**Comparison of mixing performances of T, Y and arrow-shaped micromixers using Villermaux-Dushman protocol at low Reynolds number**

ONYEKA S. OKWUNDU1, 2, [[1]](#footnote-1)\*, MOHAMMED FUSEINI1.

*1Department of Chemical and Petrochemical Engineering, Egypt-Japan University of Science and Technology (E-JUST), Egypt.*

*2Department of Chemical Engineering, University of Benin, Nigeria.*

*Abstract:*Mixing performance is commonly assessed using the Villermaux-Dushman protocol. Mixing in passive mixers may be desired at very low Reynolds number (Re). This study is aimed at comparing the mixing performances of T, Y and arrow-shaped micromixers using Villermaux-Dushman protocol at Re < 100. Mixing performance test was run at flow rates of 500 to 1 mL/hr with pressure drop measurement. Based on UV absorbance values and experimental mixing times of mixed fluids from the three micromixers, the order of mixing performance at Re > 26.5 was Y < T < arrow-shaped micromixers. At lower Re values, the order of performance based on absorbance and experimental mixing times, became inconsistent. However, comparison of mixing performance based on predicted mixing time gave consistent order of performance at all Re values. Instability in UV absorbance of mixed reagents in Villermaux-Dushman protocol was noted as the major cause of the reported inconsistency at very low Re. Inadequacy of Villermaux-Dushman protocol at low Re was verified via facile solvent extraction test. A more reliable technique should be used to assess mixing performance of micromixers at very low Re and on-line UV measurement should be adopted for Villermaux-Dushman experiment.

*Keywords:* Mixing efficiency; Villermaux-Dushman test experiment; micromixer; low Reynolds number; confluence shape.

RUNNING TITLE: LOW REYNOLDS NUMBER VILLERMAUX-DUSHMAN TEST

INTRODUCTION

Most chemical processes require contacting of different substances to achieve homogeneity, emulsification, dispersion or even chemical reaction as in the case of combination reactions where different molecular species have to contact before conversion. One of the most important methods of enhancing mixing at micro level is by using micro scale devices.1 Dating back to the early nineties, micro scale devices such as micromixers (or microreactors; when chemical reaction is involved) have attracted great attention in laboratory as well as industrial or commercial scale.2,3 The values of Reynolds number (Re = ρud/μ; where: is the density, u is the flow velocity, d is the characteristic diameter of the micro channel cross section, is the dynamic viscosity of fluid; assuming that flow regime laws apply in micro-channels) are usually very low in micro-structured devices due to their small characteristic dimension; internal cross sectional diameter in the order of 102 μm.4 Therefore, flows in micro channels fall within the laminar regime.

But, if flow in micro-channels is in the laminar regime, how then is fluid mixing possible? Based on the way mixing is achieved, there are two classes of micromixers: active and passive micromixers.5,6 Only the passive micromixer for which fluid-fluid interfacial contacting (mixing) is effected by energy of flowing fluids (no external energy source like mechanical stirring is employed, as in the case of active ones) is implied throughout this study. The reduced cross section of micro-channels leads to increased rate of fluid shearing and based on the micromixer geometry or configuration (point of confluence, obstruction, bend or twist), the fluid in laminar flow gets deformed via convection as it flows past such obstructions, bends, twists or as streams meet at point of confluence and that is the mechanism of mixing in passive micromixers.6,7 Primarily, there is diffusive mixing at molecular level and this diffusion is enhanced by the relatively reduced diffusion path or cross section of flow.7 In fact, “Molecular diffusion is the ultimate and finally the only process really able to mix components of a fluid on the molecular scale”.6

As a result of their small sized channels, micromixers offer increased fluid surface area to volume ratio and this makes them very useful in high mass transfer and heat transfer applications.5 Commenge and Falk noted some other interesting applications of micromixers arising from their compact nature, to include: safety of operation in case of highly exothermic and fast reactions involving hazardous chemicals; new and untapped reaction routes for chemical synthesis (such as direct fluorination), which are very dangerous can be accessed and there is improved efficiency in energy utilization by using passive micromixers.3 In addition, the small sized devices save materials and time; since just little volume of fluid is required to operate them and reasonably short residence time is needed. Unlike most chemical process equipment that are bulky, micromixers are very portable.

Consequent to the relevance of mixing and the beneficial nature of micromixers, assessment of the mixing performance of micromixers is a very important step for their design (making good choices). While it may be so easy to assess the performance of some micro-devices by comparison of some standard parameters like heat transfer coefficient for heat exchangers, the case of micromixers is quite difficult.2 A number of techniques have been utilized to assess mixing performance and they include in order of increasing preference: visualization of dyes as their colour fades away due to dilution by mixing or as their colour changes in case of pH sensitive dyes, visualization of reactions that progress with change in colour and most recently, monitoring of competitive test reaction schemes.1–3,8

Amongst the competitive test reaction schemes used for mixing performance assessment, Villermaux-Dushman reaction scheme which consists of two parallel reactions: neutralization and redox reactions in competition for proton from acid, is well known and most used.3,7 The neutralization reaction given by Eq. 1 is instantaneous (extremely fast) while the redox reaction (Eq. 2) is just fast.5,6 All species in Eq. 1, 2 and 3 are aqueous.

H2BO-3+ H+ ↔ H3BO3 (instantaneous) (1)

IO-3+ 5I- + 6H+ ↔ 3I2 + 3H2O (just fast) (2)

I2 + I- ↔ I-3 (3)

A strong acid is used to generate the protons in one reactant (acidic) solution while the second (buffer) solution for the mixing contains: , and . Falk and Commenge 6 require that only critical stoichiometric amount of acid needed to neutralize the borate ions according to Eq. 1 must be used for the test, while Fournier et al 9 state that the acid should just be the limiting reagent. The concept of the Villermaux-Dushman protocol is briefed as follows.3,6 When mixing is perfect, the stoichiometrically fitted instantaneous reaction (Eq. 1) completely consumes the protons, leaving no room for the slower Eq. 2 to proceed. However, when mixing is poor, there is segregation (heterogeneous fluid behavior) of the two reactant solutions into acidic and buffer segregates (local sites), making the amount of protons in every acidic segregate to be excessively high to just complete the neutralization of the borate ions in the immediate surrounding (boundary/interphase). The excess protons enable the occurrence of the redox reaction to form iodine. The extent of segregation/size of the segregates depends on the mixing efficiency/performance and that determines the amount of iodine to be produced. Eq. 3, which utilizes the iodine, is very useful for quantitative analysis because the amount of produced can be easily measured using UV spectrophotometer at a wavelength of 353 nm. Hence, relatively low absorbance values of mixed products indicate relatively high mixing performance and vice versa. Ehrfeld et al 2 share similar idea but they utilized acetate in place of borate species in Eq. 1. Some works 2,10 are reported with product absorbance measured at 352 nm noting that the UV-spectrum has a peak at that wavelength rather than at 353 nm; however, the values are quite close. Commenge and Falk 3 further noted that the test yields optimum (most sensitive) result when the rates are such that: the neutralization occurs in zero seconds (quasi-instantaneous) and the redox reaction occurs at roughly the same time as the mixing time. Villermaux-Dushman protocol is also known as the iodide/iodate test method.

Primarily following the Villermaux-Dushman protocol, performance of a mixer at certain conditions should be assessed based on the observed absorbance value of the mixed products (the higher the absorbance, the poorer the performance and vice versa). Unfortunately, several authors 3,6,11 recommend that mixing performance criterion should not be concentration dependent. Mixing time (tm), according to Commenge and Falk 3 which ought to be adopted by Asano et al,11 is given in Eq. 4. Obviously, the model is concentration dependent, since it includes absorbance and initial concentrations as variables.

tm = 0.33(OD)[H+]0-4.55 [KI]0-1.5 [KIO3]05.8 [NaOH]0-2 [H3BO3]0-2 (4)

Where: OD is optical density which is equivalent to the absorbance of mixed reagents/sample for cuvette of optical density = 1 cm; [i]0 is the initial molar concentration of chemical species ‘i’ (in the stock reagent solution).

However, satisfactory attempts to express tm as a concentration free parameter (in terms of kinematic viscosity and specific power dissipation rate) are reported somewhere.9 By analysis of literature results, Commenge and Falk 3 obtained a relationship between theoretical mixing time (tmp) in seconds and specific power dissipation (Ɛ) in W/kg as given in Eq.5. They recommend that the equation be used when pressure drop data due to flow through micromixer is available. Eq. 5 was used to predict mixing time in this work. The specific power dissipation or specific energy dissipation rate is expressed in terms of volumetric flow rate (Q), pressure drop (), density ( and control volume of the micromixer (V) as shown in Eq. 6.3

tmp = 0.15Ɛ -0.45 (5)

Ɛ = Q\*∆P/(ρV) (6)

Due to variations in channel dimensions and fluid flow conditions for different experimental set-ups, works on micromixer performance are better reported in terms of Re values rather than volumetric flow rates or velocity. Also, it may not be appropriate to compare values of performance data from different works because several authors report different reagent concentrations and reagents’ flow rate ratios.11 In the evaluation of mixing performance of T, Y, and oriented Y micromixers with spatially arranged outlet channel using Villermaux-Dushman protocol, at minimum flow rate of 10 mL/min at average fluid velocity of 0.331 m/s (minimum Re = 265), reduction in segregation index (improvement in mixing performance) with increasing flow rate is reported.5 From the result, by comparison of segregation index values at common flow rates, the oriented Y micromixers (which has arrow-shaped confluence) gave the best mixing performance followed by T and then Y-mixer.5 Also, similar result on comparison of mixer performances and effect of flow rate on mixing performance was earlier reported using an online spectroscopic analysis system (UVmini1240, SHIMADZU), still at Re > 265.7 Information on mixing performance at very low Re values is scarce and such information may be very valuable in certain applications like drug delivery and in achieving mixing down to cellular level in biological systems.

In consolidation with the works of other researchers, this study aims at comparing the mixing performances of three different configurations of micromixers (T, Y and arrow-mixers) using the Villermaux-Dushman test reaction at low Re values. To achieve this aim, the Villermaux-Dushman protocol was carried out for the micromixers with pressure measurements and then, the absorbance values of mixed products from each of the micromixers, the experimental and predicted mixing times were compared at various Re values.

MATERIALS AND METHODS

*Materials*

T, Y and arrow-shaped micromixers made by 3D printing, each with uniform internal diameter of 0.5 mm and length of 30 mm after confluence, were used in this study. Two syringes each of capacity 60 mL and diameter 26.72 mm were used as feed storage tank. Other accessories such as G28 screws, teflon and small (micro) sized pipes were used for connection.

The consumable chemicals, which include: sodium hydroxide pellets (product of AppliChem GmbH, Germany), 99 % pure potassium iodide (product of Chem-Lab NV, Belgium), boric acid (product of MP Biomedicals, LLC, France), potassium iodate (Rankem ™, RFCL Limited, India), methanol (>99.9 %, product of Fisher Scientific UK) and hydrochloric acid of 37% purity and specific gravity of 1.18 (product of Fisher Scientific UK) were all of analytical grade and accessed from Chemical and Petrochemical Engineering Laboratory, E-JUST, Egypt. Hedeya cooking oil was purchased from Fathalla-Gomla Market, Borg El-Arab, Alexandria, Egypt.

Dual-syringe infusion pump (model: 115 VAC; Cole-Parmer ™, USA), KOBOLD Hand-Held Pressure Measuring Device for Differential Pressure for 2 External Sensors (HND-P215; with accuracy of 0.0005 psi), 2 KOBOLD Pressure Sensors (HND-PS19) and HITACHI UV Spectrophotometer (U-3900; for absorbance measurement, with 0.0005 accuracy) equipped with sample cell/cuvette of optical path length = 1cm, were accessed from different laboratories in E-JUST.

*Methods*

*Villermaux-Dushman experiment with pressure measurement.* One liter each of the acid (0.03 M aqueous HCl) and buffer (0.09 M H3BO3 (aq), 0.09 M NaOH (aq), 0.006 M KIO3 (aq) and 0.032 M KI (aq)) solutions for Villermaux-Dushman reaction were prepared and labeled solution 1 and solution 2 respectively.11,12 Two 60 mL syringes were filled with solutions 1 and 2, labeled and clamped onto the dual syringe pump. The Y-mixer was connected with two pressure probes (sensors) at the mixer inlet and outlet pipes. The experimental set-up is as shown in Fig. 1a. Fig. 1b shows details of the micro-channels of the Y, T and arrow-shaped micromixers showing the confluence shapes and angular deviation of fluid streams at point of confluence (with flow directions).

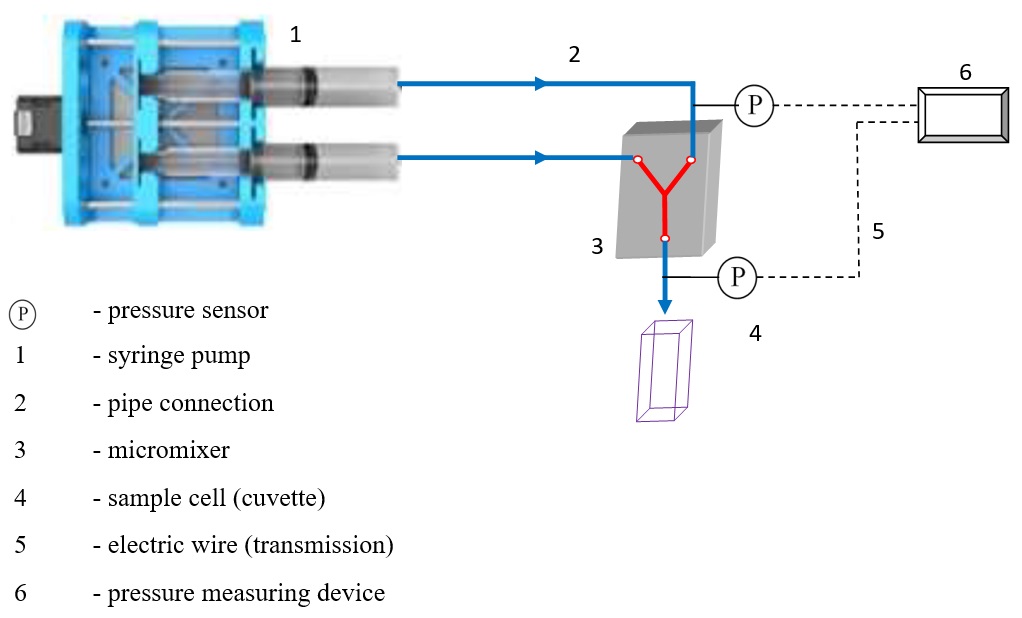


Fig. 1a. Schematic diagram of the experimental set-up

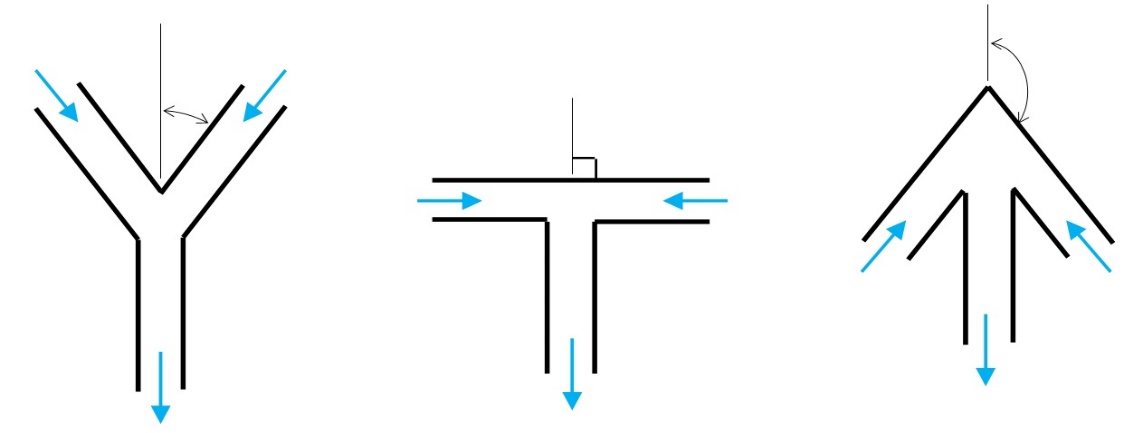


Fig. 1b. Illustrative details of the micro-channels of the mixers showing the confluence shapes and angular deviations (60, 90 and 120o) of fluid streams at point of confluence.

The syringe pump was switched on and set to: volume, diameter and flow rate of 60 mL, 26.72 mm and 500 mL/hr respectively. Afterwards, the pump was run. Pressure readings were taken after the flow had attained steady state (as indicated by constant pressure readings), while 2 mL of mixed sample was collected after discarding the first 20 mL that flowed out in order to ensure steady concentration. UV absorbance of the collected sample was measured as fast as possible within the set wavelength range of 320 to 370 nm, and recorded. Next, the flow rate was successively changed to 400, 300, 250, 200, 150, 100, 70, 50, 30, 15, 7 and 1 mL/hr while repeating the same mixing performance characterization procedure each time. Afterwards, the Y-mixer was replaced with T-mixer and then arrow-shaped mixer while repeating the same procedure. Syringes 1 and 2 were refilled with solutions 1 and 2 respectively each time their content reduced below 25 mL.

All through the experiment, the connected micromixer was fixed at a horizontal position with the pressure probes maintained at the same position to avoid changes in pressure head (variation in hydraulic pressure with height). The upper limit of flow rate used in this study (500 mL/hr) was fixed by the maximum pressure limit (5.8 psi) of the KOBOLD (HND-PS19) pressure sensors while the lower limit (1 mL/hr) was fixed by time consideration.

Finally, mixing performance of the micromixers was assessed based on UV absorbance, predicted mixing time (tmp) and experimental mixing time (tm). The density and viscosity of the dilute solutions used in the experiment were assumed to be the same as that of water (approximately 1 g/cm3 and 1 cP respectively). With these solution fluid parameters, together with the micro-channel dimension, it was possible to express flows in dimensionless form as Re.

RESULTS AND DISCUSSION

*Mixing performance characterization based on UV absorbance values*

The acid and buffer concentrations used, resulted in high absorbance values at flow rates below 150 mL/hr (Re = 26.5). And according to Falk and Commenge,3,6 the absorbance-concentration relationship otherwise known as Beer-Lambert law is valid for the tri-iodide ion at absorbance range below 2.5. Dilution of the mixed samples of high absorbance is discouraged;3 a failed attempt to characterize performance by dilution of mixed samples with high UV absorbance is reported somewhere.12 Consequently, the concentrations of solutions 1 and 2 were each halved by doubling their volumes with distilled water before proceeding with experimental runs for flow rates below 150 mL/hr. As a result of this modification, the result (Fig. 2) is presented in two parts.

Fig. 2a and 2b show the effect of Re on absorbance at the stated reagent concentration for higher flows and halved concentration for lower flows respectively. Fig. 2a clearly shows that UV absorbance increased progressively for all the micromixers with decreasing Re. By comparison, arrow-mixer gave the least absorbance (best mixing performance), while Y-mixer gave the highest absorbance (least mixing performance) for flows above Re value of 26.5. At Re equals 26.5, the three mixers measured up in absorbance. While it is clear from Fig. 2b that there is no consistent comparative trend in absorbance for the micromixers at Re < 26.5.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |
| Fig. 2. Effect of Re values on absorbance: at stated reagent concentration for higher flows (a), and with halved reagent concentration for lower flow rates (b). | |

In quest for possible reasons for the inconsistency in absorbance trend at Re < 26.5, the UV absorbance of mixed samples were measured with respect to time (age after sampling). It was found that the absorbance of mixed samples for all Re values, were not stable; the values reduced with samples’ age. Ehrfeld et al 2 noted this instability in absorbance although they report increase in absorbance using sodium acetate in place of NaOH and boric acid. The observed instability could be due to the reversible nature of most of the reactions in the Villermaux-Dushman reaction scheme. As a result of this, time lag between samples collection and measurement was kept to the minimum for greater accuracy. Also, the spectrophotometer was set to cover short range of wavelength (320 to 370 nm) to reduce response time in measurement. The observed sharp drop in absorbance at Re = 0.2 for all mixers as shown in Fig. 2b, could be due to the long time spent in collecting samples at such low flow rate – allowing such a long time lag for mixed samples absorbance to depreciate. Substantial reasons for the absorbance instability with samples’ age cannot be proffered because the kinetics of Villermaux-Dushman reaction is not well understood.13

Again, mixed samples were quickly collected and analyzed for UV absorbance at very close time intervals from the on-set of mixing till exhaustion of syringe contents, at different Re values. The result showed that steady absorbance value (with noise of at Re < 17.7 and 0.003 at Re ≥ 17.7 was attained after collecting at most 5 ml of mixed solution. The observed noise at steady state (at Re < 17.7) is quite high but too small to account for the observed inconsistency; because, the observed disorderliness in absorbance (for Fig. 2b) is greater than 0.01. Therefore, noise could have contributed only slightly to the inconsistency. This test justified the assumption of steady state concentration during sampling (discarding the first 20 mL of mixed sample).

|  |  |  |  |
| --- | --- | --- | --- |
|  | |  | |
| (a) | | (b) | |
| Fig. 3. Effect of Re values on experimental mixing time: with normal reagent concentration (a) and with adjusted reagent concentration (b). | | | |
|  |  | |  |
| Fig. 4. Effect of Re values on predicted mixing time. | | | |

*Mixing performance characterization based on mixing times.*

High mixing performance is characterized by low mixing time. Fig. 3 and 4, show the effect of changing Re on experimental mixing time (tm) and on predicted mixing time (tmp) respectively. It is clear from the figures, by comparison, that values of experimental mixing time at a given Re are more distinct than the predicted ones which are clustered together. Again, the range of values of tmp is lower than the experimental mixing time (tm). Fig. 3a and 3b were derived from the absorbance data presented in Fig. 2a and 2b, and the same discussion applies. Although it is not quite clear from Fig. 4 due to the clustered points; for all Re, tmp was least for arrow mixer and maximum for Y-mixer. tmp increased for all mixers as Re value was decreased. The increment in tmp was gradual but steeped up at Re < 12.4; similar step-up with decreasing Re is also noticeable in Fig. 3a; meaning that the sensitivity of mixing performance to changes in Re is higher at low Re than at high Re. Also, from Fig. 4, the maximum value of tmp was achieved at the least flow velocity (Re = 0.2). While from Fig. 3b, a very low tm (high mixing performance) was obtained and that appears unreasonable because at very low Re, mixing is wholly dominated by molecular diffusion without convective (vortex) enhancement. However, numerical simulations have shown that reduction of Re at certain range, could lead to increase in mixing quality.14–17 But that does not justify the inconsistency in order of performance encountered here, which is not different from an earlier report.12 Predicted mixing time of Fig. 4 does not conform to theoretical results 14–17, because the predicted model (Eq. 5),3 is independent of chemical species in the mixed stream.

Effect of confluence shape on mixing performance can therefore be explained as follows. At a given Re > 30, there is improvement in performance, since confluence shape encourages more fluid-fluid and/or fluid-wall impact when 2 fluid streams meet, and vice versa. Referring back to Fig. 1b, two factors are of importance in explaining the order of performance: impact on collision and simultaneous angular deviation in fluid flow direction. When the inlet fluid streams approach each other from opposite directions, as in the T-shaped confluence, the fluid-fluid collision impact is ‘head on’ and maximum, compared to the lower impact obtainable when the streams approach each other at an angle (as in the Y and arrow-shaped confluences). The effect of bend on fluid mixing along channels,18 also plays great role in mixing at confluence points because, with greater deviation at confluence, enhanced mixing is achievable. The angular deviation in flow direction for T-shaped confluence is just 90o while Y-shape offers the least deviation. The arrow-shaped confluence caused greatest agitation during collision of streams due to its maximum angular deviation (> 90o), coupled with its slight collision impact. T was better than Y because it offers the greatest collision impact and better deviation than Y-mixer. In all cases, mixing is enhanced with increasing Re value in the range > 30.

|  |  |
| --- | --- |
|  |  |
| Fig. 5. Effect of Re on pressure drop | Fig. 6. Effect of Re on energy dissipation rate |

*Variation of pressure drop and specific energy dissipation rate with Re.*

The modification in concentration stated in section 3.1 did not affect the pressure drop and therefore, Fig. 4 to 6 are not split into two. The effect of inlet Re on pressure drop (∆P) as a result of flow through each micromixer is shown in Fig. 5. From the figure, ∆P increased somewhat linearly as Re increased. The variation in ∆P among the three micromixers becomes wider (diverges) as one moves from low Re to higher Re. Similar trend is reported by Hossain et al,8 Jafari et al 19 and Kockmann et al.15 To understand this divergence, we consider the possible expressions for ∆P or pressure head as a function of Re or velocity; hence, Hagen-Poiseuille equation and Darcy’s equation. But, flows in micromixers are not ideally laminar to be described as Hagen-Poiseuille flow. Based on Darcy’s relationship, ∆P is proportional to *f*u2; where *f* is a dimensionless parameter (a function of flow velocity and other factors) commonly known as friction factor and u is the average velocity of flow.20

When fluid streams (from two identical branches of micromixer) collide/meet, mixing takes place at the expense of energy which is felt as drop in pressure. The effect of Re on energy dissipation rate (Ɛ) is shown in Fig. 6. From the figure, variation of Ɛ with respect to Re is very similar to the observed trend for ∆P but is more of a curve than straight line as a result of extra velocity factor as related in Eq. 6. It is clear that higher energy is spent at higher Re and consequently, improvement in mixing performance. This is in agreement with literature.6,19 The order of energy dissipation rate is Ar > T > Y-mixers.

*Verification of the inadequacy of Villermaux-Dushman protocol at low Re values.*

Simple interphase mass transfer between two immiscible liquids (water and crude biodiesel) was used to verify the observed performance inconsistency in this study.21 Briefly, hydrophobic (crude biodiesel) phase resulting from ultrasonic assisted-methanolysis of fresh cooking Hedeya oil in presence of 1 wt.% KOH as homogeneous catalyst for 40 minutes, with methanol to oil molar ratio of 6:1, at 60 oC; was contacted with alkaline water (0.016 M KOH) in the same experimental set-up of Fig 1, at flow rates of 70, 50, 20, 7 and 1 mL/hr, each for T, Y and arrow-shaped micromixers, respectively. After micromixing, 5 mL of the resulting aqueous phase was titrated over 0.03 M HCl, using phenolphthalein indicator. We are currently working to fully develop this performance characterization technique and the details would be published soon, in this journal.

Titrimetry revealed a progressive increase in alkalinity of biodiesel wash water, for all the micromixers, as the flow rate was increased. Table 1 shows the titrimetric result of aqueous extract phase. Also, at every flow rate, the order of mixing performance was arrow > T > Y mixer.

Table 1: Titrimetric result of aqueous extract phase.

|  |  |  |  |
| --- | --- | --- | --- |
| **Flow rate / mLhr-1** | **Volume of HCl used / mL** | | |
| **Arrow-mixer** | **T-mixer** | **Y-mixer** |
| 70 | 3.65 | 3.50 | 3.15 |
| 50 | 3.35 | 3.20 | 3.00 |
| 20 | 3.10 | 2.95 | 2.85 |
| 7 | 2.95 | 2.90 | 2.85 |
| 1 | 2.85 | 2.85 | 2.80 |

CONCLUSION

The mixing performances of T, Y and arrow-shaped micromixers have been characterized by Villermaux-Dushman protocol at low Re. Based on UV absorbance, experimental and predicted mixing times; comparison of mixing performance of the micromixers was made at various Re. Facile solvent extraction test was performed for result verification. From the results of this study, it can be concluded that arrow-shaped confluence offers the best mixing performance, while Y-shape offers the least of the three confluence shapes at Re > 30. Villermaux-Dushman protocol is not adequate at lower Re. Increase in Re within the range 30 < Re < 100, leads to improvement in mixing performance. Mixing performance is more sensitive to changes in Re at low Re values. Improvement in mixing performance due to: shape of confluence or increase in Re value occurs at the cost of fluid energy per unit time (power).

A more reliable mixing performance characterization method should be used to verify the inadequacy of Villermaux-Dushman protocol at very low Re. Finally, in order to reduce the effect of time lag, on-line (in-situ) absorbance measurement should be adopted.

NOMENCLATURE

Re Reynolds number

Ar Arrow (micromixer)

density of fluid, kg m-3

dynamic viscosity of fluid, kg m-1 s-1

u flow velocity of fluid stream, m s-1

d characteristic diameter of flow channel, m

UV ultraviolet

OD optical density or mixed sample absorbance

[i]0 initial molar concentration of chemical species ‘i’, mol L-1

Ɛ specific power dissipation or specific rate of energy dissipation, W kg-1 or J kg-1 s-1

Q volumetric flow rate, mL hr-1

pressure drop, Pa

V control volume for mixing, m3

experimental mixing time, s

predicted mixing time, s

*f* dimensionless friction factor in Darcy’s equation

*Acknowledgement:* The authors acknowledge the tutelage of Dr. K. Yoshimoto and Dr. Y. Muranaka of Kyoto University, and supervision of Dr. M.F. Elkady and Prof. A.H. El-Shazly during their Project Based Learning at Egypt-Japan University of Science and Technology (E-JUST), Egypt. The authors also acknowledge scholarship support from Ministry of Higher Education (MOHE) and Japan International Cooperation Agency (JICA) in E-JUST, Egypt.

REFERENCES

1. J. Aubin, M. Ferrando, V. Jiricny, *Chem. Eng. Sci.* **65** (2010) 2065 (<https://doi.org/10.1016/j.ces.2009.12.001>).

2. W. Ehrfeld, K. Golbig, V. Hessel, H. Löwe, T. Richter, *Ind. Eng. Chem. Res.* **38** (1999) 1075 (<https://doi.org/10.1021/ie980128d>).

3. J. M. Commenge, L. Falk, *Chem. Eng. Process. Process Intensif.* **50** (2011) 979 (<https://doi.org/10.1016/j.cep.2011.06.006>).

4. P. Garstecki, M. J. Fuerstman, H. A. Stone, G. M. Whitesides, *Lab Chip*. **6** (2006) 437 (<https://doi.org/10.1039/b510841a>).

5. M. Rahimi *et al.*, *Microsyst. Technol.* **23** (2017) 3117 (<https://doi.org/10.1007/s00542-016-3118-6>).

6. L. Falk, J. M. Commenge, *Chem. Eng. Sci.* **65** (2010) 405 (<https://doi.org/10.1016/j.ces.2009.05.045>).

7. M. Rahimi, P. Valeh-e-Sheyda, M. A. Parsamoghadam, N. Azimi, H. Adibi, *Chem. Eng. Process. Process Intensif.* **85** (2014) 178 (<https://doi.org/10.1016/j.cep.2014.09.001>).

8. S. Hossain, I. Lee, S. M. Kim, K.-Y. Y. Kim, *Chem. Eng. J.* **327** (2017) 268 (<https://doi.org/10.1016/j.cej.2017.06.106>).

9. M. C. Fournier, L. Falk, J. Villermaux, *Chem. Eng. Sci.* **51** (1996) 5187 (<https://doi.org/10.1016/S0009-2509(96)00340-5)>.

10. K. Kunowa, S. Schmidt‐Lehr, W. Pauer, H. Moritz, C. Schwede, *Macromol. Symp.* **259** (2007) 32 (<https://doi.org/10.1002/masy.200751305>).

11. S. Asano, S. Yamada, T. Maki, Y. Muranaka, K. Mae, *React. Chem. Eng.* **2** (2017) 830 (<https://doi.org/10.1039/c7re00051k>).

12. O. Okwundu, M. Fuseini, “Mixing performance of micromixers by Villermaux-Dushman reaction protocol at low Reynolds Number” (2018) (<https://doi.org/10.13140/RG.2.2.33028.83847/1>).

13. J. R. Bourne, *Chem. Eng. J.* **140** (2008) 638 (<https://doi.org/10.1016/j.cej.2008.01.031>).

14. M. Engler, N. Kockmann, T. Kiefer, P. Woias, *Chem. Eng. J.* **101** (2004) 315 (<https://doi.org/10.1016/j.cej.2003.10.017>).

15. N. Kockmann, T. Kiefer, M. Engler, P. Woias, *Sensors Actuators, B Chem.* **117** (2006) 495 (<https://doi.org/10.1016/j.snb.2006.01.004>).

16. N. Kockmann, C. Foll, P. Woias, *Microfluid. BioMEMS, Med. Microsystems*. **4982** (<https://doi.org/10.1117/12.478157>).

17. A. Soleymani, E. Kolehmainen, I. Turunen, *Chem. Eng. J.* **135** (2008) S219 (<https://doi.org/10.1016/j.cej.2007.07.048>).

18. N. Aoki, R. Umei, A. Yoshida, K. Mae, *Chem. Eng. J.* **167** (2011) 643 (<https://doi.org/10.1016/j.cej.2010.08.084>).

19. O. Jafari, M. Rahimi, F. H. Kakavandi, *Chem. Eng. Process. Process Intensif.* **101** (2016) 33 (<https://doi.org/10.1016/j.cep.2015.12.013>).

20. J. R. Welty, C. E. Wicks, R. E. Wilson, G. L. Rorrer, *Fundamentals of Momentum, Heat and Mass Transfer* (John Wiley & Sons Inc., ed. 5, 2007).

21. Zhao, Y., Chen, G. & Yuan, Q. Liquid–liquid two-phase mass transfer in the T-junction microchannels. *AIChE J.* **53** (2007) 3042–3053 (<https://doi.org/10.1002/aic.11333>).

1. \*Corresponding author. E-mail: [onyeka.okwundu@eng.uniben.edu](mailto:onyeka.okwundu@eng.uniben.edu) [↑](#footnote-ref-1)