Optimization in Fluid Mixing in Microchannels: A Review

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Nomenclature

Symbols	**Description**
Re	Reynolds number
θ_c	Circulation time
V	Volume flow rate
Q	Pumping capacity
P	Power consumption
N	Speed of impeller
D	Diameter of impeller
Nmin	Minimum agitation speed
t	Time
ρ	Density
$\Delta\rho$	Density difference between continuous and dispersed phase, kg/m^3
μ_c	Continuous phase viscosity, N s/m^2
μ_d	Dispersed phase viscosity, N s/m^2
σ	Interfacial tension, Nm^{-1}
C_0, a_0	Constants depend on impeller types and their locations
U	Fluid flow velocity
L	Length of the plate
ν	Viscosity

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1 Introduction

1.1 Fluid Mixing

Fluid mixing is a very crucial activity and has various applications such as food handling, drug creation, substance designing, biotechnology, agri-synthetic arrangements, paint fabricating and water sanitization, etc. [1]. Muskett [1] identified various objectives to be achieved by mixing, like liquid estimation, stage blending, mass and hotness move between the liquids, controlling the liquid speeds, and so forth. It is advised in this work that in the event of blending two fluids, one of the fluids must be made broken into tiny beads. Further, at that point, by utilizing the Laser Doppler Anemometry strategy, the speeds of the fluids must be noticed and choppiness must be made to upgrade the blending effectiveness.

Richard et al. [2] used homogeneity property to determine the effectiveness of mixing. To accomplish homogeneity in blending, two miscible liquids for mixing were considered. Thickness of the liquids was used to study mixing interaction in various systems. Different systems for different fluid were used and studied; Fierce system was picked for low thickness liquids, temporary system for respectably gooey liquids, and laminar systems for exceptionally thick liquids. Prior information about blender and characteristics of liquids is essential before carrying out mixing experiments. Classification of mixing process is shown in Fig. 1 [1, 2].

Low viscosity in turbulent, moderate in transitional, and high in laminar regimes, respectively, were the characteristics of the fluids used in the blending experiment. Improvement in the homogeneity of the final product was observed. Dispersion and emulsion are the two different processes that are applicable to the immiscible fluids to be mixed. In dispersion, when the two fluids get closed to each other, one fluid breaks down to small droplets and merged with the second one and mixing is done. An emulsion is a kind of colloid shaped by consolidating two fluids that typically don't blend. In an emulsion, one fluid contains a scattering of the other fluid.

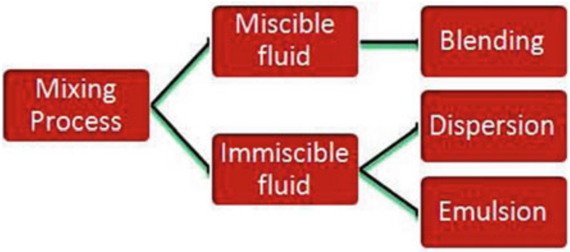

Fig. 1 Types of mixing process

1.2 Mixing Factors

The fluid mixing performance depends upon the factors like mixing time, circulation time, mixing speed and power consumption, etc. [3]. The diameter and speed of the impeller are the two parameters based on which the mixing time depends. Circulation time is the time taken to transport a huge mass of fluid from one place to another within the container. The more the mixing speed the better will be the performance. The energy required for the blending process per unit time is called as the power consumption for the same.

$$\theta_c = \frac{V}{Q} \tag{1}$$

$$N_{\min} = C_o D^{a_o} (\mu_c)^{1/9} (\mu_d)^{-1/9} \sigma^{0.3} (\Delta P)^{0.25} \tag{2}$$

$$P \propto N^3 D^5 \tag{3}$$

Here θ_c, V, and Q denote the circulation time, discharge, and pumping capacity of the fluid, respectively. $N_{\min}$ is the minimum mixing speed whereas P, N, and D are the power consumption, speed, and diameter of the impeller, respectively.

2 Microfluidic Devices

In order to have an efficiently mixed fluid [4, 5], the mixing need to be done at the molecular level which is called as micromixing. For this purpose, microfluidic devices are required. Over last few decades, there is a huge demand for the Lab-On-a-Chip technique which has a great impact in the field of biotechnology, medicine, engineering, chemical industries, etc. It is a device of very small size in which several laboratory functions can be performed. A microfluidic chip is a bunch of miniature channels carved or shaped into a material (glass, silicon, or polymer). The miniature channels shaping the microfluidic chip are associated together to accomplish the ideal elements. This organization of miniature channels caught into the microfluidic chip is associated with the outside by data sources and yields penetrated through the chip, as an interface between the large scale and miniature world.

The aim of microfluidic mixing [6] is to achieve a thorough and rapid mixing of multiple samples in microscale devices. As the Reynolds number of the fluids flowing in the microchannel is very small, turbulent mixing does not occur in this case.

$$R_e = \frac{UL}{\nu} \tag{4}$$

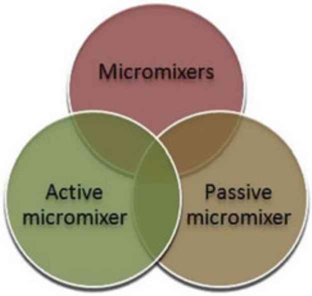

Fig. 2 Types of micro-mixers

Here diffusive species mixing assumes a significant part however it is an intrinsically sluggish interaction. Thus, the point of microfluidic mixing plans is to improve the blending productivity to such an extent that a careful mixing execution can be accomplished inside more limited blending channels, which can decrease the trademark size of microfluidic gadgets. Besides, the improvement of proficient mixing plans is fundamental for expanding the throughput of microfluidic frameworks and to understand the idea of miniature complete investigation frameworks and lab-on-a-chip frameworks. Expanding the contact region between the species to be mixed is one of the most productive methods for upgrading the diffusive-mixing impact. Likewise, past investigations introduced mixing plans by taking care of the examples of premium through discrete by means of openings, cantilever plate-valves or multi-diverts in the microfluidic gadget. An effective methodology is to expand the contact region between the mixing species by planning the microchannel designs with the goal that the species are collapsed on numerous occasions as they stream along the blending channel.

Since microfluidic gadgets are compelled to depend on lethargic diffusive-mixing process, there is a need in the field to find new methods by which mixing effectiveness can be upgraded. Shockingly, numerous laminar streams can possibly accomplish turbulent mixing, and microfluidic gadgets are presently being manufactured to exploit this marvel. Classification of micro-mixers is shown in Fig 2. Microfluidic mixing technique can be classified as either "active", where an external energy force is applied to integrate the sample species, or "passive", where the contact area and contact time of the species samples are increased through specially-designed microchannel configurations.

2.1 Active Micro-Mixer

In case of active micro-mixer, the mixing can be enhanced by stirring the fluid flow with the use of some external energy source. These types of micro-mixers can be categorized [7–9] as pressure, acoustic, thermal, magnetic, and electrical field-driven mixers. Various types of active micro-mixers are shown in Fig. 3.

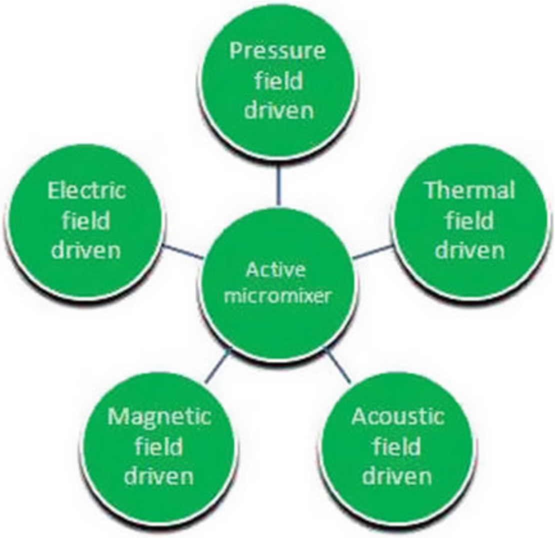

Fig. 3 Types of active micro-mixers

A functioning micro-mixer [10] utilizes unsettling influence created by an outside field for the mixing and the mixing system is fast. Using the quick mixing of the attractive mix bar, predefined convergences of arrangements can be created and gathered at the power source of the micro-mixer by ascertaining and applying fitting stream rates at the delta. The microfluidic arrangement comprises of a strain regulator, stream sensors, and a micro-mixer. The arrangements in the micro-mixer chamber are mixed constantly utilizing an attractive mix bar causing immediate mixing of the liquids. The tension-driven stream combined with stream sensors empowers exact command over the stream pace of the liquids entering the micro-mixer.

In case of pressure-driven active micro-mixer [11–13], disturbance is created by using an external micro pump that regulates the flow of the fluids inside the channel. By repeating the process of allowing and restricting the flow movement, turbulence is created which helps in better mixing. Mixing can be achieved effectively in acoustic type of micro-mixer with the help of an actuator which is used to stir the fluids in a flexible surface to generate air bubbles which in turn get energized and help in mixing. In thermal driven micro-mixer [14, 15], thermal power is used to raise the diffusion coefficient so that turbulence gets generated and mixing is done. In case of magnetic as well as electric types of micro-mixers, magnetic and electric fields are created, respectively which in turn helps in better fluid mixing.

2.2 Passive Micro-Mixer

In active micro-mixer [16] the intricacy of design and size is expanded, which requires extra human resources. Thus, the likelihood of coordinating active microfluidics with

LOCs applications has dropped off. To counter these disadvantages, the development of the test is accomplished either utilizing liquid properties or latent systems with practically no outer supporting force sources. Thus, latent microfluidics has been taken on and used generally in current examination undertakings to keep away from the utilization of outside supporting force gadgets. This strategy is basic, simple to fabricate, and needn't bother with any actuators or outer force supplies, as it utilizes fundamental research center instruments, as micropipettes, and clinical gadgets, for example, needle siphons. Passive micro-mixer [17] is one of the microfluidic gadgets. It uses no energy input with the exception of the component (pressure head) used to drive the liquid stream at a consistent rate.

2.2.1 Trends in Passive Micro-Mixer

In last few years (2000–2018), so many research works [16] have been done in passive micro-mixers and numbers of article are published on different grounds. Fig 4 represents the trends in passive micro-mixers. The different trends are pressure-driven, capillary, surface tension, vacuum-based, hydrostatic, gravity-driven, and osmosis passive micro-mixer. It is clear from the figure that pressure-driven, capillary, surface tension, vacuum-based, hydrostatic micro-mixers are the latest trends. Currently, numbers of research works are going on the same and articles are published.

Passive micro-mixer is classified into four main categories: Fig. 5 shows different types of passive micro-mixers.

The mechanism of sequential passive micro-mixer is to split the fluid streams and then recombine them in order to have better mixing efficiency. In this process, the mixing contact area of the fluids gets increased and hence the mixing time gets reduced. In droplet micro-mixer [18], the fluids need to be broken into tiny droplets. After the droplets formed, mixing occurs. Chaotic advection [19] means the movement of the substance in the transverse direction of the fluid flow. The advantage

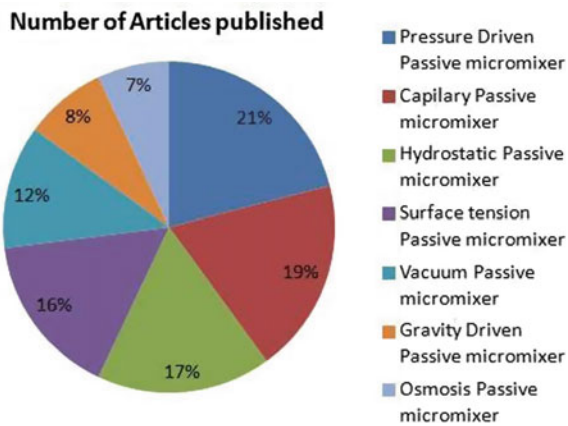

Fig. 4 Approaches in passive micro-mixers

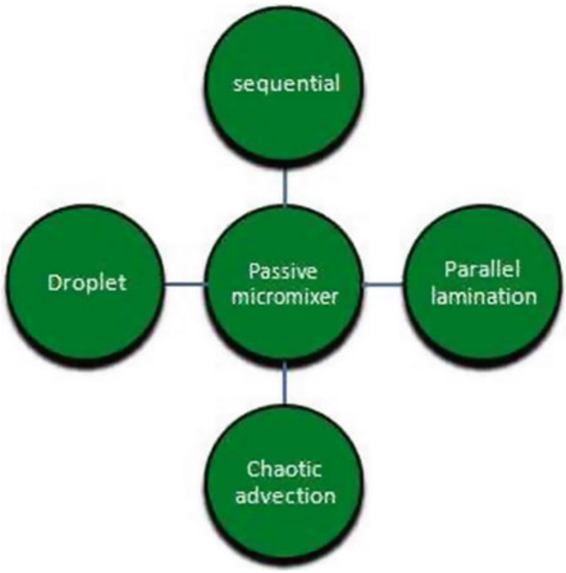

Fig. 5 Types of passive micro-mixers

of this method is that transverse components get generated which creates a better mixing surface area for mixing. In case of parallel lamination [20, 21] type of passive micro-mixer the inlet of the channel can be divided into numbers of parts but there will be a single outlet. The fluid streams coming from the inlet passage get merged and after mixing come out of the channel. The working principle of this type of micro-mixer is to improve the contact surface area by minimizing the inner diffusion duration of the fluids. This type of micro-mixer can be of two types.

2.2.2 T Type Passive Micro-Mixer

It is [22] T-shaped, hence named so. Here the inlet channel is divided into two segments. The angle between the two inlet channels is 1800. The outlet channel is perpendicular to the inlet one. Navier-Stokes equation, continuity equation, and convection-diffusion equation are required to describe the fluid flow in T channel.

$$\rho.\nabla u = 0 \tag{5}$$

$$\rho \frac{du}{dt} + \rho u(u.\nabla) = -\nabla p + \mu \nabla^2 u \tag{6}$$

$$\frac{dc}{dt} + u\nabla.C = D\nabla^2 C \tag{7}$$

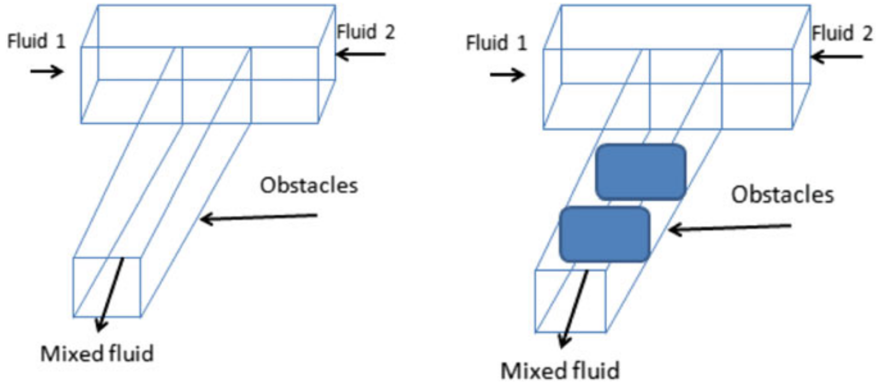

Fig. 6 T-shaped microchannel without and with obstacles

As we know, the fluid flow in microchannels mainly depends on diffusion process. Due to low Reynolds number turbulence is not created which hampers the speed of fluids and as a result, the mixing is not up to the level. In order to enhance the fluid mixing efficiency, turbulence needs to be created and that can be done with the presence of obstacles in the flow channel. Hence different types of obstacles are placed in the flow channel at different positions. Figure 6 represents the T type micro-mixer without and with obstacles.

It is found that by using either obstacle in the flow channel or baffle plates, turbulence is getting created which helps in improving the fluid velocity and in turn the mixing efficiency. As a result, the mixing quality is also getting enhanced.

2.2.3 Y-type Passive Micro-Mixer

It is one of the easiest models [23] for fluid mixing. Here the inlet channel is divided into two segments that are inclined at some angle to each other. It consists of a single outlet passage for the mixed fluid to come out. Two different fluids enter to the channel, they get mixed and the mixed one comes out of that microchannel. As we know that the Reynolds number is very low in this type of channel, hence the velocity profile is set up not a long way from the inlet channel. Here also the mixing efficiency can be improved by using obstacles in the flow passage. Figure 7 represents the Y-type microchannel without- and with- obstacles.

3 Optimization in Fluid Mixing

For fluid mixing purposes, number of devices have been designed and developed. But there is huge demand for the highly efficient device for optimizing the fluid

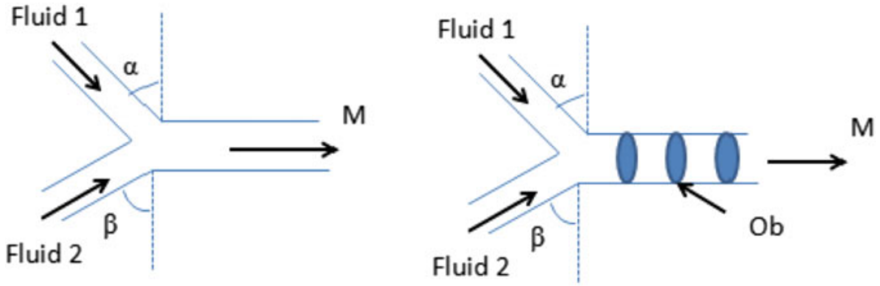

Fig. 7 Y shaped microchannel without and with obstacles

Fig. 8 Optimization approach in micro-mixers

mixing process. In this regard, Computational Fluid Dynamics (CFD) is the most accurate way to predict the flow behavior within the system which consists of efficient as well as effective designing process. In fluid mechanics, optimization relates to satisfy the objective functions like measuring the performance and the designing parameters. The optimization can be carried out in three different manners like shape optimization, size optimization, and topology optimization, etc. and are shown in Fig. 8.

3.1 Shape Optimization

Shape optimization [24] mainly relates to the shape of the microchannel so that the mixing efficiency can be enhanced at low designing cost. This concept is mostly applied to the static mixers where no moving part is there for the mixing purpose. Here the flow domain includes two inlet channels, a single outlet channel, and a mixing channel having numbers of baffles evenly spaced. Baffle plates are used in order to improve the mixing efficiency by creating turbulence in fluid flow. In this work, seven baffles are used to achieve maximum efficiency. Figure 9 shows the schematic of the experimental setup.

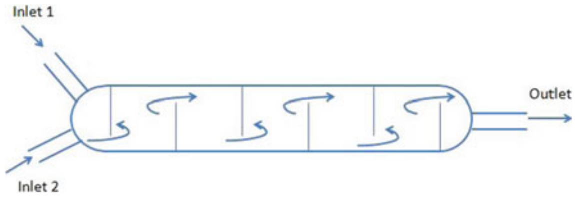

Fig. 9 Static mixer with baffle plates

3.2 Flow-Based Optimization

The best [25] presentation in the field of fluid mixing can be firmly coupled to the flow conditions. Designing and optimizing flow development requires definite information about the genuine unique circumstance. The flow analysis and optimization result in improved performance and mixing efficiency with reducing energy consumption, maximum volume flow rate, minimum maintenance and running cost, etc. Flow-based optimization can be accomplished by for example coupling of computational liquid elements (CFD) and optimization programming. The contribution of the advancement calculation is usually the recreation results relating to the different design points. Such recreations are typically directed in batch mode to kill the inactive time. In the batch mode, the solver arrangement is predefined and a similar setup is applied to all the design points. When there are huge changes in design, which prompt flow shift in power, solver would not have the option to react to the changes. To upgrade the appropriateness of CFD-based optimization, the smart CFD solver is adjusted to examine the physical science in each design point and afterward allocate fitting actual models to arrange the solver.

3.3 Topology Optimization

Topology optimization [26] is a numerical technique that enhances material format inside a given design space, for a given arrangement of loads, limiting conditions, and requirements fully intent on expanding the presentation of the framework. Topology optimization is not the same as shape optimization as this can attain any shape inside the design space, rather than managing predefined designs. The conventional topology optimization definition utilizes a finite element method (FEM) to assess the design execution.

Topology optimization has a wide scope of uses in aviation, mechanical, bio-synthetic, and structural designing. At present, designs for the most part use topology optimization at the idea level of a design cycle. Because of the free structures that normally happen, the outcome is regularly hard to make. Hence the outcome arising out of topology optimization is frequently adjusted for manufacturability. Adding requirements to the detailing to build the manufacturability is a functioning field of exploration. Sometimes results from topology optimization can be straightforwardly produced utilizing added substance fabricating; topology optimization is consequently a vital piece of plan for added substance producing.

4 Conclusion

Fluid mixing is understood with the help of works covering basic concepts to advanced experiments in microchannels. Various kinds of systems for improving mixing process in miniature mixers have been covered in this survey. It is suggested that each plan has its own pros and cons. The most appropriate method for mixing needs to be selected based upon the particular application as a primary concern. There is no single mixing idea satisfying all the desired goals. Various aspects of mixing devices such as creation cost, execution, etc. are covered. Subsequent to going through the above papers we can conclude that if a mixed sort hindrance is put in either T molded or Y formed stream channel, then the mixing effectiveness can be upgraded without expanding the tension drop.

References

1. Muskett MJ (1986) The measurement of fluid mixing processes. Mater Des 7(4):188–191. https://doi.org/10.1016/0261-3069(86)90120-2
2. Grenville RK, Nienow AW (2004) Blending of miscible liquids. Handb Ind Mixing, pp 507–542. https://doi.org/10.1002/0471451452
3. Ghotli RA, Raman AAA, Ibrahim S, Baroutian S (2013) Liquid-liquid mixing in stirred vessels: a review. Chem Eng Commun 200(5):595–627. https://doi.org/10.1080/00986445.2012.717313
4. Convery N, Gadegaard N (2019) 30 years of microfluidics. Micro Nano Eng 2:76–91. https://doi.org/10.1016/j.mne.2019.01.003
5. Asghar C, Hossein F, Aghayie H, Reza V (2015) Numerical simulation of time- dependent electro-osmotic micro-mixer for laboratory-on-a-chip applications. Res J Recent Sci 4(2):83–90
6. Seok G, Seok J, Beom CC, Sang K, Lee H (2014) Applications of micromixing technology. Analyst 135(3):460. https://doi.org/10.1039/b921430e
7. Bayareh M, Ashani MN, Usefian A (2020) Active and passive micro-mixers: a comprehensive review. Chem Eng Process 147. https://doi.org/10.1016/j.cep.2019.107771
8. Hejazian M, Nguyen NT (2017) A rapid magnetofluidic micro-mixer using diluted ferrofluid. Micromachines 8(2):37. https://doi.org/10.3390/mi8020037
9. Ward K, Fan ZH (2015) Mixing in microfluidic devices and enhancement methods 25. https://doi.org/10.1088/09601317/25/9/094001
10. Sprogies T, Köhler JM, Groß GA (2008) Evaluation of static micro-mixers for flow-through extraction by emulsification. Chem Eng J 135:199–202. https://doi.org/10.1016/j.cej.2007.07.032
11. Lee HY, Voldman J (2007) Optimizing micro-mixer design for enhancing dielectrophoretic microconcentrator performance. Anal Chem 79(5):1833–1839. https://doi.org/10.1021/ac061647q

12. Fang W, Yang J (2009) A novel microreactor with 3D rotating flow to boost fluid reaction and mixing of viscous fluids. Sens Actuators B 140(2):629–642. https://doi.org/10.1016/J.SNB.2009.05.007
13. Rao LT, Goel S, Dubey SK, Javed A (2019) Performance investigation of T-shaped micro-mixer with different obstacles. J Phy 1276. https://doi.org/10.1088/1742-6596/1276/1/012003
14. Santana HS, Júnior JLS, Taranto OP (2015) Numerical simulations of biodiesel synthesis in microchannels with circular obstructions. Chem Eng Process 98:137–146. https://doi.org/10.1016/j.cep.2015.10.011
15. Oualha K, Amar MB, Michau A, Kanaev A (2017) Observation of cavitation in exocentric T-mixer. Chem Eng J 321:146–150. https://doi.org/10.1016/j.cej.2017.03.111
16. Narayanamurthy V, Jeroish ZE, Bhuvaneswari KS, Bayat P, Premkumar R, Samsuri F, Yusoff MM (2020) Advances in passively driven microfluidics and lab-on-chip devices, a comprehensive literature review and patent analysis. RCS Adv 10(20):11652–11680. https://doi.org/10.1039/d0ra00263a
17. Wang C-T, Chen Y-M (2011) Flow mixing of double two-inlet Y-Type micro channel with optimal layout of obstacles. J Mech 27(02):N1–N4. https://doi.org/10.1017/jmech.2011.22
18. Huanming X, Jiawei W, Zhiping W (2018) A comparative discussion of different designs of passive micro-mixers: specific sensitivities of mixing efficiency on Reynolds numbers and fluid properties. Microsyst Technol 24(2):1253–1263. https://doi.org/10.1007/s00542-017-3496-4
19. Sudarsan AP, Ugaz VM (2005) Fluid mixing in planar spiral microchannels. Lab Chip 6(1):74–82. https://doi.org/10.1039/b511524h
20. Chiu PH, Chang CC, Yang RJ (2013) Electro kinetic micromixing of charged and non- charged samples near nano–microchannel junction. Microfluid Nanofluid 14(5):839–844. https://doi.org/10.1007/s10404-012-1116-2
21. Gambhire S, Patel N, Gambhire G, Kale S (2016) A review on different micro-mixers and its micromixing channel microchannel. Mater Sci, pp 409–413. https://doi.org/10.14741/Ijcet/22774106/spl.4.2016.83
22. Raza W, Hossain S, Kim KY (2020) A review of passive micro-mixers with a comparative analysis. Micromachines 11(5). https://doi.org/10.3390/mi11050455
23. Rudyak V, Minakov A (2014) Modeling and optimization of Y-type micro-mixers. Micromachines 5(4):886–912. https://doi.org/10.3390/mi5040886
24. Alexias P, Giannakoglou KC (2020) Shape optimization of a two-fluid mixing device using continuous adjoint. Fluids 5(1). https://doi.org/10.3390/fluids5010011
25. Li L, Cheng Z, Lange CF (2018) CFD-based optimization of fluid flow product aided by artificial intelligence and design space validation. Math Prob Eng https://doi.org/10.1155/2018/8465020
26. Andreasen CS, Gersborg AR, Sigmund O (2009) Topology optimization of microfluidic mixers. Int J Numer Methods Fluids 61:498–513. https://doi.org/10.1002/fld.1964