Investigating Arrangement of Composite Drops in Two-Dimensional Microchannels Using Multiagent Simulations: A Design Perspective

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ABSTRACT: Drops can self-organize in two-dimensional (2D) microchannels to form ordered arrangements. Design of microchannels that result in a particular pattern of drops for a specific purpose is difficult and nonintuitive due to the inherent complexity of the drop dynamics. We address the problem of understanding the arrangement of composite drops inside a microchannel. A multiagent modeling strategy that was recently proposed by us is employed to understand this complex design problem. We consider the design of a drop−drop contactor that results in an equal mix of A and B. We seek to find the inlet sequence of drops A and B that would result in the maximum contact between A and B in the ordered arrangement. We find that intuition-based results work well only for a single layer arrangement of drops. We attribute this anomalous behavior to the symmetry breaking instability of the drop patterns in these 2D microchannels. From the dynamic simulations, we understand why certain inlet sequences perform better than others. We then discuss the use of the simulation strategy in several possible design problems.

1. INTRODUCTION

Drop microfluidics allows the discretization of one of the phases (drop) in another continuous phase. This two phase flow finds applications in several fields such as reaction engineering, chemical and biological analysis, emulsion science,1−10 drug discovery1 and synthesis,11−14 and solute extraction.15,16 The drops can be merged,17−19 split,20−22 sorted,23−25 and incubated26−28 inside the microchannels through active control strategies3 or passive design.29−31 The tremendous application potential for drop-based microfluidics can be realized if efficient design strategies for optimized performance are available. Understanding the movement of drops inside the channel becomes crucial in device design. Presence of a drop complicates the flow fields making the flow problem nonlinear and sometimes multiscale, which renders the solution to the drop flow problem computationally demanding. However, from a design perspective, a simple model is preferred because it allows its incorporation into an optimization routine for generating designs for specific objectives.21 Drop flows in one-dimensional (1D) microchannel where the drop size is of the order of the channel diameter have been modeled using a simple network model.32−35

The simplicity of the model allowed its incorporation in a model predictive control routine36−38 for active synchronization and sorting of drops and genetic algorithm-based optimization routine39−41 for passive design of ladder networks to expand flip, contract, or synchronize drops. However, such studies are not currently available for two-dimensional (2D) channels.

One could conceive of several fascinating applications for 2D channels if rational design approaches exist. As an example, one of the applications in colloidal science could be the formation of anisotropic particles through self-assembly of drops in a 2D microchannel.42−44 2D Channels have advantages over 1D channels for such applications, where a set of parallel 1D channels can be replaced with one 2D channel, thereby increasing the operations performed per unit area resulting in a reduced footprint device. However, design and control strategies for 2D microchannels that connect the geometry and the operating conditions to the flow behavior of drops inside the channel are not well-studied in literature. A tractable computational approach to simulate drop movement inside 2D channels would seed new ideas for device designs and novel applications. On the other hand, drop dynamics in a 2D microchannel can be complex; the interactions between individual entities (drops) often result in emergent behavior, like-ordered pattern formation,45−47 propagated coalescence,48−49 dynamic clustering, and long-range dipole interactions.50−52 This is due to the nonlinear, multiscale nature of the hydrodynamic interactions between drops, which also makes it almost impossible to formulate a simple model like the network model as in the case of a 1D channel. Recently, we proposed a computationally elegant simulation strategy53 based on a simple force balance on discrete drops to understand the noncoalescing patterns of drops in a symmetric 2D diverging-converging microchannel54 (briefly presented in section 2).

In this article, we demonstrate how the collective emergent behavior of drops can make design choices nonintuitive. A design example (section 3) is discussed, where a symmetry breaking instability in a drop assembly affects design choices drastically (section 4 and 5). We strongly believe that a simulation framework such as the one proposed in this paper can be a valuable aid in understanding dynamic drop pattern formation as a function of the operating conditions and channel geometry and help researchers in designing devices that operate optimally. To highlight this point, we discuss the application of drop microfluidics in the areas of particle synthesis where we demonstrate the use of 2D channels for anisotropic particle
synthesis (section 6) and flow cytometry where the arrangement of drop dye lasers can be passively controlled to result in a low footprint device (section 7).

2. MODELING STRATEGY

2.1. Multiagent Framework (MAS).

\[ \sum \vec{F} (\vec{U}) = 0 \]
\[ \frac{d\vec{x}}{dt} = \vec{U} \]

In our multiagent simulation framework, drops are regarded as individual entities or agents inside the microchannel system where they interact with other agents and the surroundings. The interactions are through the various forces generated in the system. These could be, for example, drop—drop, drop—boundary forces, and so on. Such interactions that are significant are modeled and collectively called the interacting drop traffic models in our work. The principle interactions considered are the drop—continuous phase, drop—drop, and the drop—boundary interactions (see Table 1). The phenomenological nature of these models give rise to tuning parameters, which are functions of the system properties such as viscosities, densities, and interfacial tension. These interacting drop traffic models are incorporated in a multiagent simulation framework that solves Newton’s second law of motion along with the creeping flow approximation as shown in eq (1) for all the drops, to estimate the time evolution of the velocity and position of each of those drops inside the microchannel.

The MAS is validated using the experiments of Jose and Cubaud,28 where organization of drops is studied in a tilted-square shaped microchannel as shown in Figure 1a. Though the models for forces are simple, the MAS is able to capture the dynamic pattern formation of drops to a considerable extent: one can observe the match in the ordered arrangement of drops in Figure 1 (panels b and d). We are able to show how the numbers of drops increase as they crowd in the microchannel and later, as drops start to exit, a steady state is obtained where the number of drops inside the channel become a constant. Our simulation was able to predict the closest distance between drops in the ordered assembly, as observed in experiments,28 as a function of the operating conditions such as flow rates of the drop phase. The velocities of the drops obtained through simulation also matched the experimentally measured drop velocities. Other intricate details like the layering pattern, the way in which the drops layer near the entrance, and the breaking pattern, the manner in which drops break away from the ordered assembly to exit the 2D microchannel, were nicely captured by the MAS. For more detail on the models and quantitative validation of the results, interested readers are referred to Danny and Rengaswamy.38 Other experimental systems in the literature report dipole and quadrupole interactions that are very different from the ones that are of relevance in the experiments of Jose and Cubaud. The MAS is versatile enough to allow the incorporation of such additional force terms in the formulation. However, in this article, for the sake of simplicity, we choose to focus on applications where our model with the original force terms is adequate.

2.2. Motivation for the Current Study. The models are used to understand drop pattern formation in a 2D diverging converging microchannel (see Figure 1) similar to the one used by Jose and Cubaud in their experiments. Drops are equally spaced prior to entry into the microchannel. Drops slowdown in the diverging section and accelerate in the converging section of the microchannel. For high initial spacing, the drops form a single layer. With a decrease in the spacing before entry, drops experience layering instability due to the crowding of the drops in the diverging section of the channel and multiple layers (see Figure 1, panels a and c) are formed. The multiagent simulation is able to predict the dynamic pattern formation of drops inside the microchannel as a function of the inlet spacing and geometry (see Figure 1, panels b and d). Drops can form ordered patterns inside a converging microchannel (see Figure 1). Understanding how different drops that enter a microchannel arrange themselves to generate ordered patterns will help us in the design of novel devices for applications such as...
as particle synthesis where different components are engineered together to get complex particle shapes and anisotropies. If one were to think of large particles that are made of say 50–100 drops then one would need a 2D microchannel with ordered drop arrangement. For example, photopolymerization of the drop assembly as shown in Figure 1 would result in a spindle-shaped structure. Another application is in the field of nanoparticle synthesis. Precursors that are used in the synthesis of nanoparticles can be compartmentalized inside a drop. This results in the reduction of the control volumes involved in the synthesis of nanoparticles when compared to the conventional processes, enabling better controllability.

This is done in three steps: drop formation that contains the fluids of interest, followed by coalescence, and reaction. In a 1D microchannel one has to carry out several coalescence events in series to achieve the desired ratio of mixing reagents. One example is the multistep synthesis of CdS nanoparticles. But the topology of a 2D ordered structure allows arrangements in which drops containing one reagent can be surrounded by another agent in the desired ratio. In this case, we would have to let the whole drop assembly coalesce. Bremmond and coworkers showed that a coalescence event in a concentrated emulsion can result in similar events in its neighborhood, resulting in coalescence propagation that can destabilize the whole drop assembly. Hence an arrangement of drops can be destabilized to get the reagents to react to form the nanoparticles with desired composition. This might turn out to be a good platform to synthesize and engineer core–shell nanoparticles. Another possible application of 2D microchannels would be in the synthesis of complex double emulsions. One could envisage a setup where the diverging converging microchannel (where C1 is the continuous phase and D1 is the drop phase form patterns) can open into a bigger channel where C1 does not wet the wall and breaks into drops which contains D1 forming a double emulsion.

### 3. DROP-DROP CONTACTOR

Designing microchannel devices for any of the applications outlined in section 2.2 requires the understanding of how composite drops self-organize inside a microchannel. The interacting drop–traffic models incorporated inside the multiagent simulation outlined in section 2.1 links the pattern formation of composite drops to the operating and geometric parameters. A major focus of this paper is to computationally study this link between geometry, operating conditions, and the resulting self-organization in the 2D microchannel. We define a drop–drop contactor as the microdevice inside which the drops form patterns. A diverging converging microchannel such as the one shown in Figure 1 can function as a drop–drop contactor. It is possible to bring drops into contact as they slowdown and approach each other in the diverging section, hold them together for a specific time in the central part of the channel (during which any operations like photopolymerization can be performed), and separate the drops as they accelerate in the converging section. One may ask the question, why a 2D channel for a contactor? Other microfluidic devices that can function as a drop–drop contactor are the 1D loop and the ladder structures. Drop contacting is possible in 1D channels only with active synchronization, which happens naturally in a ladder device and through online control in the case of loop and a downstream operation for separation of the drops after contact. A contacting operation where multiple drops are involved is not possible in 1D drop–drop contactors. This makes a 2D diverging converging microchannel like the one shown in Figure 1 a better choice for a drop–drop contactor.

#### 3.1. Design Objective

In this article, we consider the case where it is necessary to contact a binary mixture of drops A (peach) and B (green). If we are designing a contactor for the double emulsion synthesis as outlined in section 2.2, we might want a pattern (like in Figure 1) that would contain a good mix of both A and B. Hence, it is important to understand the sequence in which A and B should be sent into the microchannel, to ensure maximum contact between the drops. We use the multiagent simulation (section 2.1) to understand how A and B arrange themselves as a function of the sequence in which they enter.

### 4. LAYERED CONFIGURATIONS

The microchannel used for demonstration is a rectangular microchannel [depth (h) = 250 μm; height (H) = 200 μm; and length = 19h], as shown in Figure 1. Drops with diameter 220 μm, equally spaced, enter the microchannel. Drops form one, two, and multiple layers, depending on the inlet spacing. We assume that the presence of two different drops A and B does not affect the flow and hence the patterns formed. From a drop-contactor design perspective, it is important to understand how A and B will be scattered in the layered arrangements (Figure 1) in relation to the order in which they enter. An interesting question is what inlet sequence should the drops follow to achieve an even mix of A and B. One might argue that it is intuitive to send in A followed by B to get an even mix of both drops in the channel. The MAS helps in understanding the efficiency of the operating conditions based on intuition, in this 2D microchannel system.

#### 4.1. One-Layer Arrangement

A single layer of drops is formed when the inlet spacing between the drops prior to entry is as large as 38R^2 (28,58) (see Figure 2a). One should note that the absolute values of initial spacing that result in any pattern depend on the operating conditions (initial velocity), geometry (rate of divergence and convergence), and fluid properties (viscosities, densities, and interfacial tension). In the single-layer arrangement, drops are constrained to one direction. Any drop in the layered arrangement is surrounded by two other drops on each side. In this case, the best possible arrangement would be A surrounded by B on both sides. This arrangement is...
obtained if the entry sequence is one A followed by one B (see boxed region in Figure 2a). This input sequence ABAB which gives the optimal solution is in fact the same as the one based on intuition. Drop arrangement for another inlet sequence AABB is shown in Figure 2b; local crowding of A and B results in a less efficient mixing of drops.

**4.2. Two-Layer Arrangement.** For an inlet spacing of about 18R, drops form a two layer dynamic structure. In this configuration, a drop has a maximum of four neighbors. The “intuitive” input sequence ABAB results in an arrangement as shown in Figure 2c. Drops A and B get segregated in the top and bottom layers, respectively. In the neighborhood of A, a maximum of two B can be found and vice versa (see boxed region in Figure 2c). The level of contact achieved is similar to the one-layer configuration. But for an inlet sequence AABB, we get a better arrangement as shown in Figure 2d (boxed region). Here A has a maximum of 3 B in the neighborhood and vice versa. One will find out that this is in fact the best inlet sequence to achieve even mixing of A and B, after looking at the arrangements for the inlet sequence AAABB [see Figure 2e (boxed region)], where local crowding of A and B reduce the efficiency of the microchannel device to perform as a drop–drop contactor.

**4.3. Performance Metrics.** Analysis becomes tedious with an increasing number of layers inside the microchannel. This encourages the introduction of metrics such as the sequence number and contact efficiency to compare the efficiencies of different patterns formed as a function of the entry sequence. We are interested in an equal mix of drops (A around B and vice versa) as outlined in section 3. Hence, the performance of the microchannel contactor device is compared for inlet sequences where the maximum of two B can be found and vice versa (see boxed region in Figure 2c). The level of contact achieved is similar to the one-layer configuration. But for an inlet sequence AABB, we get a better arrangement as shown in Figure 2d (boxed region). Here A has a maximum of 3 B in the neighborhood and vice versa. One will find out that this is in fact the best inlet sequence to achieve even mixing of A and B, after looking at the arrangements for the inlet sequence AAABB [see Figure 2e (boxed region)], where local crowding of A and B reduce the efficiency of the microchannel device to perform as a drop–drop contactor.

**4.4. Three or More Layers of Drops.** When the inlet spacing is reduced to about 12R, drops arrange to form a three-layer pattern (Figure 1, panels a and b, and Figure 2, panels i–f). An inlet sequence SN 1 results in an arrangement as shown in Figure 2f, where A and B segregate into two regions resulting in poor mixing. The CE for different SN is shown in Figure 3. Inlet sequences SN 2 and 3 have a high value of CE which corresponds to a good mix of A and B. The CE decreases for higher SN. Even smaller inlet spacing of ~6R results in a six-layer arrangement (Figure 1b and Figure 2, panels j–o). SN 1 and 3 result in a very poor mix of A and B (identified by the low value of CE), while the best contact is achieved when SN 2 is used (see Figure 3).

**5. SYMMETRY BREAKING AND ITS CONSEQUENCES**

From the analysis presented in section 5, it is clear that an inlet sequence SN 1 that seems like an "intuitive" choice for achieving good contact between A and B fails to do so for

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Figure 2. One-layer arrangement: (a) entry sequence: ABAB (SN = 1) and (b) entry sequence: AABB (SN = 2). Two-layer arrangement: (c) entry sequence: ABAB (SN = 1), (d) entry sequence: AABB (SN = 2), (e) entry sequence: AAABB (SN = 3). Three-layer arrangement: (f) SN = 1, (g) SN = 2, (h) SN = 3, and (i) SN = 4. Six-layer arrangement: (j) SN = 1, (k) SN = 2, (l) SN = 3, (m) SN = 4, (n) SN = 5, and (o) SN = 6.

Figure 3. Performance of the microchannel device as a drop–drop contactor. A plot of contact efficiency (CE) vs the sequence number (SN) for different layered arrangements.
multiple layer arrangements (>1). We are able to understand the reasons for this from the knowledge gained from MAS on the transient, dynamic pattern formation of drops inside the microchannel. Multiple layers are formed as a result of drops crowding in the diverging section of the channel. Figure 4 shows the snapshots of the transient pattern formation for a three-layer arrangement. One can infer that initially a single layer is formed (Figure 4 a), which is symmetric about the horizontal plane. As drops start to crowd, the one-layer configuration becomes unstable and results in layering. This leads to the formation of a two-layer structure (Figure 4b). Layering is a symmetry-breaking instability that results in one of the drops being pushed slightly away from the plane of symmetry. Drops are pushed up or down depending on local infinitesimal perturbations that all real systems undergo, which is incorporated in the MAS as a random roughness factor in the wall. Let us assume that a drop moves upward. This drop in turn forces the neighboring drops downward, through a drop—drop interaction force. This force which is directed along the line joining the radii of the drops, has a nonzero y component only when one of the drops is out of the plane of symmetry, resulting in alternate drops going upward and downward. Now, with further crowding of the drops in the diverging section of the channel, the two layer structure undergoes instability (Figure 4c) to form a three-layer arrangement (Figure 4d), which has a middle layer containing both A and B sandwiched between layers of A and B.

An inlet sequence ABAB (SN 1) clearly results in segregation of A and B. Once symmetry breaks (layering), intuition (SN 1) fails. The knowledge of layering explains not only why SN 1 performs poorly but also why SN 2 is better (Figure 3). Now that we know that a train of drops at the entrance of the diverging section alternatively go up and down, once the layering process happens, SN 2 results in a pair of A and B going up and another pair down. This maximizes the mixing of A and B, enhancing the CE for the resultant ordered arrangement.

6.2D DROP ENSEMBLES: APPLICATIONS TO PARTICLE SYNTHESIS

Particles with complex shape and composition anisotropies find applications in the fields of drug delivery, bio sensing, etc. Sung et al. have demonstrated a microfluidic route for the synthesis of particles with different local and global anisotropies based on droplet packing in a confined rectilinear channel. This method includes four steps: loading, washing, fusing, and release. During the loading stage, drops form a zigzag arrangement with a certain bonding angle depending on the amount of confinement. In the work by Sung et al., for different bonding angles one should resort to different channels. Here, we perform a computational study of a two-step process which involves dynamic assembly followed by fusion in a 2D microchannel. In this method, one can dynamically control the bonding angles by manipulating the flow rates. Also in the method proposed by Sung and co-workers, a constant bonding angle was obtained. We show that in 2D channels one could get different gradients of bonding angles in the composite particle.

6.1. Two-Step Method. To demonstrate the use of 2D microchannels for particle synthesis, two different channels are used: a channel with linearly diverging and a nonlinearly diverging (hyperbolically) entrance. Figure 5a shows the bonding angle as a function of the drop pair in self-organized clusters for different representative channel designs shown in Figure 5b. Drops are sent into the diverging channel where they slow down, crowd, and eventually layer to form a two-layer arrangement. From Figure 5b, one can infer that drops form ordered patterns similar to the ones in Sung et al., where confinement results in layering. Depending on the flow rate of the dispersed phase, the crowding of drops vary. Bonding angle between the drops vary as a function of the amount of crowding in the microchannel. Once the drops self-organize to form the particle with the required size, the composite ensemble of drops can be fused together by a photopolymerization or a thermal fusing step. If the flow rate is decreased, crowding decreases and as a result bonding angle decreases.

From Figure 5b, one can infer that the ordered arrangement I has a bond angle greater than that of II because the flow rates in I are greater than that in II. Hence, this method will allow one to control the bonding angle by manipulating the operating parameters. This is an advantage over the existing microfluidic method introduced by Sung and co-workers, where one has...
to change the microdevice to alter the bonding angle for a given particle size. The dynamics of layering also results in an anisotropic arrangement of drops, which is reflected in the magnitude of the bonding angles obtained as observed in Figure 5a. Another interesting anisotropic arrangement is obtained when the flow rate of the dispersed phase is stepped down during operation. This results in a particle with two regions with different bonding angles in each region as shown in Figure 5b III.

6.2. Embedding Method. One may be interested in particles with shapes that are difficult to engineer. We propose a different method which we call the "embedding method" to assemble complex structures. Drops that fuse upon photo or thermal treatment can be sent along with drops that will stay inert. When the drops enter the diverging channel at high frequencies, they self-organize to form crowded multilayered arrangements. Upon thermal or phototreatment, only the drops that are sensitive to the treatment polymerize and fuse with the neighboring drops of the same kind. By precisely ordering them before they enter the 2D channel, one can achieve complex patterns that are otherwise very difficult to assemble. To demonstrate the idea we show the assembly of particles with the shape of Greek alphabets α and γ (see Figure 5c). In the example simulation, the flow of two different types of drops is considered the same, but in reality flow characteristics may vary which will result in different tuning parameters for the model.

7. PATTERN FORMATION: APPLICATION TO MICROFLUIDIC DYE LASER

Microfluidics has found applications in the area of flow cytometry, where cells can be detected, counted, sorted, and engineered as they flow inside the microchannel.54−57 The particles are made to flow in a sample stream, which is generally focused in the center of the channel with the help of sheath fluids56 or to certain regions of the channel through hydrodynamic inertial migration of particles in Poiseuille flow.58,59 Once these particles are focused, they are analyzed using impedance measurements or optical techniques based on fluorescence, light-scatter, or absorption spectroscopy.57,60 We might encounter situations where different particles have different fluorescent labels. In cases like these, one would prefer a “multicolor fast-switching microfluidic droplet dye laser” like the one developed by Tang and co-workers.61 This device consists of a droplet generation system that generates binary drops in series (one A followed by another B, where A and B have different lasing frequencies) followed by a region where the drops are optically excited. When the drops have a refractive index higher than the continuous phase, it behaves like an optical microcavity that exhibits total internal reflection and shows lasing due to whispering gallery modes.61

The detection region for this lasing facility is not more than the diameter of the drop. Achieving a broad detection/interrogation zone with consistent and uniform illumination57 remains a challenge to design engineers. One could possibly address this concern if we have a group of drops vertically arranged that can lase with the same wavelength followed by another vertical layer of drops with a different frequency. The question then is can we design the input and the geometry of the microchannel which will result in a vertical arrangement of drops?

Jose and Cubaud in an attempt to analyze drop inlet and exit sequence, tracked individual drop trajectories (Figure 6 of their article28). We infer from that plot (although the authors do now account for it in their article) that six drops, sent one after the other, can arrange in a single (almost) vertical row. When we choose an SN that equals the number of layers in the microchannel, we get a front of A following a front of B (boxed regions in Figure 2, panels a, d, h, and o) in our simulations. But the front of the drops formed is not straight (centers of the drops do not fall on the same straight line). Is it possible to make changes to the geometry such that this front is indeed straight?

When we used a hybrid microchannel that consisted of hyperbolic diverging and converging sections and a rectangular midsection similar to the one used in our previous work to understand the reason for pattern formation,38 we observed that the drop front was vertical (see Figure 6). When SN equals the number of layers in the pattern (see Figure 6), the vertical fronts of A and B are indeed straight. This design modification has the possibility of delocalizing the laser source concomitantly with a broader interrogation zone resulting in a reduced footprint device.

8. OPTIMIZATION STRATEGIES FOR DESIGN AND OPERATION

Self-organization of drops is a collective phenomenon. The patterns formed inside the channel are not obvious and are complicated functions of the geometrical and operational parameters. In sections 6 and 7, different design examples that stem from the analysis of 2D microchannel systems using the multiagent simulation were discussed. But from a design perspective, searching for a design that will result in specific arrangement of drops becomes a daunting task. Rational design approaches that facilitate the discovery of application-specific device designs have the possibility of moving this field forward in major ways. The development of such a design approach requires two components: modeling (known as the forward problem) and search for a design given desired functionalities using the model (referred to as the backward problem). We have shown that a multiagent modeling approach is a viable approach for the forward problem. However, a solution to the backward problem is beset with several challenges. The first difficulty is in deriving closed-form analytical expressions for the design objectives, particularly when the design objectives could include different elements related to sequencing, geometrical arrangement of drops, and so on. Further, it is usually not possible to express the objective function directly as a function of the decision variables, and one would have to embed the simulation approach inside the optimization routines. Recently, we have proposed a genetic algorithm-based design approach for 1D microchannels that addresses...
many of the above-mentioned challenges.\textsuperscript{22,32} Our future work will focus on extending the GA approach for solving design questions in 2D microchannels.

9. CONCLUSIONS

In this article, we described the design of 2D microchannels for applications that involve organization of drops. In a 2D microchannel, drops can interact hydrodynamically, the nonlinear, multiscale nature of these interactions results in collective behavior that makes the design choices nonintuitive. We use a multigant-based simulation framework to understand the complex dynamics of drops as a function of the operating parameters and microchannel geometry. We investigate the performance of a drop—drop contactor (a diverging converging microchannel device that arranges drops together) in achieving equal mix of composite drops (A and B) in the drop assembly. Intuitively, one might realize that an entry sequence ABAB would result in maximum mix of drops. We observe that this intuition-based result fails when the symmetry of the drop assembly breaks as the operating conditions vary. Analyzing the transients using the multigant simulation helps us understand why this happens and also sheds light on how one can achieve the best mix by considering an inlet sequence AABB. In another example, we demonstrate the application of 2D microchannels for flow cytometry applications where we focus on increasing the detection area on the microchannel. To do so, we describe a conceptual microfluidic drop dye laser device that arranges drops in vertical fronts of A followed by that of B (fast switching laser). Using such a design, one could achieve a low footprint device for flow cytometry with fast switching lasing. The design changes made are unobvious and nonintuitive because of the complex nature of the interactions between the drops in the microchannel. To rationalize the design approach, we advocate a two component framework that consists of the modeling (forward problem) and an optimization-based search for a design with desired functionalities using the model (backward problem). We believe that simple modeling approaches like the multigant strategy incorporated inside optimization routines can revolutionize design of 2D microchannels.

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The authors declare no competing financial interest.

\section*{ACKNOWLEDGMENTS}

The authors would like to thank Binbin M. Jose and Thomas Cubaud of Stony Brook University for sharing their experimental video of drops moving inside a 2D microchannel, which was not available in the literature. The authors gratefully acknowledge DST, India support of this project.

\section*{REFERENCES}


(18) Gunes, D. Z.; Clain, X.; Breton, O.; Mayor, G.; Burdige, A. S. Avalanches of Coalescence Events and Local Extended Flows—Stabilisation or Destabilisation due to Surfactant. \textit{J. Colloid Interface Sci.} 2010, 343 (1), 79.


(56) Piyasena, M. E.; Graves, S. W. The Intersection of Flow Cytometry with Microfluidics and Microfabrication. Lab Chip 2014, 14 (6), 1044.


