respiratory infections (ALRI), lung cancer, chronic obstructive pulmonary disease (COPD), stroke, heart disease and annually leads to about 12% of total global deaths [1]. The World Health Organization (WHO) states that around 6.5 million deaths are caused solely by air contamination – approximately 92% of world's population is constantly exposed to pollution exceeding the permissible limits stated by the Organization [2, 4]. What is more, the developing world has imposed strict requirements for the supply of air in process engineering. Highly effective air purification has become a crucial point of the automotive industry, microelectronics, pharmacy, food processing, etc. These sectors demand strictly controlled concentrations of submicron particles.

Precise numerical models of filtrating materials are of interest for many researchers worldwide. Bearing in mind the possibilities of the CAD software, it is possible to prepare fully virtual porous media of newly developed filtering materials as well as analyze models of existing filters, although due to the challenging aspect of its discretization, the numerical studies are still not common in this area. Thus, researchers, supported by the power of modern supercomputers, are being encouraged to employ the latest achievements of computation fluid dynamics to investigate the complex phenomena occurring in a filter.

Filters are usually divided due to the filtering material or the size of filtered elements. High Efficiency Particulate Air (HEPA) is a filter with the filtering efficiency of at least 99.7% for particles below 0.03 µm in diameter. Owing to its superb effectiveness, these filters have gained a wide range of application especially in air filtration for the medical industry. However, CFD simulations are not common in the case of HEPA filters. This may be caused by the high randomness of the layout and size of fibers. Nonetheless, some research is conducted regarding the CFD performance of the fibrous filter, e.g. Mulins *et al.* [5]. The experimental setup and validation of the investigated fiberglass HEPA filter were based on the research by Wang *et al.*, and First et al [6, 7].

The intake air filter used in internal combustion engines is a mandatory protection against the negative impact of polluted air on the durability and efficiency of the engine. The materials used in the production of air filters include paper, polyurethane foam and cotton gauze. The study is focused on examining the paper filter as it is the most commonly used medium in the automotive industry. The availability of the literature on the technical aspects of inlet air filtration, such as the reports by Dziubak [8], allows a broad development of the topic. In addition to the averaged technical parameters of paper filters, there was a need to validate the model and its assumptions against real data such as the pressure drop and the flow velocity. For this purpose, a specific filter model (Filtron AP139) was chosen as the tested object, and thanks to the cooperation with the manufacturer (MANN+HUMMEL FT Poland Sp. z o.o. Sp.k.) the necessary research data was obtained to confirm the experimental results. The designed CFD model is based on the achievements of Xu [9] who proposed the geometry simplification. The model assumes that all fibers are parallel and the individual rows are shifted to increase the filtration efficiency. In addition to the fiber structure, another important parameter in the validation process is the solidity, the value of which was obtained based on the formulas presented by Hutten [10].

In spite of the fact that the literature regarding the fiberglass or foam filters is extensive, several researchers only have addressed the problem of CFD analysis of knitted wire meshes. The reason for this may be the relatively low filtration efficiency of such structures. Nevertheless, these filters can be used with great success in heavy-duty installations due to their mechanical strength. Wire meshes are commonly used as coarse filters in chimney installations and ventilation channels. Such filters are advantageous as demisters and oil filters owing to easy cleaning and regeneration. Compressed and specially prepared knitted filters are popular in the automotive industry. Bearing in mind the complex and irregular geometry of loops, the work was mainly based on mathematical and mechanical models developed by the fabric industry such as Choi *et al.* Harjakova *et al.* [11, 12]. Mullins *et al.* have also examined the influence of its complex structure in terms of the pressure drop and the filtering efficiency [5].

Foam filters made of polyurethane are used in a wide range of different fields. Purification of air and water, vacuum cleaners, compressors and pumps are some of the possible applications. The complex structure of foam filters creates a challenge in designing a realistic geometry fitting the numerical modeling. However, researchers have approached the problem and have come up with ways to overcome it. The complicated micro-geometry of foams can be recreated for CFD purposes by tomography scans and later conversion to CFD geometries. Another way is modeling by Laguerre-Voronoi tessellations [13] or by using different software such as Gmsh, OpenFOAM and Blender [14]. In this study a different approach was taken. The limited, student version of Ansys Fluent meshing forced the geometry and mesh to be simplified. The approximate structure of foams varying by the different diameters of pores and fibers as well as the angles of layers was omitted in order to achieve a design suitable for numerical modeling despite the limitations.

Table 1. Researched filter media

	A	B	C	D
Type	HEPA	Paper	Knitted wire	Foam
Material	Fiberglass	Cellulose	Copper	Polyurethane
Application	Vacuum cleaners	Automotive	Coarse filters	Compressors

The presented work aims to validate four virtual filtrating materials – a fiberglass HEPA filter, a paper filter used in the automotive industry, knitted wire mesh and polyurethane foam. Table 1 shows the investigated types of filters with their most popular applications. As the numerical studies of a whole filter would be very demanding on the computational power, we propose an approach, in which only a tiny but representative part of a filter is modeled. Thanks to this simplification, it becomes possible to investigate the small scale phenomena occurring inside the filtering material. The filter models created in this manner achieved the expected pressure drop results showing good agreement with a real model.

2. Geometry

The geometries and their pore structure were prepared based on electron microscopy scans and photos of similar filters found in the literature and shown in Figure 1 [8, 14, 15]. The geometrical details were mainly based on the data presented by Abishek *et al.* [14]. The geometries presented in this paper were created in Ansys SpaceClaim. Due to the Ansys Fluent student version limitations limiting the number of the computing cells to 512000, it was decided that the geometry should be simplified and limited to a small section of the actual model. Further simplifications of each model varied. Generally, fibers ought to be randomly placed all over the domain and crossed at different angles. Wires and threads may also differ by diameter in the actual material. Both these objectives may not have been achieved, as models were non-randomized in size, diameter and spacing. Nevertheless, the media bears a strong resemblance to the actual filters.

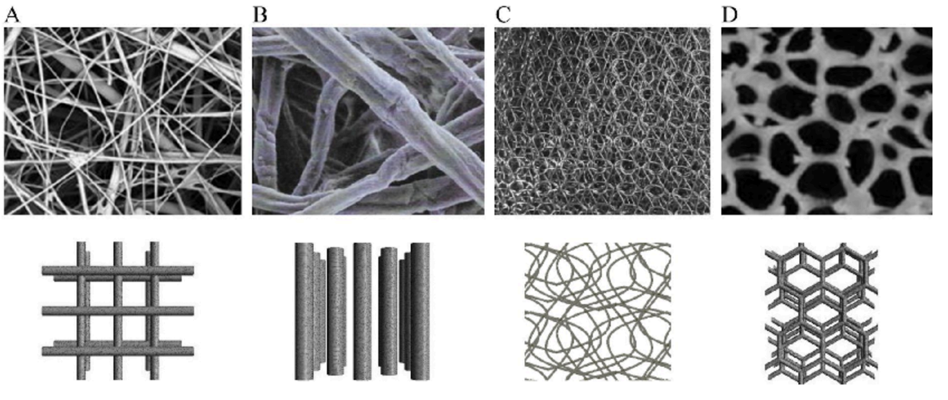


Figure 1. Comparison of real-life scans and photos of filters against their virtual approximations
A. HEPA [15] B. paper [8] C. knitted [14] D. foam [14]

The first geometry presented in Figure 1 (A), is a model of a fibrous filter made of fiberglass. All the parameters needed for construction were based on the work of Wang [6]. This geometry is a reflection of the HF0012 filter, classified as a HEPA filter and commonly used in vacuum cleaners. The exact dimensions of the domain were calculated based on the solidity presented by Wang [6] equal to 0.039. The effective diameter of all fibers is 4.9 µm.

The second geometry, Figure 1 (B), presents a Filtron AP139 filter used in gasoline engines. The calculations and design of the geometry were based on the technical data of the filter provided by the manufacturer. The shape of the geometry was assumed as a cube filled with the appropriate number of parallel fibers. The filtration papers consist of fibers with the average diameters is equal to 15 μm, hence, the concept was adopted into the geometry. The solidity of a filter is a non-dimensional number based on grammage G, thickness t of the filter and its density ρ_m, and it is given as follows:

$$X = \frac{G}{t\rho_m} \quad (1)$$

The structure of the knitted filter, Figure 1 (C), was based on an experimental data-set describing a real copper filter presented by Abishek *et al.* [14]. A single layer of the presented model consists of periodic loops, 8 mm wide and 8 mm high, created with a 137 μm copper wire. Curves are similar to those depicted in the pictures of several real knitted media in articles by Abishek et al. [14]. The packing density of the filtering media is 4.5%, which defines the thickness of each layer to be 251 μm. The skeletal structure was simplified to a three-dimensional layer, where fibers rather intersected than formed a fabric-like loop. A section used in further examination was also assessed in terms of the packing density to meet the value of overall filter media packing density (4.5%).

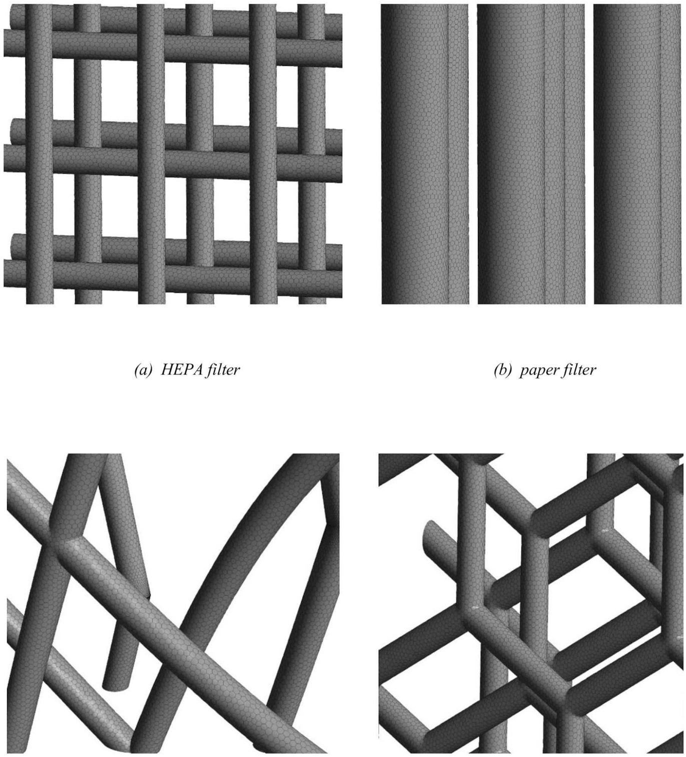
A model of a polyurethane foam filter is presented in Figure 1 (D). All the parameters needed to create the geometry were based on the reports by Abishek *et al.* [14]. The solidity of the model is the same as presented by Abishek et al. [14] which is equal to 0.04. The effective diameter of the fibers creating the foam web is 20 μm.

3. Mesh study

The advanced functionality of Ansys Fluent Meshing allowed preparing several meshes. Many challenges were faced when creating a reliable mesh for the geometry of the filters, especially if the number of the elements was limited due to the academic license, as mentioned in the previous chapter, the number of elements was limited to 512 000. Each geometry was examined under three different meshes (Figure 3). Meshes varied by the number of cells by parameterizing the minimum cell size or the growth ratio. Figure 2 shows the face mesh on the filter. The calculation grid for the fibrous HEPA filter (Figure 2 (A)) was generated by the volume poly-hexacore mesh. Other grids were created using a polyhedral volume structure. Figure 3 shows the influence of the mesh number of elements on the pressure drop in a filter. As can be seen, the results tend to a limit, therefore further studies should be conducted. However, due to the limitations of the student version of Ansys Fluent and the lack of the computational power it was not considered. Based on the mesh study, a mesh was selected for each filter to keep a reasonable accuracy to the computational power ratio. The number of mesh elements in further studies are is shown in Table 2. It is worth mentioning that to each geometry the run-up and run-out sections were added equal to 5 times the length of the considered filter element. These sections were added to restrain the influence of the used boundary conditions and to obtain a stable solution.

Table 2. Number of mesh elements A. HEPA [15] B. Paper [8] C. Knitted [14] D. Foam [14]

	A	B	C	D
Number of elements	339 805	308 794	292 018	252 779



(a) HEPA filter (b) paper filter

(c) knitted filter (d) foam filter

Figure 2. Model discretization

4. Validation

The base for the computations were the experimental studies on the basis of which the flow parameters were computed. The velocity at the inlet was completed based on the provided Reynolds number, $\mathfrak{R}$:

$$v = \frac{\mathfrak{R}\mu}{\rho d}, \tag{2}$$

where μ is the air viscosity, ρ is the density and the characteristic diameter d is the diameter of a fiber. To compare the numerical results with the experimental studies, the pressure drop was referenced to the filter length.

The validation process of the HFOO12 filter was based on the data presented by Wang [6] providing the pressure drop equal to 14.7 Pa for a filter 740 μm thick. The CFD simulation was set on the basis of experimental data. This condition allowed calculating the pressure drop expected on the model by proportion using data taken from a real model of the filter and the thickness of the domain. The relative error obtained with the numerical tool is less than 10%.

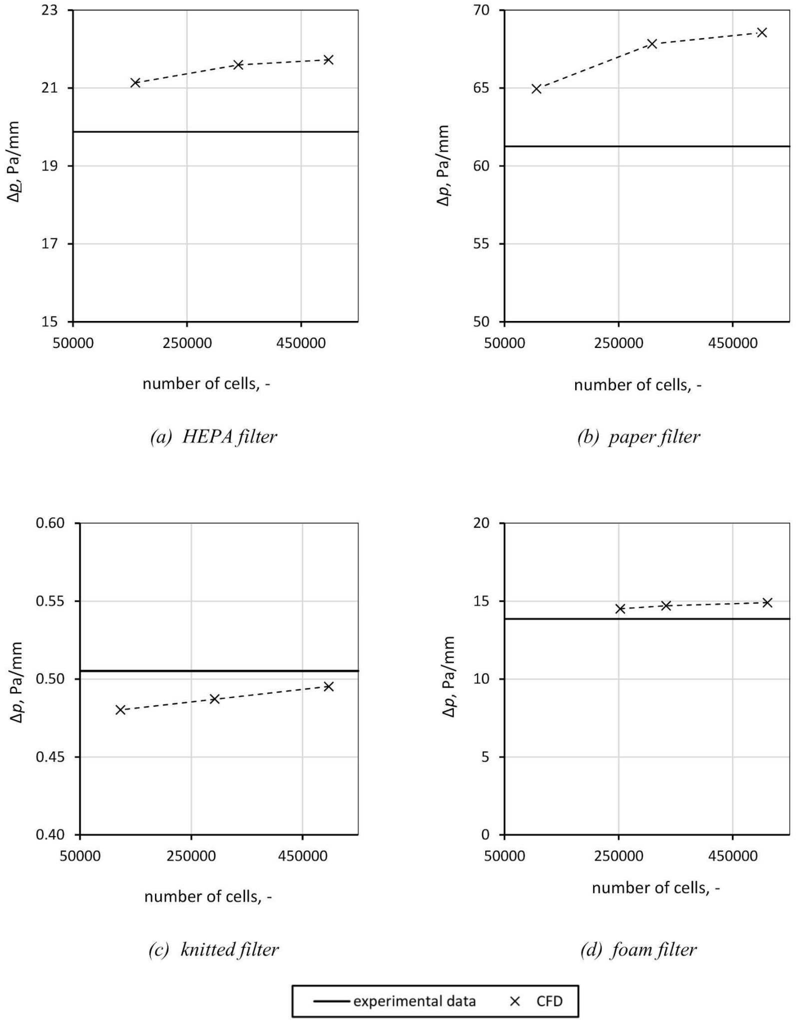


Figure 3. Effect of mesh refinement on pressure drop

One velocity, 0.0984 m/s was selected for further calculation from among the results of the research on the AP 139 filter available from the manufacturer. The expected pressure drop related to the thickness of the modeled geometry was calculated based on the ratio using the actual filter thickness and the pressure drop obtained at the selected speed. It is quite a significant simplification, however, it allows achieving the expected results. The results of the pressure drop calculations for the tested model show a relative error of 12.4%.

The knitted filter was based on the results presented by Abishek *et al.* [14]. One Reynolds number was selected for numerical studies of the knitted filter. The velocity of 0.5153 m/s is based on the Reynolds number equal to 5. The error of the model is below 4%.

The inlet air flow velocity for the foam filter mesh was set at 0.6 m/s The expected pressure drop was calculated from Equation (4) provided by Abishek [14] from the results determined for different solidity values. The error is about 6.08%, meaning that although the falsity is significant there is room for improvement, for example, by using more accurate geometry models.

Table 3 shows the velocity of the flow and the experimental and numerical pressure drop. The velocity path lines presented in Figure 4 provide a better understanding of the airflow through each geometry, depicting significant diversities between the presented models of fiberglass, paper, knitted wire and foam filtering materials.

Table 3. Numerical and experimental results A. HEPA, B. paper, C. knitted, D. foam

	A	B	C	D
Mesh	Poly-hexcore	Polyhedral	Polyhedral	Polyhedral
v, m/s	0.053	0.0984	0.5315	0.6
Δp_{real}, Pa/mm	19.88	61.26	0.51	13858
Δp_{CFD}, Pa/mm	21.60	67.83	0.49	14755
Error, %	10	12.4	3.9	6.08

5. Conclusions

The presented paper regards the research flow through porous media represented by four types of air filters. The numerical studies shown in the paper were conducted with the use of the commercial ANSYS Fluent software. The computational analysis provided a good insight into the complex porous character of each filtering media. The model was validated against the data available in the literature. The authors studied the influence of the construction of geometry. Due to the low Reynolds number the CFD models were examined as laminar.

Diverse problems were encountered during the generation of each geometry, which resulted in implementing specific simplifications. It is worth mentioning that the geometries are a simplified projection of real-life scans of the applied filtering materials, see Figure 1.

The results acquired from the calculations varied significantly for each case. The studies of HEPA, paper, knitted and foam filters enabled the models to reach an accuracy of 8.7%, 12.4%, 3.9% and 6.08%, respectively, see Table 3.

The methodology employed in the executed simulations was in good agreement with the predicted pressure drop related to Pa/mm which allowed validating the proposed geometries. Nonetheless, the data acquired from the CFD models leaves room for further optimization and improvement.

The obtained results are in relatively good convergence with the experimental studies and show promising opportunities for further development. It is planned to employ the Discrete Phase Modeling approach to track the path of pollu-

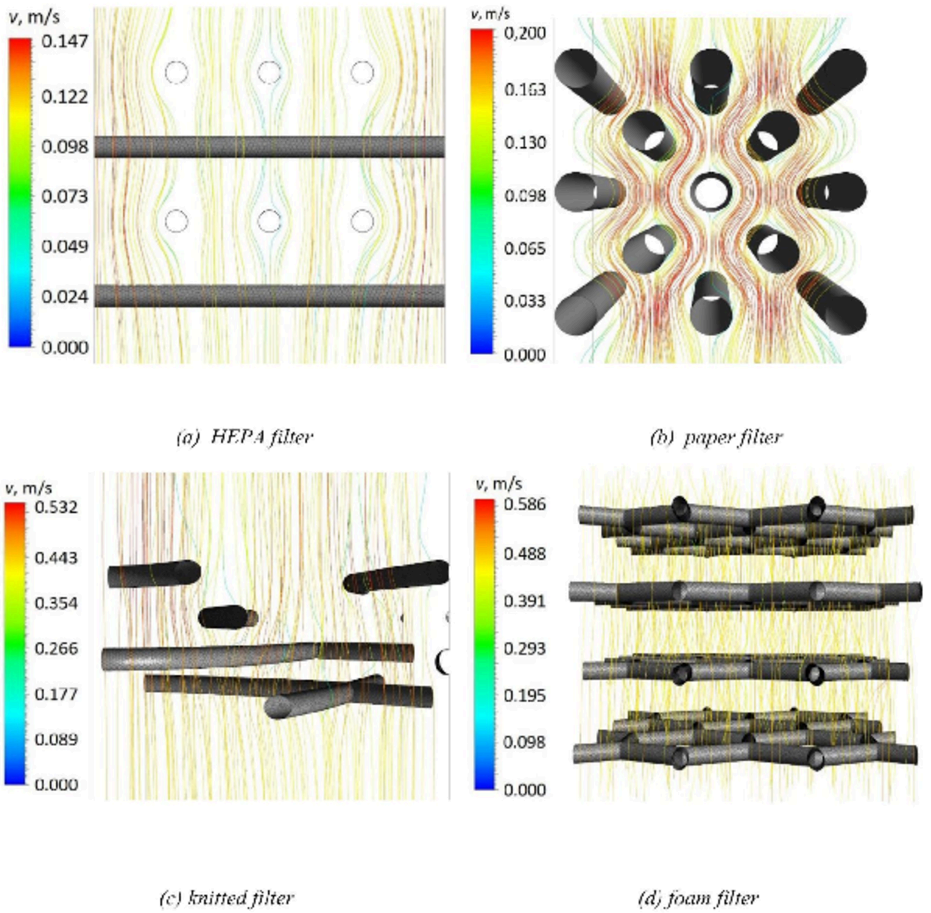


Figure 4. Pathlines colored by fluid velocity

tion particles in the filter. The future work can be also focused around the core problem of the filtrating efficiency of each filtrating media.

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References

[1] *Health effects of particulate matter- Policy implications for countries in eastern Europe, Caucasus and central Asia* 2013, The World Health Organisation

[2] *Ambient air pollution, A global assessment of exposure and burden of diseas* 2016, *Report No.: ISBN 978 92 4 151135 3*, The World Health Organisation

[3] Robert D. Brook R. D., Rajagopalan S., Pope C. A., Brook J. R., Bhatnagar A., Diez-Roux A. V., Holguin F., Yuling Hong Y., Luepker R. V., Mittleman M. A., Peters A., Siscovick D. and Smith S. C., Whitsel L. and Kaufman J. D. 2010 *Particulate Matter Air Pollution and Cardiovascular Disease*, *Circulation* **121** (21) 2331

[4] Roy A. 2019 *A review of general and modern methods of air purification*, *Journal of Thermal Engineering* **5** (9) 22

[5] Mullins B. J. 2011 *Modelling the influence of filter stuctrure on efficiency and pressure drop in knitted filters*, Griffith University, Queensland, Australia

[6] Jing W., Seong C. K. and Pui D. Y.H. 2008 *Figure of Merit of Composite Filters with Micrometer and Nanometer Fibers*, *Aerosol Science and Technology* **42** (9) 722

[7] *First MW. HEPA FILTERS* 1998, Harvard School of Public Health

[8] Dziubak T. 2012 *Filtracja powietrza wlotowego do silników spalinowych pojazdów mechanicznych*, Wojskowa Akademia Techniczna

[9] Bin X., Ya W. and Pengyi C. 2014 *Semi-analytical and computational investigation of different dust loading structures affecting the performance of a fibrous air filter*, *Particuology* **13** 60

[10] Hutten I. 2016 *Chapter 6: Testing of Nonwoven Filter Media*, Elsevier Science

[11] Choi K. F. and Lo T. Y. 2003 *An Energy Model of Plain Knitted Fabric*, *Textile Research Journal* **73** (8) 739

[12] Barburski M., Harjkova G., Lomov S., Kononova O. and Verpoest I. 2004 *Weft knitted loop geometry of glass and steel fibre fabrics measured with X-ray micro-computer tomography*, *Textile Research Journal* **84** 500

[13] Wejrzanowski T. 2013 *Structure of foams modeled by Laguerre–Voronoi tessellations*, Warsaw University of Technology

[14] Abishek S., King A. J. C., Mead-Hunter R., Golkarfard V., Heikamp W. and Mullins B.J. 2017 *Generation and validation of virtual nonwoven, foam and knitted filter (separator/coalescer) geometries for CFD simulations*, *Separation and Purification Technology* **188** 493

[15] *SMARTFILTERS* 2018, *smart-filters.com*

[16] Jing W. and Seong C. K. and Pui D. Y. H. 2008 *Figure of Merit of Composite Filters with Micrometer and Nanometer Fibers*, *Aerosol Science and Technology* **42** (9) 722