

Jolanta Kałużka,
*Elżbieta Jankowska,
*Małgorzata Pośniak,
Danuta Ławniczak

Textile Research Institute (IW),
ul. Brzezińska 5/15, 92-103 Łódź, Poland,
E-mail: kaluzka@iw.lodz.pl

*Central Institute for Labour Protection
– National Research Institute (CIOP-PIB),
ul. Czerniakowska 16, 00-701 Warsaw, Poland,
E-mail: eljan@ciop.pl

Testing the Efficiency of the Simultaneous Air Cleaning of Dust and Gases by Fibrous Filtering and Sorptive Structures

Abstract

This study presents an evaluation of the filter-sorptive properties of multi-layer fibrous structures containing highly efficient polypropylene nonwovens formed with the melt-blown technique and a composite nonwoven with active carbon. Simultaneous tests of the air cleaning of fine particles (size range: 9 nm – 154 nm) and toluene vapour as a test solvent, introduced into the atmospheric aerosol, were performed. It was discovered that the supply of toluene vapour to the measuring system did not significantly impact the curves of the average filtering efficiency with respect to particle size. All the multi-layer filter-sorptive structures tested had a very high average fractional filtering efficiency, greatly exceeding the filtering efficiency of a componential mono-layer composite nonwoven with active carbon. The toluene vapour sorption efficiency of the structures (with a simultaneous supply of atmospheric aerosol) was very similar to the sorption efficiency of the composite nonwoven.

Key words: filter-sorptive structures, melt-blown nonwovens, composite nonwovens, fractional filtering efficiency, sorption efficiency.

Introduction

The development of industry and introduction of new technologies contribute to an increased exposure of contemporary humans to the action of a number of factors harmful and hazardous for the health. These factors include various types of dust, gases and vapour. The substances are absorbed through the respiratory system, as well as through the skin and alimentary tract. In particular, a great amount of toxic pollution can be found in the air. The work environment and natural environment are often polluted with both dust particles and toxic gases as well as with the vapour of organic compounds, including that of organic solvents. The protection of human health or even life against the harmful effect of pollution requires the use of highly efficient filter-sorptive systems allowing for the simultaneous removal of dust and gaseous pollution from the air. Highly efficient filtering materials [1 – 5] are used for removing dust, particularly of nanometric dimensions, from the air, whereas fibrous composite fabrics containing sorbents, mainly active carbon, [6 – 10] are used for removing toxic gases and vapour from the air. The use of multi-layer filter-sorptive structures containing both materials with a high dust capturing efficiency and materials which

absorb volatile toxic substances seems to be an optimum solution for complex air cleaning.

The purpose of the study was to develop fibrous filter-sorptive structures and to test their efficiency in the simultaneous air cleaning of fine particles and the vapour of chemical substances (toluene).

Experimental part

Making multi-layer filter-sorptive structures

The assumed action of multi-layer filter-sorptive structures was to provide the complex air cleaning of fine dust particles and the vapour of chemical substances. The structures with such properties designed were based on using polypropylene filtering nonwovens formed with the melt-blown method and on filter-absorbing composite materials with powder sorbent formed based on them.

Two filtering nonwovens without sorbents and one filter-absorbing composite nonwoven with active carbon were used to make the filter-sorptive structures. The filtering nonwovens were supposed to increase the filtering efficiency of the composite nonwovens and to prevent the release of sorbent particles from the com-

posite nonwoven and their getting into the cleaned air.

Melt-blown nonwovens made on a laboratory device with AXON worm extruder (model BX 12; worm diameter: 12 mm) and a defibering head with polymer nozzles of 0.35 mm diameter were used within the highly efficient filtering materials in the structures created. Borflow granulated fibre-forming polypropylene made by Borealis, with a high mass flow rate (MFR), was the raw material used for making melt-blown nonwovens. The nonwovens were formed in technological conditions ensuring the formation of thin fibres, which determined the high filtering efficiency of fine particles.

Table 1 contains a list of the physical properties of both of the filtering nonwovens mentioned above. The surface mass was determined according to PN-EN 29073-1:1994, and the nonwoven thickness – according to PN-EN ISO 9073-2:2002; method A (0.5 kPa pressure). The thickness of elementary fibres was determined by a microscopic method, with instruments for image analysis. The tests were carried out according to PN-86/P-04761.08 (the only deviation being in the number of measurements and preparation development) with a projective microscope (PROJECTINA Ltd., Switzerland) connected to a camera and PC. The magnitude was 500×.

Both filtering nonwovens had a similar value of the average diameter of elementary fibres; however, their surface mass and thickness were different, which allowed to model the filtering properties

Table 1. Physical properties of melt-blown filtering nonwovens used for the multi-layer filter-sorptive structures.

Nonwoven symbol	MFR polypropylene, g/10 min.	Surface mass, g/m ²	Nonwoven thickness, mm	Average fibre diameter, μm
0	1200	197	4.1	2.40
1	800	104	1.9	2.13

of the filter-sorptive structures created based on them.

Besides polypropylene filtering nonwovens, a filter-absorbing composite nonwoven with powder active carbon was used in the structures created. The nonwoven was obtained as a result of padding the basic fibrous matrix with acrylic-resin based sorbent dispersion. The polypropylene filtering nonwoven previously mentioned, marked as '0', was used as the padded matrix. The process of obtaining the composite nonwoven consisted of two stages:

- 1) preparing a stable powder solvent dispersion,
- 2) padding melt-blown nonwoven with the dispersion prepared.

The main dispersion ingredients included PICTACTIF W9P active carbon powder (PICA) and Acronal® S 747 S acrylic resin (BASF). The active carbon grain size was between 8 and 15 µm, and its specific area was 1500 – 1700 m²/g. The carbon mass share in the padding dispersion was 20%.

The process of melt-blown nonwoven padding with active carbon dispersion was carried out using a three-shaft padding machine (Benz) with a horizontal shaft layout. Having been padded, the nonwoven was dried in a dryer until a stable weight was obtained. The dispersion application rate was determined for the dried nonwoven (gravimetric method), and then (after the percentage of the active carbon content in the dry dispersion was calculated) the sorbent quantity in the composite was evaluated. The dry composite obtained, marked as 'Cz', had a surface mass of 350 g/m², was 1.8 mm thick and contained 26% of active carbon.

Based on the nonwovens created, three multi-layer filter-sorptive structures, presented in **Figure 1**, were made. Each of the structures was composed of two filtering nonwovens and a composite nonwoven with active carbon deposited between them.

Methods of evaluating the filter-sorptive properties of the filter-sorptive structures

The fractional filtering efficiency of the filter-sorptive structures was determined with respect to fine particles within the size range from 9 nm to 154 nm. Atmospheric aerosol was used as the test aero-

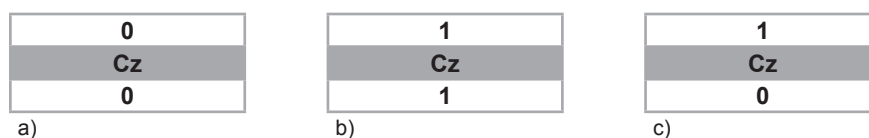


Figure 1. Schemes of the filter-sorptive structures; Structure: a) '0-Cz-0', b) '1-Cz-1' c) '1-Cz-0'.

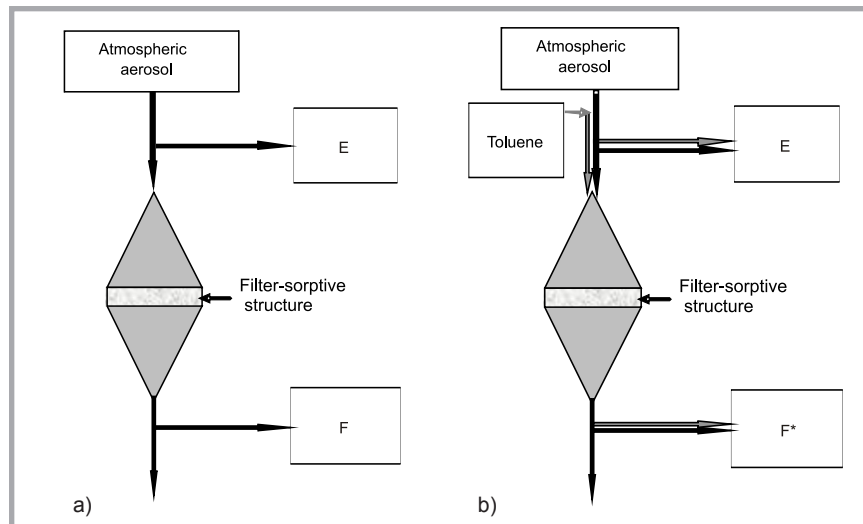


Figure 2. Scheme of the measuring stand to collect air samples 'before' and 'after' the test filter-sorptive structures to determine the filtering and sorptive efficiency; a) Situation A - without supplying test solvent vapour; b) Situation B - with supplying toluene; E - Sample collection to determine the concentration and particle size distribution 'before' the filter-sorptive structure tested; F - Sample collection to determine the concentration and particle size distribution 'after' the filter-sorptive structure tested, F* - Sample collection to determine the concentration and particle size distribution 'after' the filter-sorptive structure tested and to determine the organic solvent contents.

sol. Tests of the simultaneous air cleaning of fine particles and vapours of chemical substances were carried out when toluene was supplied to the atmospheric aerosol as the test solvent. Air samples 'before' and 'after' the filter-sorptive structures tested were collected on a stand, whose diagram is presented in **Figure 2**.

The tests of each structure covered the following situations:

- Situation A: without supplying test solvent vapour to the measuring system containing the filter-sorptive structures,
- Situation B: supplying toluene vapour to the measuring system.

The stream of air flowing through the measuring system was the same for all filter-sorptive structures tested in the two situations: A (atmospheric aerosol) and B (atmospheric aerosol + toluene), which was 2900 dm³/h.

In situation A, the atmospheric aerosol samples were collected twelve times alternately "before" and "after" the structure tested, whereas in situation B it was

sixteen times. The numeric concentration of particles was determined with a scanning mobility particle sizer (SMPS) containing a condensating particle counter (CPC), model 3022A (TSI), and a differential mobility analyser (DMA), model 3080L (TSI).

The fractional filtering efficiency η for individual particle size fractions was calculated according to the formula:

$$\eta = \left(\frac{N_0 - N}{N_0} \right) \times 100 \text{ in \%} \quad (1)$$

where:

N_0 - numeric concentration of the test aerosol particles measured 'before' the filter-sorptive structure tested: number of particles/cm³,

N - numeric concentration of the test aerosol measured 'after' the filter-sorptive structure tested: number of particles/cm³.

The values of fractional filtering efficiency calculated (six measurements in situation A and eight measurements in situation B) were averaged, and the fractional filtering efficiency of the specific

filter-sorptive structure in both situations (A and B) was compared.

Test solvent (toluene) vapour sorption tests of the multi-layer filter-sorptive structures were carried out simultaneously with respect to the filtering properties of the structures using the test stand presented in **Figure 2** – situation B. An HP 6890 gas chromatograph with a flame-ionisation detector and a chromatographic column for separating volatile organic compounds (RTX-5MS capillary column, 60 m long, 0.32 mm diameter) were used for the tests. The methods of determining the efficiency of the filter-sorptive structures consisted of two stages:

- 1) Determining the toluene content in the air stream passing through the measuring system without the test structures – reference sample,
- 2) Determining the toluene content in the air stream after the test structure – test sample.

In the first stage, the toluene tested was introduced into atmospheric air with a 2900 dm³/h stream flow passing through a system without the test structure (flow rate through the system was 8 cm/s). The toluene tested was introduced with a micro-syringe at a concentration of 17.5 mg/m³ and rate of 1 µl/min. The total introduction time was 10 minutes. At the same time, air samples were collected from the stream passing through the system to the absorptive tube with active carbon. The sampling time was 10 minutes and the sampling rate - 1 dm³/min. After the time, the tube with active carbon was disconnected from the system and closed tightly, followed by carbon disulphide (CS₂) desorption of the toluene vapour adsorbed on active carbon. Next, a chromatographic analysis of the solution obtained was carried out in the following conditions:

- initial temperature of the column: 100 °C,
- column temperature increase: 15 °C/min to 130 °C,
- dispenser temperature: 200 °C,
- FID temperature: 250 °C,
- carrier gas (helium) volume stream: 2.0 cm³/min,
- hydrogen volume stream: 35.0 cm³/min,
- air volume stream: 350.0 cm³/min,
- sample divisor: 20:1

Toluene peak areas were read from the chromatographs obtained. The average area of the peaks was the reference sample value – P_d .

Table 2. Results of the fractional filtering efficiency of the mono-layer composite nonwoven „Cz” without a toluene supply (situation A) and with a toluene supply (situation B). Average efficiency from 6 measurements (situation A) and 8 measurements (situation B).

Particle diameter, nm	Average fractional efficiency, %		Standard deviation, %	
	Situation A	Situation B	Situation A	Situation B
9	78.68	74.07	3.63	11.69
12	75.66	75.71	1.54	2.95
15	74.43	72.64	2.25	2.37
21	71.61	70.87	1.52	2.08
27	68.46	69.78	2.46	1.01
37	66.65	69.98	2.12	2.86
49	69.66	73.13	2.92	4.48
65	70.07	71.94	2.67	5.79
87	69.55	69.39	1.92	5.92
115	69.07	69.06	2.39	5.96
154	68.19	68.91	3.48	4.71

Table 3. Average fractional filtering efficiency of the multi-layer „0-Cz-0” structure without a toluene supply (situation A – average from 6 measurements) and with a toluene supply (situation B – average from 8 measurements).

Particle diameter, nm	Average fractional efficiency, %		Standard deviation, %	
	Situation A	Situation B	Situation A	Situation B
9	97.55	97.71	1.29	1.87
12	98.70	98.63	1.20	1.34
15	99.46	99.03	0.28	0.54
21	99.66	99.58	0.36	0.26
27	99.75	99.65	0.18	0.26
37	99.79	99.73	0.15	0.19
49	99.61	99.78	0.22	0.23
65	99.89	99.75	0.11	0.18
87	99.72	99.71	0.43	0.23
115	99.78	99.69	0.17	0.24
154	99.75	99.62	0.11	0.20

Table 4. Average fractional filtering efficiency of the multi-layer „1-Cz-1” structure without a toluene supply (situation A – average from 6 measurements) and with a toluene supply (situation B – average from 8 measurements).

Particle diameter, nm	Average fractional efficiency, %		Standard deviation, %	
	Situation A	Situation B	Situation A	Situation B
9	97.99	99.12	1.87	0.78
12	99.53	99.65	0.48	0.32
15	99.84	99.89	0.23	0.23
21	99.85	99.85	0.14	0.15
27	99.96	99.88	0.09	0.20
37	99.94	99.86	0.07	0.14
49	100.00	99.94	0.00	0.08
65	99.93	100.00	0.08	0.00
87	99.98	99.98	0.05	0.06
115	99.98	100.00	0.05	0.00
154	100.00	100.00	0.00	0.00

In the second test stage, the filter-sorptive structure tested was placed in a filter holder, and the procedure was the same as when making the reference sample (the aerosol flow rate through the system with the test structure was 8 cm/s).

After carrying out a chromatographic analysis, toluene peak areas were read from the chromatographs obtained. The average area of the peaks was the sample value tested – P .

The efficiency of the air cleaning of toluene vapour S_n for each filter-sorptive structure was calculated according to the formula:

$$S_n = \left(\frac{P_d - P}{P_d} \right) \times 100 \text{ in \%} \quad (2)$$

where:

P_d - average toluene peak area in the air sample collected without the filter-sorptive structure (reference sample)

Table 5. Average fractional filtering efficiency of the multi-layer „1-Cz-0” structure without a toluene supply (situation A – average from 5 measurements) and with a toluene supply (situation B – average from 7 measurements).

Particle diameter, nm	Average fractional efficiency, %		Standard deviation, %	
	Situation A	Situation B	Situation A	Situation B
9	93.20	98.39	10.44	1.38
12	97.88	99.76	4.36	0.41
15	99.69	99.44	0.56	0.59
21	99.90	99.74	0.07	0.27
27	99.82	99.52	0.22	0.72
37	99.88	99.83	0.14	0.14
49	99.83	99.89	0.26	0.17
65	99.89	99.89	0.18	0.16
87	99.93	99.97	0.07	0.08
115	99.97	99.97	0.07	0.08
154	99.75	100.00	0.55	0.00

P - average toluene peak area in the air sample ‘after’ the filter-sorptive structure tested (tested sample).

Test results

Results of the filtering efficiency tests of the multi-layer filter-sorptive structures and the mono-layer composite nonwoven with active carbon are presented in **Tables 2 – 5** and **Figures 3**. The results are the fractional average of the filtering efficiency determined for the filter-sorptive structures developed in situations A and B.

The tests performed indicated that the fractional average of the filtering ef-

iciency for the mono-layer composite nonwoven ‘Cz’ in both measuring situations (A and B) was very similar, ranging from 67% to 79%, which allowed to use the nonwoven for making multi-layer structures with filtering nonwovens without a sorbent.

According to the data presented (**Table 2**), it results that for the filter-absorbing composite nonwoven ‘Cz’ in situation A (without a supply of toluene to the measuring system), the fractional filtering efficiencies for six measurements did not differ significantly, which is confirmed by the standard deviation values, which did not exceed 3.7%. The greatest standard deviation values

occurred for particles with extreme dimensions measured with SMPS, i.e. 9 nm (3.63%) and 154 nm (3.48%). In the case of atmospheric aerosol flowing with toluene supplied (situation B), the efficiency values for each particle dimensional fraction in eight subsequent measurements differed more than in situation A, with the greatest differences in filtering efficiency occurring for 9 nm particles (standard deviation 11.69%).

The test results show that in the case of all three multi-layer filter-sorptive structures, both in situations A and B, the fractional filtering efficiencies determined for each measurement differed significantly only for the smallest particles (9 nm and 12 nm). For other particle sizes, the standard deviation values ranged from 0% to 0.59%.

Analysis of the data presented in **Tables 2 – 5** and **Figure 3** leads to a conclusion that supplying toluene to the measuring system had little impact on the fractional efficiency curve with respect to particle size. The average fractional filtering efficiencies for each multi-layer structure in both situations (A and B) were similar and usually ranged from 99.0% to 100%. Only for a particle size of 9 nm and 12 nm was the average fractional efficiency below 99%, indicating the greatest standard deviation, which may result from the fact that it is the area of the

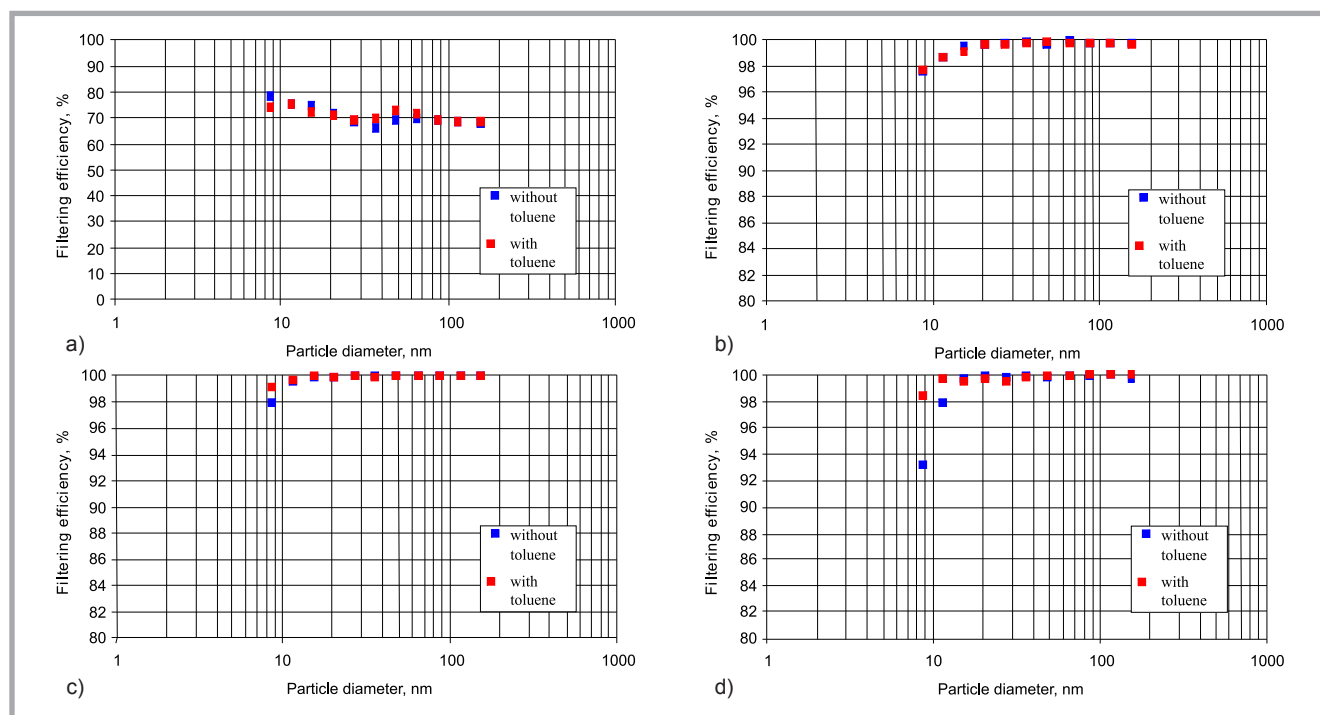


Figure 3. Comparison of the average fractional filtering efficiency of the composite nonwovens: a) ‘Cz’, b) ‘0-Cz-0’, c) ‘1-Cz-1’, d) ‘1-Cz-0’ in situation A (without a toluene supply) and situation B (with a toluene supply).

Table 6. Results of the sorptive efficiency of toluene vapour by the filter-sorptive structures with a simultaneous supply of atmospheric aerosol.

Structure symbol	Average area of toluene peaks		Sorptive efficiency, %
	Sample tested	Reference sample	
Cz	1669.6	2784.8	40.1
0-Cz-0	1795.1	3091.9	41.9
1-Cz-1	1719.4	2954.6	41.8
1-Cz-0	1618.5	2821.8	42.6

SMPS with the lowest detecting capacity range.

Results of the efficiency tests of air cleaning the test substance vapour - toluene – by the multi-layer filter-sorptive structures and the mono-layer filter-absorbing nonwoven with active carbon used for making the structures are presented in **Table 6**. The results show that the toluene vapour sorption efficiency (at a simultaneous supply of atmospheric aerosol) of the three multi-layer structures was almost the same (from 41.8% to 42.6%) and very similar to the sorption efficiency of the mono-layer filter-absorbing nonwoven with active carbon ('Cz') used for making the structures (40.1%). Therefore the conclusion is that the filtering nonwovens without a sorbent ('0' and '1') used in the filter-sorptive structures did not have a significant impact on the sorptive properties of the structures.

Based on the visual observation of the nonwoven surface in the filter-sorptive structures, it can be concluded that the filtering nonwovens prevented carbon particle release from the composite nonwoven as well as sorbent penetration into the cleaned air. In no case was there observed the easily noticeable phenomenon of black particles of active carbon deposition on the surface of white filtering

non-woven placed in the structure after the composite nonwoven with a sorbent.

Conclusions

All three multi-layer filter-sorptive structures tested had a very high average fractional efficiency, significantly exceeding the filtering efficiency of the component – mono-layer filter-absorbing nonwoven with active carbon. The use of melt-blown filtering nonwovens in the structures constructed resulted in a greater increase in the filtering efficiency of the multi-layer structure, usually over 99%.

During the simultaneous air cleaning of fine particles and the solvent (toluene) vapour tested, the average filtering efficiency for the atmospheric aerosol particle size fraction, ranging from 9 nm to 154 nm, was very similar to that obtained in the situation where no solvent vapour was supplied to the measuring system. Supply toluene vapour to the measuring system did not significantly impact the filtering efficiency curve with respect to particle size.

The toluene vapour sorption efficiency (at a simultaneous supply of atmospheric aerosol) of the three multi-layer structures was almost the same (about 42%) and very similar to the sorption ef-

iciency of the mono-layer filter-absorbing nonwoven with active carbon used for making the structures. The filtering nonwovens without a sorbent used in the filter-sorptive structures did not have a significant impact on the sorptive properties of the structures.

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