A Concept Towards Pressure-Controlled Microfluidic Networks

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***Abstract*—Droplet-based microfluidic networks interconnect multiple microfluidic modules which allow to process (e.g., mix, sort, heat, incubate) so-called *payload* droplets (i.e., droplets containing a biological sample) on a single microfluidic chip. Inside such networks the path of a droplet and, thus, the module which processes it, can be controlled by microfluidic switches. Thus far, these switches are realized by injecting additional control droplets into the network which allow to trigger the switching mechanism by solely exploiting passive hydrodynamic effects. While this eliminates the need of expensive components such as valves, this droplet-controlled switching concept is very sensitive and already slight deviations, e.g., in the control droplet injection could lead to incorrectly triggered switches. In this work, we address this issue by proposing a new concept of *pressure-controlled networks* which omit the control droplets (and their drawbacks) and, instead, use a single pump in order to drive the switches. Using design automation expertise together with established models, we derive a corresponding blueprint which realizes this idea for a specific network architecture. Simulations based on established methods and design tools confirmed the suitability of the proposed pressure-controlled networks.**

I. INTRODUCTION

Microfluidic devices are widely used in domains such as medicine, (bio-)chemistry, biology, pharmacology, etc. and aim to minimize, integrate, automate, and parallelize bulky and expensive lab operations on a single chip – often also called *Lab-on-a-Chip* (LoC) [1], [2]. This miniaturization provides several advantages compared to conventional methods, since it requires significantly less reagent and sample volumes (e.g., relevant for restricted or costly reagents), facilitates shorter reaction times and, hence, higher throughput of numerous laboratory activities [3].

Especially the LoC-platform of droplet-based microfluidics is a promising technology [3], [4]. Here small droplets (which confine certain biochemical samples and are called payload droplets in the following) are transported by a immiscible fluid (called continuous phase) inside closed micro-channels. The droplets and, thus, the samples inside them, can be used to conduct specific experiments/operations such as mixing, heating, incubation, etc. inside the LoC [5]. However, such LoCs typically perform these operations in a predefined way and, thus, lack in flexibility when different operations should be performed for different droplets.

Here *microfluidic networks* come into play, which allow to control the paths of droplets inside the network and route them towards specific components/modules, where they get finally processed [6], [7], [8]. This enhances conventional droplet-based LoCs and allows for a much better flexibility [9]. In order to manipulate and route droplets inside a microfluidic network, so-called microfluidic switches are required [10], [11]. These switches allow to change the path of a droplet and, thus, are essential for the controllability of the droplets inside the network.

Thus far, the common way of controlling such a switch is to inject additional control droplets into the network which, compared to payload droplets, do not contain any biochemical samples [10], [12]. Instead, these control droplets are only used to drive the switching mechanism by exploiting passive hydrodynamic effects, i.e., the effect that a droplet increases the hydrodynamic resistance of the channel if it is present [13]. This has the big advantage that no active components such as expensive valves are required to control a switch. On the other hand, also this solution has its challenges. In fact, the droplet-controlled switching concept depends on various factors and is rather sensitive – requiring a dedicated and precise injection procedure. Already slight deviations could lead to incorrectly triggered switches – making droplet-based microfluidic networks a highly sensitive platform.

In this work, we aim to address this problem by proposing an alternative switching concept for microfluidic networks while still aiming for a network which is as simple as possible and does not require expensive components like valves. To this end, we propose a *pressure-controlled microfluidic network* which allows to completely omit the control droplets (as well as the challenges coming with them) and, instead, uses an additional *control pump* to drive the switching mechanism. This is achieved by introducing a *control-network* which connects the control pump with the switches and ensures the correct behavior of them. In order to validate this new concept, we utilize our design automation expertise together with common models to derive a blueprint that realizes pressure-controlled microfluidic networks. Based on this blueprint, a corresponding design can automatically be generated. Simulations based on methods and design tools (which have been used for establishing other microfluidic networks in the past) confirmed the suitability of the proposed solution.

The findings eventually show a path towards microfluidic networks that still allow to flexibly route payload droplets along different paths, but do not suffer from the disadvantages caused by the control droplets needed thus far. By this, we utilize design automation expertise to provide the basis for the development of better microfluidic networks. Discussions on how the microfluidic community can materialize these findings (in particular with respect to manufacturing and using the newly proposed solution) complete our considerations.

The remainder of this work is structured as follows: In the next section, we discuss the challenges of microfluidic networks and review the disadvantages of the droplet-controlled switching concept in more detail. In Sec. III, we introduce the proposed pressure-controlled switching approach and discuss how the correspondingly needed control-network can be realized. Afterwards, we describe how to derive a working network blueprint from these concepts in Sec. IV and validate its feasibility in Sec. V. Finally, we discuss how these findings

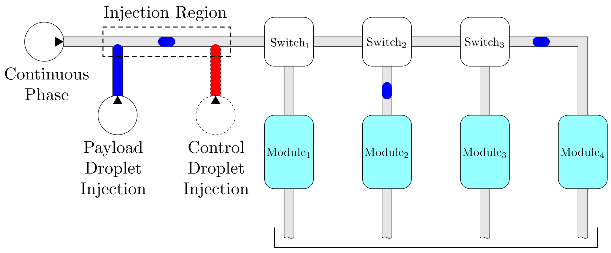
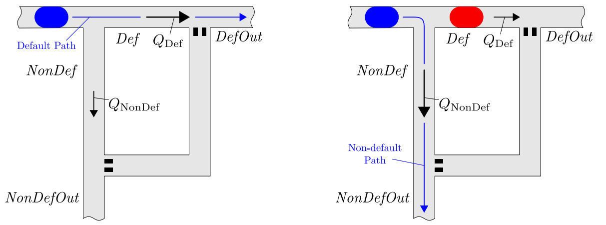


Fig. 1: Microfluidic network



(a) OFF-state: $Q_{\text{Def}} > Q_{\text{NonDef}}$ (b) ON-state: $Q_{\text{Def}} < Q_{\text{NonDef}}$

Fig. 2: Droplet-controlled switch

can be materialized by the microfluidic community in Sec. VI, before the paper is concluded in Sec. VII.

II. Microfluidic Networks and Their Challenges

Droplet-based microfluidic networks interconnect multiple microfluidic components/modules which allow to process (e.g., mix, sort, heat, incubate) so-called *payload* droplets (i.e., droplets containing a biological sample) on a single microfluidic chip. The basic idea of them is illustrated in Fig. 1: Here, droplets are injected into a continuous phase and, afterwards, travel in it through different channels that lead to the respective modules. The network itself is used to explicitly control the destination of each payload, i.e., to control which paths the droplets take. This way, a microfluidic platform results which is flexible and allows the user to route droplets towards specific modules – realizing different operations for different payload droplets on a single chip.

In order to realize this controlability, so-called *microfluidic switches* are employed. As the name suggests, they are able to *switch* whether a droplet enters a *default channel Def* (if the switch is in an *OFF-state*), or whether it enters a *non-default channel NonDef* (if the switch is in an *ON-state*). Thus far, the established way of realizing such a switch in microfluidic networks is to use further droplets called *control* droplets [10], [12], [11]. They do not contain any biological samples and are only used to control the switching mechanism. Those additional droplets increase the hydrodynamic resistance of the channels they are currently in [13] and, by this, can be utilized to temporarily put the switch in an ON-state.

Example 1. *Let's consider Fig. 2 and assume that no droplet is present inside the channel* Def *(i.e., the switch is in the OFF-state). Then, the flow rate Q_{Def} of this channel is larger than the flow rate Q_{NonDef} of the channel* NonDef, *i.e., $Q_{Def} > Q_{NonDef}$. Hence, a droplet arriving at the switch is routed towards the channel* DefOut, *since a droplet always flows into the channel with the highest instantaneous flow rate. In contrast, when a droplet (now, assumed to be a control droplet) is present inside the channel* Def *(i.e., the switch is in the ON-state), then the additional hydrodynamic resistance of the droplet changes the flow rates in such a way that now $Q_{Def} < Q_{NonDef}$ holds. As a result, a second droplet (assumed to be the payload droplet) closely following the first on is now routed towards the channel* NonDefOut.

Such passive hydrodynamic effects are well established and have successfully been utilized in applications such as [5]. However, when the network becomes more complex, e.g., when multiple switches are connected in series, this concept reaches its limits. In particular, the following challenges become pressing:

Correct Droplet Distance: A switch is only activated (i.e., in the ON-state) if a control droplet occupies the channel *Def* and, by this, increases its resistance. Then, a following payload droplet gets routed into the channel *NonDef*. However, the moment the control droplet leaves its channel, the switch falls back into the OFF-state and the payload droplet is routed again into the channel *Def*. Because of this, it is essential that the distance between the control droplet and the payload droplet are perfectly adjusted (i.e., that the droplets are injected into the network with proper distance). However, depending on the complexity of the network (e.g., when more switches are present in the network), it can be very difficult to determine the correct droplet distance. It even might be impossible at all due to an inappropriate network design.

Droplet-on-Demand: Even if the proper droplet distances at the input channel are known, the droplets still must be injected at the right times to establish them. This requires a dedicated droplet-on-demand process. Since slight differences of the droplet distances at the input channel will likely lead to large differences at the switch, this droplet-on-demand process has to be very precise, which usually requires a lot of experience and effort [14].

Droplet Resistance: As already mentioned before, the hydrodynamic resistance of a droplet plays an important role in the droplet-controlled switching mechanism. In fact, the whole design of the switch (and also the network) needs to be designed in such a way that it behaves as expected with the assumed droplet resistance. However, this value depends on several factors and often cannot be predicted as accurately as needed. Hence, inaccurate droplet resistances could lead to incorrectly working networks, which would trigger additional and time consuming design iterations.

Overall, these challenges make droplet-controlled microfluidic networks hard to design and particularly difficult to control.

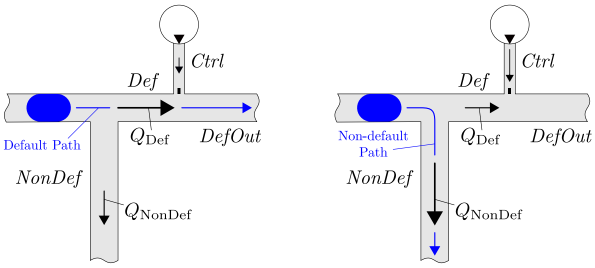
III. Pressure-Controlled Networks

In order to overcome the drawbacks of droplet-controlled networks, we propose an alternative switching concept which does not rely on control droplets anymore. Instead, we aim for controlling the paths of droplets through additional pumps which drive the switching mechanism. In this section, we first sketch the main idea and basic concepts we are utilizing for the proposed idea. Afterwards, we illustrate how, based on that, a new microfluidic network architecture can be derived.

A. Main Idea and Basic Concepts

The basic idea of the proposed switching concept is illustrated in Fig. 3. Here, an additional continuous phase is injected into the switch through a control channel *Ctrl*, which is connected to a pump. Depending on the actual pressure/flow rate of this pump, droplets get either routed into the *Def* or *NonDef* channel, respectively.

Example 2. *Let's consider Fig. 3 and assume that the newly added pump produces a very small flow rate. This hardly*



(a) OFF-state: $Q_{\text{Def}} > Q_{\text{NonDef}}$ (b) ON-state: $Q_{\text{Def}} < Q_{\text{NonDef}}$

Fig. 3: Pressure-controlled switch

affects the flow rates of the original channels and, hence, results in $Q_{Def} > Q_{NonDef}$. Consequently, the switch is in the OFF-state and a droplet arriving at the switch would be routed into the default path towards the channel DefOut. *In contrast, if the flow rate of the pump increases, then the flow rate Q_{Def} automatically becomes smaller while Q_{NonDef} gets larger. Eventually, this will lead to a point where $Q_{Def} < Q_{NonDef}$ is satisfied. Hence, the switch is in the ON-state and a payload droplet arriving at the switch would be routed into the non-default path towards the channel* NonDef. *By this, the pump becomes a substitute for the control droplet of the droplet-controlled approach of Ex. 1.*

While this concept still allows to change the path of the payload droplet, it eliminates the drawbacks of the droplet-controlled switches, since no dedicated droplet distances need to be established anymore and, therefore, the precision for the droplet-on-demand process is not that crucial. Additionally, the value for the correct droplet resistance is not as relevant as in the droplet-controlled switch, because the switching mechanism in pressure-controlled networks is only slightly affected by this factor and, thus, can be omitted when designing such networks.

However, realizing this idea in a naive fashion where, for each switch, an own dedicated pump is applied obviously would easily become infeasible. Despite the massive overhead caused by the resulting high number of pumps, this would lead to a complex system where the effects of the different pressures and flow rates onto the whole microfluidic system would be hard to comprehend and to control. This very likely is also the reason why, although rather obvious, a pressure-controlled mechanism for microfluidic switches has not been considered intensely in microfluidics yet (and, instead, droplet-controlled switches with the drawbacks discussed above remained the state of the art until today). Hence, to really bring the proposed idea to life, it needs to be further extended and incorporated into a working architecture.

B. Control Networks and Resulting Architecture

In order to realize the idea and concepts proposed above and, at the same time, get rid of the severe disadvantages, the number of pumps has to be reduced. To this end, we propose a solution, which is able to control the switching mechanism inside a network with only one single pump – the so-called *control pump*. This pump is connected to the control channel *Ctrl* of *all* switches inside a network. That is, a single pump is used to drive all switches, i.e., to set all switches to the OFF- or ON-state. To explicitly control this behavior, i.e., to realize the respectively needed flow rates as illustrated in Ex. 2, a *control-network* is utilized. In combination with the main-network, this finally leads to *pressure-controlled networks*.

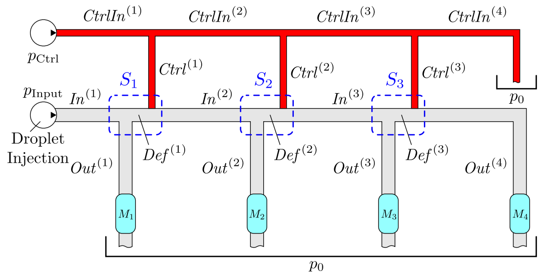


Fig. 4: Pressure-controlled network

In the following, we describe the concepts of such a network using the architecture shown in Fig. 4 as a representative (however, the proposed concepts can, in general, also be applied to other network architectures). Here, the main network (marked in gray) has one input channel to inject the payload droplet and multiple output channels, typically leading to different modules M_i. Furthermore, the path of the payload droplet and, thus, the module that processes the droplet can be controlled by the switches S_i. These switches are connected with the control network (marked in red) which is driven by the control pump. If the control pump and, thus, the switches are in the OFF-state, then a droplet arriving at a switch would flow into the default channel $Def^{(i)}$ towards the next switch. In contrast, when a droplet reaches a switch during the ON-state of the control pump, then it gets routed into the corresponding output channel $Out^{(i)}$.

Example 3. *Let's assume a payload droplet should be routed into the third output channel* $\text{Out}^{(3)}$ *towards the module* M_3. *Then, the third switch* S_3 *must be in the ON-state when the droplet arrives at it, while the first two switches must be in the OFF-state when the droplet passes them. In other words, the control pump is only allowed to activate the switches (i.e., set them to the ON-state) when the payload droplet is between the second and third switch, i.e, in channel* $\text{In}^{(3)}$. *Once the droplet is inside the output channel* $\text{Out}^{(3)}$, *the control pump can be put into the OFF-state again.*

While this conceptually allows to route the payload droplet into the desired path and towards the corresponding module, there are still some challenges left which need to be addressed in order get a pressure-controlled network that works as expected. In particular, how to choose the channel dimensions in order to satisfy the conditions establishing an OFF- or ON-state is highly non-trivial but necessary for a properly working switching mechanism inside the network. How to derive these channel dimensions and, by this, generate a working blueprint for a pressure-controlled network is described in the next section.

IV. Determination of a Blueprint

In this section, we describe the dimensioning process for the pressure-controlled network discussed above (cf. Fig. 4) and, by this, supply designers with a network blueprint, which is capable of routing payload droplets to desired modules. To this end, a physical model is required which describes the behavior of microfluidic networks and operates as the basis for the dimensioning process. Hence, in the following we first briefly introduce the one-dimensional (1D) analysis model before, based on that, the dimensioning process is described in detail.

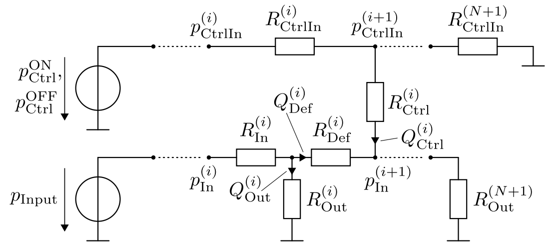


Fig. 5: Equivalent electrical network

A. 1D-Analysis Model

The 1D-analysis model can be applied in scenarios, where a fully developed, laminar and incompressible flow (usually at low Reynolds numbers) occurs, which is typically satisfied in microfluidic networks. This allows to describe the flow inside a microfluidic channel by Hagen-Poiseuille's law [15]

$$\Delta p = Q \cdot R \ , \tag{1}$$

where Q is the volumetric flow rate, R the hydrodynamic resistance, and Δp the pressure drop along the channel. The hydrodynamic resistance depends on the channel dimensions (i.e., length l, width w, and height h) as well as the dynamic viscosity of the continuous phase μ_{C} and can be computed (for rectangular channels with a section ratio $h/w < 1$) by [16]

$$R\left(l, w, h, \mu_{\text{C}}\right) = 12 \left[1 - \frac{192h}{\pi^5 w} \tanh\left(\frac{\pi w}{2h}\right)\right]^{-1} \frac{\mu_{\text{C}} l}{w h^3} \ . \tag{2}$$

Additionally, a droplet with the length l_{D} increases the resistance of the segment it occupies inside a channel by $b = 2 \ldots 5$ times [13]. Hence the resistance of a droplet can be computed by

$$R_{\text{D}} = b \ R\left(l_{\text{D}}, w, h, \mu_{\text{C}}\right) \ . \tag{3}$$

The 1D-analysis model can now be utilized to describe the behavior of a microfluidic network by representing the channels inside the network with their corresponding hydrodynamic resistances, leading to a so-called *equivalent electrical network* [17]. By applying Kirchhoff's laws to this network, the pressure drops as well as the flow rates of the channels can be obtained, which are essential for the upcoming dimensioning process.

Example 4. *Let's consider the pressure-controlled network in Fig. 4. Converting all channels of this network as well as the pumps into their electrical counterparts results in the equivalent electrical network illustrated in Fig. 5, where* N *represents the number of switches and the index is defined as* $i = 1, \ldots, N$*. For simplicity, we also included the hydrodynamic resistance of the modules* M_i *inside the resistances for the output channels* $R^{(i)}_{Out}$*.*

B. Network Dimensioning

Having the 1D analysis model, we can now describe how the network blueprints can be generated. As it can be observed from Fig. 5, this basically requires the determination of precise values for all $5N + 2$ channel resistances as well as all 3 pump pressure values (namely, the input pressure p_{Input} and the pressures $p^{\text{OFF}}_{\text{Ctrl}}$ and $p^{\text{ON}}_{\text{Ctrl}}$ for the control pump during the OFF- and ON-state, respectively). A majority of these values can be chosen by the designer's needs, while other values are directly derived from certain conditions which ensure the desired behavior of the network.

In order to obtain these values, we first introduce the so-called *switching factor*

$$q^{(i)}_{\text{S}} = \frac{Q^{(i)}_{\text{Out}}}{Q^{(i)}_{\text{Def}}} \ , \tag{4}$$

which is the ratio between the flow rate of the channels *Out*$^{(i)}$ and *Def*$^{(i)}$ inside the i^{th} switch (cf. Fig. 5). As already mentioned before, when the control pump is in the OFF-state[1], a payload droplet should always flow along the default path of a switch and, thus, the condition $Q^{(i)}_{\text{Def}} > Q^{(i)}_{\text{Out}}$ must hold. During the ON-state on the other hand, the payload droplet should flow into the output channel *Out*$^{(i)}$, which implies that $Q^{(i)}_{\text{Def}} < Q^{(i)}_{\text{Out}}$ must be satisfied in each switch. Hence, when utilizing the switching factor, these two conditions can be reformulated as

$$q^{(i),\text{OFF}}_{\text{S}} < 1 \text{ and} \tag{5}$$

$$q^{(i),\text{ON}}_{\text{S}} > 1 \ , \tag{6}$$

where $q^{(i),\text{OFF}}_{\text{S}}$ and $q^{(i),\text{ON}}_{\text{S}}$ are the switching factors for the i^{th} switch in the OFF- and ON-state, respectively. Overall, when the switching mechanism of the pressure-controlled network should work as expected, then the conditions stated in Eqs. (5) and (6) must be satisfied. Therefore, the first step in the dimensioning process is to specify these values accordingly.

In the next step, the resistances of the channels inside the main- and control-network are computed. To decouple the dimensioning process of these two network parts, we assume that, during the OFF-state of the control-network, the flow rates through the control channels are zero, i.e., $Q^{(i)}_{\text{Ctrl}} = 0$. In fact, this allows to dimension the main-network completely independently from the control-network. Usually, the values for the input pressure and the resistances in the main-network have to be defined in such a way that the condition from Eq. (5) is satisfied for all switches during the OFF-state. However, since the values for $q^{(i),\text{OFF}}_{\text{S}}$ are already defined by the designer, not all resistances in the main-network have to be specified. More precisely, when N switches are present, then the values of N resistances can be directly derived from the already known values of $q^{(i),\text{OFF}}_{\text{S}}$. This can be accomplished by establishing an equation system utilizing Kirchhoff's laws[2].

Once all channel dimensions of the main-network are obtained, the channel resistances of the control-network can be computed (except the values for $R^{(i)}_{\text{Ctrl}}$ which are derived in a later step). When we assume that the input pressure of the control pump during the OFF-state $p^{\text{OFF}}_{\text{Ctrl}}$ is defined by the designer, then $N + 1$ values for the resistances $R^{(i)}_{\text{CtrlIn}}$ must still be obtained. However, since we assumed $Q^{(i)}_{\text{Ctrl}} = 0$ during the OFF-state, we also know the N values for the pressures $p^{(i+1)}_{\text{CtrlIn}} = p^{(i+1)}_{\text{In}}$ (cf. Fig. 5). As a result, only one value of the $N+1$ resistances has to be specified, while all other resistances can be derived by an equation system which can be established with the help of Kirchhoff's laws again.

At this point, all resistances and pump pressures are already defined, except the N control resistances $R^{(i)}_{\text{Ctrl}}$ and the pressure for the control pump during the ON-state $p^{\text{ON}}_{\text{Ctrl}}$. However, since the N values for the switching factors during the ON-state

[1]Please note that this does not necessarily mean the pump produces no pressure.

[2]Please note, the resistances which should be derived must be chosen in such a way, that the resulting equation system is solvable.

TABLE I: Basic parameters

μ_c	V_D	h	w
$5\,\text{mPa s}$	$4.5\,\text{nL}$	$30\,\mu\text{m}$	$100\,\mu\text{m}$

TABLE II: Channel dimension

		i^{th} Switch				
		1	2	3	4	5
Defined:						
$q_S^{(i),\text{OFF}}$		1.1	1.1	1.1	1.1	1.1
$q_S^{(i),\text{ON}}$		0.9	0.9	0.9	0.9	0.9
p_{Input} in Pa	1000					
$p_{\text{Ctrl}}^{\text{OFF}}$ in Pa	700					
$p_{\text{Ctrl}}^{\text{ON}}$ in Pa	1100					
$l_{\text{Out}}^{(6)}$ in µm	10000					
$l_{\text{CtrlIn}}^{(6)}$ in µm	1523					
$l_{\text{In}}^{(i)}$ in µm		1000	1000	1000	1000	1000
$l_{\text{Def}}^{(i)}$ in µm		100	100	100	100	100
Derived:						
$l_{\text{Out}}^{(i)}$ in µm		3243	3840	4974	7129	11222
$l_{\text{CtrlIn}}^{(i)}$ in µm		1100	2089	1099	579	305
$l_{\text{Ctrl}}^{(i)}$ in µm		3903	4892	4891	4370	3575
$w_{\text{Ctrl}}^{(i)}$ in µm		50	63	61	48	50

$q_S^{(i),\text{ON}}$ are already defined by the designer, only one element ($p_{\text{Ctrl}}^{\text{ON}}$ or a resistance $R_{\text{Ctrl}}^{(i)}$) has to be specified. Again, all other values can be derived from a corresponding equation system, which is established by utilizing Kirchhoff's laws.

Since all values for the resistances are now available, the actual dimensions of the channels (i.e., length, width, and height) can be easily derived by utilizing Eq. (2). Usually this is done by computing the length of the channels, while the width and height are fixed values inside a network and are mostly equal for all channels. Overall, this dimensioning process allows a flawless definition of all elements inside the network, while the switching conditions stated in Eq. (5) and (6) are also satisfied.

V. Generation & Validation

In this section, we demonstrate the concept of pressure-controlled microfluidic networks as well as validate the proposed network blueprint and the corresponding dimensioning process. To this end, we use an example network (similar to Fig. 4), which consists of 5 switches and, therefore, 6 output channels. More precisely, we generate the channel dimensions according to Sec. IV-B and, afterwards, validate the switching mechanism of the network by means of simulations. Additionally, we discuss the steps that still need to be done to implement the new network concept.

A. Generation

Using the methods described in Section IV, the channel dimensions and pressure values of the corresponding network blueprint can be easily determined. To this end, the designer has to provide the basic parameters of the intended realization, i.e., the height h and the width w of all channels, as well as the properties of the used fluids, namely, the viscosity of the continuous phase μ_C and the volume V_D of a payload droplet. The values used in this demonstration here are provided in Tab. I. Together with the actual length of a channel, these values can be used to compute the channel resistance by utilizing Eq. (2). This also works vice versa, i.e., having the resistance of a channel, the length of it can be derived. Therefore, we will only deal with the channel lengths in the following and not with the actual resistances, since it is more intuitive for the reader.

According to Sec. IV-B, most of the channels inside the main-network can be chosen accordingly to the designers needs, while the remaining channels are derived from certain conditions during the OFF- and ON-state. Overall, the first half of Tab. II shows the values the designer defined, namely the switching factors $q_S^{(i),\text{OFF}}$ and $q_S^{(i),\text{ON}}$ (which have to satisfy the conditions from Eqs. (5) and (6), respectively), the different pump pressures p_{Input}, $p_{\text{Ctrl}}^{\text{OFF}}$, and $p_{\text{Ctrl}}^{\text{ON}}$, the channel lengths $l_{\text{In}}^{(i)}$ and $l_{\text{Def}}^{(i)}$ for each switch, as well as the length of the last channels $l_{\text{Out}}^{(6)}$ and $l_{\text{CtrlIn}}^{(6)}$ inside the main- and control-network, respectively. The second half of the table shows the remaining channel dimensions, which were derived from the already defined values according to Sec. IV-B. Please note that the width of each control channel $w_{\text{Ctrl}}^{(i)}$ is different from the width w of the other channels. The reason for this is that the lengths of these channels $l_{\text{Ctrl}}^{(i)}$ should have a certain value in order to get a properly looking network. However, the resistances also have to match the derived values and, thus, the width of these channels must be varied accordingly.

Overall, all these channel dimensions eventually describe a network that realizes the proposed concept of pressure-controlled microfluidic networks.

B. Validation

To confirm the suitability of the obtained design, i.e., to show that the proposed concept actually works, we finally simulated the resulting design using the simulator from [18]. This tool is publicly available, based on established methods as well as design tools such as [19], [20], and has recently been utilized to confirm the suitability of other microfluidic networks such as [21]. To this end, the simulator is initialized with the values from Tab. I and Tab. II.

In the following, we present the results of 6 different scenarios, where in each scenario a payload droplet gets routed into one of the 6 output channels *Out*$^{(i)}$. As described in Ex. 3, this can be achieved, by putting the control pump into the ON-state when the payload droplet reaches the channel right before the corresponding switch (i.e., channel *In*$^{(i)}$). Once routed into the correct output channel, the control pump can then be put back into the OFF-state again. Hence, we instruct the simulator to manage this properly before we start the simulation.

While a video of the simulation results of all six scenarios can be found under the link https://youtu.be/15ZoJ4RN_pU, an exemplary simulation screenshot is provided in Fig. 6. The screenshot sketches the entire network (with red channels representing the control-network and gray channels representing the main-network) as well as the moment right before the payload droplet (shown as blue dot) is routed into the third output channel *Out*$^{(3)}$. In this moment, the switches are already in the ON-state (indicated by the ON label at the input of the control-network) and the switching factor of the third switch yields $q_S^{(3),\text{ON}} = 1.190$. Hence, the condition from Eq. (6) is satisfied and, as a result, the payload droplet will be routed into the output channel *Out*$^{(3)}$.

Overall all these simulations confirmed that the design resulting from the blueprint indeed work as intended and realize the concept of pressured-controlled microfluidic networks.

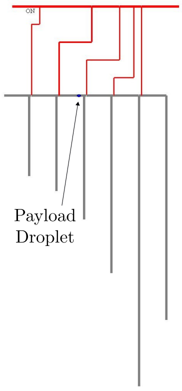


Fig. 6: Simulation screenshot

VI. Benefits for the Microfluidic Community

The considerations from above showed that pressure-driven microfluidic networks do provide a promising alternative to the currently used droplet-based microfluidic networks. By this, we used design automation expertise to provide the basis for the development of better microfluidic networks. We strongly believe that these findings (and the benefits they promise) can now be materialized by the microfluidic community.

More precisely, the simplicity in the design, coupled with the fact that there are no electrical on-chip components required, makes the proposed idea feasible for various well-known microfluidic technologies. Considering the geometries we have used for our simulation results, the microfluidic chips could be fabricated using the state-of-the-art PDMS soft lithography or even some of the rapid prototyping technologies that rely on laser engraving or even 3D printing. In order to supply the liquids into the chips, a highly automated pressure controller would be required (simple syringe pumps cannot be used in this case). The lower the response time of the controller, the more precise the controller over the switching process would be. The state-of-the-art pressure controllers currently offer a response time of approx. $9\,\mathrm{ms} - 40\,\mathrm{ms}$, which is more than sufficient for conducting experiments to validate the proposed concept.

Overall, the concepts proposed in this work seem very feasible for a number of microfluidic technologies – motivating a deeper consideration to be conducted by the microfluidic community. A first step obviously includes the physical realization and validation of the concepts. Afterwards, investigations towards possible applications of this concept in the medical or (bio-)chemical domain are logical next steps. For all these endeavors, the findings in this work provide an ideal basis.

VII. Conclusion

In this work, we proposed pressure-controlled microfluidic networks as an alternative for a droplet-based switching concept. To this end, we first discussed the basic concepts of a corresponding pressure-controlled switching mechanism and, based on that, show how a blueprint realizing this concept can be determined for a specific network architecture. Simulations based on methods and design tools (which have been used for establishing other microfluidic networks in the past) confirmed the suitability of the proposed solution.

By this, a very promising alternative for microfluidic networks is proposed which still allows to flexibly route payload droplets along different paths in a microfluidic network, but does not suffer from the disadvantages caused by the control droplets needed thus far. The results from this work motivate a deeper consideration of this concept which, besides a physical realization of the proposed concepts, also includes the utilization of pressure-controlled microfluidic networks in medical or (bio-)chemical applications.

Acknowledgments

This work has partially been supported by the FFG project AUTOMATE (project number: 890068) as well as by BMK, BMDW, and the State of Upper Austria in the frame of the COMET Programme managed by FFG.

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