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TRIBOLOGICAL ASPECT OF ASSESSMENT OF EFFICIENCY OF FILTRATION USING MULTI-LAYER MATERIALS

ASPEKT TRIBOLOGICZNY OCENY SKUTECZNOŚCI FILTRACJI Z WYKORZYSTANIEM WIELOWARSTWOWYCH MATERIAŁÓW FILTRACYJNYCH

Key words: filtration efficiency, filtration effectiveness, filter materials.

Abstract: This study presents the results of testing for the efficiency and effectiveness of filtration using multi-layer filter materials, and briefly presents a new technology for manufacturing filter media using these materials. The first part of the article describes the causes of the formation of impurities in operating fluids and the tribological effects of their impact. The second part is dedicated to testing for filtration efficiency and effectiveness for different filter materials. The third part of the article briefly describes the technology for manufacturing filter media using efficient but difficult-to-form materials. The testing results showed significant differences in filtering efficiency and effectiveness between the cellulose samples and the samples of filter materials based on glass microfibre layers. All of the tested multi-layer materials allow filtration effectiveness of over 90% to be achieved over the entire range of impurity sizes included in the experiment. The results of a comparative test for pressure change during filtration also indicate that glass microfibre materials have a considerably longer operating life than cellulose materials. The time after which a sharp increase in pressure occurs (due to the filter layer being filled with impurities) is nearly four times longer for multi-layer materials than for cellulose materials. The methods for cutting, forming, and joining filter materials have been developed by the authors of this article.

Słowa kluczowe: skuteczność filtracji, efektywność filtracji, materiały filtracyjne.

Streszczenie: Celem pracy jest przedstawienie wyników badań skuteczności i efektywności filtracji z wykorzystaniem wielowarstwowych materiałów filtracyjnych oraz skrótowe zaprezentowanie nowej technologii wytwarzania przegród filtracyjnych z zastosowaniem tych materiałów. W pierwszej części artykułu opisano przyczyny powstawania zanieczyszczeń w płynach eksploatacyjnych i skutki tribologiczne ich oddziaływania. Cześć druga poświęcona jest badaniom skuteczności i efektywności filtracji dla różnych materiałów filtracyjnych. Trzecia część artykułu zawiera skrócony opis technologii wytwarzania przegród filtracyjnych z wykorzystaniem skutecznych, ale trudno formowalnych materiałów. Wyniki badań wykazały istotne różnice w skuteczności i efektywności filtrowania między próbkami celulozowymi a próbkami z materiałów filtracyjnych opartych na warstwach mikrowłókna szklanego. Wszystkie badane materiały wielowarstwowe pozwalają na osiągnięcie efektywności filtracji powyżej 90% w całym zakresie wielkości zanieczyszczeń uwzględnionych w eksperymencie. Również wyniki badania porównawczego na zmianę ciśnienia w czasie filtracji wskazują na znacznie dłuższą trwałość eksploatacyjną materiałów typu mikrowłókno szklane niż celulozowe. Czas, po którym następuje gwałtowny wzrost ciśnienia (spowodowany wypełnieniem warstwy filtracyjnej zanieczyszczeniami), jest prawie czterokrotnie dłuższy dla materiałów wielowarstwowych w porównaniu z celulozowymi. Przedstawione metody cięcia, kształtowania i łączenia materiałów filtracyjnych zostały zaprojektowane przez autorów niniejszego artykułu.

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INTRODUCTION

In the field of vehicle and heavy machinery operation, due to considerably increased requirements for the operating fluid purity, increased expectations have occurred for the filtration methods, particularly the separation of fine particles of sizes in the micro- and nanometre range. In most cases, depth filters characterised by a high impurity accumulation capacity are used as operating filters. Filter materials for depth filtration primarily include mats made of various fibres and matted masses. These are used for liquid-solid phase separation and for separation in gas-liquid or solid particle systems [**L. 1, 3**].

A variety of sources, both scientific and informational [**L. 4–8, 11, 14, 15**], have reported on filtration problems and indicate the need to use new, efficient filter materials. However, the problem also exists in filter production technology, i.e. manufacturing filter cartridges from these materials. Materials exhibiting good filtration properties are generally difficult to form and join.

THE CAUSES OF THE FORMATION OF IMPURITIES IN OPERATING FLUIDS, AND THE EFFECTS OF THEIR IMPACT

The basic operating fluid and, at the same time, the basic component of the operating media of internal combustion engines and many heavy (e.g., construction, agricultural, or mining) machines is the atmospheric air. The systems of these machines suck in considerable amounts of impurities along with the air, particularly when the machines or vehicles are operated at heavily dusty sites. Impurities can get into operating fluids from the atmosphere, during transport, reloading, or storage, through leaks in the systems being operated and during maintenance operations. Impurities are also formed as a result of tribological processes.

Particularly detrimental impurities are those found in the atmospheric air, which accelerate the wear of interacting surfaces. Polydispersed dust rises from the surface of roads, production halls, and excavations, thus creating a suspension that is sucked in along with the air by air intakes. Dust grains with a diameter of up to 10 µm persist in the air for a long time and are thus sucked in by fuel systems virtually for the entire operating time of vehicles and heavy machines. Dust grains with a diameter of 10–50 µm fall more quickly, yet they account for a significant proportion in the total volume of the air being sucked in. Dust grains with a diameter of over 50 µm persist in the air for the shortest time, but they can also be sucked in by fuel systems [**L. 3, 6, 14**].

Dust primarily contains silica (SiO_2). According to the one-to-ten Mohs scale of mineral hardness, silica has a hardness of 7 and is significantly harder than construction materials. Under certain operating conditions, other air impurities are found as well, including sand or quartz dust (**Fig. 1a**) and dust generated by machining operations, particularly grinding (**Fig. 1b**). The dust concentration in the air, measured by the weight of dust contained in 1 m³ of the atmospheric air, is a variable quantity determined by numerous factors. This article does not consider this topic, but it can be concluded that nearly all engines of agricultural tractors, construction vehicles, and even regular vehicles are exposed to the effects of dust containing impurities of various forms and sizes.

a)

b)

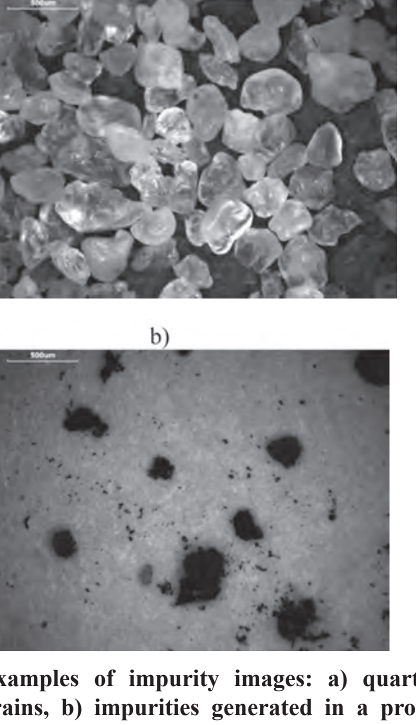

Fig. 1. Examples of impurity images: a) quartz sand grains, b) impurities generated in a production hall by machining operations

Rys. 1. Przykładowe obrazy zanieczyszczeń: a) ziarna piasku kwarcowego, b) zanieczyszczenia powstające w hali produkcyjnej z obróbką skrawaniem

External impurities get into engine oil or the oil for lubricating operational systems of heavy machinery, mainly as mineral dust particles (via the fuel or air supply system). Oil also contains internal impurities, i.e. dust and metal particles that have not been removed at the time of manufacturing, operating part wear products, incomplete combustion products, and physicochemical transformation products.

The impurity concentration in oil is a function of its operating time and is determined by the oil type and properties, the amount of oil to be added, the type of oil filtration system, and the operating conditions. There have been numerous studies on the composition and percentage contents of impurities in engine and gear oils and hydraulic fluids **[L. 4, 5, 9, 11, 12, 13]**. These issues are not addressed in this study, but it should be noted that the problem of the filtration of particles smaller than 5 µm also concerns these oils. Certainly, the abrasive aggressiveness of the dust decreases when the dust grain sizes are smaller. However, even impurity particles of less than 2 µm are harmful, because they impact the sliding surface of the engine or machinery parts like abrasive compounds. Oil particles do not adhere to a polished surface, which leads to oil film disruption and accelerated wear.

The third fluid in which impurities contributing to the wear of vehicle and heavy machinery internal combustion engine parts can be found is liquid or gas fuel. Internal impurities form in fuels due to the effects of oxygen, elevated temperatures, and metal interactions. External impurities present in fuels as a result of their distribution and storage include environmental dust, tank corrosion products and microorganisms, and the products of their metabolism. This problem is illustrated with a photograph (**Fig. 2**) of an unpurified diesel fuel tank in a passenger car supply system.

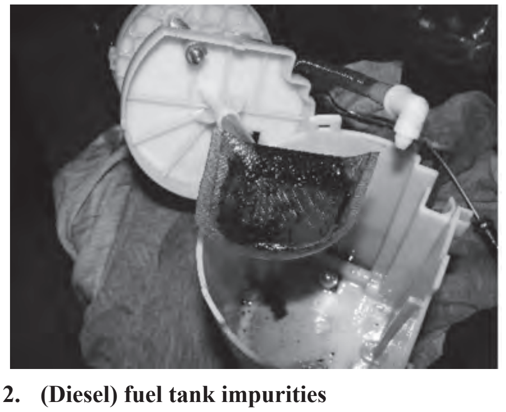

Fig. 2. (Diesel) fuel tank impurities
Rys. 2. Zanieczyszczenia zbiornika paliwa (oleju napędowego)

Abrasive wear occurs when hard foreign bodies get between two interacting surfaces, resulting in the deformation and cutting of micro-volumes of the surface layers of the interacting parts. The greatest wear is caused by dust particles of sizes d_z equal to the minimum depth of the oil layer h_{min} needed to form an oil wedge between the interacting surfaces:

$$\frac{d_z}{h_{min}} = 1 \rightarrow \text{maximum risk of abrasive wear} \tag{1}$$

For other values of quotient (1), the risk of wear of the combination decreases [**L. 3]**. This can be explained as follows:

- If solid particles are of a size that prevents them from getting between two interacting surfaces, the system may get blocked, but no abrasive impact will occur.
- If the diameter d_z is smaller than h_{min}, then the impurities are not supposed to directly affect the surface of operating parts (however, there is a risk of the impact of the oil and impurities mixture acting as an abrasive compound).

The rate of wear of engine or heavy machinery components due to the effect of impurities is determined by:

- The parameters of the impurities being sucked in,
- The acceptable values of clearance between interacting parts,
- Design and constructional parameters (including the design of filtration systems), and
- The mechanical properties of materials.

For example, dust entering operating parts along with the air affects the first piston ring, the piston, and the upper part of the cylinder.

Impurities can be deposited in the slide bearing (bearings and journals) material and cause abrasive wear. As a consequence of abrasive wear, which generally causes a pressure drop in the lubrication system, other types of wear develop in the bearing units, including the 2nd type bond (thermal wear), which can result in the seizure of these bearing units (**Fig. 3**).

As for an unpurified fuel, the most common types of part wear include:

- Plastic deformations as well as ridging and micro-cutting of the surfaces caused by hard impurities with grain sizes of the order of 1–2 µm;
- Erosive wear, e.g., occurring in injectors (an impact with high speed and pressure of fuel with impurities); and
- Corrosive wear, e.g., due to poorly separated water from the environment.

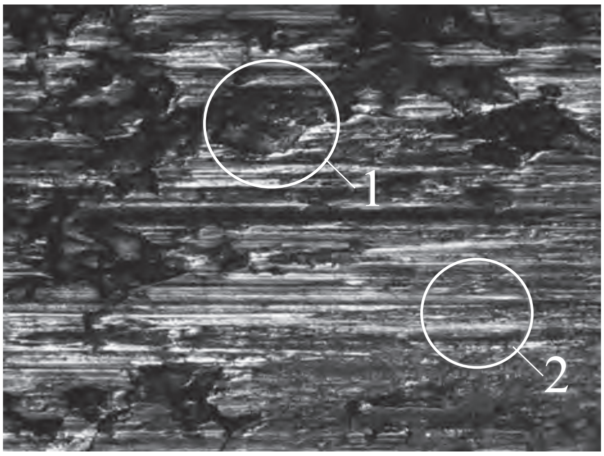

Fig. 3. A microscopic image of a bearing, magnification x10: 1 – thermal and adhesive wear, 2 – abrasive wear

Rys. 3. Obraz mikroskopowy panewki powiększenie x10: 1 – zużycie cieplno-adhezyjne, 2 – zużycie ścierne

There are many more examples of the effect of unpurified operating fluids to be cited here, e.g., [**L. 1, 3, 4, 7, 9, 10, 13**] and the examples provided in this article are only intended to show the scale of the problem of the lack of efficient filtration.

FILTRATION EFFICIENCY TESTING

The aim of the study was to determine the filtration efficiency of filter cartridges made from cellulose materials (standard, single-layer materials to be regarded as reference) and those containing multi-layer glass microfibres (materials to be used in the new filter manufacturing technology). The characteristics of test materials are provided in **Table 1**. Examples of microfibre density in the test samples are shown in microscopic photographs (**Fig. 4**).

The tests for filtration efficiency were performed by the Multi-pass method, in accordance with the *standards ISO 16889* and *ISO 4545-12*. The test stand diagram is shown in **Fig. 5**. The oil

Table 1. Test filter materials

Tabela 1. Badane materiały filtracyjne

Item	Material designation	Description of filter material
1	SB19/MFPS 1302/SB19	Two-layer glass microfibre with polyester fibre laminate on both the inflow and outflow side (20 g/m^2 of the polyester fibre laminate on the inflow side + a pre-filter layer on the inflow side, 70 g/m^2 + a filter layer on the outflow side, 30 g/m^2 + 20 g/m^2 of polyester fibre laminated on the outflow side)
2	MFPS 1302	Two-layer glass microfibre (the prefiltration layer on the inflow side, 70 g/m^2 + the filtration layer on the outflow side, 30 g/m^2)
3	MFPS1302/SB19	Two-layer glass microfibre with polyester fibre laminate on the outflow side (a pre-filter layer on the inflow side, 70 g/m^2 + a filter layer on the outflow side, 30 g/m^2 + 20 g/m^2 of polyester fibre laminated on the outflow side)
4	30/66 AD	Cellulose filter paper with a weight of 126 g/m^2, impregnated with phenolic resin in an amount of 14%
5	60/66 P AD	Cellulose filter paper with a weight of 192 g/m^2, impregnated with phenolic resin in an amount of 18%
6	20/66 P AD	Cellulose filter paper with a weight of 134 g/m^2, impregnated with phenolic resin in an amount of 14%

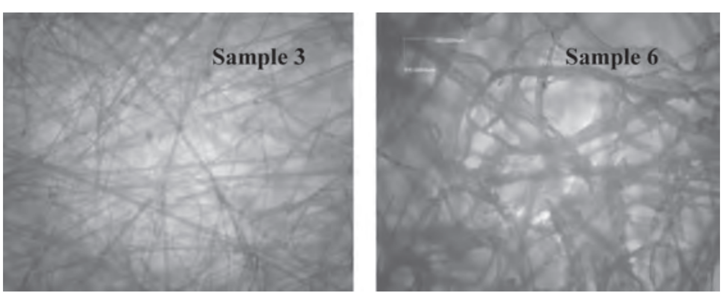

Fig. 4. Microscopic images of the test samples. Sample 3 – MFPS1302/SB19 – two-layer glass microfibre with polyester fibre laminate at the output. Sample 6 – 20/66 P AD - cellulose filter paper with a weight of 134 g/m^2

Rys. 4. Obrazy mikroskopowe badanych próbek. Próbka nr 3 – MFPS1302/SB19 – mikrowłókno dwuwarstwowe szklane z laminatem włókien poliestrowych po stronie wyjścia. Próbka nr 6 – 20/66 P AD – celulozowa bibuła o gramaturze 134 g/m^2

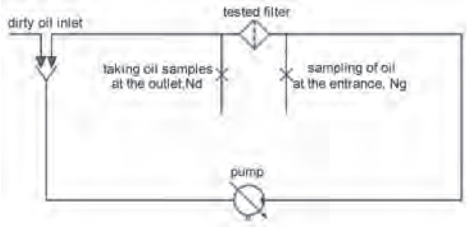

Fig. 5. Test stand diagram
Rys. 5. Schemat stanowiska badawczego

circulates in the circuit (as shown in the diagram) along with the dust continuously fed into the circuit, thus ensuring that its amount in the oil is constant.

The basic parameter describing a filter is the filtration accuracy index β_x (the "filter beta ratio"). The β_x parameter for a filter is determined experimentally using the "multi-pass testing" procedure, which involves adding a specified amount of an "impurifying" substance containing particles of a known size *x*, to the liquid continuously and uniformly pumped through the filter. In the liquid samples collected upstream and downstream, the numbers of impurities N_g and N_d are determined using an automatic counting system (three such tests were conducted, and the results are provided as a mean value of these test results), and the β_x value is then determined using the following formula:

$$\beta_x = \frac{N_g}{N_d} \tag{2}$$

where:
N_g – the amount of particles at the entrance (upstream),
N_d – the amount of particles at the outlet (downstream),
β_x – filtration index for the *x*-th particle size.

For a particular particle size, the efficiency is evaluated based on the n_f indicator:

$$n_f = \left(1 - \frac{1}{\beta_x}\right) \cdot 100\% \tag{3}$$

The testing conditions were as follows:
- Flow rate: 100 dm^3/h,
- Oil temperature: 40°C,
- Test dust (ISO Medium A3 Test Dust (ISO MDT): 2 g/h,
- Sample surface: 95 cm^2.

The cumulative filtration efficiency results are presented in **Fig. 6**.

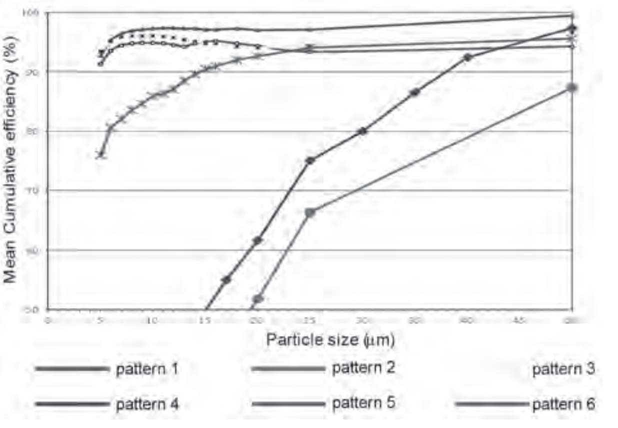

Fig. 6. Filtration efficiency testing results
Rys. 6. Wyniki badań skuteczności filtracji

Testing results show significant differences in filtering efficiency between the cellulose samples and the samples of filter materials based on glass microfibre layers. As regards the base material, i.e. cellulose filter paper, only one type of material (60/66 PAD) allows a filtration efficiency of over 90% to be achieved, but only for impurities with a diameter of more than 15 µm. All the tested multi-layer materials allow filtration effectiveness of over 90% to be achieved over the entire range of impurity sizes included in the experiment.

Other study results, e.g., **L. 4**, already demonstrated that multi-layer filter material with a weight of 120 g/m^2, comprised of cellulose, polyester, and nanofibre, offers a greater filtration accuracy than a cartridge made from single-layer cellulose (by 40% for dust grains with a diameter of 5 µm, and the difference is even greater for impurities with a smaller diameter). The study L.X also noted that a high filtration efficiency did not necessarily translate into longer life of filters.

The phenomenon of large dust grains appearing in the air downstream the filter cartridge A (cellulose) is associated with a noticeable decrease in its filtration efficiency to φwA = 99.73%, which indicates that the grains pass to the downstream side of the filter material. At the final stage of the cartridge operation on the filter material fibres, a considerable number of dust grains are accumulated in the form of proliferated tree-like dendrites. The dust grains found on the very top of the dendrites are captured and transported onto the downstream side of the filter material. This phenomenon results in dust entering the engine cylinders along with the intake air.

EFFECTIVENESS TESTING

The aim of the study was to assess the effectiveness of the filter materials presented in **Table 1**. This effectiveness was determined by a measure of filtration pressure drop depending on the time of exposure to the unpurified oil.

The study used the stand presented in **Fig. 5**, with the oil flow rate of 170 dm^3/h, and the test dust being fed at 5 g/h. The resistance in the filter medium occurs in series (filter material + deposit), i.e. the total change in pressure is:

$$\Delta p = \Delta_{pt} + \Delta_{po} \tag{4}$$

where:
Δp_m – pressure increase in the material,
Δp_o – pressure increase caused by the deposit.

The conducted tests were not aimed at distinguishing the filter medium resistance types but only at assessing the effect of impurity accumulation on the filtration rate and the total filter resistance. These relationships can be described using the following formula:

$$\frac{dV}{dt} = \frac{dp}{\Delta p} \tag{5}$$

where:
V – filtrate volume,
t – time,
R – total resistance of the filtration system.

Figure 7 presents diagrams representing the change in filtration pressure depending on the time of exposure to the unpurified oil.

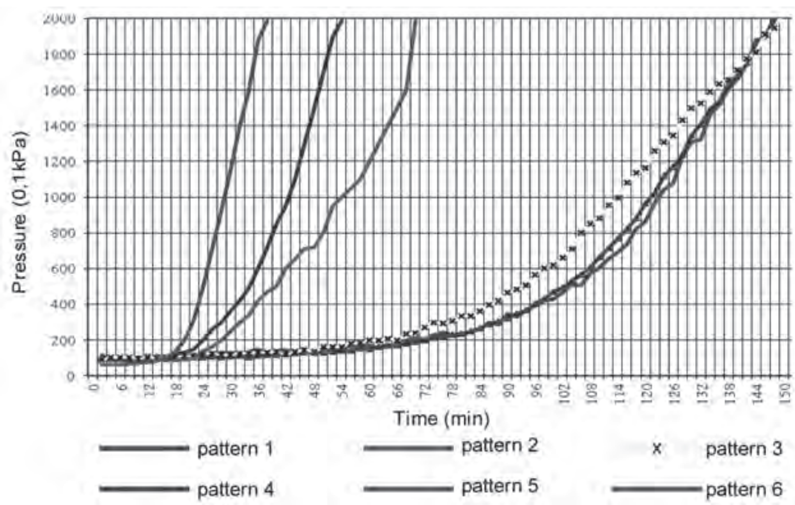

Fig. 7. The results of tests on changes in filtration pressure
Rys. 7. Wyniki badań zmian ciśnienia filtracji

The results of a comparative test for pressure change during the filter operation indicate that glass microfibre-type materials have a considerably longer operating life than cellulose materials. Achieving a pressure increase up to 120 kPa due to the capture of impurities for a cellulose material required approx. 30–40 min (under the testing conditions) while, for microfibre materials, this time was approx. 120 min, i.e. four times longer. Formula 3.2 shows that the filtration rate (derived from changes in filtrate volume over time) is proportional to the pressure change in the filter layer. Therefore, the filtration rate of filters made from cellulose materials will decrease earlier and more rapidly than the rate for the filters with multi-layer materials.

IMPLEMENTATION OF TECHNOLOGY FOR MANUFACTURING FILTERS WITH MULTI-LAYER FILTER MATERIALS

In order to achieve a practical effect, a new technology [**L. 9**], enabling the series production of filters using multi-layer materials, has been developed.

Key elements of the new technology include:

- An active method for filter material forming;
- An integrated method for transverse cutting, including the entire pleating process; and
- An ultrasound method for joining filter materials.

The **active method for filter material forming** achieved an accurate shape of the pleats and its uniform, repeatable distribution irrespective of the filter material type and its mechanical properties. In the implemented method for filter material forming, a characteristic feature is the **vertical holding down,** i.e. a very important operation in view of the durability of geometric characteristics of the pleats formed (**Fig. 8**). Standard methods lack this operation, which prevents the pleated material from keeping its shape permanently (**Fig. 9b**).

Transverse cutting is performed to obtain an appropriate number of pleats for the required filtration surface. The developed method for transverse cutting was integrated with the entire pleating cutting process (**Fig. 10**). This, certainly, offers the possibility to achieve considerable production efficiency as well as the high quality of cutting (with no shreds left), which, in turn, is a prerequisite for achieving the appropriate quality of the pleat joint and its tightness. In the standard methods applied, the operations of transverse and longitudinal cutting and pleating proceed independently and prevent the achievement of such a high quality of the filter material edges.

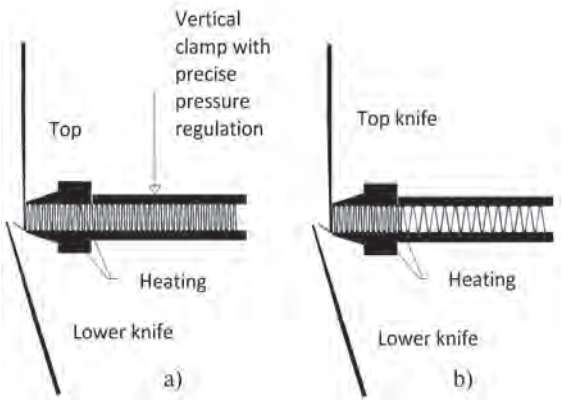

Fig. 8. The pleating method and its effects: a) with vertical holding down, b) without vertical holding down [L. 12]

Rys. 8. Metoda plisowania i jej efekty: a) z dociskiem pionowym, b) bez docisku pionowego **[L. 12]**

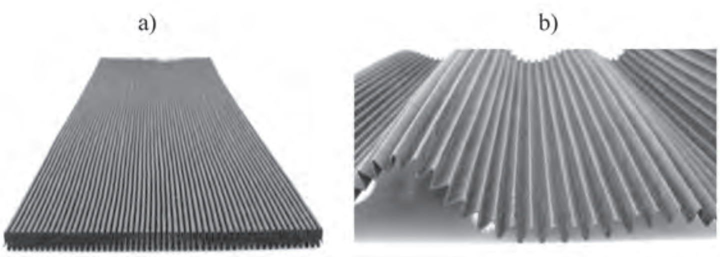

Fig. 9. A comparison of pleated materials: a) with vertical holding down, b) without vertical holding down

Rys. 9. Porównanie splisowanych materiałów: a) z dociskiem pionowym, b) bez docisku pionowego

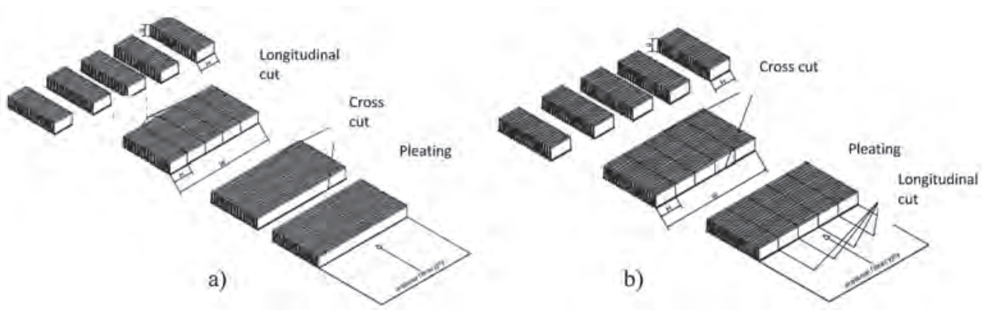

Fig. 10. Organisation of the technological operations of cutting and pleating: a) new process, b) standard process

Rys. 10. Organizacja operacji technologicznych cięcia i plisowania: a) nowy proces, b)standardowy proces

Joining the pleated filter material should provide a durable and tight joint, which has a direct influence on the quality of the filter medium and the entire filter. The standard methods include joining using a hot-melt adhesive or the metal clamp method. In the new joining method, an ultrasound welding machine was used. The elimination of additional joining elements and the associated waste in the form of metal elements and degraded or leaked adhesive contributes both to an improvement in labour safety, the elimination of an adverse environmental impact, and material savings.

SUMMARY

The study results demonstrated that the use of multi-layer filter materials with glass microfibres allows filtration efficiency at a level of $\beta_{5\mu m}$= 92–95% to be achieved. The conducted study into filtration efficiency recorded no impurities smaller than 5 μm, while other studies, e.g., **[L. 1, 4]**, indicate that an efficiency indicator value of up to 99% can be achieved for smaller impurity sizes.

The results of comparison tests for a change in filtration pressure indicate that multi-layer materials have a considerably longer operating life than standard materials. The duration of efficient filtration was found to be up to four times longer for the filters manufactured according to the developed technology.

Thanks to technical and technological advances in the manufacturing process, the possibility of pleating materials with high filtration parameters was achieved. These include the following: impregnated cellulose materials, microfibres, glass materials, composite materials with nanofibres, synthetic materials from plastic, and metal meshes.

A finished filter should contain a uniform, straight, rigidly formed pleat. This is an important prerequisite for obtaining a stable laminar flow of the filtered medium, uniform over the entire surface and thus for its effective functioning. The application in the pleating operations of precisely controlled holding down of each previously cut pleat contributes to the preservation of the pleat shape and their uniform spacing, even during the subsequent storage in an expanded state.

Achieving greater durability of filters due to the manufacturing methods (mentioned but not described in this article, but already implemented, e.g., joining the filter medium core by clamping a formed expanded mesh along the core's height, and obtaining an S-shaped joint) can be considered an "Ecotribology" practice **[L. 2]**.

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