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Dynamic Changes in the Filtration Efficiency of Cooling Oil Filter Media

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Abstract
Metal-working fluids are used in machining and grinding operations to cool the tool and work piece, reduce the friction between the tool and work, improve the surface integrity of the work piece and increase tool life and productivity. The removal of oil mists from air streams is very important in a wide range of industrial applications, and filtration is by far the most effective method for this task. This article presents the results of changes in the fractional efficiency of the filtration process of the test aerosol through multistage filtering systems of different thickness and miscellaneous structural characteristics in the cross-section. The efficiency of filtration through multistage filtering systems was tested with the use of DEHS and DOP aerosol. Research results indicate the functional dependence of filtering properties on the structural parameters of nonwovens and machining process parameters, as well as on the physicochemical parameters of liquid aerosols. This may be of essential importance in forecasting the use of multistage filtering systems as filtering media for a given process of liquid aerosol filtration, given the maintenance of the most advantageous filtration conditions, i.e. high efficiency of filtration and low resistance of aerosol flow.

Key words: *aerosols, filtration efficiency, oil mists, fibrous filters.*

Introduction

The main pollutant emitted during mechanical working with the use of oil coolants is mineral oil mist. High mechanical cutting efficiency needs high values, which in connection with a temperature rise leads to an increased emission of oil mist [1, 2]. Oil mist may arise as a result of a dynamic or thermal process. During a dynamic process, coolant atomisation by rotating machine elements appears. A thermal process occurs as a result of coolant evaporation during contact with hot surfaces and further condensation in air.

In order to reduce or eliminate the risks caused by the spread of pollutants emitted during mechanical working, in particular of liquid aerosols, oil mist of different design solutions is used for the decontamination and separation of liquid aerosol particles of various sizes, starting from nanometric dimensions. Multistage filtering systems are usually used as the last stage of the process of air decontamination from liquid aerosols.

In recent years there has been a need for carrying out experimental tests with respect to characteristic analysis of the relationship between filtering properties and the changeable structure of multistage filtering systems from the point of view of eliminating the risks of liquid aerosol particles of a specific dimensional distribution, particles of nanometric dimensions included, with the use of the aerosol particles counting technique.

Numerous scientific research works have been carried out worldwide [among other 3 ÷ 5], as well as in Poland [6 ÷ 11], focusing primarily on dust filtration mechanisms.

At present a great number of studies concerning liquid aerosol filtration is being carried out [12 ÷ 18] as well as studies concerning the harmful influence of liquid aerosol particles on humans, particularly particles of nanometric dimensions (below 100 nm) [19 ÷ 22].

Hazards from oil mist during metalworking

Hazards caused by oil mist may exist especially during mechanical working with the use of oil based coolants [19 ÷ 23]. Metalworking processes belong to the basic industrial processes that widely use oil based coolants [1].

Metal finishing means technological operations aimed at obtaining a final product part from a metal block by removing material excess with the use of cutting tools. Depending on the cutting tool contour and angles, machining and abrasive machining are commonly used to do this [24].

During the machining process, most of the energy is converted into heat. The high temperatures of the cutting tool may cause its premature wear and may also adversely affect the condition of the top layer of the metalworked surface.

In order to lower the temperature of the cutting tool's cutting edge and thus increase its durability as well as lower the temperature of the machined material surface and its protection against corrosion, the cooling of the cutting tool, machined material and machining area was performed.

In order to do this, the external cooling method is most often used, which consists in directing a cooling fluid stream at the machined layer, tool face and chip from the top or at the tool flank surface from the bottom. In some special cases internal cooling is used, which consists in feeding cooling fluid via the cutting tool itself.

The huge capacity of machining needs large revolution speeds, which in conjunction with a rise in temperature leads to an increased emission of oil mist consisting of liquid phase (oil drops) and gas phase (oil fumes) [1, 25].

The highest permissible values of mineral oil aerosol liquid phase concentration in air at workplaces are as follows:
- OEL – 5 mg/m^3,
- STEL – 10 mg/m^3.

Mineral oil mist may be formed as a result of a dynamic or thermal process. During a dynamic process, coolant atomisation caused by the rotating machine elements occurs. Liquid aerosol emission during the dynamic process is a function of the following:
- volume stream of oil coolant,
- rotation speed of rotary workpiece.

A thermal process occurs as a result of coolant evaporation in contact with hot surfaces and its further condensation in air. Liquid aerosol emission depends

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Table 1. *Structural characteristic of spun-lace and melt-blown nonwovens.*

Type of nonwoven fabrics	Thickness - $L_{śr}$, mm	Surface mass - M_p, g/m^2	Packing density - $α_{śr}$, kg/m^3	Total porosity, - $ε_{śr}$, %	Average fibre diameter - $d_{śr}$, μm	Main pore diameter - D_p, μm
A	5.31	282.37	53.14	96.03	54.77	160.47
B	6.21	346.17	55.76	95.84	18.06	48.59
C	2.16	532.24	246.83	81.58	16.52	34.95
K	2.55	67.97	26.60	97.08	2.86	11.26
L	2.85	91.04	31.99	96.49	3.16	5.99
M	2.86	92.47	32.29	96.45	2.94	5.38

mainly on the amount of heat generated during the machining process. The amount of heat generated during machining is the sum of heat emitted due to friction and heat emitted due to the plastic strain of the workpiece's machined layer (e.g. metal).

Materials

Six commercially available nonwoven fabrics made of synthetic polyester (PES) fibres with the use of the 'spun – lace' technique (marked with symbols A, B, C) and of polypropylene (PP) fibres with the use of the called 'melt – blown' technique (marked with symbols K, L & M) were chosen. The nonwoven fabrics considerably varied from one another with respect to their structural parameters, such as thickness, surface unit mass, fibre packing density, average fibre diameter and porosity. The 'spun – lace' and 'melt – blown' nonwovens were characterised by a range of structural parameters, as shown in ***Table 1***.

The structure of nonwoven fabrics of the 'spun – lace' type was different from the structures created with the use of different textile techniques, including stitching with the use of barber needles. The effect of fibre bonding into a fixed product was obtained as a result of water jets striking the web. Water jets of defined geometrical dimensions were pumped out of the nozzles under a given pressure. As a result of this, fibres strongly knotted about one another, the friction force between fibres increased and the material thickness grew to the value required, giving, in effect, a nonwoven fabric of physical and chemical properties suitable for the desired purpose.

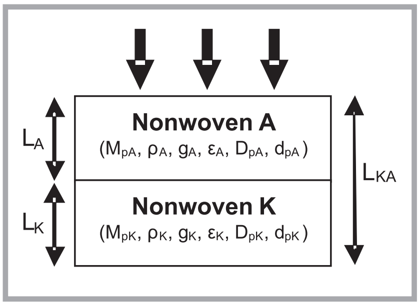

Figure 1. *Example diagram of a two-stage composition of spun-lace „A" and melt-blown „K" nonwovens.*

Producing nonwoven fabrics with the 'melt – blown' method consisted in extruding molten polymer into elementary fibres of various thickness and length. The 'melt – blown' technique is a technologically flexible process. The choice of proper processing conditions enables to obtain fibres of a given diameter, while the choice of the receiver's work conditions enables to control the values of nonwoven fabric porosity. Nonwovens produced with the use of the 'melt – blown' method are characterised by a dense structure that enables them to have a higher primary packing density as compared to nonwoven fabrics produced by the 'spun – lace' technique, without the need for additional processes and technological operations.

As part of the research, it was proposed to examine the filtration properties of multistage filtration systems consisting of the nonwoven fabrics described above. The filtration systems created mixed two-stage compositions consisting of the selected nonwovens of various morphology (***Figure 1***).

Test methods

Examinations were made in the aspect of oil mist emission as a result of a dynamic process or thermal process, as well as concerning the relationship between dynamic changes in the flow resistance and efficiency of liquid aerosol filtration and the following:

- structural parameters of multistage filtration systems, especially:
  - thickness of the filtration layer in multistage filtration systems,
  - porosity of the multistage filtration systems,
  - method of filtration layer arrangement in the multistage filtration systems,
- process parameters of mechanical working simulated by:
  - the liquid aerosol's flow velocity through the multistage filtering system,
  - the inlet concentration of liquid aerosol in the measurement system,
- physiochemical parameters of the liquid aerosols, represented by:
  - the type of test aerosol,
  - the temperature of the flowing air together with liquid aerosol particles.

As part of the research, the characteristics at the initial stage and at the stage of dynamic changes in fractional efficiency were determined, as well as the characteristics of flow resistances during the filtration process for multistage systems of nonwoven fabric of various thickness and structure in the cross-section.

Measurement of the aerosol flow resistance and concentration of liquid aerosol particles before and after the test filtration material was made for four variable parameters:

- four velocity values of flow through the measure holder, adjusted with the use of valves integrated with a set of flow meters and fan duct damper ($U_{1-4} = 0.05 \div 0.20$ m/s),
- four values of the numerical inlet concentration of liquid aerosol created with the use of an atomising generator and controlled by a diluting system ($C_{1-4} = 1.78 \cdot 10^4 \div 2.70 \cdot 10^6$ particles/cm^3) - ***Figure 2***,
- two types of liquid aerosol determined by the type of test, in conformity with EN 1822-2:2009 [26],
- four values of the temperature of air flowing together with suspended liquid aerosol particles controlled by a duct heater thermostat ($T_{1-4} = 20 \div 35$ °C).

The process conditions chosen were characteristic for examining aerosols with dispersed liquid phase emitted during mechanical working with the use of oil coolants.

Two tests were conducted in order to examine the filtration efficiency of the multistage filtration systems chosen:

- bis (2-ethylhexyl) sebacate aerosol test (DEHS),
- bis (2-ethylhexyl) phthalate aerosol test (DOP).

The choice of test aerosols for simulating pollutant emission during mechanical working with the use of oil coolants was made in accordance with recommendations of EN 1822-2:2009 [26]. The distribution of DEHS and DOP aerosol particles applied to the tested multistage filtration systems is presented in ***Figure 2***. A diagram of the set-up for testing the multistage filtration systems' properties is presented in ***Figure 3***.

Air is sucked in from the environment and flows through the electrical duct heater (7) DH-100/03, where it is heated to the temperature required with the use of a thermostat TK-1 (8).

Liquid aerosol of specified concentration and dimensional distribution is produced in an atomising generator - AGF 2.0 iP (3). The air flow at the inlet to the generator is cleaned in a pre-filter and a highly effective filter (1). Liquid aerosol particles generated with the use of a built-in pump (2) are fed to the diluting system - VKL-10 (5) at a constant speed, causing a lowering of aerosol concentration. The system enables a ten-fold dilution of the aerosol through its mixing with purified compressed air (6). Then the mixture of test aerosol and air is fed to the testing stand with the use of a dosage unit (9).

The liquid aerosol's flow is forced by a duct fan VENT-100L (21) with a suppressor (20) with a continuous controller of the rotational speed, due to which a steady change in the air volume stream value in the measurement system is possible. Moreover the air volume stream in the measurement system is controlled by valves (4) integrated with the set of flow meters (19) and control damper (18).

A sample of the multistage filtering system is placed in the lower part of the measure holder (12), which is the central part of the liquid aerosol sampling unit. Filtration material is pressed by the upper movable part of the holder to its lower part with the use of distance rings.

In the liquid aerosol sampling unit before (10) and after (11), measure holder (12) probes with replaceable heads of internal intake diameter in the range of 0.5 to 6.0 mm were used.

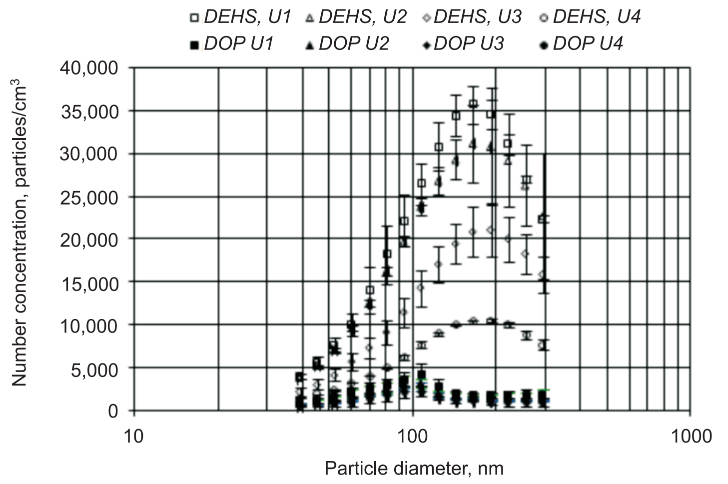

Figure 2. *Distribution of DEHS and DOP aerosol particles at different aerosol velocities.*

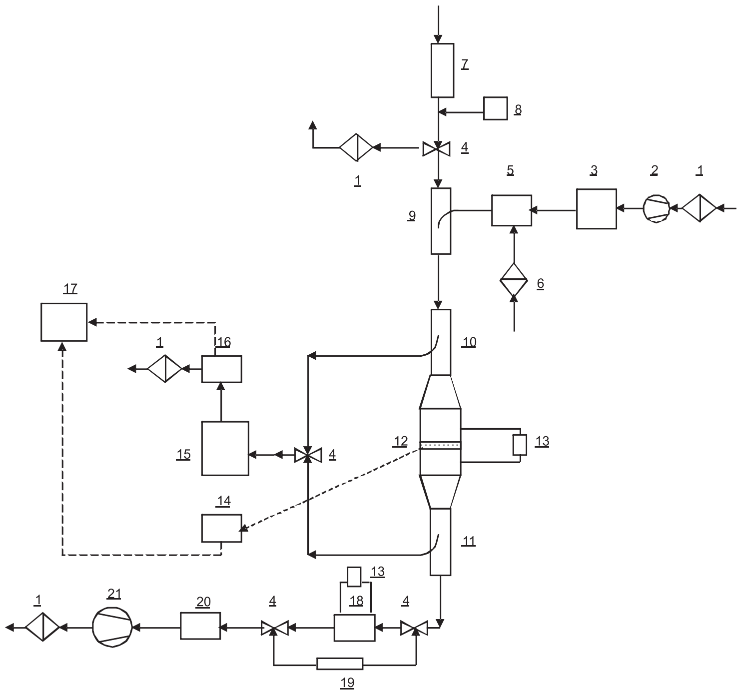

Figure 3. *Experimental set-up; 1) highly effective filter, 2) built-in pump, 3) atomising generator - AGF 2.0 iP, 4) valves, 5) diluting system - VKL-10, 6) purified compressed air, 7) electrical duct heater, 8) thermostat TK-1, 9) dosage unit, 10) sampling unit before, 11) sampling unit after, 12) measure holder, 13) electronic differential micro manometer, 15 - long differential mobility analyser LDMA, Model 3080L, 16 - condensation particle counter, 18) control damper, 19) flow meters, 20) suppressor, 21) duct fan VENT-100L.*

The initial flow resistances through the sample of a multistage filtering system of known structural parameters should be measured before applying liquid aerosol to the measuring system. Initial flow resistance testing is conducted after the measuring system gains stability, which also involves an electronic differential micro manometer (13). The measurement is made at various values of air flow velocity through the measure holder. Air flow is forced by a duct fan (21) placed after the measure holder (12), and the speed value is controlled with the use of valves (4) integrated with the set of flow meters (19) and control damper (18). For each nonwoven fabric sample six measurements of pressure differences were carried out before and after the filtration material tested.

Then liquid aerosol particles were produced and fed to the measurement system at a constant speed. During the flow

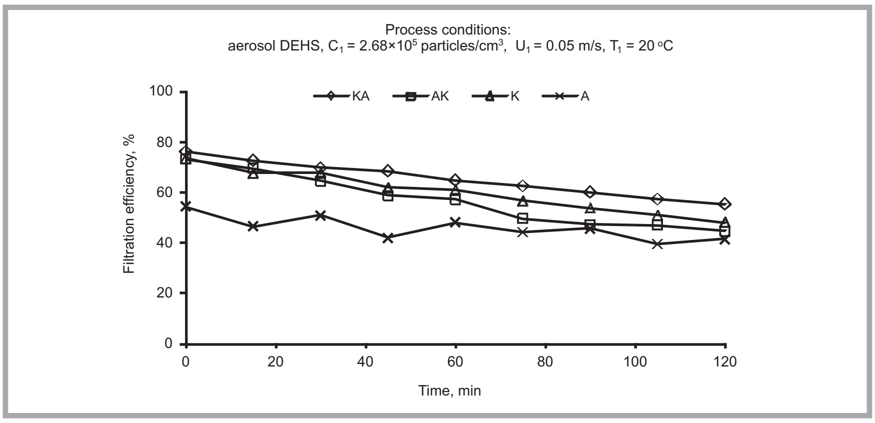

Figure 4. *Effect of the thickness of the multistage filtering systems on the aerosol filtration efficiency.*

of liquid aerosol, changes in the flow resistance were determined for each sample of a multistage filtering system.

Filtration efficiency in the function of particle sizes for a given sample in a multistage filtering system is determined on the basis of test aerosol particles numerical concentration measurement before and after the filtration material tested. Liquid aerosol samples are measured before and after the test filtration material with the use of probes (10, 11) designed for isokinetic sampling, and then the particles are counted with the use of a condensation particle counter (16) in the diameter range of 40 to 300 nm (long differential mobility analyser LDMA, Model 3080L) (15).

For each sample of a multistage filtering system, three aerosol particles number concentration measurements are taken both before and after the filtration material tested.

The average efficiency of filtration through the sample of a multistage filtering system for a given dimensional range of particles is determined on the basis of the following formula:

$$E_{total} = \left(\frac{C_{av}^{before} - C_{av}^{after}}{C_{av}^{before}} \right) \times 100 \quad (1)$$

where:

C_{av}^{before} - average aerosol particles number concentration measured before the nonwoven fabric sample in particles/cm^3,

C_{av}^{after} - average aerosol particles number concentration measured after the nonwoven fabric sample in particles/cm^3.

During the liquid aerosol flow (total time of measurement - 120 minutes, average time - 5 minutes), changes in the filtration efficiency of each sample of a multistage filtering system are determined.

For the most penetrating particle size (MPPS) through the multistage filtering system, the minimum filtration efficiency is also determined E_{MPPS} in %.

In order to obtain a simultaneous evaluation of filtration property changes and compare the quality of the multistage filtering systems, the filter quality factor (*QF*), described by formula [27], is determined:

$$QF = \frac{-\ln(1 - E_{total})}{\Delta p} \quad (2)$$

where:

E_{total} - total filtration efficiency of the multistage filtering system,

Δp - flow resistance through the multistage filtering system.

Results and discussion

Studies of the fractional efficiency and flow resistance changes at the initial stage and during the process of the filtration of liquid aerosols were performed for a multistage filtering system consisting of nonwoven fabrics made with the use of the ‘spun – lace’ technique (marked with symbols A, B & C) and ‘melt – blown’ technique (marked with symbols K, L & M).

Due to the wide range of process and structural parameters, the results of tests for the two multistage filtering systems consisting of nonwoven fabrics K, A, M and C are presented below.

Effect of structural parameters of the multistage filtering systems on their filtering properties

Examination of the results of relations between changes in flow resistances and liquid aerosol filtration efficiency and the structural parameters of the multistage filtering systems shows that:

- an increase in filtration layer thickness in the multistage system causes a rise in liquid aerosol flow initial resistances (e.g. the initial flow resistance for the ‘A’ system equals 1 Pa, and for the ‘AK’ system it is 16 Pa),
- an increase in filtration layer thickness in the multistage system does not always cause a rise in the initial filtration efficiency (e.g. initial filtration efficiency for the ‘K’ system equals 73.57%, and for ‘AK’ it is 73.12%),
- the flow resistances of multistage filtering systems of various filtration layer thickness practically do not change during the process of liquid aerosol filtration (e.g. the initial flow resistance for the ‘KA’ filtration system is 15 Pa, and the final one is 16 Pa),
- the filtration efficiency in multistage filtering systems of various filtration layer thickness decreases during the process of liquid aerosol filtration (e.g. the initial efficiency of filtering system ‘KA’ equals 76.25%, and the final one is 55.37% - ***Figure 4***),
- in two-stage systems the initial filtering layers of bigger pores play a dominant role, occurring before the filtering layer of higher efficiency,
- smaller initial aerosol flow resistances and higher values of filtration efficiency and the filter quality factor are typical for systems where the frontal layer is made of nonwoven fabrics of bigger pores (***Figure 5***),
- the flow resistances of multistage filtering systems of various porosity values of the filtration layer practically do not change during the process of liquid aerosol filtration (e.g. the initial flow resistance for the ‘MC’ filtration system is 64 Pa, and the final one is 65 Pa),
- the filter quality factor and filtration efficiency in multistage filtering systems of various filtration layer porosity values decrease during the process of liquid aerosol filtration (e.g. the initial QF of the ‘MC’ filtration system is 0.054 1/Pa, and the final one is 0.022 1/Pa - ***Figure 6***).

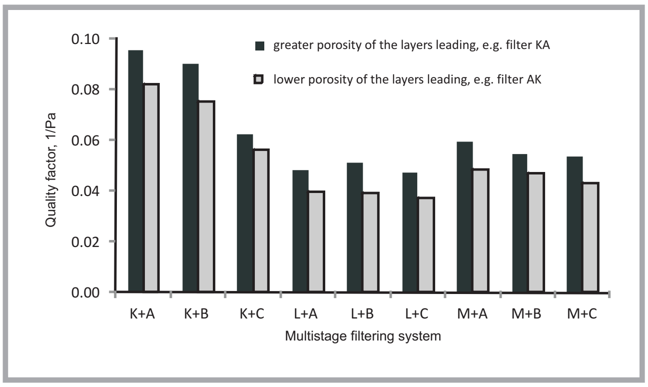

Figure 5. Values of the quality factor for multistage filtering systems of different porosity layers leading.

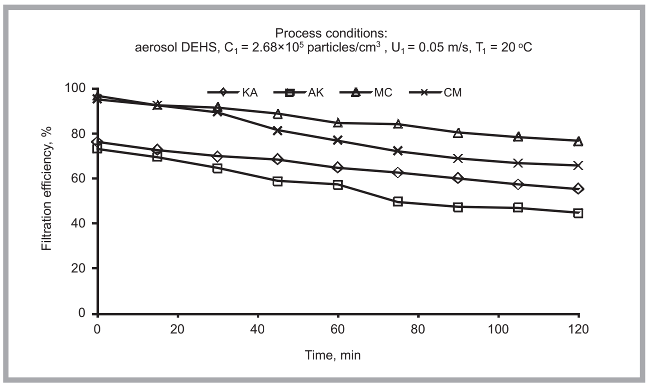

Figure 6. Changes in aerosol filtration efficiency during the working of multistage filtration systems with different porosity layers leading.

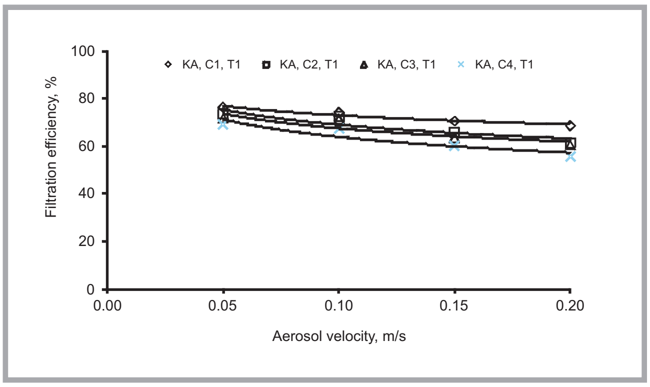

Figure 7. Values of the initial filtration efficiency through the multistage filtering systems as a function of the liquid aerosol's velocity.

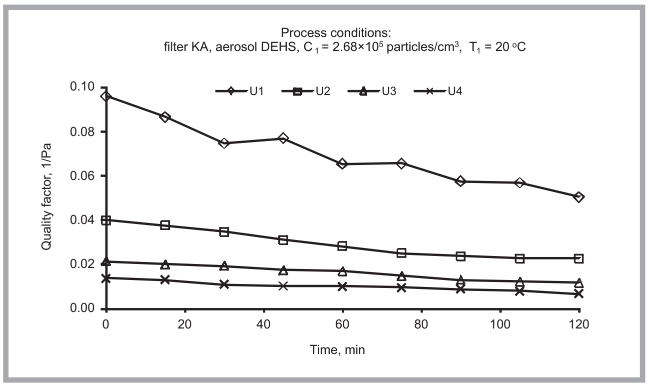

Figure 8. Effect of aerosol velocity on values of the quality factor of multistage filtration systems at specified times.

Effect of parameters of the mechanical working process

Examination of the results of relations between dynamic changes in flow resistances and liquid aerosol filtration efficiency in the multistage filtering systems and process parameters of mechanical working with the use of oil coolants shows that:

- an increase in the aerosol's flow velocity through the multistage filtering system causes:
  - a rise in the initial resistances of liquid aerosol flow (e.g. the initial flow resistance for U_1 = 0.05 m/s equals 15 Pa, and for U_4 = 0.20 m/s it is 84 Pa),
  - a drop in the initial filtration efficiency (e.g. the initial filtration efficiency for U_1 = 0.05 m/s equals 76.25%, and for U_4 = 0.20 m/s it is 68.57% - ***Figure** 7*),
  - a decrease in the filter quality factor in the exponential function (e.g. the initial QF for U_1 = 0.05 m/s equals 0.096 1/Pa, and for U_4 = 0.20 m/s it is 0.014 1/Pa),
- the flow resistances of multistage filtering systems in the function of the liquid aerosol's flow velocity practically do not change during the process of filtration (e.g. the initial flow resistance for U_1 = 0.05 m/s equals 15 Pa, and the final one is 16 Pa),
- filtration efficiency in multistage filtering systems in the function of the aerosol's flow velocity decreases during the process of liquid aerosol filtration (e.g. the initial efficiency of filtering system 'KA' for U_1 = 0.05 m/s is 76.25%, and the final one is 55.37%),
- QF in the function of the aerosol's flow velocity decreases during the process of aerosol filtration, and the drop dynamics are independent of the velocity value, e.g. (***Figure 8***):
  - the initial QF of the 'KA' filtration system for U_1 = 0.05 m/s is equal to 0.096 1/Pa, and the final one is 0.050 1/Pa, respectively,
  - the initial QF of the 'KA' filtration system for U_4 = 0.20 m/s is equal to 0.014 1/Pa, and the final one is 0.007 1/Pa, respectively.

It results from the present data regarding relations between dynamic changes in flow resistances and liquid aerosol filtration efficiency in multistage filtering systems and the intake concentration of liquid aerosol emitted during machining with the use of oil coolants that:

- an increase in aerosol intake concentration does not cause a rise in the aerosols initial flow resistances (e.g. the initial flow resistance for $C_1 = 2.68\times10^5$ particles/cm^3 is equal to 34 Pa, and for $C_4 = 2.44\times10^6$ particles/cm^3 it is equal to 32 Pa at an aerosol flow velocity of U_2 = 0.10 m/s,
- an increase in aerosol intake concentration causes a slight drop in the following:
  - the initial filtration efficiency (e.g. the initial filtration efficiency for $C_1 = 2.68\times10^5$ particles/cm^3 is equal to 74.26%, and for $C_4 = 2.44\times10^6$ particles/cm^3 it is 67.44%, respectively, at an aerosol flow velocity of U_2 = 0.10 m/s - ***Figure 9***),
  - the filter quality factor in the exponential function (e.g. the initial QF for $C_1 = 2.68\times10^5$ particles/cm^3

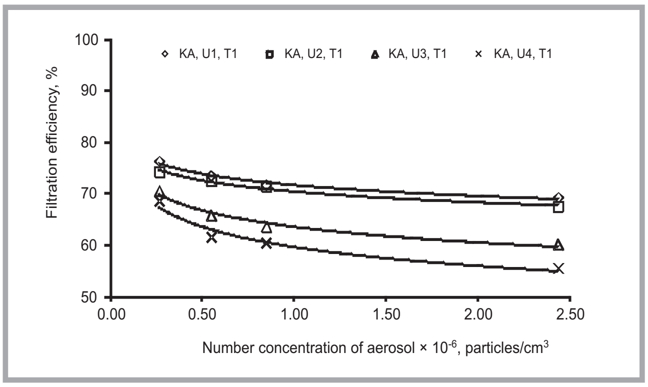

Figure 9. Values of the initial filtration efficiency through the multistage filtering systems as a function of the inlet number concentration of liquid aerosol.

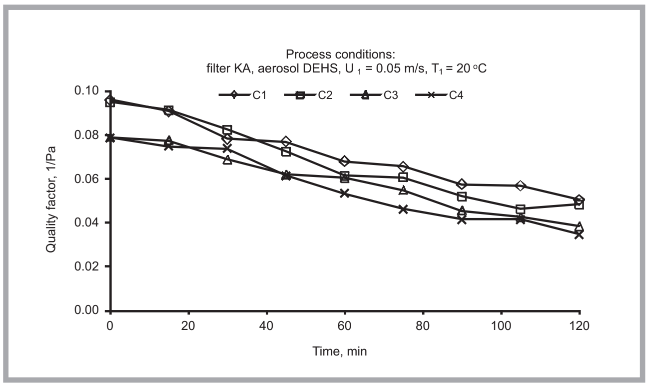

Figure 10. Effect of the inlet number concentration of liquid aerosol on values of the quality factor of multistage filtration systems at specified times.

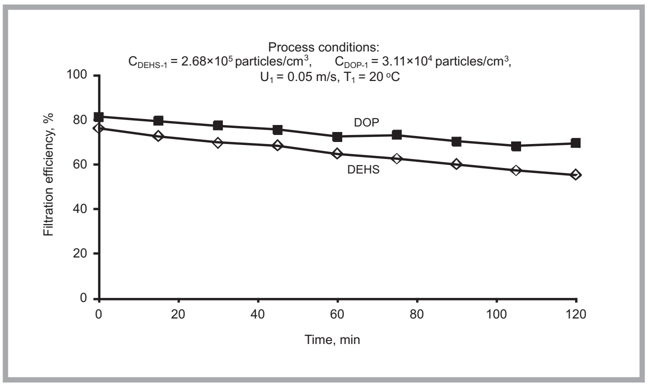

Figure 11. Effect of the type of test aerosol on values of filtration efficiency through multistage filtration systems at specified times.

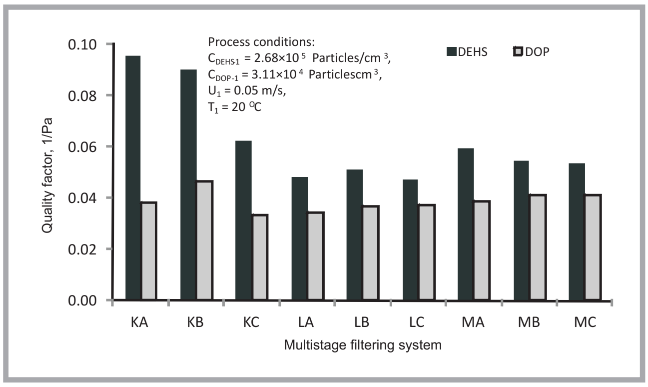

Figure 12. Values of the initial quality factor of the multistage filtering systems as a function of the type of test aerosol.

is equal to 0.040 1/Pa, and for $C_4 = 2.44×10^6$ particles/cm^3 it is 0.036 1/Pa, respectively, at an aerosol flow velocity of $U_2 = 0.10$ m/s,

- the flow resistances of multistage filtering systems in the function of the aerosol intake concentration practically do not change during the process of filtration (e.g. the initial and final flow resistances for $U_1 = 0.05$ m/s and $C_4 = 2.44×10^6$ particles/cm^3 are 15 Pa,
- the filtration efficiency in multistage filtering systems in the function of aerosol intake concentration decreases during the process of liquid aerosol filtration (e.g. the initial efficiency of filtering system 'KA' for $U_1 = 0.05$ m/s and $C_4 = 2.44×10^6$ particles/cm^3 is equal to 69.26%, and the final one is 44.57%, respectively.
- the difference between the final filtration efficiency for the lowest aerosol intake concentration C_1 and the highest concentration C_4 is over 10%,
- QF in the function of the aerosol intake concentration decreases during the process of aerosol filtration, the drop dynamics are similar for all values of aerosol intake concentration used, e.g. (**Figure 10**):
  - the initial QF of the 'KA' filtration system for $C_1 = 2.68×10^5$ particles/cm^3 is equal to 0.096 1/Pa, and the final one is 0.050 1/Pa, respectively.
  - the initial QF of the 'KA' filtration system for $C_4 = 2.44×10^6$ particles/cm^3 is equal to 0.079 1/Pa, and the final one is 0.035 1/Pa, respectively.

Effect of physicochemical parameters of liquid aerosol

Examination of the results of relations between changes in the flow resistances and liquid aerosol filtration efficiency in multistage filtering systems and process parameters of machining with the use of oil coolants shows the following:

- the type of liquid aerosol has an influence on the diversification of initial filtration properties of multistage systems:
  - definitely higher initial flow resistances were observed in the case of DOP aerosol flow (oil density - 985 kg/m^3 and dynamic viscosity in the range of 0.077 ÷ 0.082 kg/m×s) than in the case of DEHS aerosol flow (oil density - 912 kg/m^3 and dynamic viscosity in the range of 0.022 ÷ 0.024 kg/m×s) - e.g. for the 'KA' system, the initial DEHS aerosol flow resistances are equal to 15 Pa and for the DOP aerosol they are respectively 44 Pa, respectively
  - a slight difference between DEHS aerosol filtration efficiencies (76.25 ÷ 96.75%) and DOP aerosol filtration efficiencies (81.36 ÷ 98.48%) - ***Figure 11***,
  - definitely higher values of the quality factor (QF) were observed for DEHS aerosol filtration (ranging from 0.047 to 0.096 1/Pa) than those of the QF for DOP aerosol filtration (0.033 ÷ 0.047 1/Pa) - ***Figure 12***,
- various liquid aerosol flow resistances through multistage filtration systems practically do not change during the process of aerosol filtration,
- the filter quality factor and filtration efficiency of various liquid aerosols in multistage filtering systems decrease during the process of liquid aerosol filtration (e.g. the initial QF of the 'KA' filtration system for DOP aerosol flow is 0.038 1/Pa, and the final one is 0.026 1/Pa, respectively).

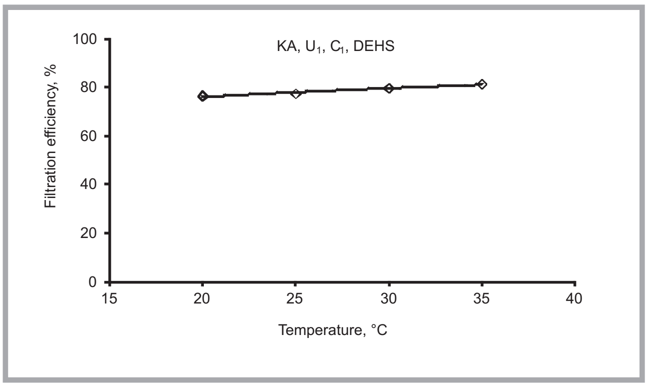

Figure 13. *Effect of the temperature of the air flowing along with suspended particles of liquid aerosol on values of the initial filtration efficiency through multistage filtration systems.*

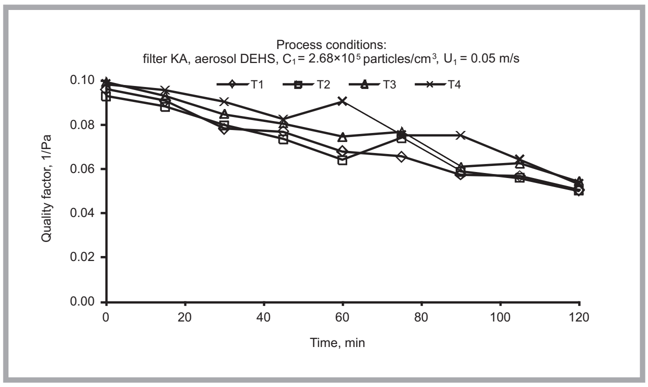

Figure 14. *Effect of the temperature of air flowing along with suspended particles of liquid aerosol on the values of the quality factor of multistage filtration systems at specified times.*

It results from the present data regarding relations between changes in the flow resistances and liquid aerosol filtration efficiency in multistage filtering systems and the air flow temperature with suspended liquid aerosol particles emitted during machining with the use of oil coolants that:

- the temperature growth of air flowing through the measurement system does not bring about a considerable increase in initial liquid aerosol resistances (e.g. the initial resistances of flow through the 'KA' system for T_1 = 20 °C are 15 Pa, and for T_4 = = 35 °C they are 17 Pa, respectively, with fixed remaining process conditions),
- an increase in air flow temperature together with suspended liquid aerosol particles causes a slight increase in:
  - filtration initial efficiency (e.g. the initial filtration efficiency for T_1 = 20 °C is equal to 76.25%, and for T_4 = 35 °C it is 81.22%, respectively, with fixed remaining process conditions - ***Figure 13***),
  - the filter quality factor (e.g. the initial QF for T_1 = 20 °C is equal to 0.096 1/Pa, and for T_4 = 35 °C it is 0.098 1/Pa, respectively, with fixed remaining process conditions),
- the flow resistances of multistage filtering systems in the function of air flowing through the measurement system's temperature practically do not change during the process of filtration in the 'KA' system (e.g. the initial and final flow resistances for T_3 = 30 °C are equal to 16 Pa with fixed remaining process conditions,
- the filtration efficiency in multistage filtering systems in the function of air flowing through the measurement system's temperature decreases during the process of liquid aerosol filtration (e.g. the initial efficiency of filtering system 'KA' for T_3 = 30 °C is equal to 79.57%, and the final one is 63.21%, respectively),
- QF in the function of air flowing through the measurement system's temperature also decreases during the process of liquid aerosol filtration, and the drop dynamics are similar for all values of air flow temperature, e.g. (***Figure 14***):
  - the initial QF of the 'KA' filtration system for T_2 = 25 °C is equal to 0.093 1/Pa, and the final one is 0.050 1/Pa, respectively,
  - the initial QF of the 'KA' filtration system for T_4 = 35 °C is equal to 0.098 1/Pa, and the final one is 0.053 1/Pa, respectively.

Conclusions

An analysis of the test results demonstrates the dependence of filtration properties on the structural parameters of the nonwoven fabrics tested (above all the thickness and porosity), process parameters like flow velocity and the intake concentration of aerosol, as well as on the physicochemical parameters of liquid aerosols.

An assessment of the quality factor shows that the change in structural parameters of nonwoven fabrics, filtration process parameters and the physicochemical parameters of test aerosols has an impact on the change in the operation efficiency of multistage systems, especially in connection with particles of dimensions lower than the most penetrating particle sizes (MPPS).

The filtration efficiency of MPPS decreases regardless of the test aerosol type during the process of aerosol filtration (e.g. for DEHS aerosol - from 69.43 to 47.58% and for DOP aerosol - from 75.49 to 51.43%). The course of filtration efficiency changes in the function of liquid aerosol particle dimensions was similar, i.e. a decrease in efficiency values for particles lower than MPPS, the filtration efficiency of which had a minimum value and then a rise in filtration efficiency together with an increase in particle diameter. There are differences between MPPS diameters for separate aerosol types in fixed remaining processing conditions:

- range of most penetrating particles of DEHS aerosol - 107 ÷ 143 nm,
- range of most penetrating particles of DOP aerosol - 81 ÷ 93 nm.

This may be connected with various inlet distributions of aerosol particles produced in the generating and diluting unit of the test stand.

Determination of the influence of separate parameters on dynamic changes in the filtration parameters of multistage systems of nonwoven fabrics is of great importance for the evaluation of the risk to workers in conditions of operating multistage filtering systems during machining using oil coolants.

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- Hexachlorocyclohexane (lindane)
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- Benzene, Hexachlorobenzene
- Phthalates
- Carbohydrates
- Glycols
- Polychloro-Biphenyls (PCB)
- Glyoxal
- Tin organic compounds

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