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IMPROVEMENT OF A MICROFILTER PROTOTYPE AND ITS REALIZATION: CHEMICAL APPLICATIONS

The object of this research is microfilters. This study aims to develop a microfilter that can be used, for example, for air or water filtration as traditional applications. The closed indoor environments demand the control of the air quality for the health of humans who work there. The implementation of different technologies as MicroElectroMechanical Systems (MEMS), NanoElectroMechanical Systems (NEMS) and MicroEquipment Technology (MET) for microcomponents production is analyzed. The advantages and disadvantages of these technologies are described. MET was used to produce and develop microfilter structure.

The structffure and model of the microfilter is presented. The problem to be solved is connected with microfilter structure simplification and preparation it for the use of new technologies for their production. For its realization the 3D printer was used. 3D printers are the equipment that realizes an additive technology that has been actively developed in recent years. From computer 3D model it is possible to build the 3D prototype. The essence of the results is the possibility of mass production of microfilters. Different possible applications, not only filtration of air and liquid are described, but applications in chemistry for microreactions module and microseparation units.

It was compared new microfilter design with our previous prototype of microfilter developed and produced using the MET. The MET has advantage that it works with various materials and not just those used in microelectronics. Their tests and investigations demonstrated that the microfilters can be used in practice. New prototype was made by 3D printer. Comparative assessment of the first microfilter prototype and new prototype shows that the new prototype has a simplified structure and is easier to manufacture. One of the most interesting areas of their applications is for chemical microreactors. It is one of the new, interesting and promising areas of application.

Keywords: *MEMS, NEMS, MET, 3D printer, microfilter, microfabrication, chemical microreactor, microseparation unit, air and liquid filtration, human health.*

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1. Introduction

MEMS and MET: To produce micropieces, microcomponents, microequipments or microdevices it is possible to apply different modern technologies. One of most popular technology for micropieces production is a MicroElectroMechanical System (MEMS) [1] or at last years the NanoElectroMechanical Systems (NEMS) [2]. MEMS has relations with micrometer range of pieces. NEMS has relation with nanometers range. NEMS typically integrate transistor-like nano electronics with mechanical actuators, pumps, or motors, and may thereby form physical, biological, and chemical sensors, for example, described in [3, 4].

In 1996, the first article devoted to the microequipment technology (MET) was published by us [5]. It was beginning of the development of the MET technology. Following years were dedicated to improve this technology and demonstrated different prototypes made due to this technology [6, 7].

The main idea is to create new equipment as new generations every time with sizes, for example, two times less than previous generation. With every new generation it is possible to obtain equipment with is comparable with sizes of microcomponents that it is necessary to produce. Using this type of equipment, it is possible to consume less energy, less materials and less work space. But it is possible to produce the components with more precision.

An additive manufacturing that was actively developed last ten-fifteen years permits from 3D computer models of the objects create their prototypes. 3D printers are widely used for manufacturing different types of reactors and filters. The following section is dedicated to 3D printer applications.

Additive technology and 3D printers for chemical applications: the past decades have seen increasing progress in microfluidic systems for use in chemistry and biochemistry. Different approaches to develop the microreactors, microseparation modules, microfilters will be discussed in this section.

The recent achievements in microreaction modules and microseparation units are described in [8]. They analyzed development of microreaction systems fabricated by various 3D printing techniques for chemical synthetic applications.

In [9] the authors proposed special technologies (rapid prototyping (RP) and rapid manufacturing (RM)) such that three-dimensional parts can be fabricated directly from computer aided design (CAD) data with a very short lead-time. The RP techniques, such as selective laser sintering (SLS), stereolithography (SLA), 3D printing, fused deposition modeling (FDM) and direct metal laser sintering (DMLS) are able to produce prototypes in different kind of materials. In this article the authors present high precision microfabrication facilities to design and construct two micro-reactor components (housing structure and microchannels plate) using aluminum powder. As a result, they produce the microreactors are compact devices.

A miniaturized polypropylene reactor was fabricated by 3D printing using fused deposition modeling [10]. A stainless steel nanoelectrospray ionization capillary and a magnetic stir bar were integrated into the reactor during the printing process. The integrated nanoelectrospray ionization capillary allows direct sampling of a reaction solution without external pumping. Therefore, rapid online mass spectrometric chemical reaction monitoring is possible.

The versatility of 3D-printing can be combined with the processing advantages of flow chemistry for the synthesis of organic compounds [11]. Robust and inexpensive 3D-printed devices can be easily connected using standard fittings resulting in complex, custom-made flow systems, including multiple reactors in a series with in-line, real-time analysis.

Droplet microfluidic technologies reduce channel fouling and provide an improved level of control over heat and mass transfer to control reaction kinetics [12]. However, in conventional geometries, the droplet size is sensitive to changes in flow rates. So, it is necessary to develop a three-dimensional droplet generating device that exhibits flow invariant behavior and is robust to fluctuations in flow rate. The droplet generator is capable of producing droplet volumes spanning four orders of magnitude [12]. The authors apply this device in a parallel network to synthesize platinum nanoparticles using an ionic liquid solvent, and demonstrate reproducible synthesis after recycling the ionic liquid, and double the reaction yield compared with an analogous batch synthesis.

The authors [13] proposed the thiolene-based microfluidic reactor. They have demonstrated that a chip IMER (thiolene-based pepsin microreactor) can achieve, under similar conditions, a digestion performance comparable to that of a classical pepsin column IMER, in which a column is packed with pepsin immobilized on agarose beads. IMER has great potential not only as a small, inexpensive, and low volume alternative to the currently available commercial columns but also as a platform for further development into a fully contained micro total analysis system for proteomics [13].

The investigators [14] show that the 3D-printed eggbeater structure could have numerous applications, including water droplet manipulation, 3D cell culture, micro reactor, oil spill clean-up, and oil/water separation. Biomimetic functional surfaces are attracting increasing attention for these technological applications, especially the superhydrophobic surfaces inspired by plant leaves. However, the replication of the complex hierarchical microstructures is limited by the traditional fabrication techniques. The superhydrophobic micro-scale artificial hairs with eggbeater heads inspired by Salvinia molesta leaf was fabricated by the Immersed surface accumulation three-dimensional (3D) printing process. Multi-walled carbon nanotubes were added to the photocurable resins to enhance the surface roughness and mechanical strength of the microstructures. The 3D printed eggbeater surface reveals interesting properties in terms of superhydrophobilicity and petal effect [14]. The results show that a hydrophilic material can macroscopically behave as hydrophobic if a surface has proper microstructured features. Furthermore, a new energy-efficient oil/water separation solution based on our biomimetic structures was demonstrated.

3D printing technology has an enormous potential to apply to chemical engineering education [15]. Several designs of 3D printed mesoreactors (Y-shape, T-shape, and Long channel shape) using the following steps: reactor sketching, CAD modeling, and reactor printing were described in [15]. The small channel of mesoreactors facilitates the stability of a laminar flow in the system at low Reynolds number. Their results provided that 3D printed mesoreactors can be possibly used in teaching fluid dynamics, chemical kinetics, and reaction engineering, which are main courses of the chemical engineering undergraduate program. The cost of mesoreactor printing was suitable.

A photochemical microreactor filled with fluorescent fluid is fabricated by a 3D printing technique [16]. The light-converting medium in the fluorescent fluid is used to collect and convert light, and then delivers light energy to the embedded continuous-flow reaction channels to promote the chemical reaction process. The photochemical microreactor has been a burgeoning field with important application in promoting photocatalytic reactions. The integration of light-converting media and microflow chemistry renders new opportunity for efficient utilization of light and high conversion rate [16].

The article [17] describes the development and manufacturing of lab equipment, which is needed for the use in flow chemistry. The authors developed a rack of four syringe pumps controlled by one Arduino computer, which can be manufactured with a commonly available 3D printer and readily available parts. They printed various flow reactor cells, which are fully customizable for each individual reaction. With this equipment they performed some multistep glycosylation reactions, where multiple 3D-printed flow reactors were used in series.

Nanotechnology field (NEMS) is booming in an impressive manner. Activated carbon and fiberglass are widely used in air filtration industry [18]. Nanofibers are one of the unique materials which have one order of magnitude smaller than conventional fibers. The high surface-to-volume ratio, low resistance and enhanced filtration performance make nanofibers an attractive material for many applications such as healthcare, energy and air filtration. Recent advancements in the removal of volatile organic compounds (VOC), nanoparticles and airborne bacterial contaminates in the air are highlighted. The aerosol filtration performances of nanofibers are also described in [18]. The enhanced activity of nanofibers due to the nanosize and their applications such as in protective clothing are highlighted.

Conventional manufacturing of microfluidic devices from glass is time-consuming and expensive, in particular for the prototyping of microfluidic devices in low quantities [19]. The authors of [19] describe a laser-based process that enables the rapid manufacturing of enclosed micro-structures by laser micromachining and microwelding of two 1.1-mm-thick borosilicate glass plates. The fabrication process was carried out only with a picosecond laser. It was used for:

1) the generation of microfluidic patterns on glass;

2) the drilling of inlet/outlet ports into the material;

3) the bonding of two glass plates together in order to enclose the laser-generated microstructures [19].

From these publications it is possible to see the importance of microreactors, microgenerators and microfilters development and 3D printers using for these goals.

The aim of this research is improvement of microfilter structure to provide massive production.

2. Materials and Methods

2.1. The object of research

The object of this research is microfilters. The problem being solved is connected with simplification of the microfilter structure.

Our first proposal of microfilter prototype was developed in 2018–2022 and described in [20, 21]. This work was based on investigation of microequipment technology (MET) [5–7, 21].

2.2. Microchannel filter

The double-chamber microchannel filter allows measurements to be made in isolation at the input and output of the microchannels. It has a pair of cameras that only communicate with each other through the microchannels, thanks to which it is possible to carry out measurements reliably (Fig. 1).

The material used for the manufacture of the double-chamber micro channel filter can be acrylic or polycarbonate. The material allows the visualization of the air flow through dyes, allowing the behavior of the flow to be observed in a practical way when passing through the microchannel.

The interchangeable chamber micro channel filter has four main parts, bottom wall and top wall, head with micro channels, main support frame (Fig. 2).

The number of machining processes increases considerably.

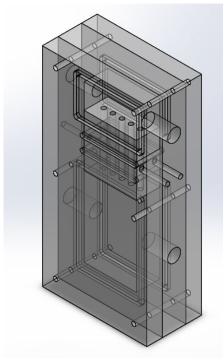


Fig. 1. Microchannel filter

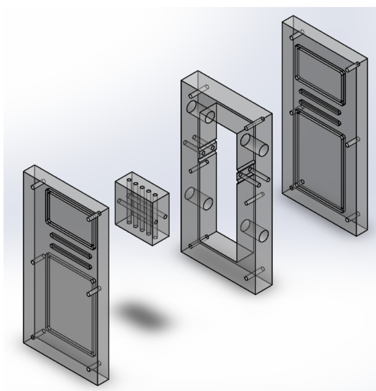
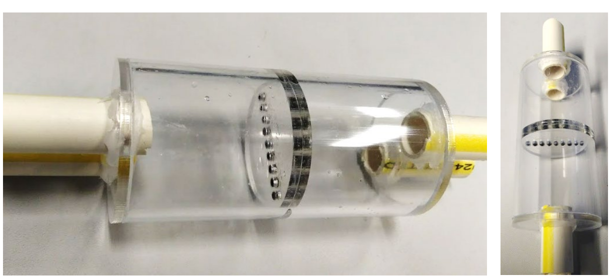


Fig. 2. Components of microchannel

Food-grade Viton gaskets are used to prevent the entry of contaminants into the filtration chambers by means other than the filter intakes, guaranteeing the flow of air through the micro channels.

It was a plan, a principal idea. But the first prototype was made a little bit another manner. It is possible to use the material more accessible in our laboratory.

The prototype of microchannel filter is presented in Fig. 3.



a *b*

Fig. 3. Prototype of filter with microchannel: *a* – side view; *b* – view pipes from above [21]

For its manufacture let's use equipment that was developed by MET.

2.3. Main elements of theory of flow

Poiseuille's law allows determining the stationary laminar flow of a Newtonian fluid through a cylindrical tube of constant circular section (Fig. 4).

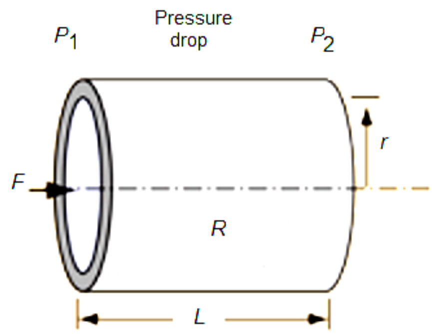


Fig. 4. Volume flow representation [22]

Volume flow is calculated as

$$F = \frac{P_1 - P_2}{R} = \frac{\pi r^4 \Delta P}{8\eta L}, \qquad (1)$$

where P_1–P_2 – a pressure difference; r – the radius of the channel; R – the resistance to flow, η – the viscosity of the fluid; L – the length of the channel.

Flow resistance is calculated as

$$R = \frac{8\eta L}{\pi r^4}. \qquad (2)$$

Poiseuille's law can be used to calculate the volume flow rate only in the cases of laminar flow (Fig. 4).

3. Results and Discussion

3.1. Calculations for open channels

To calculate the flow in a channel other than circular, it is necessary to consider the diameter hydraulic, this is a term commonly used in hydraulics when handling fluids in channels and non-circular tubes. Using this term, it is possible to study the behavior of the flow in the same way as if it were a pipe with a circular section.

The hydraulic radius is an important parameter in the dimensioning of channels, tubes and other components of hydraulic works. It is generally represented by the letter R, and expressed in meters is the relationship between the wetted area (A, in m^2) and the wetted perimeter (P, in m) [23]. In [23] the different profiles of tube are presented, for example, rectangular, triangular, trapezoidal, circular, etc. There the wet perimeter, hydraulic radius and others parameters are calculated.

Wet area. In a channel, the wet area is understood as the surface occupied by the water in a section perpendicular to the flow. This section is defined, at the top by the water line, and at the bottom by the channel itself. In a pipe working at full section, the wet area coincides with the section of the tube.

Wet perimeter. In a channel, the wet perimeter is the contour of the channel that is in contact with water. In a tube, working at full section, the wet perimeter coincides with the inner circumference of the tube.

Considering that the water flows through a tube of length 20 cm and radius 1 mm. If the pressure difference between two points is 0.77 atm at an ambient temperature of 20°C, the volume of water flowing every second is determined as presented in 3.2.

3.2. Two examples of calculation of flow

Case 1. Considering that the water flows through a tube of length 20 cm and radius 1 mm. The volume of water flowing every second is determined. Let's consider the scheme of Fig. 5 for pressure.

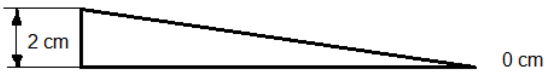


Fig. 5. Case 1

Case 1, where 1000 cm = 1 Atm. Considering the pressures: $P_1 = 0.002$ Atm; $P_2 = 0$ Atm. Considering Poiseuille's law (1) $L = 20 \cdot 10^{-2}$ m; $r = 1 \cdot 10^{-3}$ m; $\eta = 0.01002$ kg · m · s^{-1}; $\Delta P = 0.002$ Atm = 202.65 N · m^2 = 202.65 kg · m^3/s^2.

Substituting

$$F = \frac{\pi \cdot 0.001^4 \cdot 202.65 \left(\frac{\text{kg} \cdot \text{m}^3}{\text{s}^2}\right)}{8 \cdot 0.01002 \left(\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}\right) \cdot 20 \cdot 10^{-2} (\text{m})} = 3.97 \cdot 10^{-8} \left(\frac{\text{m}^3}{\text{s}}\right). \quad (3)$$

Case 2. Considering that the water flows through a tube of length 20 cm and radius 1 mm, the volume of water flowing every second is determined.

For pressure consider the case 2 presented in Fig. 6.

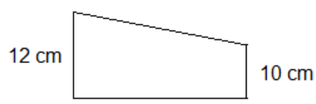


Fig. 6. Case 2

Case 2, where 1000 cm = 1 Atm. Considering the pressures: $P_1 = 0.012$ Atm; $P_2 = 0.01$ Atm. Considering Poiseuille's law (1); $L = 20 \cdot 10^{-2}$ m; $r = 1 \cdot 10^{-3}$ m; $\eta = 0.01002$ kg · m · s^{-1}; $\Delta P = (0.012 - 0.01)$ Atm = 0.002 Atm = 202.65 N · m^2 = 202.65 (kg · m^3)/s^2.

Substituting

$$F = \frac{\pi \cdot 0.001^4 \cdot 202.65 \left(\frac{\text{kg} \cdot \text{m}^3}{\text{s}^2}\right)}{8 \cdot 0.01002 \left(\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}\right) \cdot 20 \cdot 10^{-2} (\text{m})} = 3.97 \cdot 10^{-8} \left(\frac{\text{m}^3}{\text{s}}\right). \quad (4)$$

These two examples presented in Fig. 5 and Fig. 6 have different initial parameters of tube but demonstrate the same force calculated by formula (3) and formula (4).

3.3. Selection of 3D printer

The design of the air microfilter that uses water to clean small particles found in the air is presented in Fig. 7. It can be used in closed areas such as at home or in the office. It is worth mentioning that the design of this first prototype can be varied in future as tests will be carried out to improve its performance.

To manufacture this microfilter let's use 3D printing. Two techniques are used to evaluate their performance. The techniques are digital light processing (DLP) and fused deposition modeling (FMD). The short description of the both technologies are presented below.

The DLP technique projects a UV light onto the photo resin curable. This method allows a faster construction compared to the other techniques [24]. The parameters that affect the construction time are the thickness of the layer and the required exposure time, and not the length of the *X* and *Y* axes. The resolution of the printed structures depends on the size of the projected pixel.

The FDM technique uses a thermoplastic filament to build three-dimensional structures. The printer nozzle melts the filaments in a viscous liquid and extrudes the material in the desired places to fabricate the desired 3D structure. Resolution depends on nozzle size of the printer [25].

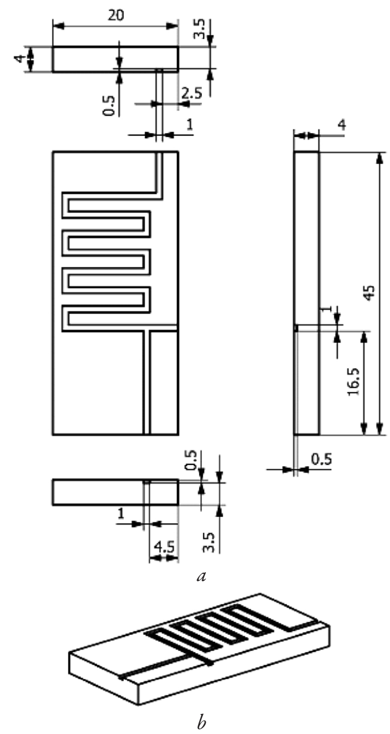


Fig. 7. Microfilter scheme: *a* – drawing with dimensions; *b* – 3D design

3.4. Proposed prototype

The proposed prototype is presented in Fig. 7. It was modeled with the help of CAD software (Fig. 7).

The microfilter has the base dimensions of 45 × 20 × 8 mm. Inside it has a zigzag channel of 8 segments. Its shape is square. It can be modified to evaluate its performance. The dimensions of the square channel are 1mm both high and wide.

It has two inlets, one for air at the bottom (right side part) and one for water. It has a single outlet at the top (Fig. 8). The microfilter has an upper part and a lower part, both parts are symmetrical.

A small pump will be added to the microfilter. It will be in charge of sucking the air and water. The pressure must be low, since to filter the particles of the air with the help of water it is required that the process be slow. The time later will be calculated with tests. The process is as follows: polluted air as well as clean water will enter the microfilter, firstly, the water will enter the bottom of the microfilter and the air will enter from the side, as the air meets the water particles. This will help contaminant particles to be absorbed by the water. At the exit let's obtain clean air, which will be evaluated to verify the microfilter performance. Also, at the output let's obtain water with the polluting particles that demonstrate that the air could be filtered.

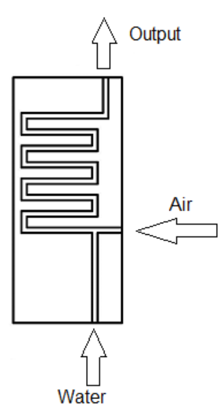


Fig. 8. Channel form of microfilter

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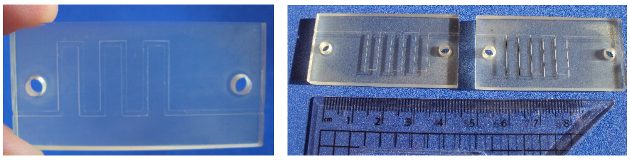
3.5. Prototype

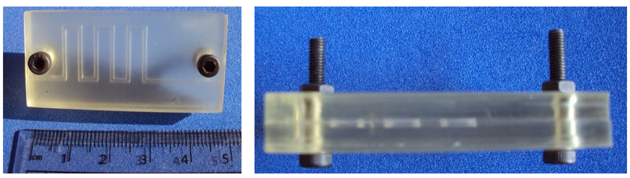
The main elements of prototype that was realized with 3D printer and its size is presented in Fig. 9. The upper (or top) element is presented in Fig. 9, *a*. The microfilter contains two symmetrical parts (Fig. 9, *b*).



a *b*

Fig. 9. Prototype components of microfilter: *a* – upper (top) element; *b* – the both elements top and bottom

In Fig. 10, *a* the assembled microfilter is presented. Two plates are connected with screws (Fig. 10, *b*).



a *b*

Fig. 10. Assembled microfilter: *a* – top view; *b* – side view

The second step near future is connected with experimental investigation of created microfilter.

3.6. Limitations of research and directions of its development

This research is the first step of the microfilter development and its investigation. The structure and parameters of microfilters are important from point of view of their realization. The follow step is connected with conducting the experiments with the developed prototypes to demonstrate their effectiveness in different applications. Everything that was described in this article is reproducible and can be used by other researchers and engineers to repeat it. The main direction of further development is related to specifics of area of applications. The conditions of different applications, especially in chemical applications, may vary significantly.

4. Conclusions

The results of this research are the development and comparison of the models of microfilter prototypes. They can be used not only for filtration of air and water but can be used for chemical reactors with low-speed reactions. Practically, one of the models was produced by MET developed by authors. The alternative technologies that can be used are MEMS and NEMS. The structure and parameters of microfilters are important from point of view of their realization. The new microfilters may be produced and really made using 3D printers. Due to production with 3D printer, it is possible to organize their massive production.

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Conflict of interests

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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