Adv Syst Sci Appl 2021; **04**; 57-64

The Multidimensional Network Models Method of Developing Discrete Microfluidics

Andrey V. Balabanov [1]*, Asim M. Kasimov [2]

V. A. Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, Moscow, Russia

1) *E-mail: fca07@mail.ru*

2) *E-mail: kasimov@ipu.ru*

Abstract: The performances of the microfluidic units may vary within a wide range depending on the design, even if the operational geometry remains the same. In order to obtain the most effective results of the designing, it is reasonable to use the formal procedures of systematizing possible variants of the design, analyzing these variants, and selecting the best design variant based on the preset criteria. In this context, the problem of creating the effective formal methods of designing the microfluidics is topical. The main purpose of this paper is to propose a decision of this problem. To solve the problem mentioned above, the authors devised a method of analyzing and synthesizing the designs based on the multidimensional network models (MNM-method). The MNM-method provides the possibility of generating and in-computable-form-analyzing qualitatively different variants of the design on the principle of the unity of the geometrical, structural-hierarchical, and functional characteristics, as well as the possibility of selecting the best design variant on the basis of the preset criteria by means of analyzing both the structure and features of the multidimensional networks.

Keywords: multidimensional network model, design analysis and synthesis, microfluidics, reserve control system

1. INTRODUCTION

The experimentally validated high performances of microfluidic control elements, in combination with the small sizes, in large part, set the trend for the implementation of microfluidic devices in the form of integrated circuit units – monolithic (indivisible) designs, without using discrete components.

The integrated form of the control microfluidics provides possibilities to avoid (or to significantly minimize) mounted interconnections, reduce the energy loss in transmitting the data, and provide the high performances like those of the discrete microfluidic elements. Therefore, the main directions of developing the control microfluidics, at present, are improvement of the weight-size parameters as well as transition to the integrated technology. To effectively develop these trends it is necessary to bring the gap between, at the one hand, the conceptual, schematic and algorithmic decisions, and, at the other hand, the design implementation. As a solution, this paper represents the formal method of designing of the microfluidics, which is based on the multidimensional network models – the MNM-method.

The MNM-method of designing the microfluidics is a new formal method of the design analysis and synthesis, with the effectiveness proved by practice. The method uses a new kind of the generalized models – the multidimensional network models – that are based on the ‘structure class’ entity. In order to design the microfluidics, the formal definitions of the geometrical, structural-hierarchical, and functional structure classes have been developed.

---

[*] Corresponding author: fca07@mail.ru

In this paper, the key stages of applying the MNM-method are represented by the example of designing the microfluidic generator of the 100-µm feature size. This is very important from the practical viewpoint, because the microfluidics is increasingly used to create high-technology products. For instance, the microfluidics provides potential to create promising non-electric *reserve control systems* (RCS). The prospectivity of RCS is mainly determined by the resistance of the microfluidics to multiple destabilizing factors resulting in failures of electronics (for instance, radioactive and corpuscular emissions, electromagnetic emission, high temperatures, etc.). The microfluidics has its own approaches to generating, saving, transforming, and transmitting the data. Therefore, the microfluidics allows new original cybernetic systems to be developed by means of the non-electronic element base. At the present time, the fields taking advantage of the microfluidics also are microanalytics, micromechanics, biotechnology, bioengineering and other complex scientific areas.

This paper represents one of the possible applications of the MNM-method – designing the microfluidics. In general, the field of application is wider than the above one. However, not to disturb the monographic composition of the paper, no alternative was considered within the research undertaken. Therefore, the authors do not declare the universality of the MNM-method, despite its large potential to be used as a development tool.

2. BACKGROUND

There are a number of the researches devoted different aspects of creating the microfluidics. These are the schematic development, the investigation of microfluidics features, the modelling, and the manufacturing. In this context, what should be noted firstly are [2-11]. However, having performed the literature overview, the authors revealed no formal methods to aid the microfluidics designing. That the microfluidics has no formal tools to be designed is a circumstance that has been inhibiting and would have inhibited the development in this field – if this had been ignored. This paper is an attempt to make the microfluidics designing both more comprehensive and more scientific-proved, at least, in relation to the devices similar those represented bellow in order to give an instance of the MNM-designing.

3. MNM-METHOD

Analyzing and synthesizing the microfluidic design, it is necessary to take into consideration the set of the possible variants of this design in order to select the best design structure based on the requirements for its characteristics.

The MNM-method supposes that the main origin of generating the implementation set is the decomposition of the characteristics into the functional, geometrical, and structure-hierarchical classes, with these classes systematized in the form of MNMs. Identifying the classes within the microfluidics (MF) is performed by means of the following formal procedures of the decomposition:

$$O_g: \ MF \to \left\{S_g^i\right\}_{i=1}^m \mid \forall\left(s_g^{ia}, s_g^{ib}\right) \in S_g^i, E\left(F_g^{ia}\right) - E\left(F_g^{ib}\right) \leq \Delta_g \tag{3.1}$$

The procedure of the geometrical decomposition (O_g) is represented by (3.1) and allows the set of the geometrical implementations of the design to be generated. The result of O_g is the S_g^i set of the structure classes, such that for any pare of the instances (s_g^{ia}, s_g^{ib}) of any of these classes, the value areas of the geometrical functionals (F_g^{ia}, F_g^{ib}) of the instances can differ by up to Δ_g. The completion of the O_g procedure results in the set of structure classes defining the geometrical structure of the microfluidic unit being designed:

$$O_h:\ MF \to \left\{S_h^i\right\}_{i=1}^n \mid \forall\left(s_h^{ia}, s_h^{ib}\right) \in S_h^i, D\left(F_h^{ia}\right) - D\left(F_h^{ib}\right) \le \Delta_h \tag{3.2}$$

The formula (3.2) reflects the procedure of the structure-hierarchical decomposition. The result of O_h is the S_h^i set of the structure classes, such that for any pare of the instances (s_h^{ia}, s_h^{ib}) of any of these classes, the definition domains of the geometrical functionals (F_h^{ia}, F_h^{ib}) of the instances can differ by up to Δ_h . Thus, setting different requirements for O_h , it is possible to obtain qualitatively different sets of the structure classes. For instance, the structure-hierarchical decomposition can be performed by the criteria of the standardization, the product kind (assembly, detail, kit, and complex), and so on. It is the requirement setting that is the main origin of formation of a variant set of the hierarchical structure of the microfluidics:

$$O_f: MF \to \left\{S_f^i\right\}_{i=1}^k \mid \forall\left(s_f^{ia}, s_f^{ib}\right) \in S_f^i, \left(D\left(F_f^{ia}\right) - D\left(F_f^{ib}\right) \le \Delta_{fD} \wedge E\left(F_f^{ia}\right) - E\left(F_f^{ib}\right) \le \Delta_{fE}\right) \tag{3.3}$$

The procedure of the functional decomposition is described by (3.3). The result of O_f is the S_f^i set of structure classes, such that for any pare of the instances (s_f^{ia}, s_f^{ib}) of any of these classes, the definition domains and the value areas of the geometrical functionals (F_f^{ia}, F_f^{ib}) of the instances can differ by up to Δ_{fD} and Δ_{fE} , correspondingly. The functional decomposition provides formation of a set of the classes defining the functional structure of the microfluidics.

MNMs are built on the basis of the sets of the structure classes resulting from the decomposition procedures. To design a microfluidic unit with required parameters it is necessary to systematize the sets of the instances of the structure classes by means of MNMs. These models have the *i*, *j*, and *k* dimensions. The subranges of *i*, *j*, and *k* depend on the cardinalities of the classes sets obtained as the result of decomposition. For example, let the two functional classes would be generated. Then, the number of *i*-subranges is equal to two (i.e. one has i_1 and i_2). Thus, the MNM dimensions correspond to the classes sets. Given below is the case of MNM-designing involving the *i*, *j*, and *k* simple (single-member) subranges. In general, the number of the dimension subranges may be varied, and it is chosen depending on the complexity of both analyzing and synthesizing the design being created.

4. PRACTICE

In this section, the discrete-microfluidics designing based on MNMs is considered by the example of the microfluidic three-stage generator. At the first stage of the designing, it is necessary to carry out the analysis and the classification of the product requirements in terms of the preset features, with the number of these features depending on the task being solved. In relation to the generator, three groups of the features are specified: geometrical, structural-hierarchical, and functional. Corresponding to the three groups of the features, the set of the structure classes (in this case, these are the geometrical, structural-hierarchical, and functional classes) is to be formed. For each of the structure classes, the fixed-cardinality set of the instances representing possible physical implementations of the class within the design to be created shall be generated and rated by the implementation costs.

Given in Fig. 4.1 are the schematic diagram of the generator as well as the common operational geometry of its elements. The operational element of the generator under design is a microfluidic trigger. It is the trigger function that represents the main functional class. As the generator is a three-stage one, it consists of three triggers. These may be both identical and different in implementation. Each original implementation of the trigger is an instance of the corresponding structure class.

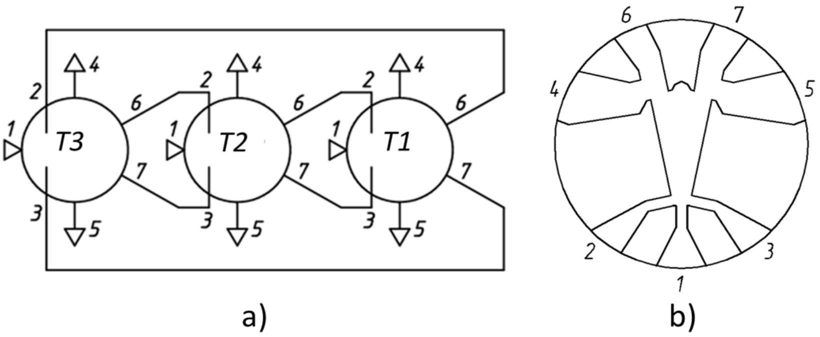

Fig. 4.1. Schematic diagram (a) and operational geometry (b) of three-stage microfluidic generator

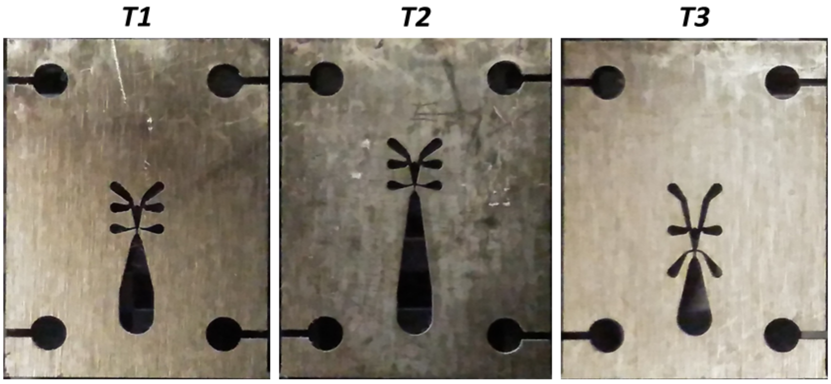

Fig. 4.2. Example of possible implementations of microfluidic trigger

To form the sets of the geometrical and structural-hierarchical classes, one considers the three available implementations of the microfluidic trigger. These are represented in Fig. 4.2. They are different in the operational geometries, but have the same functions (memory cell) and the same design kinds (in the form of a sheet detail). It means that T1, T2, and T3 belong to same functional and structural-hierarchical classes, but to different geometrical classes. It should be noted that this example of dividing into the classes relates to the elements, but not to the generator as a whole. However, it is the classification by the feature groups specified that is the basis to form the classes sets.

At the second stage of designing, the sets of the classes instances shall be systematized in the form of a multidimensional network model (MNM). Building the MNM is to arrange the instances by placing the corresponding nodes along the i, j, k axes in order of increasing the implementation costs. This process is equivalent to generating a set of the possible variants of the design. Each of these design variants is represented by a unique path from the input to the output of the MNM.

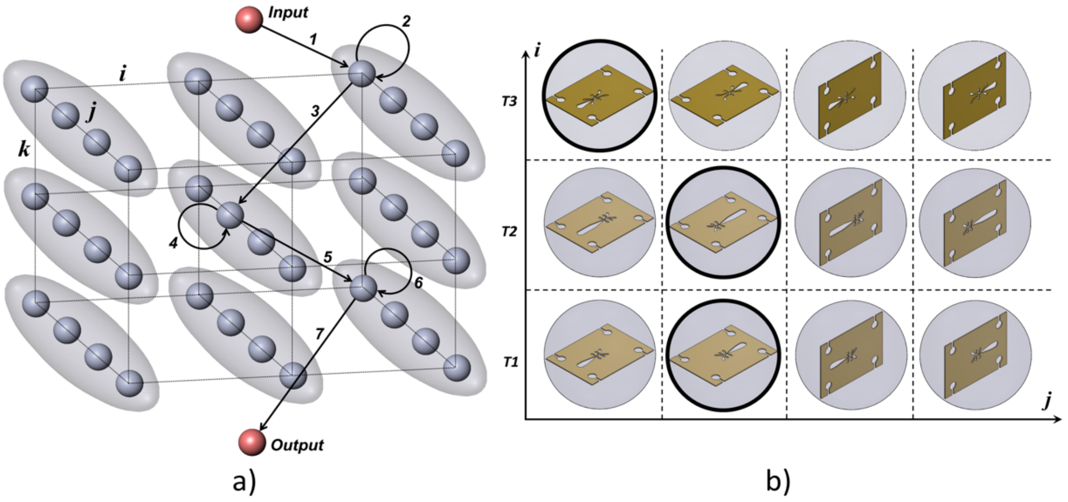

Fig. 4.3. MNM of microfluidic generator (a) and MNM-level example (b)

Fig. 4.3a demonstrates the three-dimensional MNM of the microfluidic generator, built on the basis of the previous procedures of designing. The number of the dimensions (three) of this MNM is determined by that, as an example, one class of each of the feature groups has been specified: 1) the functional class (i) is defined as the trigger function, 2) the geometrical class (j) is defined as the operational profile core, and 3) the structural-hierarchical class (k) is defined as the design kind. In general case, the number of the dimensions is determined by the sets of the structure classes, and can be varied.

Thus, the nodes of the MNM are the instances of the structure classes, i.e. the elements of the generator design. Each of the ellipsoids includes the set of physical implementations of one of the functional-class instances. The loops of the MNM correspond to the operations of building the instances of the structure classes. In Fig. 4.3a, the loops reflect the assembly operations involving the operational elements (triggers). Other edges (excepting the input and output ones) of the MNM represent the transition operations between the pairs of the class instances (for example, making interconnections of the triggers). The end nodes of the transition edges shall be matched by the input and output characteristics (flow-rate, frequency, pressure, etc.). The input and output edges of the MNM reflect the complex assembly operations of mounting the terminal elements (base, covers, external interconnections) of the design. The MNM having been built, the edges shall be weighted. A required design variant within the MNM is selected by means of the procedures of analyzing the MNM features, evaluating the weights of the edges, and calculating the MNM shortest path in terms of the preset criteria. Given that the generator design must provide the maximally possible frequency, the main criterion to be used in selecting would be reasonably assumed as being defined by the hydraulic resistance of the connection channels. Consequently, the selecting is to evaluate the different combinations of the cross-section and the route, which are available in the MNM. As an example, Fig. 4.3a explicitly shows the set of the edges, which renders the shortest path calculated by the criterion of the minimal coefficient of the hydraulic resistance of the connection channels. Calculating of the resistance as depended on the design parameters is described in [1]. The determination the hydraulic resistance coefficient aids MNM-modelling the generator design in the part which is concerned with forming and estimating the physical implementations involving different sets of the MNM-levels. This part of the MNM-modelling is very important due to its large structure forming influence on the design.

The nodes corresponding to the physical implementations are placed in the MNM-levels and are, in fact, reference decisions to design. As an example, given in Fig. 4.3b is one of the levels of the MNM. The instances of the functional structure class (trigger) represented in Fig. 4.3b are assigned as T1, T2, and T3. The figure shows that these instances are three different operating geometries (the i-dimension). Each of these geometries is represented by four implementations (the j-dimension) differing in relative positions within the reference system of the generator. Provided the structure-class instances are those represented in Fig. 4.3b, possible variants of the generator design could be built with different sets of the MNM-levels (in this case, from one to three – the k-dimension) and, accordingly, would be different in interconnections (lengths, cross-sections, trajectories).

The MNM given in Fig. 4.3a encapsulates a set of the design variants of the generator, with each of the variants modelled by an original path from the input to the output of the network (a set of the nodes and the edges). The path to be selected should meet the criteria of the design quality most advantageously. The influence this path has on the performances is reflected by the weights of the MNM edges. For example, if two paths would represent two different variants of the allocation of the operational elements, the interconnections should be routed differently. The differences would influence such performances of the generator as the frequency, the branching factor, the hydrodynamic resistance, and others. Therefore, the total weights of the two paths should differ in value. If some of the interconnections cannot be implemented because of design and technological factors, or the implementation results in inoperable state of the device, the weight of the corresponding edge is set equal to infinity (given that the best design variant is to provide the minimal total path weight). Thus, the selection of the shortest path is defined as depended on the criteria of estimating the quality of the device being designed. The generator is given to be designed in order to evaluate the maximal frequency response of the operational elements. Therefore, it is this response that is the main criterion of estimating the design. In general, the criteria of estimating the design quality by using the MNM-method may be both elementary and complex (taking into account technical, economic, ergonomic and other characteristics). The MNM shown in Fig. 4.3a is a generalized design model of the generator. This model represents the generator in the form of the set of the structure class instances (nodes) and the operations (edges) on these instances. This set is ordered by the specified (meaningful) characteristics of the generator. The i and j dimensions define, correspondingly, functional and geometrical characteristics of the elements (triggers) at the MNM-levels of the design. The k dimension defines the number of these levels.

As a result of analyzing the MNM, the following is revealed. Allocation of the elements in the only planar level provides a possibility of manufacturing the generator as a detail, i.e. in the form of a monolithic design, without using assembly operations. However, the planar design does not allow the length of the interconnections between the generator stages to be reduced to minimum, which decreases the generator frequency. Therefore, allocation of all the operational elements on the only plane does not provide a possibility of experimentally investigating the extreme frequency response. In addition, the use of the initial operational elements (see Fig. 4.2) in the form of discrete units causes the need for assembly operations. The element designs given in Fig. 4.2 provide the minimal length of the feed-back channels under the condition of the three-level generator design, with the structure class instances of this design outlined with the thick circle lines in Fig. 4.3b. The figure shows that the orientations of the operational elements T1, T2 coincide. The element T3 is rotated by 180° in relation to the two others. Therefore, the j-coordinates of T1 and T2 instances coincide, and the j-coordinate of T3 is different. It should be noted that Fig. 4.3b demonstrates the differences in the i and j coordinates, but it does not determine allocation of the instances to the MNM-levels. As it is mentioned above, the design must be three-level. Hence, the outlined instances are to be allocated to the three different levels, i.e. they are to have different k-coordinates.

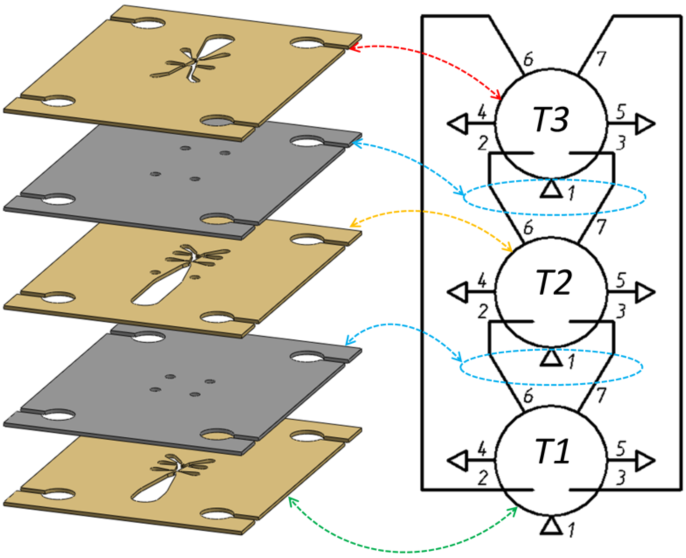

Fig. 4.4. Schematic and assembly diagrams of generator

Fig. 4.4 represents the schematic and assembly diagrams of the generator. The output signal of the first stage is transmitted to the input of the second stage directly, without using mounted connections. The same is truth in relation to the output of the second stage and the input of the third stage. Then, the signal is looped from the output of the third stage to the input of the first stage. The thicknesses of the matching boards are negligible. In this case, the lengths of the feed-back channels between the first and third stages are approximately equal to the thickness of the operational element (200 µm), which allows the design frequency to be considered as close to the maximum. Thus, the design variant represented in Fig. 4.4 is the best one from the view point of investigating the frequency response. The shortest path rendered in Fig. 4.3a in the form of the set of the MNM edges and their end nodes corresponds to this design.

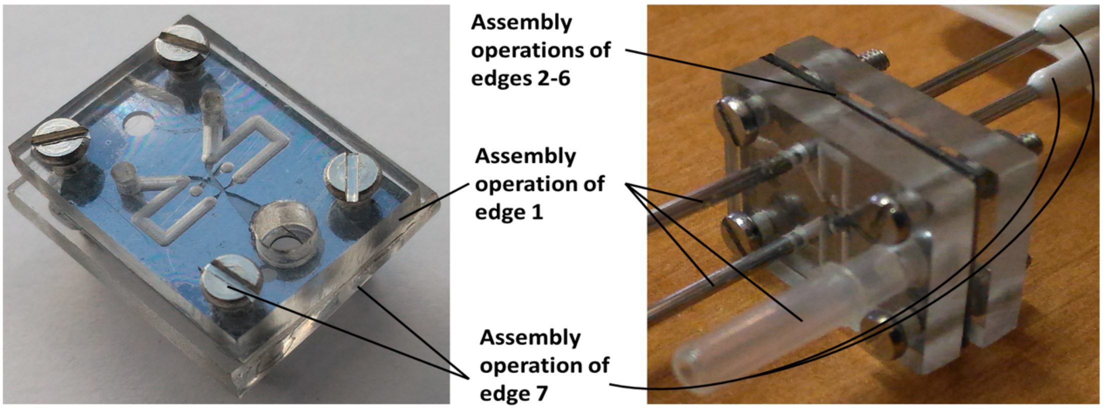

Fig. 4.5. Experimental model of generator

In accordance to the design variant selected by means of the MNM, the experimental model of the three-stage microfluidic generator has been created (see Fig. 4.5). The MNM edge 1 in Fig. 4.3a corresponds to the technological operation of mounting the top cover featuring the in/outlets in order to supply the power and transmit the data signals from the monitoring points of the first stage to a pneumoelectric converter. The further operations are concerned with mounting the three operational elements (edges 2, 4, 6) and their interconnections in the form of matching boards (edges 3, 5). The edge 7 corresponds to the technological operation of mounting the bottom cover, as well as the fixings and the output connectors.

5. CONCLUSION

The undertaken research has given rise to the development of the MNM-method regarding the discrete microfluidics. MNMs are proved by the authors to be applicable to generate and compactly represent sets of the possible variants of microfluidics designs, as well as select the best design variant through calculating the shortest path within the network. Using MNMs, the designs may be synthesized, comprehensively analyzed, variously modified and repeatedly transformed, estimated, and ultimately properly structured. The number of the possible variants and the best design variant may be varied with requirements for the quality of the microfluidic device being created. These requirements may cover multiple aspects concerned with the creating, the exploitation, the repair, and the service. Focused in this paper is the frequency response of the generator. More concretely, it is the maximal performance. This characteristic is provided by the corresponding design decision made by means of the MNM involving the structure and technology aspects. Thus, the results reported in the paper prove both the reasonability and the feasibility of using the MNM-method to create devices of the discrete microfluidics.

REFERENCES

1. Balabanov, A. V., Kasimov, A. M. & Dolgov, I. V. (2018). Method of Calculating Design Parameters of Communication and Throttle Channels of Microfluidic System, *Sensors & Systems*, 5, 39–44.
2. Channon, R. B., Menger, R. F., Wang, W., Carrão, D. B., Vallabhuneni, S., et. al. (2021). Design and application of a self-pumping microfluidic staggered herringbone mixer. *Microfluidics and Nanofluidics*, 25(4), 31, https://doi.org/10.1007/s10404-021-02426-x.
3. Hamilton, E. S., Ganjalizadeh, V., Wright, J. G., Pitt, W. G., Schmidt, H., et. al. (2019). 3D hydrodynamic focusing in microscale channels formed with two photoresist layers. *Microfluidics and Nanofluidics*, 23(11), 122, https://doi.org/10.1007/s10404-019-2293-z.
4. Huang, C., Kuo, Y., Chen, Y., Huang, P., & Lee, G. (2021). A miniaturized, DNA-FET biosensor-based microfluidic system for quantification of two breast cancer biomarkers. *Microfluidics and Nanofluidics*, 25(4), 33, https://doi.org/10.1007/s10404-021-02437-8.
5. Lai, R. L., & Huang, N. (2019). Dimensional analysis and parametric studies of the microwell for particle trapping. *Microfluidics and Nanofluidics*, 23(11), 121, https://doi.org/10.1007/s10404-019-2289-8.
6. Liu, B., Li, M., Tian, B., Yang, X., & Yang, J. (2018). A positive pressure-driven PDMS pump for fluid handling in microfluidic chips. *Microfluidics and Nanofluidics*, 22(9), 94, https://doi.org/10.1007/s10404-018-2112-y.
7. Liu, X., Dong, Z., Zhao, Q., & Li, G. (2020). Optimization of micromilled channels for microfluidic applications using gas-blowing-assisted PDMS coating. *Microfluidics and Nanofluidics*, 24(1), 11, https://doi.org/10.1007/s10404-019-2315-x.
8. Şahin, M. A., Çetin, B., & Özer, M. B. (2020). Investigation of effect of design and operating parameters on acoustophoretic particle separation via 3D device-level simulations. *Microfluidics and Nanofluidics*, 24(1), 8, https://doi.org/10.1007/s10404-019-2311-1.
9. Shum, C., Rosengarten, G., & Zhu, Y. (2017). Enhancing wicking microflows in metallic foams. *Microfluidics and Nanofluidics*, 21(12), 177, https://doi.org/10.1007/s10404-017-2018-0.
10. Wu, J., Cui, Y., Xuan, S., & Gong, X. (2018). 3D-printed microfluidic manipulation device integrated with magnetic array. *Microfluidics and Nanofluidics*, 22(9), 103, https://doi.org/10.1007/s10404-018-2123-8.
11. Yin, Z., & Zou, H. (2017). Multilayer patterning technique for micro- and nanofluidic chip fabrication. *Microfluidics and Nanofluidics*, 21(12), 174,https://doi.org/10.1007/s10404-017-2013-5.