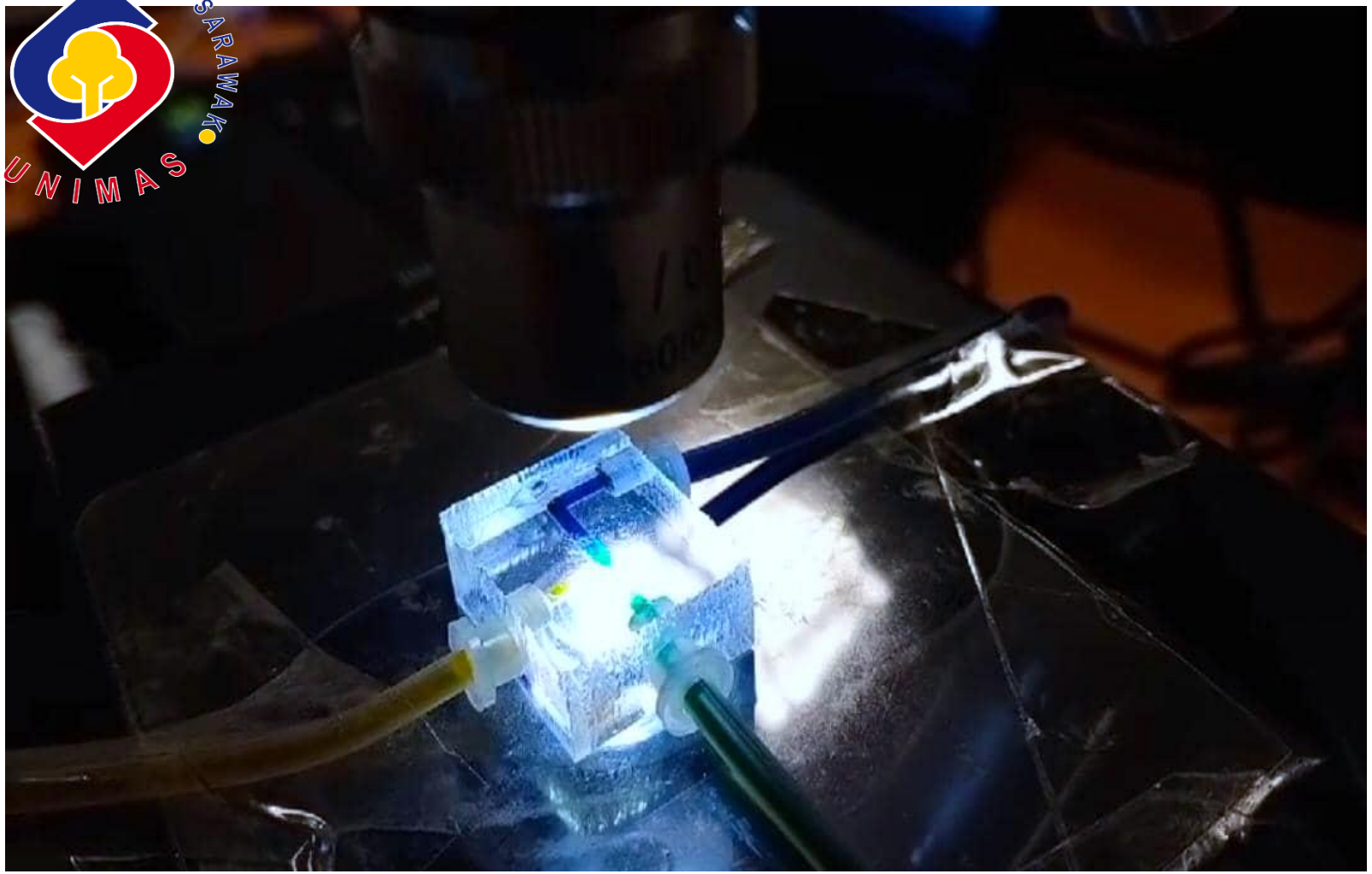

INVESTIGATION ON MIXING PERFORMANCE AND DROPLET GENERATION OF DISSIMILAR LIQUIDS THROUGH T-JUNCTION AND OFFSET T-JUNCTION MICROCHANNELS

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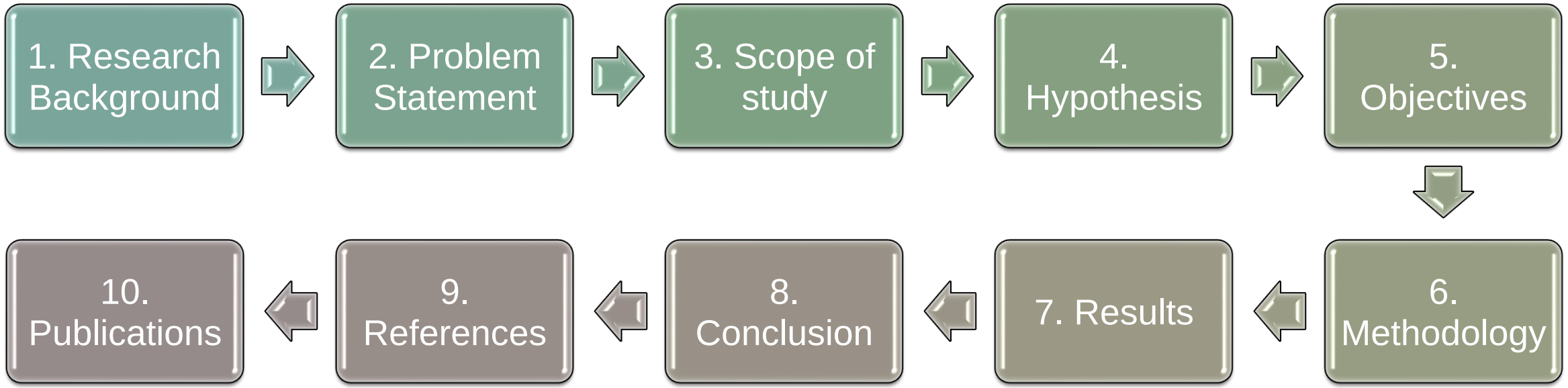
SUPERVISOR: IR DR KHAIRUL FIKRI BIN TAMRIN

Presentation Overview



Research Background

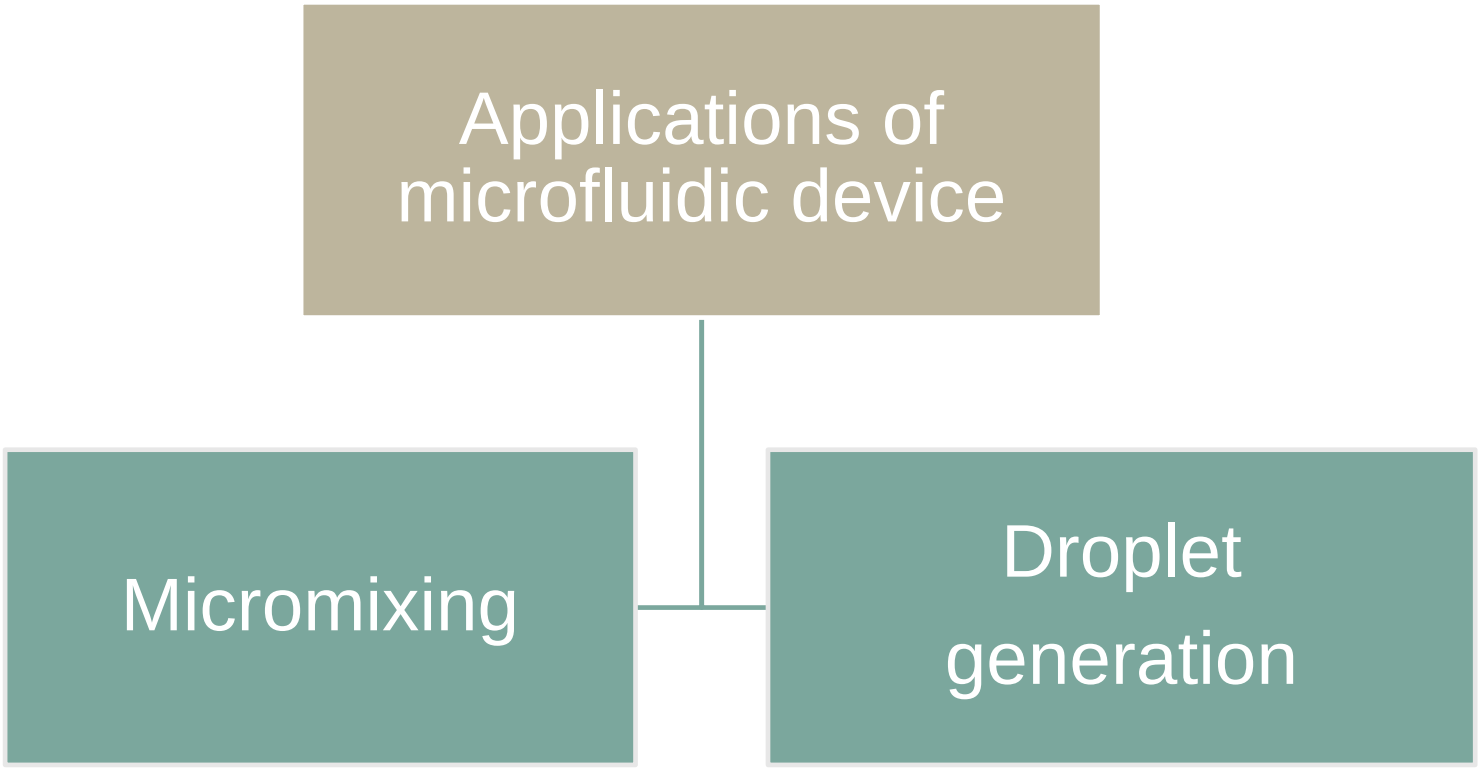


***Figure 1**: Microfluidic device applications*

Research Background - Micromixing

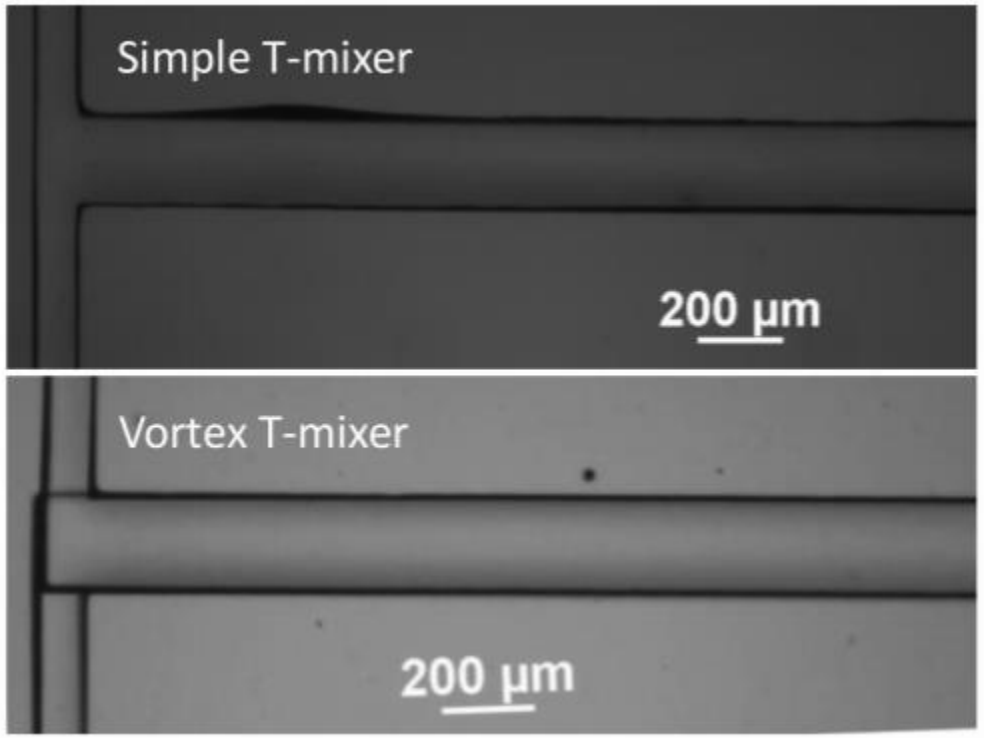


***Figure 2**: Microfluidic device for water-water micromixing (Ansari et al., 2018)*

Research Background - Micromixing

- To improve the efficiency of mixing by reducing the characteristics size of microscale devices within shorter mixing channels.
- To reduce the cost of laboratory equipment as it diminishes the consumption of specimens.
- To achieve quick and complete mixing of different samples especially in the microfluidic devices.

Research Background - Micromixing

***Table 1**: Micromixing past studies*

	Title	Methodology
Wang et al. (2012)	Visualization of micro-scale mixing in miscible liquids using μ-LIF technique and drug nano-particle preparation in T-shaped micro-channels	Similar liquids: Water-water Dissimilar liquids: water-ethanol
Orsi et al. (2013)	Water–ethanol mixing in T-shaped microdevices	Numerical method Dissimilar liquids: Water-ethanol
Solehati et al. (2014)	Numerical investigation of mixing performance in microchannel T-junction with wavy structure	Numerical method
Ansari et al. (2018)	Numerical and experimental study on mixing performances of simple and vortex micro T-mixers	Similar liquids: Water-water
Dundi et al. (2019)	Characterization of enhanced liquid mixing in T-T mixer at various Reynolds numbers	Numerical method Similar liquids: Water-water
Zhang et al. (2019)	Investigation of three-dimensional flow regime and mixing characteristic in T-jet reactor	Numerical method Similar liquids: Water-water

Research Background – Droplet Generation

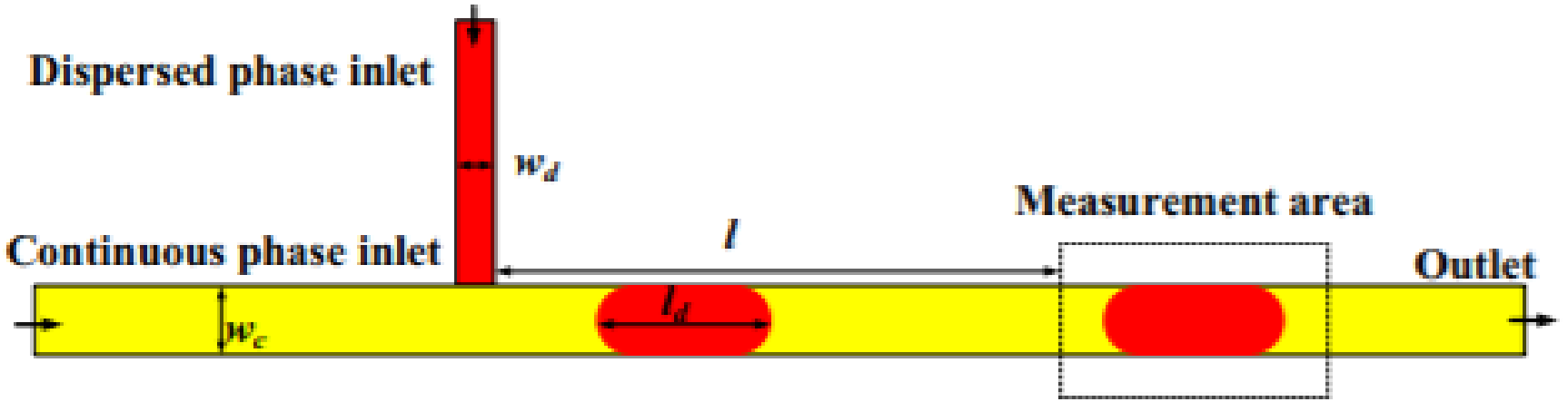


***Figure 3**: Microfluidic device for generation of water-in-oil droplets (Liu et al., 2017)*

Research Background – Droplet Generation

***Table 2**: Droplet generation past studies*

	Title	Factors
Zhu et al. (2016)	Droplet generation in co-flow microfluidic channels with vibration	Mechanical vibration
Liu et al. (2017)	Micro-PIV investigation of the internal flow transitions inside droplets traveling in a rectangular microchannel	Viscosity ratio
Shen et al. (2017)	Study of flow behaviors of droplet merging and splitting in microchannels using Micro-PIV measurement	Shape of microchannel
Deng et al. (2018)	Preparation of Micron-Sized Droplets and Their Hydrodynamic Behavior in Quiescent Water	Shape of microchannel
Yao et al. (2019)	The effect of oil viscosity on droplet generation rate and droplet size in a T-junction microfluidic droplet generator	Viscosity of the continuous phase

Problem Statement - Micromixing

- There are limited experimental studies investigating the mixing process between two miscible or immiscible liquids in relation to microfluidics.
- Most miscible mixing research in the literature are studied by numerical simulation. The simulation results of the mixing quality are qualitative and there is some difference of mixing degree among them (Zhang et al., 2019).
  - ➢ Therefore, the experimental investigations about the mixing quality are needed for verification.

Problem Statement – Droplet Generation

- The existed studies focused on the viscosity and shape of the microchannels for droplet merging and splitting process, with less consideration given to the size or diameter of the microchannels (Darekar et al., 2017; Kashid & Agar, 2007; Salim et al., 2008), which also one of the properties that can affect the flow characteristics of the droplets.

Scope of Study:

1. Design and fabrication of T-junction and offset T-junction microchannels using electric drill machine.
2. Characterization of dissimilar liquids' mixing performance inside T-junction and offset T-junction microchannels in the range of $5 \leq Re \leq 50$.
3. Comparison and investigation of droplet behaviours inside offset T-junction microchannel having different inlet and outlet radiuses i.e., 400 µm, 500 µm, 750 µm and 1000 µm via micro-PIV technique.

Hypothesis:

1. For miscible mixing experiments, the mixing performance for low Re is directly proportional to the mixing time. This is because higher residence time inside the microchannel allows for higher molecular diffusion as the flow rate of the mixing liquids is low. As Re increases, massive convective diffusion dominates the flow which will influence the mixing process and performance.

2. Viscosity-density difference contributes to the increases of mixing index as high viscous and more dense liquid pushes a low viscous and less dense liquid from the channel wall which will result in an increase of the interface area and consequently improves the mixing in this regime.

Hypothesis:

3. Molecular diffusion process between immiscible liquids is difficult compare to the miscible mixing liquids. Chaotic mixing may take place at the direct intersection of T-junction microchannel which will make offset T-junction microchannel offer better mixing performance due to the more space (indirect collision) and less momentum between the liquid-liquid interaction.

4. The microchannel with smaller radius has higher disperse phase's velocity than the channel with bigger radius. An increase in cross-sectional area and a decrease in disperse phase's velocity could result from increasing the radius of offset T-junction microchannel.

Hypothesis:

5. The size of the droplets is getting bigger and may nearly equal to the microchannel's width as the radius of microchannel increases.

6. The vector and velocity magnitude data of this droplet generation experiment should be in an agreement with Hagen-Poiseuille flow equation, which explains a minor increase in the channel's internal diameter results in a substantial increase in overall liquid flow.

Objectives:

1. To design and fabricate T-junction and offset T-junction microchannels
2. To characterize mixing index of dissimilar liquids inside T-junction and offset T-junction microchannels
3. To investigate the effect of offset T-junction microchannel's size on water-in-oil droplet's behaviors using micro-PIV technique

Methodology (Objective 1)

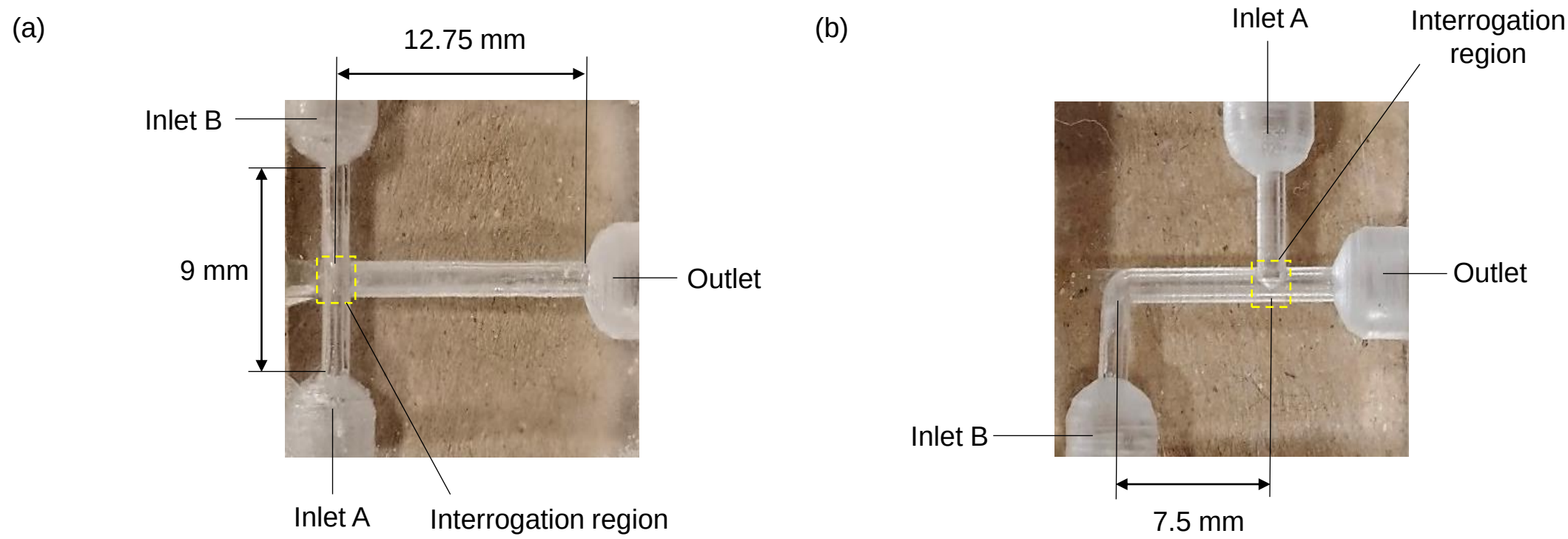


***Figure 4**: Fabricated microfluidic (a) T-junction and (b) offset T-junction channels with inlets and outlet radius of 750 µm for micromixing experiment (20 × 17 × 8 mm^3)*

Methodology (Objective 1)

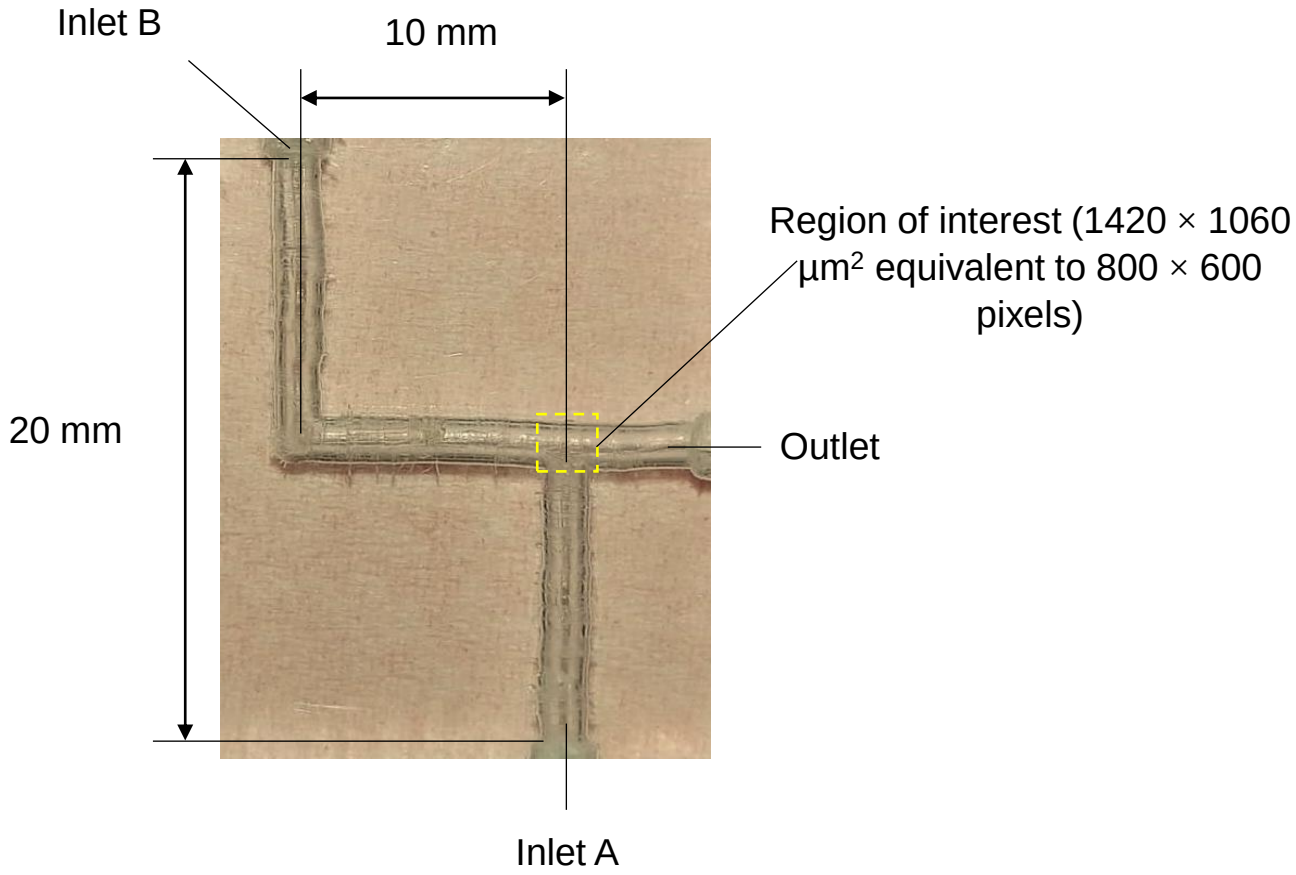


***Figure 5**: Fabricated offset T-junction microchannel with inlets and outlet radius of 750 μm for droplet generation experiment (25 × 20 × 6 mm^3)*

Methodology (Objective 2)

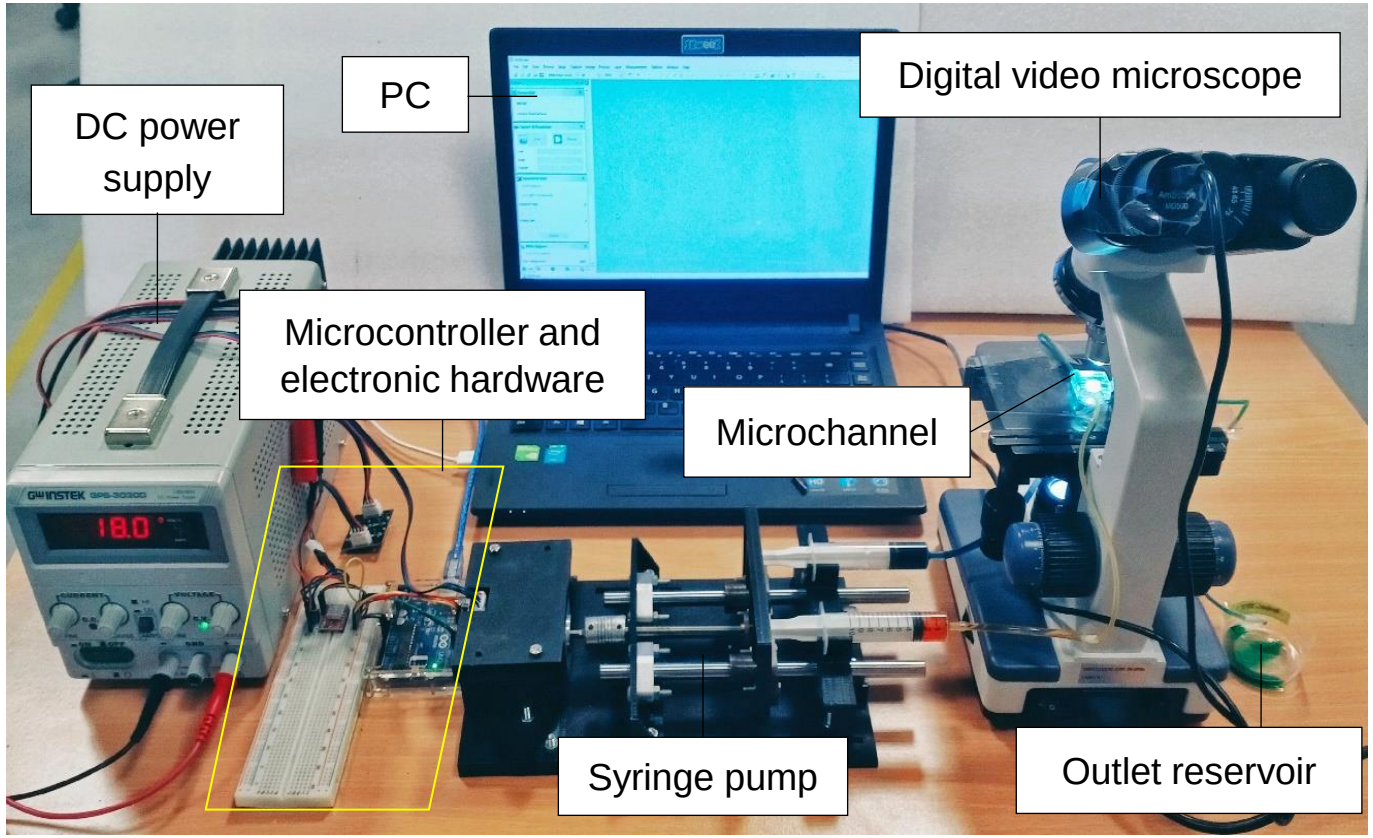


***Figure 6**: Micromixing experimental setup*

Methodology (Objective 2)

***Table 3**: Dissimilar liquids for micromixing experiment*

Experiment	Inlet A	Inlet B	Miscibility
1	Propan-2-ol + blue dye	Water + yellow dye	Miscible
2	Water + yellow dye	Sodium chloride solution + blue dye	Miscible
3	Propan-2-ol + blue dye	Sodium chloride solution + yellow dye	Immiscible

- Each food grade dyes was mixed with the chosen liquids with ratio of 1:100 for each mixing experiment.
- Since during the processes of mixing, the density as well as dynamic viscosity of the mixture were different, the properties of water were taken as the reference for the whole experiments (Wang et al., 2012; Viktorov et al., 2016; Mahmud & Tamrin, 2020).

Methodology (Objective 2)

RGB Colour Model by (Mahmud & Tamrin, 2020):

$$Mixing\ Index = \frac{N_{mixed}}{N_{mixed} + N_{unmixed}} \quad \text{(Equation 1)}$$

N_{mixed} and $N_{unmixed}$ are the number of pixels classified as mixed and unmixed solution, respectively, based on the following:

$$N_{mixed} = n(\{r_{g,min} \leq R \leq r_{g,max} \cap g_{g,min} \leq G \leq g_{g,max} \cap b_{g,min} \leq B \leq b_{g,max}\}) \quad \text{(Equation 2)}$$

$$N_{mixed} = n(\{r_{b,min} \leq R \leq r_{b,max} \cap g_{b,min} \leq G \leq g_{b,max} \cap b_{b,min} \leq B \leq b_{b,max}\}) + n(\{r_{y,min} \leq R \leq r_{y,max} \cap g_{y,min} \leq G \leq g_{y,max} \cap b_{y,min} \leq B \leq b_{y,max}\}) \quad \text{(Equation 3)}$$

The number of pixels, satisfying RGB conditions, is specified using n while ∩ symbolizes for the Boolean AND operation. The letters *'r'*, *'g'* and *'b'* are used to identify the red, green and blue values respectively. The letters in the subscripts (g, b and y) denote the respective intensity values of the RGB for green, blue and yellow pixels. Their values range between 0 (unmixed solution) to 1 (fully mixed solution).

Methodology (Objective 3)

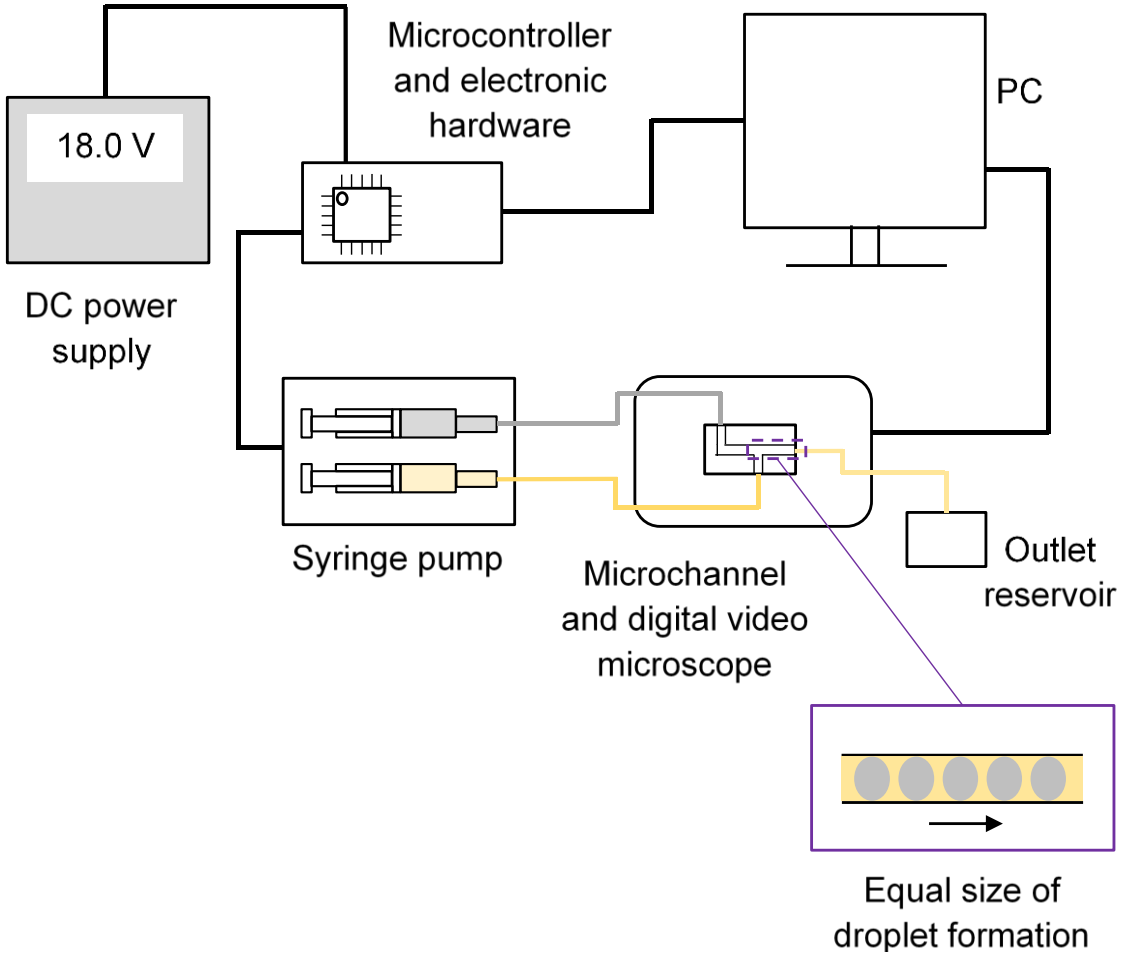


***Figure 7**: Schematic diagram of the experimental setup for droplet generation*

***Table 4**: Controlled parameters for droplet generation experiment*

Parameter	Value
Exposure time	3.906 ms
Colour temperature	5547
Frame rate	21.8 fps
Resolution	800 × 600 pixels
Motor step	5
Flow rate of liquid at the inlets	0.16 mm^3/s

Methodology (Objective 3)

***Table 5**: Specification of continuous and dispersed phase*

Food grade palm olein (Siddique et al., 2010)	Parameter	Distilled water
917	Density (kg/m^3)	997
7.97 × 10^{-2}	Dynamic viscosity (Pa·s)	8.90 × 10^{-4}

- The seeding particles was mixed with distilled water with ratio of 1:4 for each experiment.
- The food grade palm olein and the seeding particles were assumed to have the same density and dynamic viscosity as distilled water.

***Table 6**: Specification of seeding particle (Turner et al., 2018)*

Composition/ Material	Polystyrene
Manufacturer	Thermo Scientific™ 4210A
Diameter	10 µm ± 0.08 µm
Concentration	0.2% solids
Density	1050 kg/cm^3
Refractive index	1.59 at 589 nm (25°C)

- Due to the particles small size and minimal density difference between the particles and water, they are assumed to faithfully follow the flow of water (Santiago et al., 1998; Tamrin et al., 2015).

Methodology (Objective 3)

Micro-PIV Lab (Thielicke & Stamhuis, 2014; Thielicke, 2014):

- The region of interest was set to the whole area of the 800×600 pixels frame (1420×1060 μm^2).
- For image pre-processing, contrast limited adaptive histogram equalization (CLAHE) was applied to the images for visibility enhancement (Yadav et al., 2014).
- It is noted that the average seeding density is 5 particles per 32×32 window while the threshold parameter for the signal-to-noise ratio was set at 1.5.
- The resulting velocity fields have a spatial resolution of 28.4 µm × 28.4 µm × 55.5 µm. Then, the images were processed by cross-correlation function in order to obtain the raw velocity vectors of the liquids.
- To compensate for aberration (Tamrin et al., 2015; Tamrin et al., 2015), the calibration was performed using the image of 10 µm polystyrene microsphere flowing inside the microchannel, which resulted to 6×6 pixels based on 4× magnification of digital video microscope.
- The vector validation was done to eliminate some incorrect vectors remaining from noise peaks in the correlation function.

Results - Micromixing

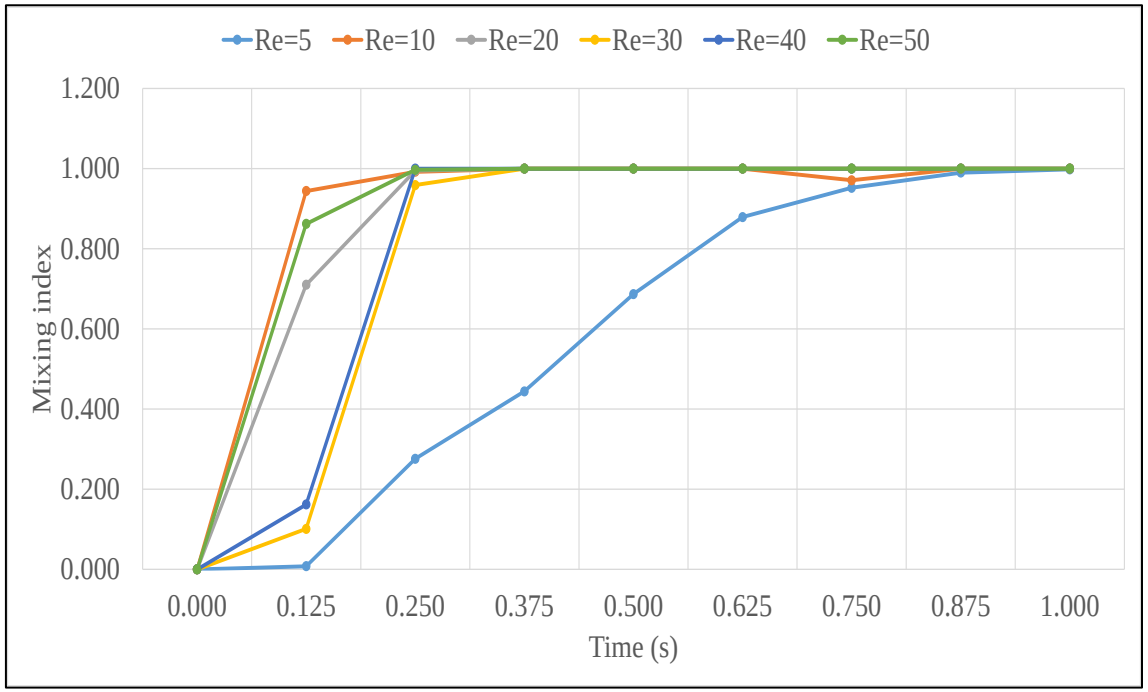


***Figure 8**: Mixing index of propan-2-ol and water at T-junction*

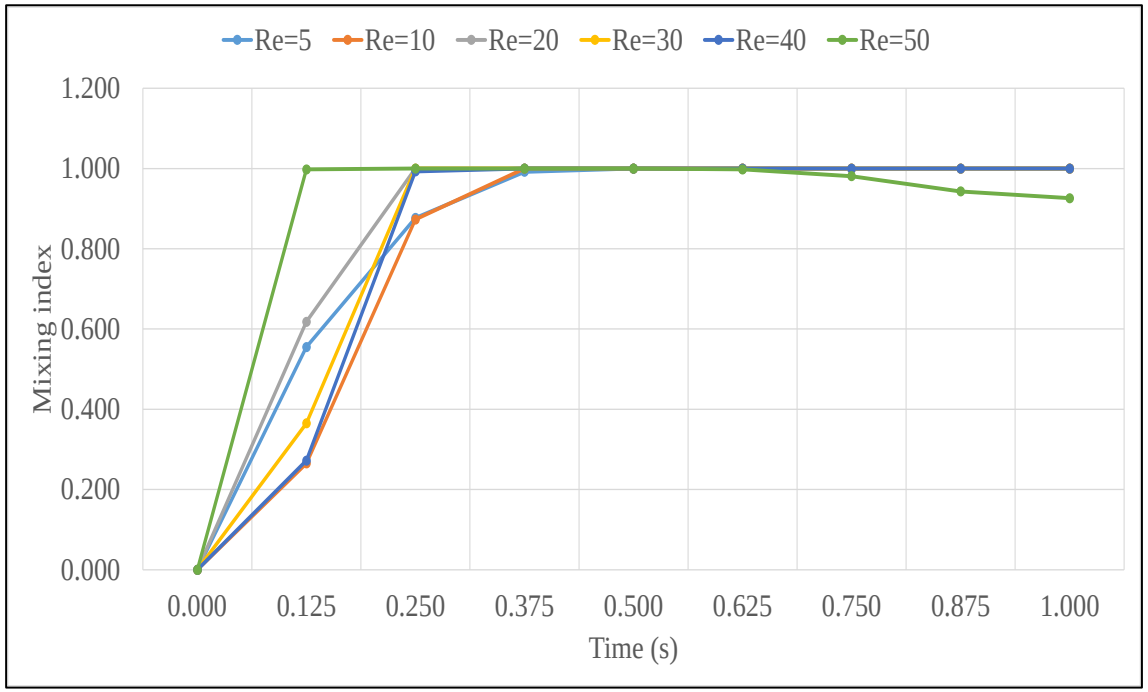


***Figure 9**: Mixing index of propan-2-ol and water at offset T-junction*

Results - Micromixing

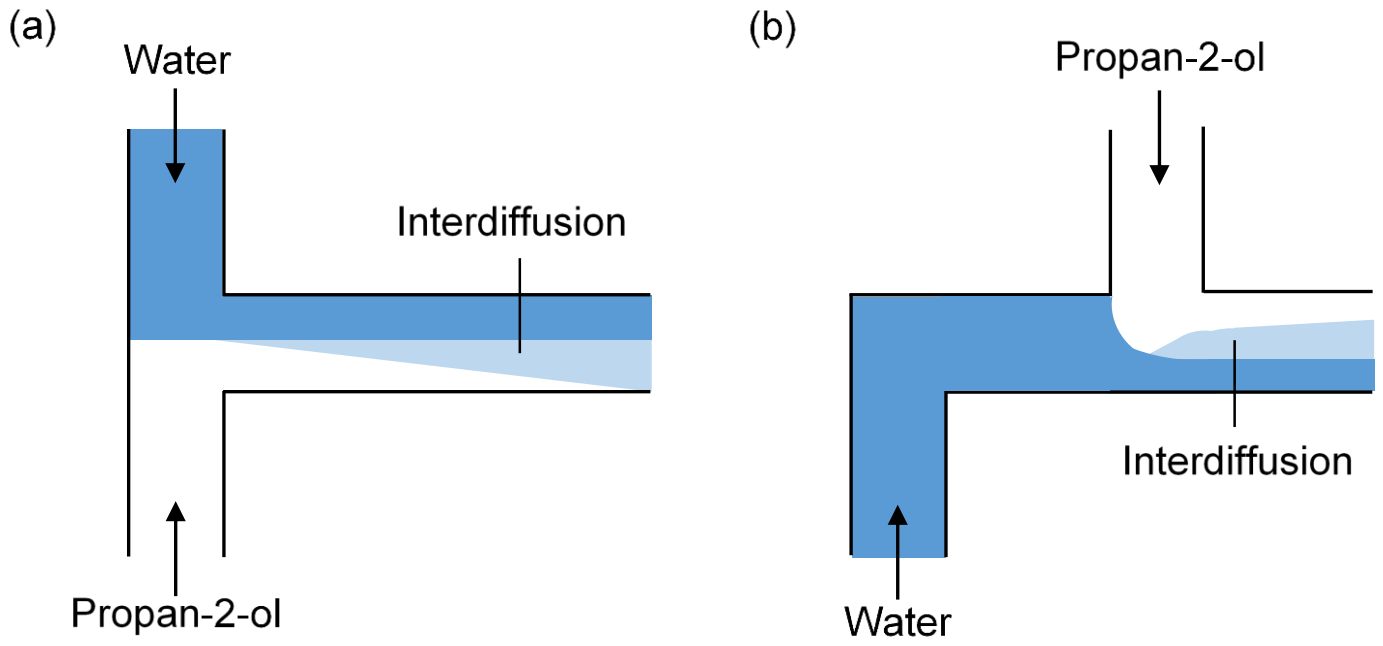


***Figure 10**: Top view indicating schematically the interdiffusion layer of miscible propan-2-ol-water micromixing in (a) T-junction and (b) offset T-junction microchannels*

Results - Micromixing

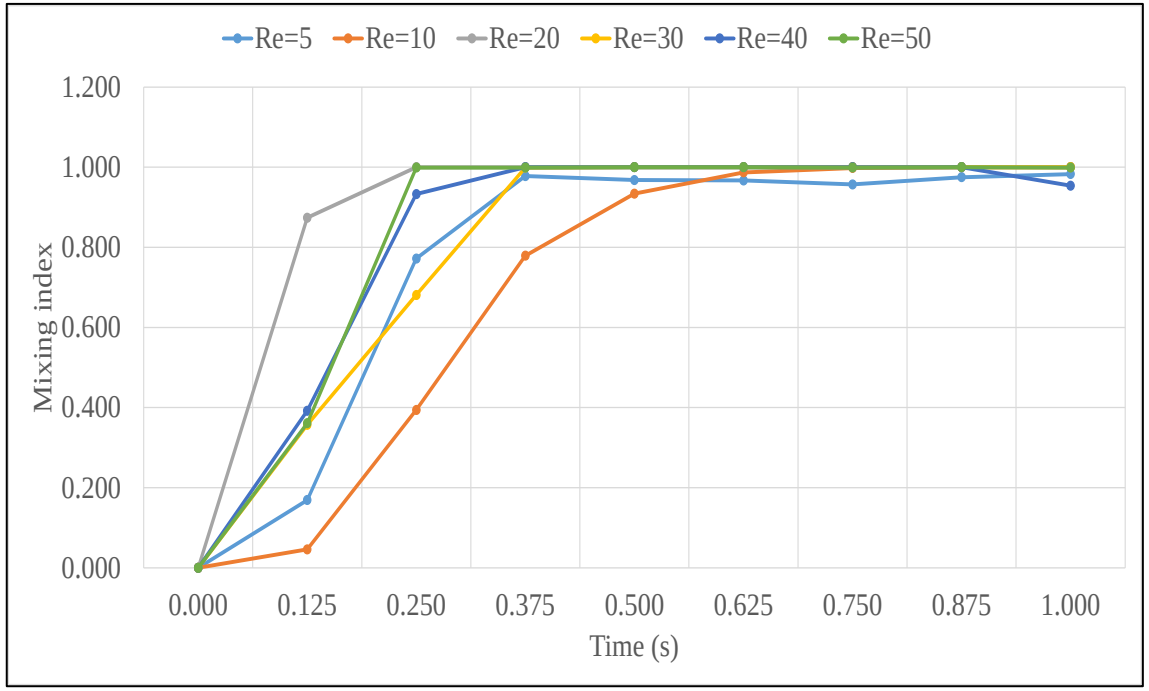


***Figure 11**: Mixing index of water and sodium chloride solution at T-junction*

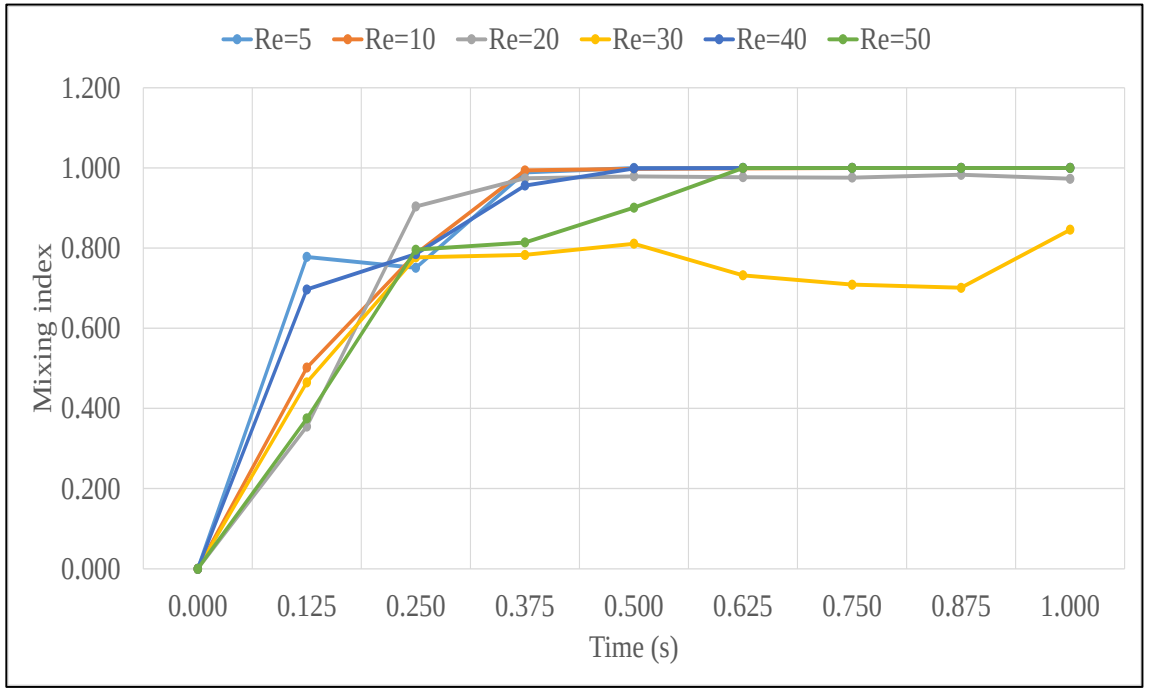


***Figure 12**: Mixing index of water and sodium chloride solution at offset T-junction*

Results - Micromixing

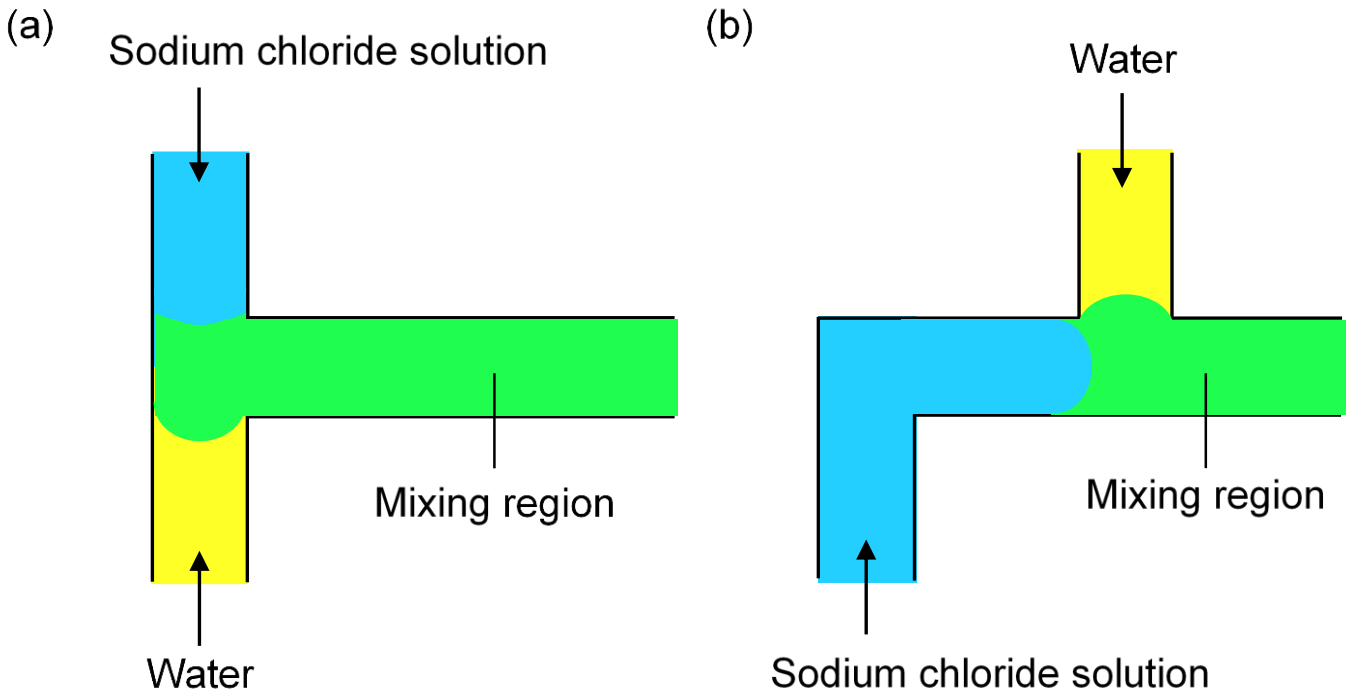


***Figure 13**: The schematic diagram mixing of water and sodium chloride solution in (a) T-junction, and (b) offset T-junction microchannels*

Results - Micromixing

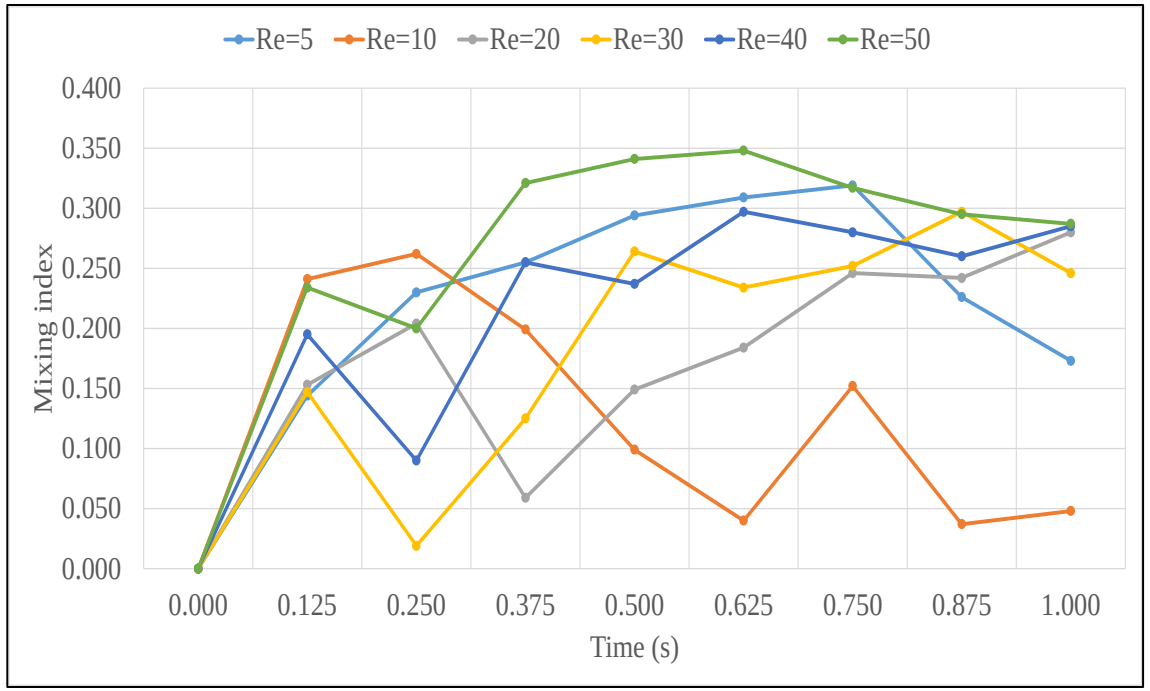


***Figure 14**: Mixing index of propan-2-ol and sodium chloride solution at T-junction*

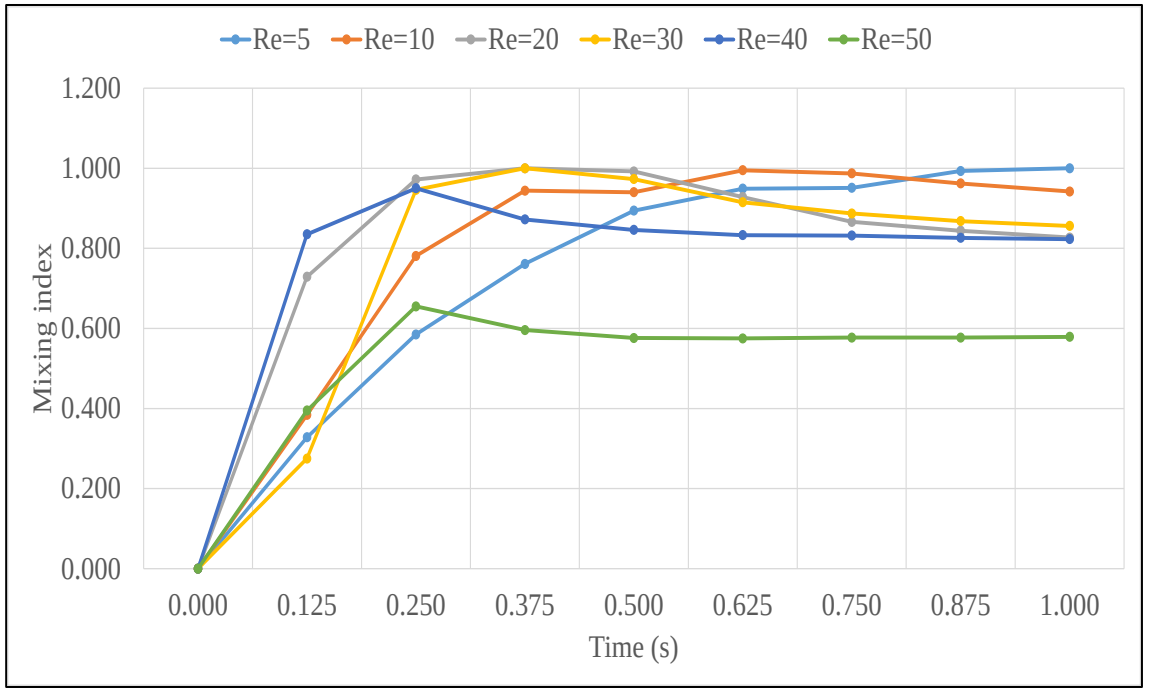
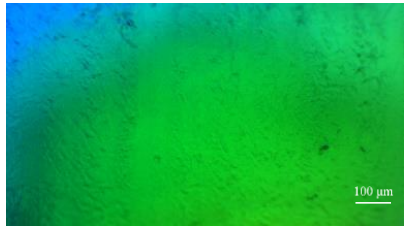


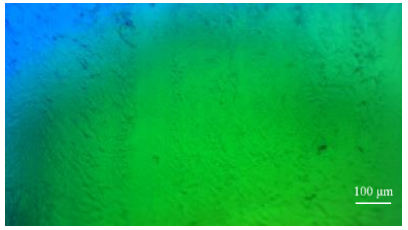
***Figure 15**: Mixing index of propan-2-ol and sodium chloride solution at offset T-junction*

Results - Micromixing



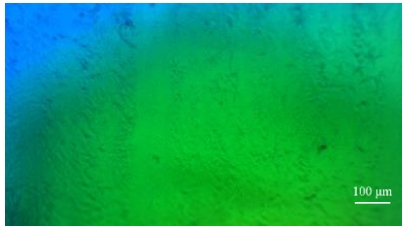
t = 0.375 s

MI = 0.872



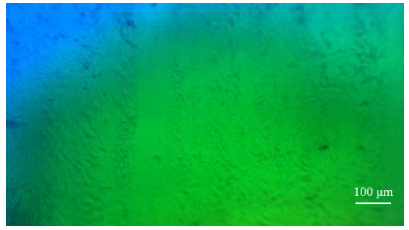
t = 0.500 s

MI = 0.846



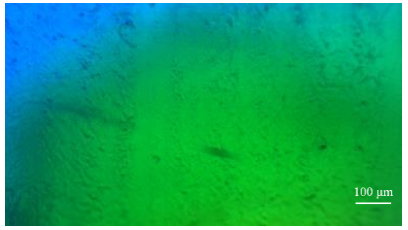
t = 0.625 s

MI = 0.833



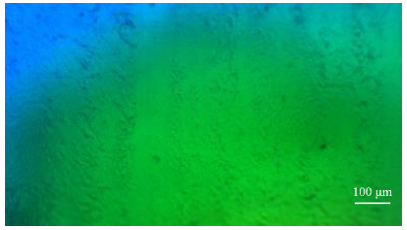
t = 0.750 s

MI = 0.832



t = 0.875 s

MI = 0.826



t = 1.000 s

MI = 0.823

***Figure 16**: Actual mixing images (1400 µm length and 790 µm width) of blue dye in propan-2-ol and yellow dye in sodium chloride solution within offset T-junction microchannel at Re of 40. MI stands for mixing index.*

Results - Micromixing

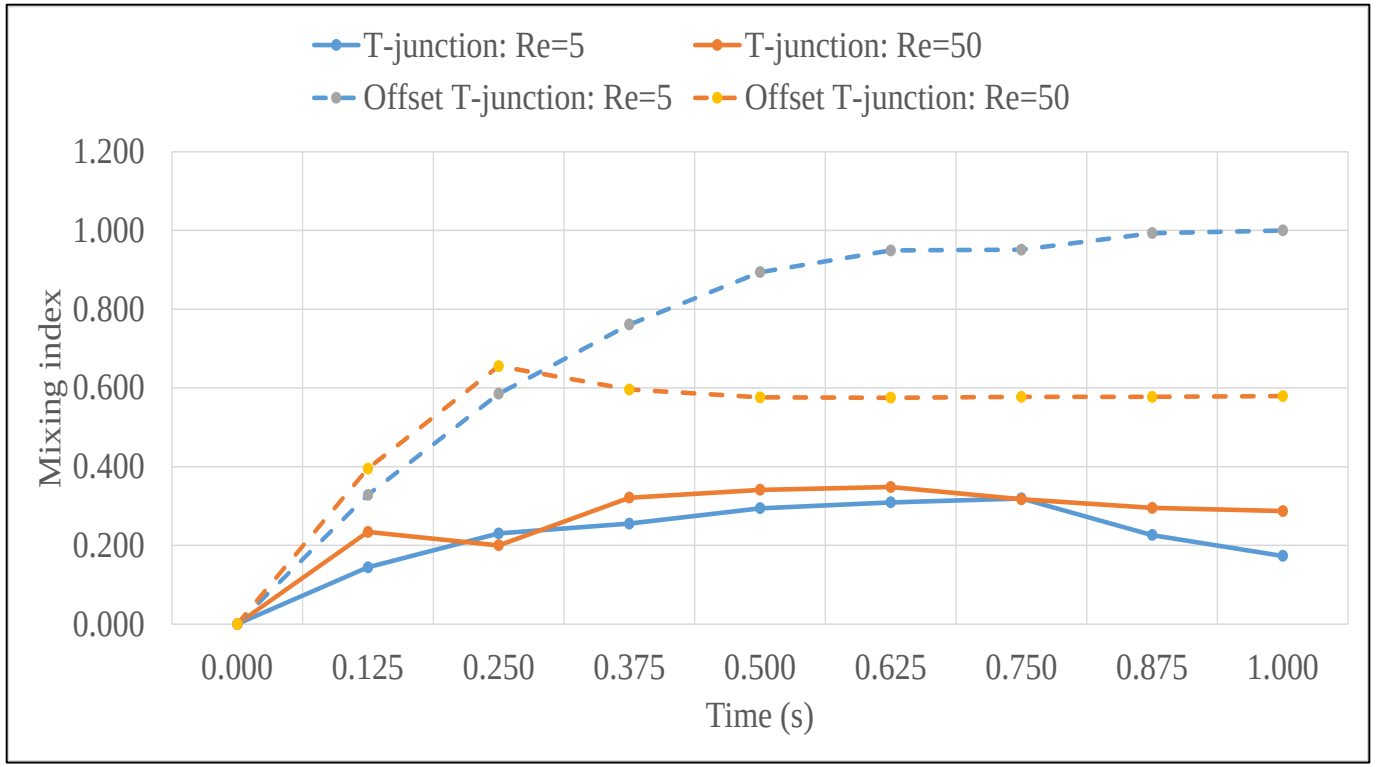
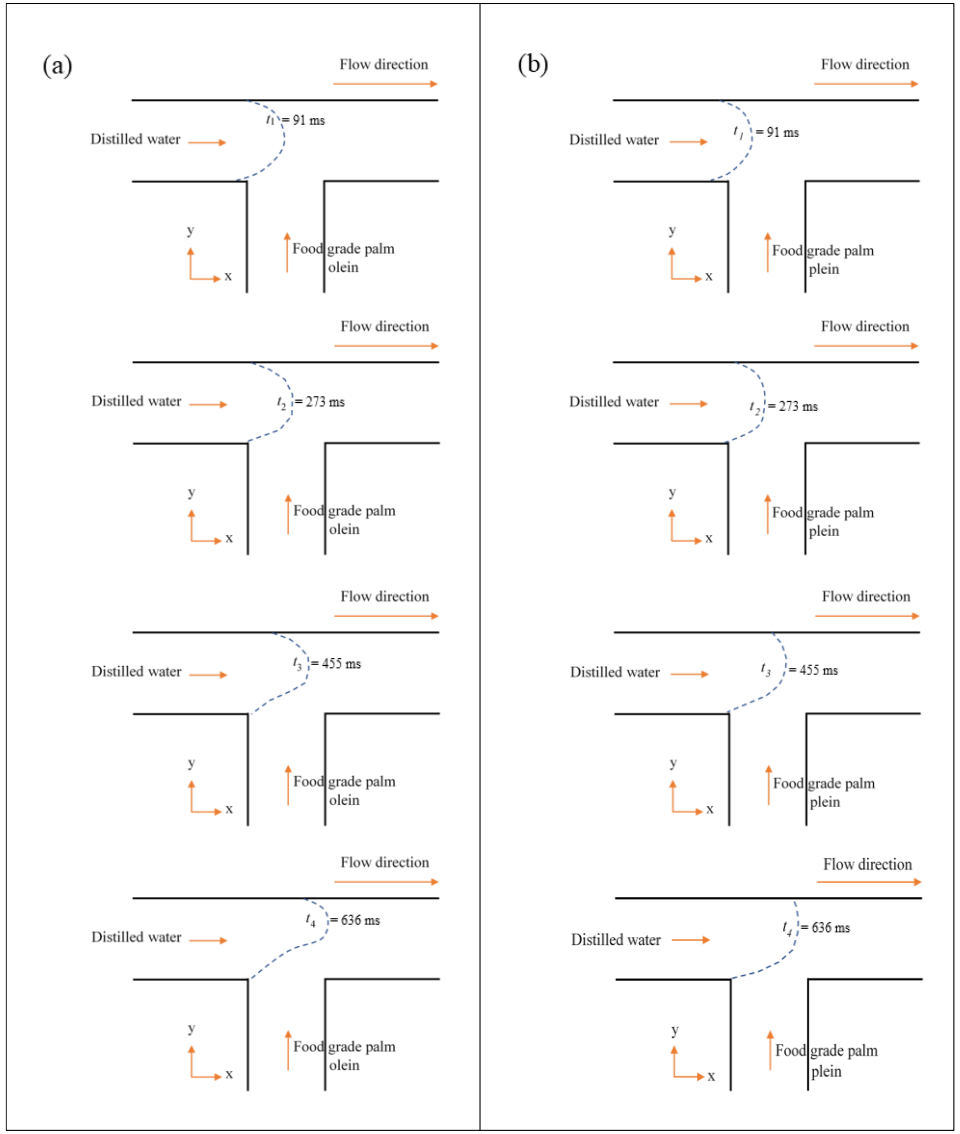


***Figure 17**: Comparison of mixing index between propan-2-ol and sodium chloride solution at different Re in T-junction and offset T-junction microchannels*

Results – Droplet Generation



- When the droplet reached the junction, the oil pushed the water droplet upwards and cause an irregular shape at the bottom of the droplet as can be seen at t = t3.
- This point is named as thread expansion stage and the period is called expansion time (Fu et al., 2009). The droplet is likely starting to be in the break-up process. The length increases gradually while the width increases moderately.
- As it reached t = t4, the cross-flowing liquids drove the thread in its axial direction and a visible neck formed.

***Figure 18**: The evolution of water droplets for offset T-junction microchannels with radius of (a) 400 µm, and (b) 750 µm*

Results – Droplet Generation

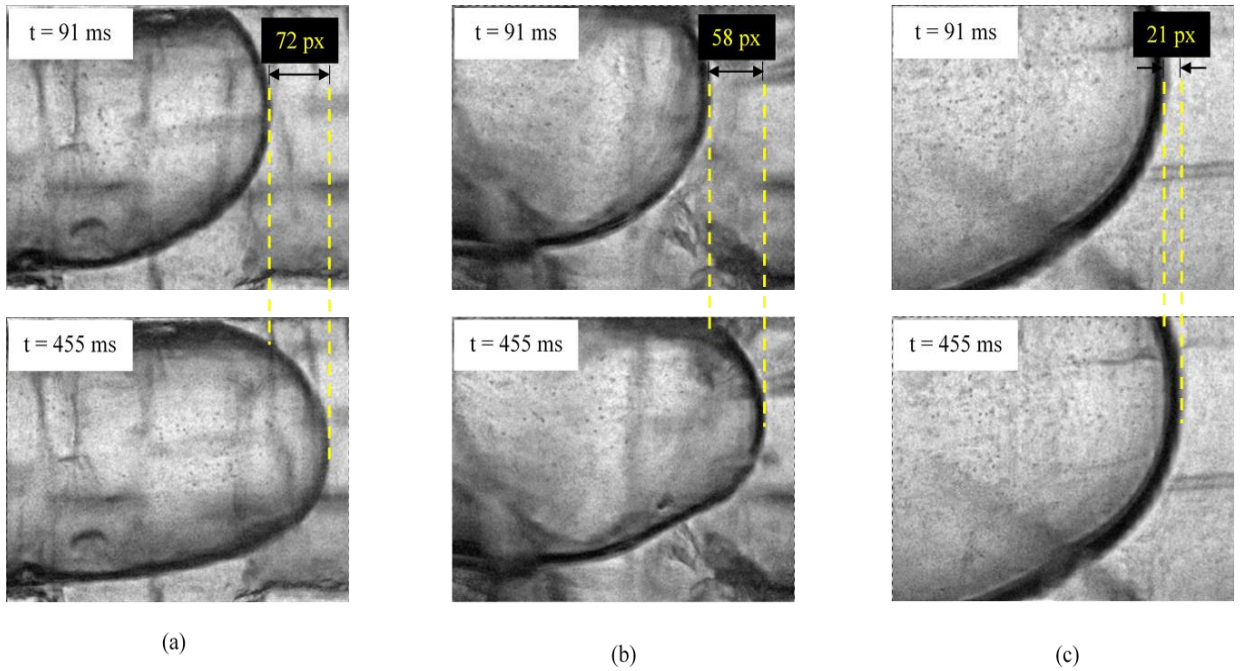


***Figure 19**: The motion of water droplets after 364 ms within radius of (a) 400 µm, (b) 500 µm, and (c) 750 µm offset T-junction microchannels*

***Table 7**: Theoretical and experimental velocity of water droplets*

Inlet and outlet radius of offset T-junction microchannel (µm)	Theoretical velocity based on Re (mm/s)	Experimental velocity (mm/s)
400	0.322	0.330
500	0.206	0.266
750	0.092	0.096
1000	0.051	

Results – Droplet Generation

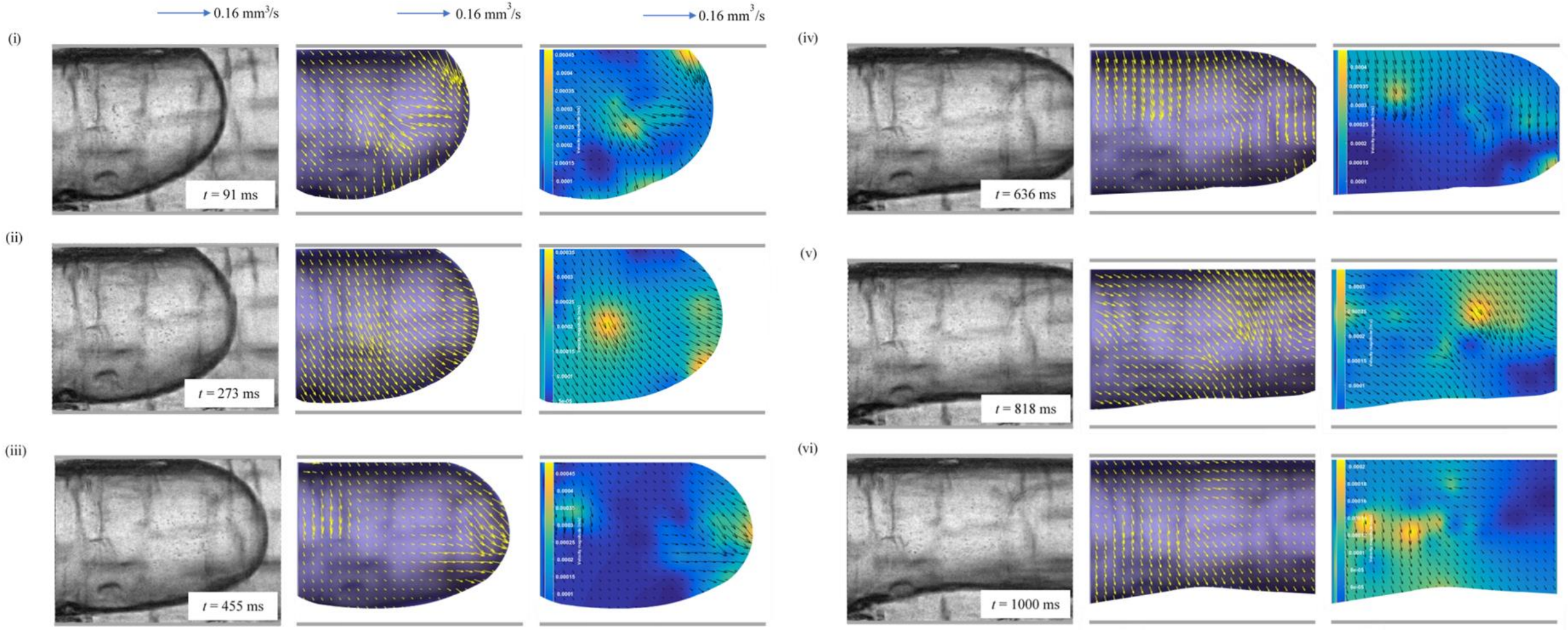


***Figure 20**: Pre-processing image, vector and velocity magnitude for offset T-junction microchannel with radius of 400 µm*

Results – Droplet Generation

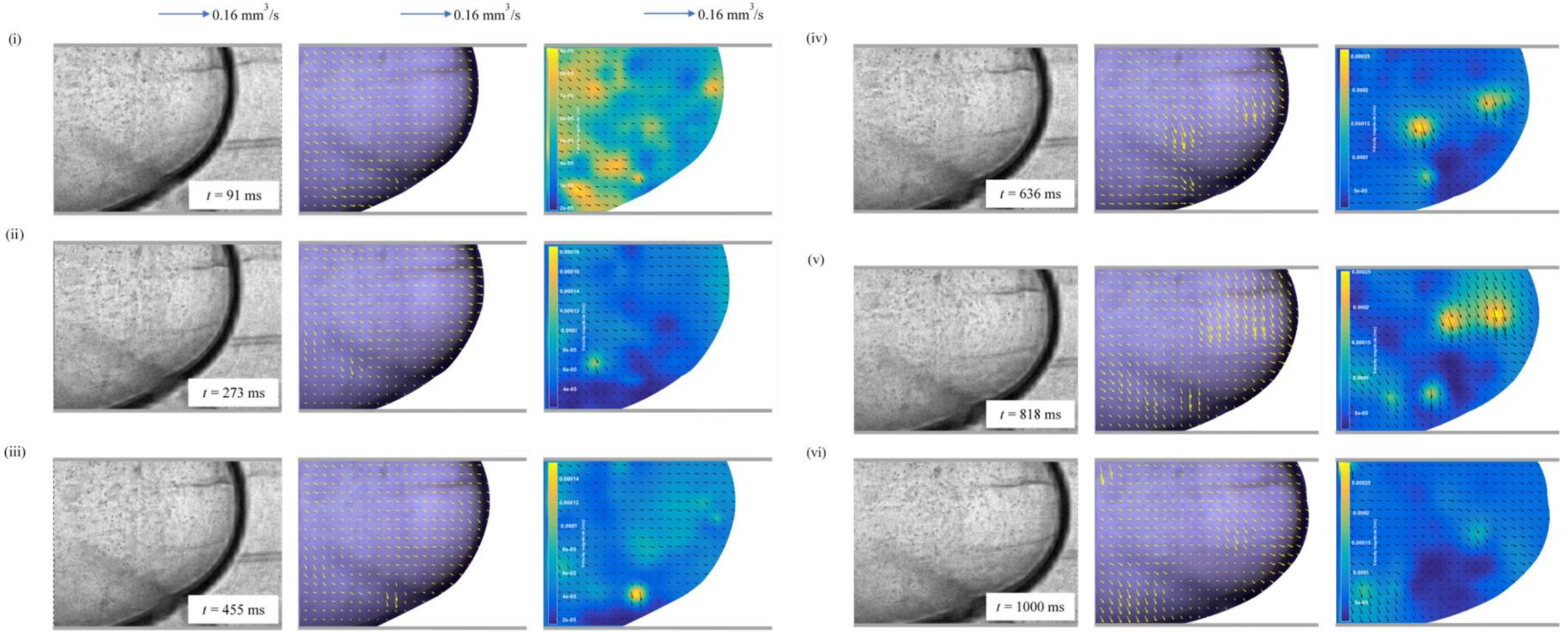


***Figure 21**: Pre-processing image, vector and velocity magnitude for offset T-junction microchannel with radius of 750 µm*

Conclusion - Micromixing

- For miscible mixing experiments i.e., propan-2-ol and water, water and sodium chloride solution, both microchannels show that mixing performance of these liquids for each Re is directly proportional to the mixing time.
- On the other hand, it is nearly impossible to mix propan-2-ol and sodium chloride solution in the microchannel. Nevertheless, offset T-junction microchannel offers better mixing of these two immiscible liquids compared to T-junction microchannel at both low and high Re. When the inlets of T-junction having an offset of 7.5 mm, the mixing quality increases by twice or more.

Conclusion – Droplet Generation

- The experimental results show that increasing in the radius of offset T-junction microchannel leads to the increase in cross-sectional area and the decrease of distilled water phase's velocity.
- The size of the droplets is getting bigger and nearly equal to the microchannel's width as the radius of microchannel increases.
- This concludes that the vector and velocity magnitude data in a good agreement with Hagen-Poiseuille flow equation, meaning that a small increase in the channel's internal diameter yields a significant increase in overall flow of a liquid.

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Publications

1. Ringkai, H., Tamrin, K. F., Sheikh, N. A., & Barroy, P. (2021). Characterization of dissimilar liquids mixing in T-junction and offset T-junction microchannels. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 235(6), 1797-1806. *(Published, ISI Q3, Impact factor 1.606)*

2. Ringkai, H., Tamrin, K. F., Sheikh, N. A., & Mohamaddan, S. (2021). Evolution of water-in-oil droplets in t-junction microchannel by micro-piv. Applied Sciences, 11(11), 5289. *(Published, ISI Q2, Impact factor 2.474)*