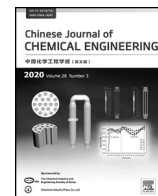




Contents lists available at ScienceDirect

Chinese Journal of Chemical Engineering

journal homepage: www.elsevier.com/locate/CJChE

Article

Comparative analysis of different static mixers performance by CFD technique: An innovative mixer

M.M. Haddadi¹, S.H. Hosseini^{2,*}, D. Rashtchian¹, Martin Olazar³¹ Chemical and Petroleum Engineering Department, Sharif University of Technology, Tehran, Iran² Department of Chemical Engineering, Ilam University, Ilam 69315–516, Iran³ Department of Chemical Engineering, University of the Basque Country (UPV/EHU), Sarriena s/n, Leioa, Spain

ARTICLE INFO

Article history:

Received 31 May 2019

Received in revised form 3 August 2019

Accepted 6 September 2019

Available online 15 October 2019

Keywords:

CFD

New static mixer

Coefficient of variation

Pressure drop ratio

ABSTRACT

The flow and mixing behavior of two miscible liquids has been studied in an innovative static mixer by using CFD, with Reynolds numbers ranging from 20 to 160. The performance of the new mixer is compared with those of Kenics, SMX, and Komax static mixers. The pressure drop ratio (Z-factor), coefficient of variation (CoV), and extensional efficiency (α) features have been used to evaluate power consumption, distributive mixing, and dispersive mixing performances, respectively, in all mixers. The model is firstly validated based on experimental data measured for the pressure drop ratio and the coefficient of variation. CFD results are consistent with measured data and those obtained by available correlations in the literature. The new mixer shows a superior mixing performance compared to the other mixers.

© 2019 The Chemical Industry and Engineering Society of China, and Chemical Industry Press Co., Ltd. All rights reserved.

1. Introduction

Mixing is one of the most important unit operations in many processes, which has a major role on the quality of the final product. Improper mixing can result in a lower quality of products, and therefore the need for more sophisticated separation systems, which in turn increases waste management costs. Therefore, determining mixing characteristics is extremely important, especially in flows with low Reynolds numbers, as they involve non-homogenous and imperfectly mixed flow. Mixing is carried out as a batch operation in agitated vessels and as a continuous operation in static mixers [1]. The static mixers are composed of numerous motionless elements installed in a fixed pipe or channel. The aim of these elements is to split, rotate, and then recombine the input streams. Since there are no moving parts in static mixers, the only power required is the one of the external pump in order to overcome the pressure loss generated by the mixing elements and fluid movement. Some benefits of static mixers in comparison with dynamic ones can be listed as follows: small space required for installation, low maintenance costs, low power consumption, absence of moving parts, short residence times of the fluids, near plug flow behavior of the fluids, efficient heat and mass transfer, good mixing at low shear rate, and capability for self-cleaning [2–4]. The static mixers are used in many processing applications, such as mixing of miscible liquids [5], immiscible liquids [6,7], dispersion of viscous liquids [8], mass transfer [9], heat transfer [10], and gas–liquid dispersion [11,12]. These

applications are available in many industries, such as polymer processing [13], biotechnology [14], wastewater treatment [15–18], food processing [19], and petrochemistry [20,21]. The wide range of applications of static mixers in various industries is evidence of the importance of this equipment.

The performance of a static mixer can be mainly specified by its mixing efficiency and pressure drop. First, they are assessed by the pressure drop ratio (pressure drop of the mixer to pressure drop of the empty pipe). Then mixing efficiency parameters are considered by using the coefficient of variation, the extensional efficiency, and the residence time distribution. The coefficient of variation characterizes the effectiveness of distributive mixing. When distributive mixing occurs, droplets or bubbles are distributed in the mixer. This mechanism differs from dispersive mixing, which corresponds to size reduction [22]. In order to perform distributive mixing, a component A is mixed in a main-stream with another component B. Then, the concentration of component A is monitored and mapped as a function of position in a specified cross-section. Afterwards, the standard deviation of the concentration is calculated and then the coefficient of variation (CoV) is specified. If component A is uniformly distributed in a cross-section, the CoV tends to zero. The residence time distribution is sometimes used as a mixing criterion, especially when the systems include a chemical reaction. A narrower distribution leads to better mixing [23]. Moreover, the extensional efficiency is introduced in order to investigate dispersive mixing [24].

In the last few decades, computational fluid dynamics (CFD) has become an essential numerical tool in the prediction of fluid dynamics, heat transfer and also mass transfer in packed beds, which are

* Corresponding author.

E-mail address: s.h.hosseini@ilam.ac.ir (S.H. Hosseini).

used in various industries [25,26,36]. Therefore, CFD can be successfully applied to the design and analysis of pieces of equipment like static mixers.

Different aspects of the static mixers have been studied both experimentally and numerically. For instance, Liu *et al.* [27] and Baumann *et al.* [28] performed numerical and experimental studies, respectively, to measure the pressure drop in SMX static mixers. Rauline *et al.* [22] studied the velocity field for creeping flow in six static mixers using three-dimensional finite volume CFD code. They used the numerical results of the extensional efficiency, pressure drop, mean shear rate, stretching, and coefficient of variation to compare the performances of those mixers. They proved that the SMX mixer was the most efficient amongst all configurations. Moreover, by studying the Kenics mixer they showed that this mixer is more efficient when certain space is left between the mixing elements. Zalc *et al.* [29,30] investigated the hydrodynamics and mixing behavior in an SMX mixer at Reynolds number in the range of 10^{-4} –100. Their results revealed that when the injection is made at the center of the tube, the mixing efficiency is higher than for off-center injection. In addition, they showed that the pressure drop ratio does not change for Reynolds numbers lower than 10. Several CFD simulations of flow behavior through Kenics mixers are found in the open literature [31–36]. Furthermore, some experimental studies have also been conducted by several researchers on the flow behavior in Kenics static mixers [37,38]. However, there are few numerical studies about the Komax mixer.

Most of the studies about designing novel static mixers or modifying static mixers available at laboratory scale have been limited to creeping flows and laminar flows at higher flow rates, *i.e.*, to a low Reynolds number range, in which the influence of internals, such as blade shape, number of elements, and other design factors, have been assessed by numerical tools [34,39–42].

Regner *et al.* [34] studied the characterization of two static mixers, namely, Kenics KM and Lightnin Series 45, by evaluating Z factor, helicity and the rate of striation thinning based on CFD. The Reynolds number they used was in the 0.1–160 range. Singh *et al.* [39] analyzed, and subsequently optimized, the various design parameters of SMX mixers, namely, N_p , the number of parallel cross-bars per element and, N_x , the number of cross-bars over the width of the channel, by the mapping method (MM) under a low Re number (0.44). They obtained that the optimum design obeys the rule of $N_p = (2/3)N_x - 1$. To achieve the enhanced mixing performance of the SMX geometry, Soman and Madhuranthakam [40] simulated different SMX static mixer geometries by COMSOL Multi-physics software to investigate mixing performances at Re numbers ranging from 30 to 100. They compared the results in terms of velocity field, pressure field, shear rate and extensional efficiency for dispersive mixing, and the standard deviation of the concentration for distributive mixing. They found that circular serrations in SMX mixers reduce the pressure drop by 33%–35% of that corresponding to the standard SMX mixer. Meng *et al.* [41] compared (using a CFD tool) the mixing performance of Kenics and Lightnin static mixers for a high-viscosity fluid at low Reynolds numbers in the 0.1–100 range and different aspect ratios, as well as different elements. They proposed a new mixing factor η to evaluate the micro-mixing performance in the mixers. In another work, Meng *et al.* [42] studied the mixing performance of a high-viscosity fluid in novel static mixers with multitwisted leaves by CFD code FLUENT at Reynolds number in the 0.1–150 range.

In addition to their use for the laminar flow, some numerical works in the open literature deal with novel static mixers or modifications to the existing ones for use in turbulent flow. For instance, Meng *et al.* [43] simulated perforations in the standard Kenics mixer by CFD tool and studied the impact of their size and spacing, as well as the number of segments, on the heat transfer under the turbulent condition. They achieved outstanding results using $d/W = 0.3$ and $s/W = 0.6$ in terms of friction loss and heat transfer rate in the modified Kenics mixer. Zhou *et al.* [44] proposed a new static mixer of hollow cross disk in

order to increase the turbulent reactive mixing in the tubular pipe under turbulent flow.

Few studies have been reported in the literature regarding static mixers with complex fluids, such as non-Newtonian and immiscible ones. In this respect, Jegatheeswaran *et al.* [45] studied the intensification of non-Newtonian fluid mixing in chaotic SMX static mixers at low Reynolds numbers. They also reviewed process intensification by mixing non-Newtonian fluids in static mixers, and suggested to perform CFD studies to shed light on the impact the geometry and design parameters of static mixers have on fluid deformation and mass transfer under low Reynolds numbers for both Newtonian and non-Newtonian fluids [46]. Mihailova *et al.* [47] evaluated a Newtonian fluid (glycerol) and a non-Newtonian one (guar gum solution) in a SMX mixer, and found that their velocity distribution is hardly affected by rheology at the same low flow rate. Concerning the performance of immiscible fluids in static mixers, few studies have been reported in the literature, and they use Eulerian–Lagrangian and Eulerian–Eulerian approaches combined with the population balance in order to study particle trajectories and particle size distributions, respectively [48,49].

The general goal of this study is to investigate the effects of Reynolds number and length of the mixer on the hydrodynamics and mixing behavior of brine 25% (wt) by using CFD in four static mixers at low Reynolds numbers. In view of the brief review done above, the mixing behavior of the new static mixer is firstly analyzed at low Reynolds numbers due to the high probability of having fluid inhomogeneity under those conditions. Accordingly, this study covers a wide range of Reynolds numbers from 20 to 160 as a benchmarked to evaluate the mixing performance of the new simple static mixer inspired by the behavior of dynamic mixers in vessels. Amongst the different criteria, extensional efficiency, pressure drop ratio and the coefficient of variation have been chosen to evaluate the performance of the well-known Kenics, SMX and Komax mixers and of an innovative static mixer. The simulation results are validated by comparing the predicted results with the existing correlations for the pressure drop ratio in a Kenics mixer and the experimental data for the coefficient of variation in a mixer with baffle shape elements.

2. Numerical Methodology

2.1. Physical model and fluid properties

This study analyses the performance of four static mixers, namely, Kenics, SMX, Komax, and a new static mixer proposed by the authors. Furthermore, in order to validate the CFD model, another two other static mixers have been used, namely, a static mixer with staggered semicircular baffle shape elements [50] and a Kenics static mixer [51] with the same geometrical dimensions and operating conditions as those used in the mentioned four static mixers. Based on the previous works [50,51], it is assumed that the tube and internal elements of the static mixers are made of Plexiglass. Fig. 1 shows the computational domains of Kenics, SMX, Komax and the new static mixer. Moreover, Fig. 2a illustrates the geometry of the blades in the new mixer. More information about the static mixer with baffle shape elements can be found elsewhere [50]. In Fig. 1, the computational domain comprises a horizontal tube with a diameter of D and four mixing elements. Two empty tubes of $3D$ length are added prior and subsequent to the mixing elements in order to provide developmental flow length and to avoid creating backflow in the simulations. As shown in Fig. 2b, the injection tube is a curved 3-mm diameter tube aligned with the main axis, with the injection point being located at a distance of 15 mm from the tube inlet. The detailed dimensions of the static mixers and the properties of the fluid are set out in Tables 1 and 2, respectively. Each element of the Kenics mixer is a twisted plate that is alternated and oriented so that each leading edge is at 90° of the trailing edge of the next one. The mixing elements in the SMX mixer comprise inclined bars crossed to one another. Each element is rotated 90° with respect to the

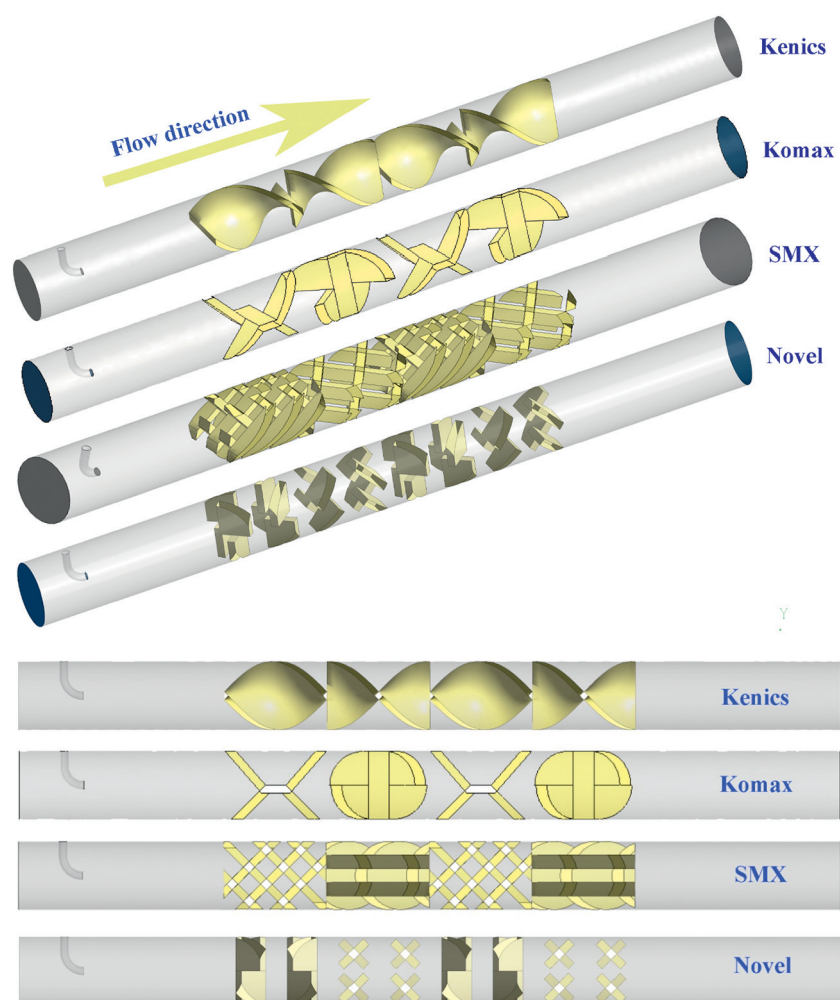


Fig. 1. Geometries of various static mixers, namely, Kenics mixer, SMX mixer, Komax mixer, and novel mixer in different views.

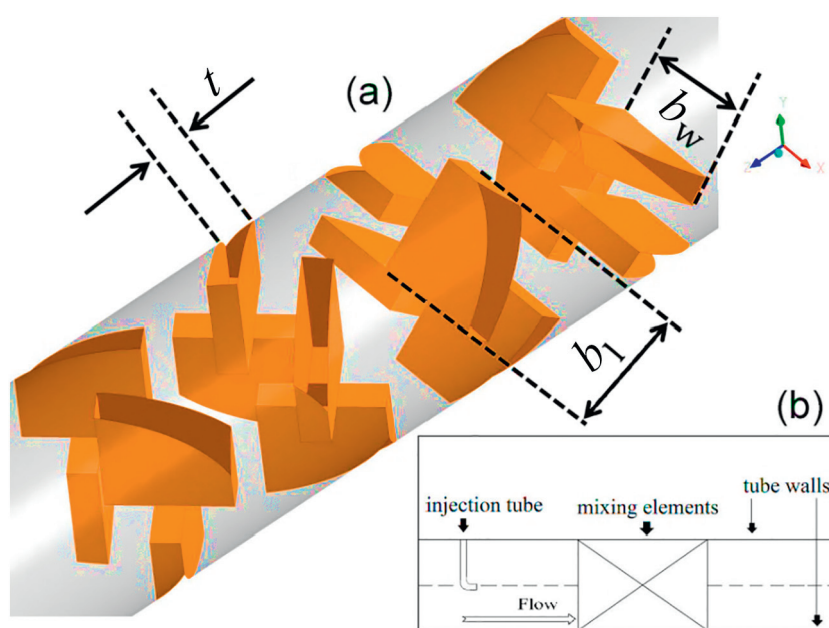


Fig. 2. (a) Geometry of the blades in the new static mixer, (b) sketch of the pipeline equipped with mixing elements.

Table 1
Geometrical parameters of static mixers

Parameter	Kenics	SMX	Komax	New mixer
Tube diameter, D/mm	25	25	25	25
Aspect ratio, A_R	1.5	1.5	1.5	1.5
Blade thickness, t/mm	3	3	3	3
Blade width, b_w/mm	–	5	–	12.5
Blade length, b_l/mm	–	–	–	12.5

foregoing element. The Komax static mixer is manufactured from slot-
ted plates with inclined ends. The flow channels with triangular shapes
are created by pushing the elements together in a pipe.

The first mixing element of the new mixer consists of two rows of
blades at a distance of $D/2$ from each other with 90° differences in
angle. Each row has four blades, which form two crosses with an
angle of 45° with respect to the tube axis at a distance of $D/2$ from
each other. The second element of the new mixer is the same as the
first element with the difference that all blades are rotated 90° around
the pipe axis. Thus, the number of required elements to construct the
new mixer should be at least two. It is interesting to note that the design
of the proposed mixer is inspired by the dynamic mixers in stirred
vessels, which include several blades at various angles along the central
axis.

2.2. Model equations and numerical details

The general assumptions of the model used are as follows: the flow
is single-phase, three-dimensional, steady state, incompressible,
isothermal and without any reaction (without mass production or
mass consumption). The continuity, momentum, and species transport
equations are solved by a finite volume method (FVM). The mentioned
equations are expressed as follows [52]:

$$\nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

$$\nabla(\rho \mathbf{V} \mathbf{V}) = -\nabla P + \nabla \cdot [\mu \nabla \mathbf{V}] + \rho \mathbf{g} \quad (2)$$

$$\nabla \cdot (\rho \mathbf{V} Y_A) = \nabla \cdot (\rho D_{AB} \nabla Y_A) \quad (3)$$

where μ , ρ , $\mathbf{g}$, $\mathbf{V}$, P , Y_A , and D_{AB} stand for the bulk dynamic viscosity, bulk
density, gravity acceleration vector, mean velocity vector, pressure,
mass fraction of component A, and molecular diffusivity respectively.

The governing equations are discretized on an unstructured tetrahe-
dral mesh as algebraic equations. The origin of the z-axis is positioned at
the inlet of the tube, and its direction is opposite to the main flow. The
convective terms in the governing equations are discretized by a second
order upwind scheme, and the SIMPLE algorithm is used for pressure-
velocity coupling. Gradients are essential to compute diffusion terms
and velocity derivatives. Moreover, the values of the scalar at the cell
faces should be created. To solve the conservation equations and calcu-
late the gradients, a commercial ANSYS FLUENT 16.0 software is used
in order to apply a Least-Square cell-based discretization method. The con-
vergence limit is set to a scaled residual lower than 10^{-5} for all the men-
tioned equations. The various geometries of the mixers and the
corresponding computational grids have been created by ANSYS

Table 2
Properties of the fluids

Parameter	Main liquid water	Tracer brine 25wt%
Density/ $\text{kg} \cdot \text{m}^{-3}$	1000	1190
Viscosity/ $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$	0.001	0.00167
Diffusion coefficient/ $\text{m}^2 \cdot \text{s}^{-1}$	1.44×10^{-9}	1.44×10^{-9}
Flow rate/ $\text{L} \cdot \text{s}^{-1}$	0.00035–0.0026	0.000035–0.00026
Reynolds number	20–160	105–796

DESIGN MODELER and ANSYS MESHING, respectively. The simulations
are performed on an Intel Core™ i7-6700HQ CPU@ 2.60 GHz running
on Windows 10 Professional 64 bit with 12 GB of RAM.

2.3. Boundary conditions

The Reynolds number is expressed by:

$$Re = \frac{\rho \bar{V} D}{\mu} \quad (4)$$

where $\bar{V}$ stands for the mean velocity and D for the diameter of the tube
including the mixing elements. The boundary condition at the inlet of
the mixer is a fully developed velocity profile, which has been intro-
duced into the software using a user-defined function (UDF). According
to previous modeling of static mixers [5,53,54], the no-slip boundary
condition is utilized on the tube wall and element surfaces. The atmo-
spheric pressure, i.e., zero gage pressure, is utilized at the outlet of the
static mixers. Brine 25% (wt) is injected into the tube co-currently to
the main flow. The tracer (brine) velocity chosen at each Reynolds num-
ber (based on the inlet condition of the main liquid) is that correspond-
ing to a ratio of 0.1 between the tracer flow rate and the main flow rate.

2.4. Grid independence test

Grid independence test is performed to determine the proper grid
size, ensuring that the numerical results are independent of the grid sys-
tem. The maximum values of Equisize skew for all geometry meshes are
lower than 0.79, which is evidence of the good quality of the meshes
based on the FLUENT criterion. In addition, the geometries and grids
have been created by DesignModeler, from ANSYS productions. In
order to perform the grid independence test, four static mixers (Kenics,
Komax, SMX and the novel one) with a length of 300 mm and a diame-
ter of 25 mm are used with six different grid sizes ranging from 0.5 to
3 mm (0.5 mm is chosen for the step size) at $Re = 160$. Tables 3 to 6
show the results of the grid independence test. As shown in these tables,
both Z-factor (related to pressure drop) and CoV (related to the concen-
tration at the plate located 1.5D downstream) decrease as the grid size
is increased above 1.5 mm. In addition, by changing the grid size from
1 to 0.5 mm, Z-factor and CoV change by less than 0.7% and 0.5%, respec-
tively. Tables 3 to 6 summarize the key characteristics of the grids, and
they clearly show that CFD simulation time is highly dependent on the
grid size. Given the slight difference between 1 and 0.5 mm grid sizes,
medium grid size (1 mm) strikes the balance between accuracy and
computational time, and has been used for further simulations.

2.5. Model validation

The accuracy of the numerical model is an essential aspect to be
quantified prior to use it for predicting new situations. To assess the va-
lidity of the CFD results, the simulated pressure drop ratio and the coef-
ficient of variation are compared with the experimental data and
available correlations. The Z-factor is defined as the ratio of the static
mixer pressure drop, ΔP , to the pressure drop in the empty tube, ΔP_0 :

$$Z = \frac{\Delta P}{\Delta P_0} \quad (5)$$

In this study, the pressure drop is calculated as the absolute difference
between the area-weighted average pressure at the planes located at
1.5D upstream and downstream the mixing elements. This is an impor-
tant parameter for static mixers and provides a measure of the energy
required for the static mixer in the pipeline.

Table 3Grid size, CFD simulation time, number of elements, estimated Z and CoV for the Kenics mixer at $Re = 160$

Grid size/mm	0.5	1	1.5	2	2.5	3
Number of elements	9,393,720	1,203,476	380,517	185,645	115,263	86,139
CFD simulation time/min	970	55	14.1	6	3.5	2.7
Simulated CoV	0.185	0.187	0.15	0.07	0.04	0.02
Simulated Z	10.23	10.22	10.27	10.14	9.95	9.85

Table 4Grid size, CFD simulation time, number of elements, estimated Z and CoV for the Komax mixer at $Re = 160$

Grid size/mm	0.5	1	1.5	2	2.5	3
Number of elements	9,464,131	1,210,219	384,182	186,300	116,473	86,452
CFD simulation time/min	1000	56	14.2	6.1	3.6	2.7
Simulated CoV	0.04665	0.047	0.044	0.041	0.039	0.037
Simulated Z	36.18	36.34	35.48	34.35	31.7	31.56

Moreover, the coefficient of variation is calculated at different points in a specified cross-section, with the usual definition being as follows:

$$\text{CoV} = \sqrt{\frac{\sum_{i=1}^N (Y_i - Y_{\text{mean}})^2}{N-1}} \frac{1}{Y_{\text{mean}}} \quad (6)$$

where Y_i is the local mass fraction of the tracer at the i th point, N is the number of evaluation points and Y_{mean} is the mean mass fraction of the tracer on the cross-section of the tube. Therefore, values of the CoV are calculated in various points of the tube cross-section following previous works [18,50]. Fig. 3(a, b) compares the values computed for Z-factor in the range $Re = 20 - 160$ and for CoV in the range $Re = 70 - 480$ with the data measured in the Kenics mixer [52] and in a static mixer with baffle shape elements [50], respectively. Fig. 3a shows that an increase in the Reynolds number leads an increase in pressure drop, which in turn leads to an increase in Z-factor.

$$\text{MRE} = \frac{1}{N} \sum_{i=1}^N \frac{|\text{Simulation}_i - \text{Experimental}_i|}{|\text{Experimental}_i|} \quad (7)$$

The mean relative error (MRE) between the data measured by Sir and Lecjaks [51] and the CFD results is approximately 2.3%. Accordingly, a quite good quantitative agreement between the simulated data and the experimental ones by Sir and Lecjaks [51] is found for Z-factor. Fig. 3b compares the computed values of CoV with the corresponding experimental data provided by Al-Atabi [50] in a static mixer with baffle shape elements for $Re = 70 - 480$. The MRE between the experimental

data (Al-Atabi, 2011) and the simulated results is of around 6%. Therefore, a good agreement between the results is also attained for CoV. Overall, Fig. 3(a, b) shows that the current model is able to predict the hydrodynamics and mass transfer of brine into water flowing through the various static mixers at different Reynolds numbers with a reasonable accuracy. As a result, the current CFD model is suitable for studying the other static mixers.

2.6. Comparison with some existing empirical equations

Fig. 4 compares the CFD results with those for well-known available correlations developed by Wilkinson and Cliff [55], Cybulski and Werner [19], Sir and Lecjaks [51], Shah and Kale [56], and Grace [57] for a Kenics mixer including four elements. These empirical expressions that are commonly used for estimating Z-factor in Kenics static mixers are listed in Table 7. There is a considerable discrepancy in the results predicted by the different correlations for Z-factor. This discrepancy is explained by the differences in the dimensions of the static mixers, such as diameter and length, and because the impact of some geometrical features has been ignored in the correlations. Unlike the variability predicted by the existing correlations for the Kenics static mixer, the numerical results are consistent. In the mentioned range of Reynolds numbers, the computed Z-factors have 3.6% and 8% MRE compared to the correlations by Cybulski and Werner [19], and Sir and Lecjaks [51], respectively.

2.7. Numerical diffusion

One of the most important sources responsible for numerical errors in CFD is numerical diffusion. This type of error stems from the discretization of convective terms in the governing equations. To investigate the numerical diffusion and select the appropriate discretization scheme for the convective terms, five discretization schemes (first order upwind, the second order upwind, QUICK, MUSCL and Power law) have been compared with each other. The results of this comparison are shown in Fig. 5. This figure clearly shows that except the first order upwind and power law schemes, the other discretization schemes lead to similar results. Therefore, the use of QUICK, MUSCL and second order upwind schemes do not lead to significant error in the computation. The percentages have been calculated for the numerical differences between the accurate scheme of second order upwind and the other schemes. The minimum and maximum differences for mass transfer are obtained by the QUICK scheme with a MRE of 0.37% and by the first order upwind with a MRE of 78%, respectively. The minimum and maximum differences for pressure are obtained by the QUICK scheme with a MRE of 0.64% and by the first order upwind with a MRE of 45%, respectively. In addition, the second order upwind scheme was specifically used in many studies to simulate flow in static mixers and other

Table 5Grid size, CFD simulation time, number of elements, estimated Z and CoV for the SMX mixer at $Re = 160$

Grid size/mm	0.5	1	1.5	2	2.5	3
Number of elements	8,807,816	1,139,632	360,097	180,105	112,442	84,964
CFD simulation time/min	750	53.5	13	5.3	3.1	2.3
Simulated CoV	0.00695	0.007	0.0065	0.006	0.0055	0.005
Simulated Z	98.3	98.67	96.15	94.2	93.5	89.3

Table 6Grid size, CFD simulation time, Number of elements, estimated Z and CoV for the new mixer at $Re = 160$

Grid size/mm	0.5	1	1.5	2	2.5	3
Number of elements	9,323,515	1,195,094	378,079	184,912	115,256	85,647
CFD simulation time/min	950	54	14	6	3.5	2.5
Simulated CoV	0.001997	0.002	0.0017	0.0015	0.0012	0.001
Simulated Z	63.2	63.5	66	64.2	62	60.5

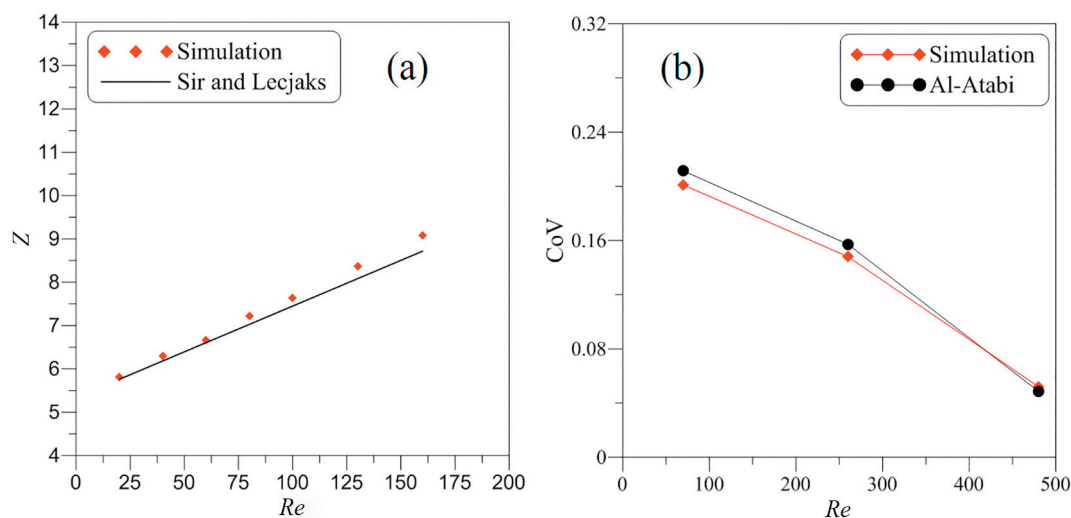


Fig. 3. (a) Experimental and computed pressure drop ratios for various Reynolds numbers (b) Experimental and computed CoV values for various Reynolds numbers.

systems [32,58,59]. Accordingly, the second order upwind discretization scheme has been used in this study for all simulations.

3. Results and Discussion

By utilizing the numerical technique described in the previous sections, the flow behavior in the four static mixers has been evaluated and the results are discussed for various conditions.

3.1. Velocity profiles

The contour plots of cross-sectional velocity profiles for different static mixers are shown in Fig. 6(a–d) at different locations from the inlet of the first mixing element to the end of each mixing element at $Re = 60$. This figure clearly shows that the maximum values of the fluid velocity are quite different in the mixers due to their different structure. Fig. 6a shows the contour of fluid velocity in the Kenics mixer. As observed, four velocity zones are formed at the end of the first element. As the flow passes through the mixer, these zones combine together and create new zones with different velocities. As expected from the mass conservation, the velocity is proportional to the Reynolds number and is the same at the end of the first and third mixing

elements. In the fourth element, the four velocity zones combine together again and two velocity zones with lower pressure are created.

Fig. 6b shows the velocity distribution in the Komax mixer. When the fluid flow enters the first mixing element, it splits into two streams. As the cross-sectional area of each stream decreases, the stream velocity increases. It is obvious from Fig. 6b that a high velocity zone near the wall mixer is created in each stream. This is due to the rotation of the fluid, which causes a centrifugal force and creates high speed zones at a distance far from the center of rotation. This phenomenon is also observed in the Kenics mixer. The velocity profiles of the new mixer are shown in Fig. 6c. Similarly to the Komax mixer, there are two zones with high velocity in this mixer. It is remarkable that these zones are created when the fluid passes through the first mixing element, which is not the case in the Komax mixer where they are created after the second mixing element. This means that the new mixer can create more disturbances compared to the Komax one. In addition, the velocity contours of the SMX mixer are shown in Fig. 6d. As can be seen, the cross-bars divide the input fluid into several streams with different velocities. Furthermore, the high velocity zone in the SMX mixer is only in a region after the first and the third mixing elements.

3.2. Pressure drop ratio

Fig. 7a shows the values of Z-factor computed for different static mixers with the same dimensions and four mixing elements. As expected, Z-factor increases by increasing the Reynolds number. It is clearly seen that there is a great difference in Z-factor for the different static mixers. The Z-factor in the SMX mixer is higher than in the other mixers. This is due to the complex geometry and the small space between the cross-bars in the SMX mixer. Moreover, Fig. 7a shows that the Z-factor for the new mixer is about 45% lower than for the SMX mixer at all Reynolds numbers, whereas this factor is higher than those in the Kenics and Komax mixers. In addition, the Z-factor of the new mixer has a lower slope than for the SMX mixer. Thus, it is

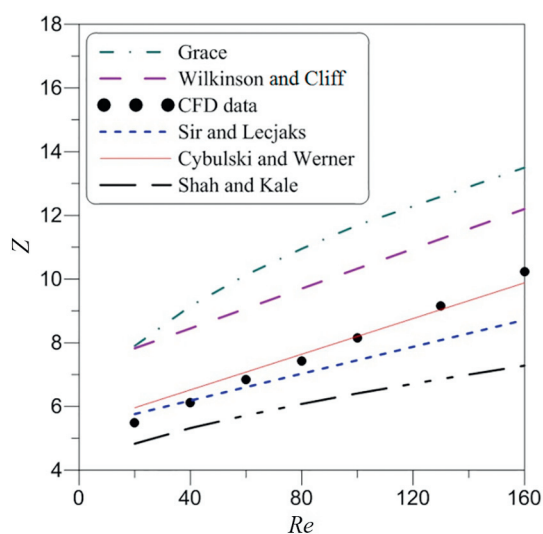


Fig. 4. Comparison of CFD results with those calculated using the correlations available for the Kenics mixer at various Reynolds numbers.

Table 7
Correlations for calculating Z-factor in Kenics static mixers

Authors	Correlation	Reynolds range
Grace [57]	$Z = 4.86 + 0.68\sqrt{Re}$	$Re < 1000$
Wilkinson and Cliff [55]	$Z = 7.2 + 0.031Re$	$Re < 50$
Sir and Lecjaks [51]	$Z = 5.34 + 0.021Re$	$Re < 2300$
Cybulski and Werner [19]	$Z = 5.4 + 0.028Re$	$Re < 50$
Shah and Kale [56]	$Z = 4 + 0.115Re^{0.66}$	$0.01 < Re < 300$

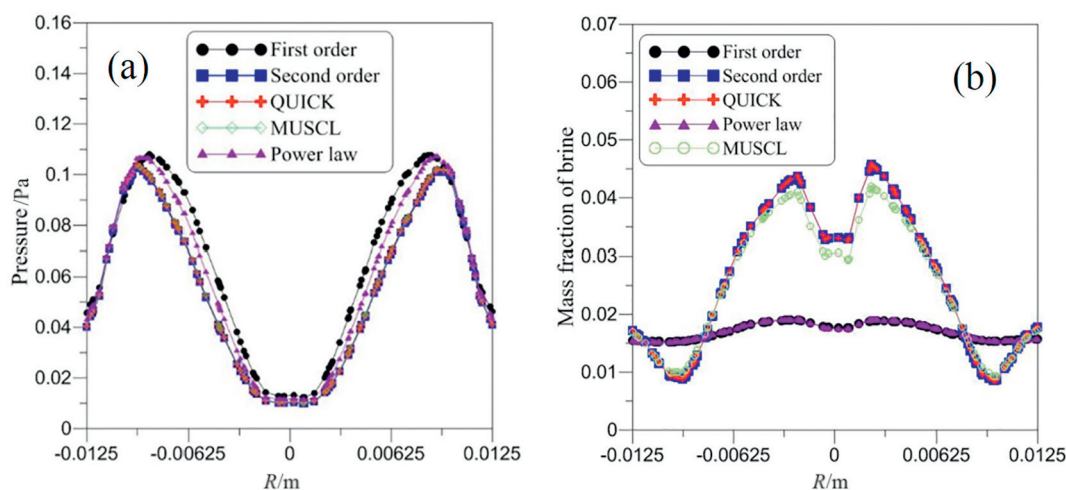


Fig. 5. Radial distribution of (a) total pressure, (b) mass fraction of the brine at the outlet of Kenics static mixer with four mixing elements.

concluded that even for Reynolds numbers above the range studied, the Z-factor of the new mixer is lower than that of the SMX mixer, with the trends of Z-factors being approximately parallel in these mixers. Nevertheless, the lowest computed Z-factor corresponds to the Kenics mixer. In order to investigate more accurately pressure drop in the static mixers, their Z-factor for attaining a value of $\text{CoV} = 0.05$ have been plotted in Fig. 7b. As shown in Fig. 7b, when the Reynolds number is greater than 40, the new mixer leads to a lower pressure drop compared to the

other mixers to achieve $\text{CoV} = 0.05$. Moreover, high mixing qualities in the Kenics mixer require high pressure drops. This difference in the pressure drop produced by the mixers is due to the difference in the number of mixing elements required to reach a given degree of mixing. Another point to be noted in Fig. 7b is the decrease in Z-factor when the Reynolds number (flow rate) is increased. In fact, an increase in flow rate increases the rate of mixing, and therefore less mixing elements are required and so pressure drop decreases.

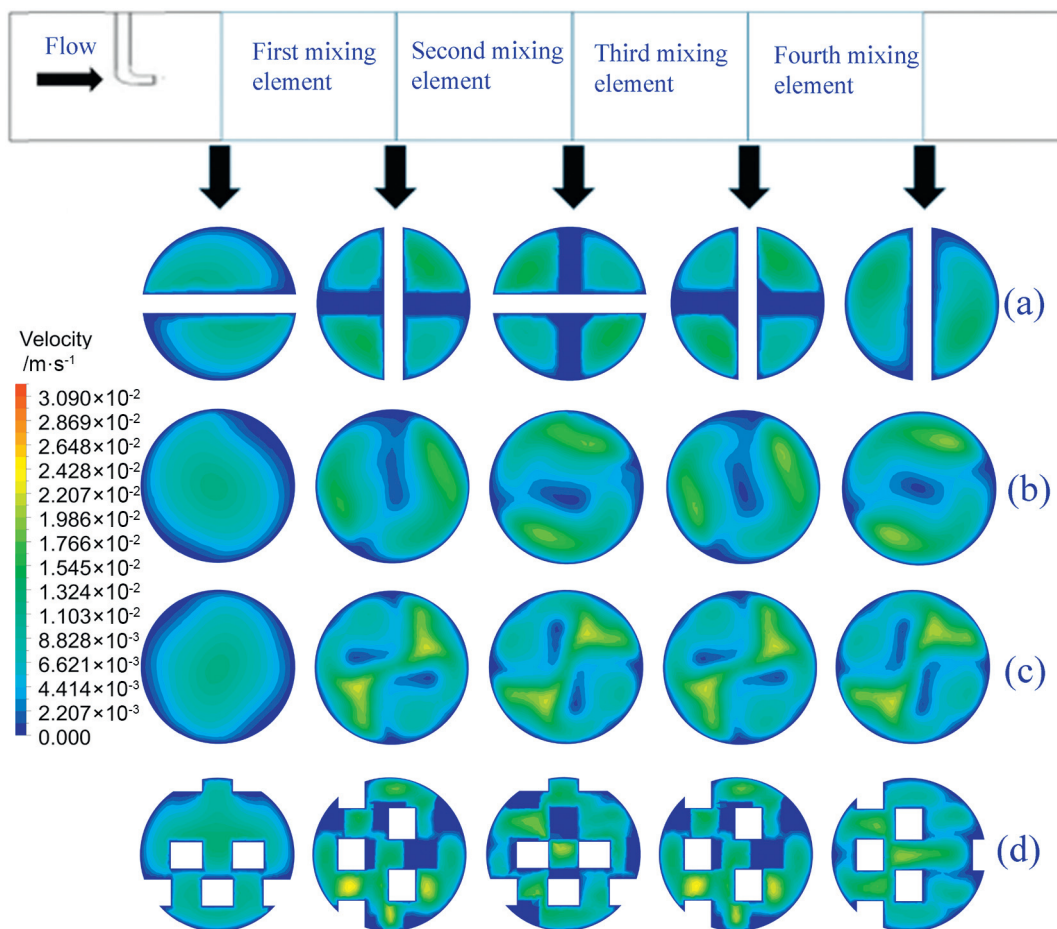


Fig. 6. Cross sectional profiles of velocity at $Re = 60$ for: (a) Kenics mixer (b) Komax mixer (c) Proposed mixer (d) SMX mixer.

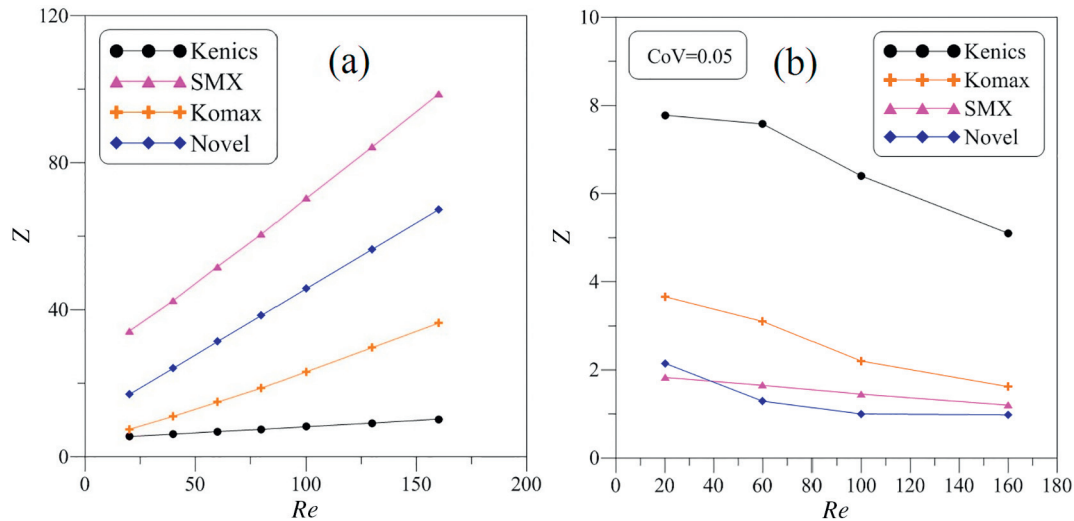


Fig. 7. (a) Comparison of Z-factor in the different static mixers with four mixing elements, (b) Z-factors in the static mixers for different Reynolds numbers when the target is $CoV = 0.05$.

3.3. Coefficient of variation

Fig. 8a shows the relationship between the Reynolds number and the coefficient of variation for the different static mixers. From this figure, it is clear that an increase in Reynolds number leads to a reduction in CoV. At all ranges of Reynolds number, the Kenics mixer has the highest CoV value. Moreover, for $Re < 40$ the new static mixer provides a higher CoV in the tube cross-section than the SMX mixer, and therefore has a lower mixing efficiency. Nevertheless, for $Re > 40$, the new mixer shows a better performance in the distributive mixing compared to the other static mixers. Fig. 8b shows the relationship between the coefficient of variation and the length of the mixer at a constant Re number of 60. By increasing the mixer length, the CoV value decreases gradually. For $L/D > 9$ in the SMX and new mixer, CoV reaches almost a constant value. In addition, the new mixer shows the best performance in the distributive mixing compared to the other mixers for all ranges of L/D . Overall, the new static mixer shows an attractive mixing performance because pressure drop is considerably lower (about 45%) than for the SMX mixer. Therefore, to achieve a desired mixing efficiency, the new static mixer leads to a reduction in pressure drop and requires a shorter length.

3.4. Extensional efficiency

One of the most important parameters in the evaluation of dispersive mixing is extensional efficiency, α , which is calculated as follows [24]:

$$\alpha = \frac{|\gamma|}{|\gamma| + |\omega|} \quad (8)$$

where $|\omega|$ and $|\gamma|$ are the norms of the rate of vorticity and deformation tensors, respectively, which are given by:

$$|\gamma| = \frac{1}{2} [\nabla V + \nabla V^T] \quad (9)$$

$$|\omega| = \frac{1}{2} [\nabla V - \nabla V^T] \quad (10)$$

where ∇V is the velocity gradient. Generally, a higher value of α means a higher dispersive mixing in a static mixer.

The general trend in a static mixer is that a fluid with a high extensional efficiency has both high velocity gradient and high deformation

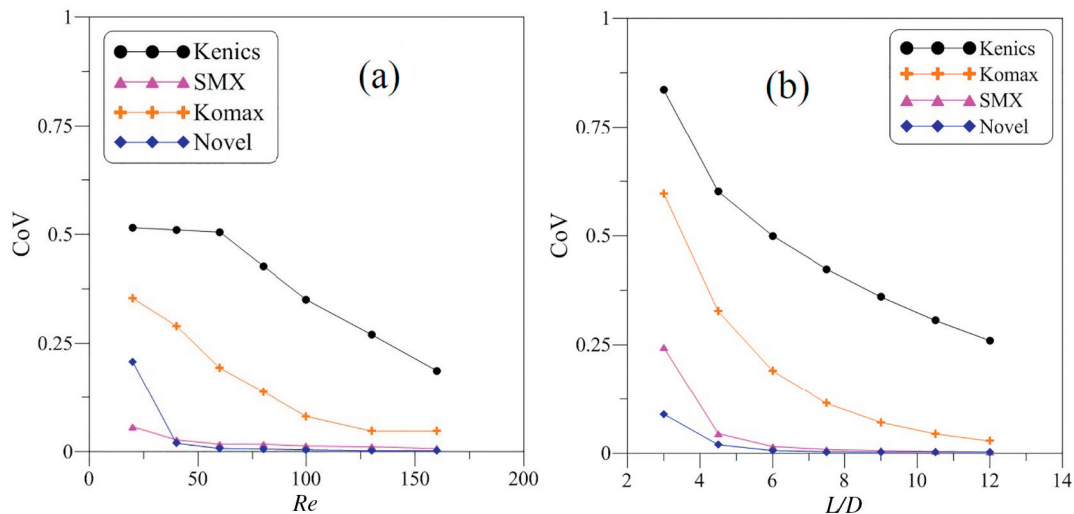


Fig. 8. Comparison of CoV values in the different static mixers: (a) Influence of the Reynolds number on the coefficient of variation (b) Effect of L/D on the coefficient of variation at $Re = 60$.

tensor. According to the correlation shown below (Eq. (11)) proposed by Das *et al.* [60], as the velocity gradient, and therefore the extensional efficiency, is higher the static mixer may produce finer droplets in multi-phase systems.

$$d_{\max} = Ca_{\text{crit}} \frac{2\sigma}{\dot{\gamma}\mu_c} \quad (11)$$

where $d_{\max}$ is the maximum equilibrium droplet diameter, Ca_{crit} is the critical capillary number, σ is the surface tension between the dispersed and continuous phases, μ_c is the continuous phase molecular viscosity and $\dot{\gamma}$ is the strain rate, which depends on the velocity gradient.

Fig. 9 shows the extensional efficiency over a line with coordinates ($x = D/6$), ($y = D/6$), ($-0.225 < z < -0.075$ m) for various static mixers. The horizontal axis represents the number of elements. As observed in Fig. 9a, the parts between the elements in the Kenics static mixer cover greater areas for higher values of α , which means that the parts between two mixing element groups have a significant effect on the dispersive mixing. For the Komax mixer (Fig. 9b), the maximum value of α is observed at element 0 and element 2, which corresponds to the inlet of the first and third mixing elements, respectively. Three smaller peaks are observed at the mixing elements 1, 3 and 4, which correspond to the inlet of the second and the outlet of the third and fourth mixing elements, respectively. The wide ranges of extensional efficiency observed in Fig. 9c and d reveal that more complex flow

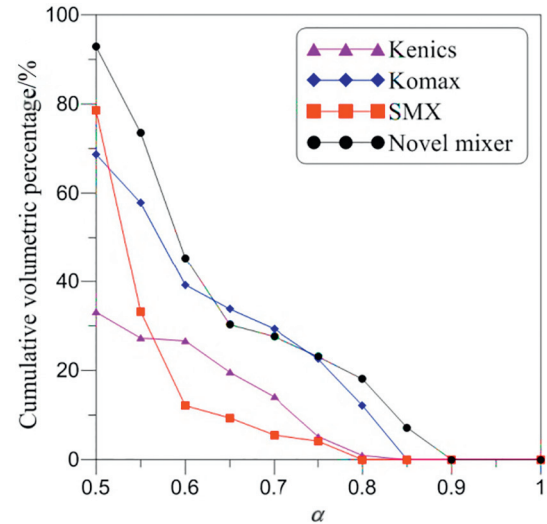


Fig. 10. Cumulative volumetric percentage in the different static mixers.

patterns are predicted for the SMX and the new mixer than those for the Kenics and Komax mixers. From the average extensional efficiency values shown in Fig. 9, it can be deduced that the new static mixer is

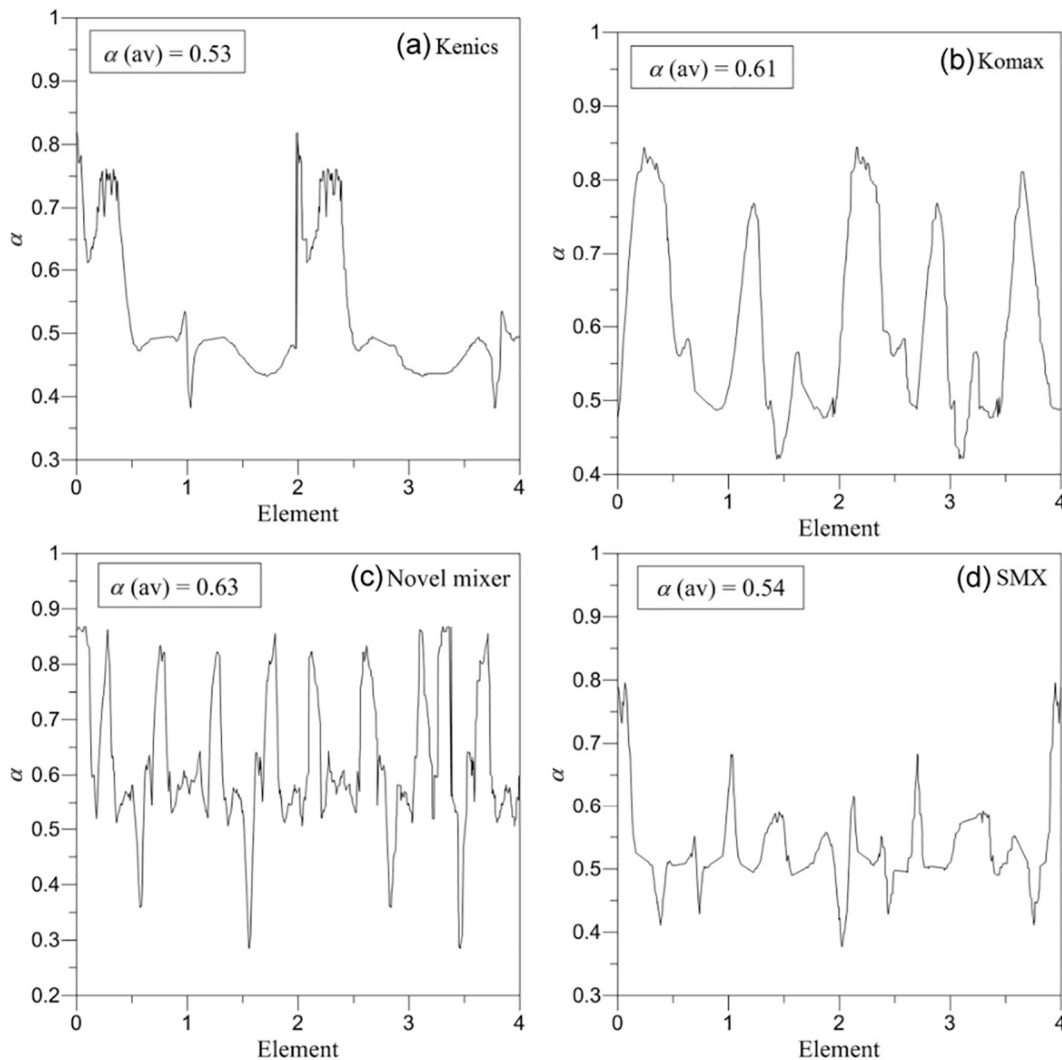


Fig. 9. Extensional efficiency of the (a) Kenics mixer (b) Komax mixer (c) Proposed mixer (d) SMX mixer.

the most efficient one concerning dispersive mixing, with the Komax one being second, followed by the SMX and the Kenics mixers. Moreover, the two different types of static mixers (the new one and the Komax mixer) have almost the same values of average extensional efficiency, but different CoV values. This means that the two mixers that have the same dispersive mixing, but not necessarily lead to the same distributive mixing. The average value is not the only way to analyze this criterion. Thus, a high extensional efficiency is required to deform a single-phase fluid or break a drop in a two-phase fluid.

The cumulative volumetric distributions of α in Kenics, Komax, SMX and in the new mixer are shown in Fig. 10. These percentages are the volume percentages of the mixers in which the extensional efficiency is greater than the value in the abscissa. Thus, the extensional efficiency is higher than 0.5 for 36% of the Kenics volume, 68% of the Komax volume, 79% of the SMX volume, and 92% of the new mixer volume. For any value, the Kenics mixer is less efficient than the Komax and

the new mixer, since for any value of α the cumulative volumetric percentage is lower. On the other hand, the SMX mixer is more efficient than the Kenics mixer only if α is below 0.56. Moreover, it can be seen that the new mixer is more efficient than the other static mixers, except in the range from 0.63 to 0.75, in which its efficiency is slightly lower than that of the Komax mixer.

3.5. Concentration distribution

The CFD results of brine concentration distribution at different cross-sections of the static mixers have been evaluated before and after the mixing elements. Fig. 11 shows a sample of the computed brine concentration distribution at $Re = 60$ and $z = -0.075$ m. Both liquids (water and brine) enter the first element and split into two (Kenics and Komax) or more (SMX and new mixer) streams along the surfaces of the elements, which promote mixing compared to the flow at different

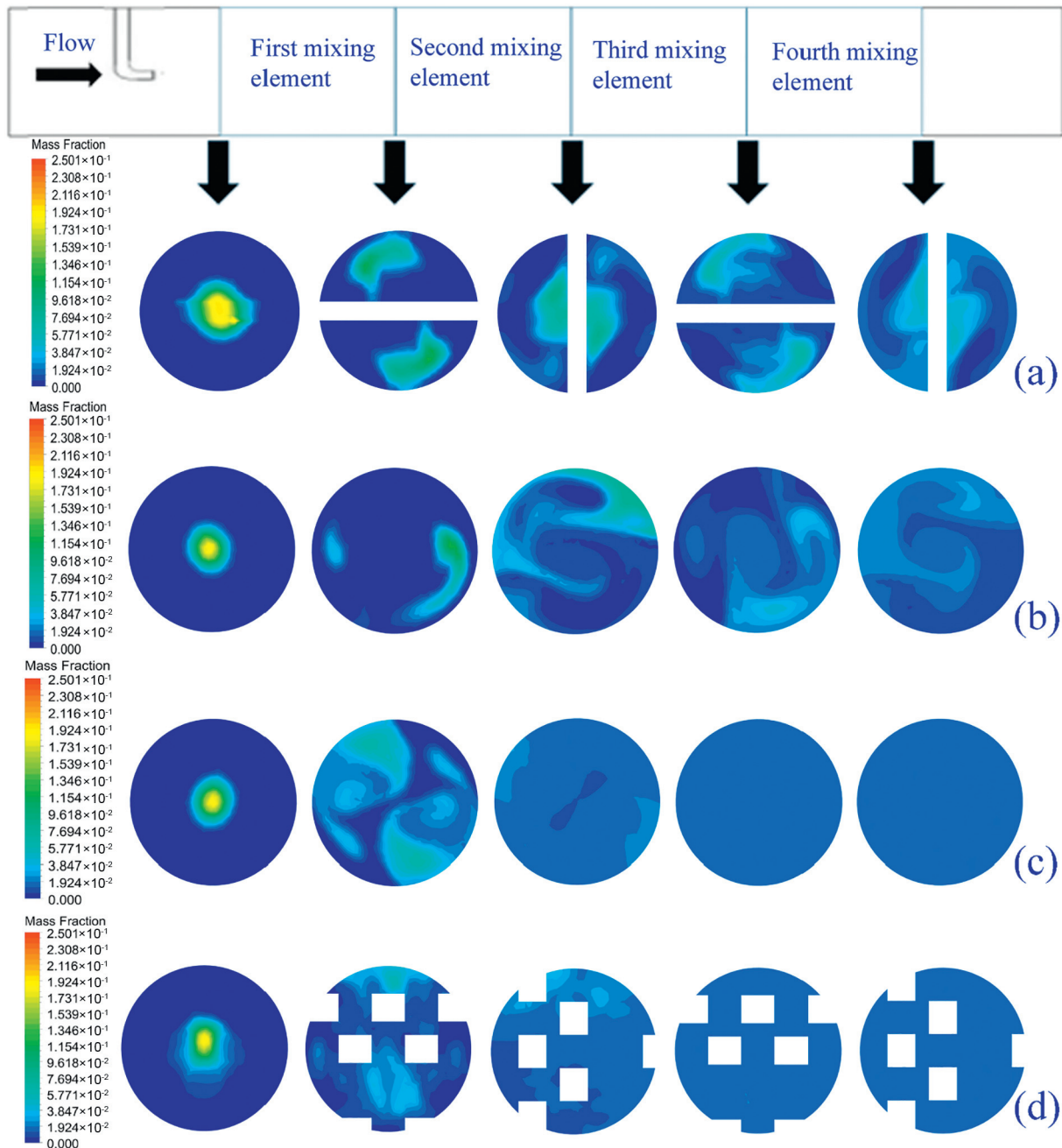


Fig. 11. Mass fraction distribution of brine at different cross sections for different static mixers at $Re = 60$: (a) Kenics mixer (b) Komax mixer (c) Proposed mixer (d) SMX mixer.

sections of an empty tube. By analyzing the brine distribution at various cross sections, it is found that after the third element the homogenization reaches a satisfactory level ($\text{CoV} < 0.05$) for the SMX and the new mixer, whereas for the Kenics and Komax mixers the brine was not uniformly distributed across the mixers subsequent to the fourth element. Overall, the differences in the mixing intensity of the brine shown in Fig. 11 are evidence that the shape of the mixer geometry significantly affects distributive mixing.

Fig. 12 shows the contour plots of the mass fraction of the brine at $Re = 60$ along the static mixers. As observed in Fig. 12, two streams from two different boundaries (the inlet of the main pipe and the injection tube) enter the first element, and the mixing elements change the direction of the flow. This issue leads to full mixing of the fluids at the end of the SMX and the new mixer.

4. Conclusions

A three-dimensional CFD simulation was performed for different static mixers, namely, Kenics, SMX, Komax and a novel static mixer,

for Reynolds numbers ranging from 20 to 160. There are a number of correlations in the open literature to predict the pressure drop ratio for well-known static mixers, such as the Kenics one. These correlations have been mainly developed for laminar and turbulent flow regimes. However, most of these correlations do not consider the geometric parameters, such as the blade thickness and the number of elements, and they are therefore under great uncertainty. To validate the numerical model, experimental data available for a static mixer with a baffle shape element (Al-Atabi [50]) and a correlation proposed for the Kenics mixer (Sir and Lecjaks [51]) have been taken as benchmarks. The pressure drop ratio and the coefficient of variation predicted by the CFD model have been compared with experimental data reported in the open literature, and a good agreement (2.3% and 6% for Z-factor and CoV, respectively) has been found. Moreover, some available correlations for Z-factor have been evaluated for a Kenics mixer and the best fit was obtained for the one proposed by Cybulski and Werner [19] for $Re = 20 - 160$. After the validation of the CFD model, the computational method was extended to the other static mixers in order to examine the effect operating and geometric parameters have on the

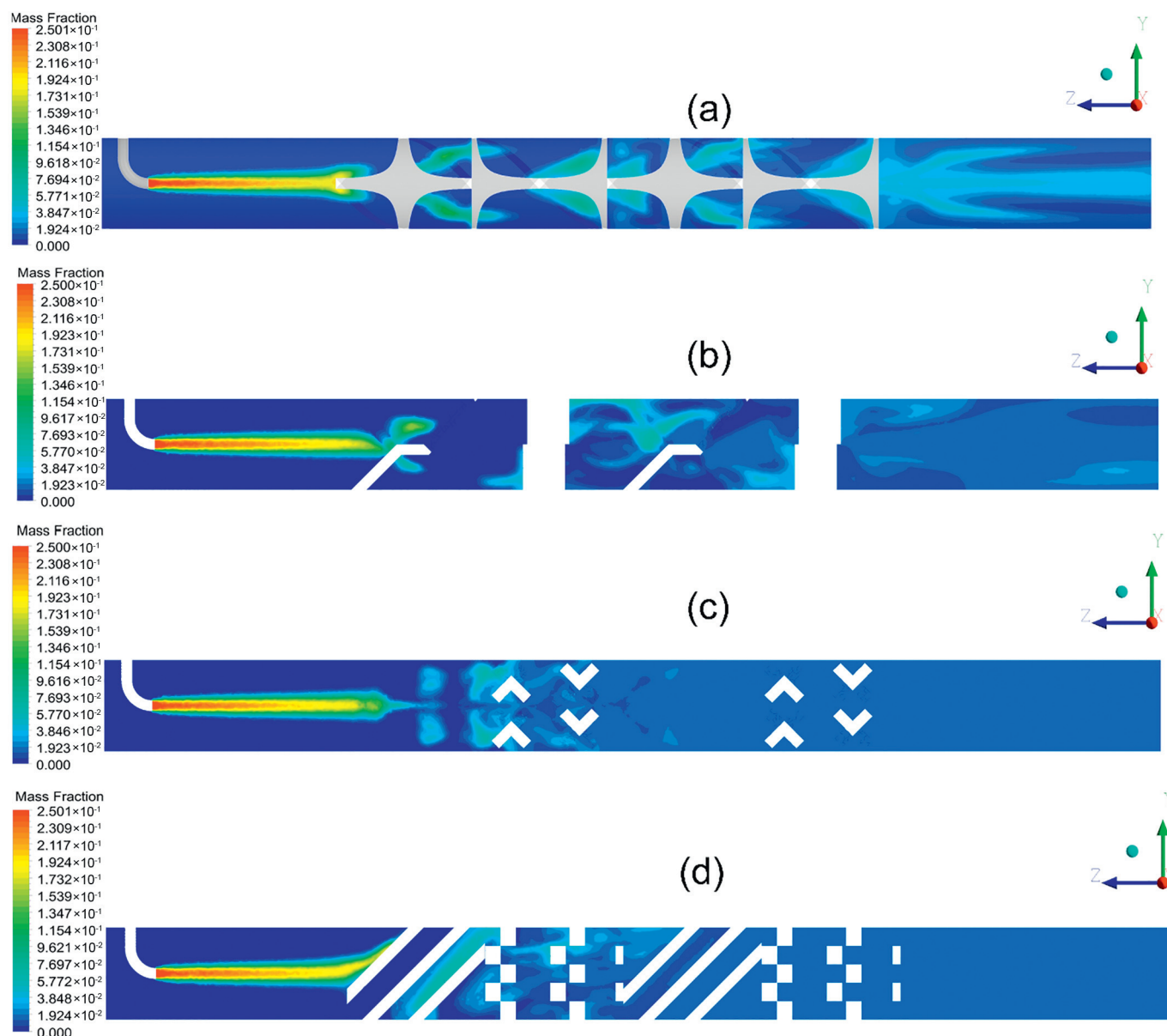


Fig. 12. Mass fraction distribution of brine on a diametrically vertical plane in the static mixers at $Re = 60$: (a) Kenics mixer (b) Komax mixer (c) Proposed mixer (d) SMX mixer.

hydrodynamics and mixing performances. The velocity field, pressure drop ratio, coefficient of variation, concentration distribution and extensional efficiency have been determined at various conditions in different mixers. The proposed static mixer has a much better performance than the other static mixers. Finally, the following remarks may be drawn from this study:

- 1) The Z-factor generated in the new static mixer is about 45% lower than that corresponding to the SMX mixer under the same conditions.
- 2) The mixing efficiency of the new mixer is higher than those of the other static mixers. Actually, this mixer generates a lower coefficient of variation and higher extensional efficiency than the other mixers.
- 3) Two mixers with the same dispersive mixing do not necessarily lead to the same distributive mixing.
- 4) The new static mixer is more efficient than the other mixers in deforming fluid (single-phase) and breaking drops (two-phase) because it creates high extensional efficiency.
- 5) The methodology described here can be applied to simulate and design other mixers in order to evaluate their mixing performances.

Finally, given that the information about use of static mixers with complex fluids is scarce, the mixing performance of this new mixer will be assessed in a future study involving complex fluids, such as non-Newtonian and immiscible ones.

Nomenclature

AR	aspect ratio
b_l	blade length, mm
b_w	blade width, mm
Ca_{crit}	critical capillary number
CoV	coefficient of variation
D	tube diameter, mm
D_{AB}	molecular diffusivity, $m^2 \cdot s^{-1}$
d_{max}	maximum equilibrium droplet diameter, m
F	flow rate ratio
f	friction factor
g	gravity acceleration, $m^2 \cdot s^{-1}$
L	length of the mixer, mm
N	number of evaluation points
P	total pressure, Pa
ΔP	pressure drop in a static mixer, Pa
ΔP_0	pressure drop in an empty tube, Pa
Re	Reynolds number
t	blade thickness, mm
V	velocity, $m^2 \cdot s^{-1}$
$\bar{V}$	mean velocity, $m^2 \cdot s^{-1}$
∇V	velocity gradient, s^{-1}
x	transversal coordinate, mm
Y_i	local mass fraction of the injected fluid at the i th point
Y_{mean}	mean mass fraction of the injected fluid
y	height coordinate, mm
Z	pressure drop ratio
z	length coordinate, mm
α	extensional efficiency
γ	deformation tensor, s^{-1}
μ	viscosity, $kg \cdot m^{-1} \cdot s^{-1}$
ρ	density, $kg \cdot m^{-3}$
σ	surface tension, $N \cdot m^{-1}$
ω	vorticity tensor, s^{-1}

References

- [1] K.J. Myers, A. Bakker, D. Ryan, Avoid agitation by selecting static mixers, *Chem. Eng. Prog.* 93 (1997) 28–38.
- [2] T. Bor, The static mixer as a chemical reactor, *Br. Chem. Eng.* 16 (1971) 610–612.
- [3] J.R. Baker, Motionless mixers stir up new uses, *Chem. Eng. Prog.* 87 (1991) 32–38.
- [4] R.K. Thakur, Ch. Vial, D.P. Nigam, E.B. Nauman, G. Djelveh, Static mixers in the process industries—A review, *Chem. Eng. Res. Des.* 81 (2003) 787–826.
- [5] G. Montante, M. Coroneo, A. Paglianti, Blending of miscible liquids with different densities and viscosities, *Chem. Eng. Sci.* 141 (2016) 250–260.
- [6] F. Theron, N. Le Sauze, Comparison between three static mixers for emulsification in turbulent flow, *Int. J. Multiph. Flow.* 37 (2011) 488–500.
- [7] P. Pianko-Oprych, Z. Jaworski, CFD modelling of two-phase liquid-liquid flow in a SMX static mixer, *Pol. J. Chem. Technol.* 11 (2009) 41–49.
- [8] P.D. Berkman, R.V. Calabrese, Dispersion of viscous liquids by turbulent flow in a static mixer, *AIChE J.* 34 (1988) 602–609.
- [9] C.U. Ugwu, J.C. Ogbonna, H. Tanaka, Improvement of mass transfer characteristics and productivities of inclined tubular photobioreactors by installation of internal static mixers, *Appl. Microbiol. Biotechnol.* 58 (2002) 600–607.
- [10] R. Rakoczy, S. Masiuk, M. Kordas, P. Gradzik, The effects of power characteristics on the heat transfer process in various types of motionless mixing devices, *Chem. Eng. Process.* 50 (2011) 959–969.
- [11] S. Rabha, M. Schubert, F. Grugel, M. Banowski, U. Hampel, Visualization and quantitative analysis of dispersive mixing by a helical static mixer in upward co-current gas-liquid flow, *Chem. Eng. J.* 262 (2015) 527–540.
- [12] F. Zidouni, E. Krepper, R. Rzehak, S. Rabha, M. Schubert, U. Hampel, Simulation of gas-liquid flow in a helical static mixer, *Chem. Eng. Sci.* 137 (2015) 476–486.
- [13] S. Middleman, Fundamentals of Polymer Processing, McGraw-Hill, New York, 1977.
- [14] E.L. Paul, Design and scaleup of an anchorage-dependent mammalian cell bioreactor, *Ann. N. Y. Acad. Sci.* 589 (1990) 642–649.
- [15] Z. Qing-shi, Ozone disinfection of sewage in a static mixer contacting reactor system on a plant scale, *Ozone Sci. Eng.* 13 (1991) 313–330.
- [16] N. Martin, C. Galey, Use of static mixer for oxidation and disinfection by ozone, *Ozone Sci. Eng.* 16 (1994) 455–473.
- [17] P.B. Clancy, Treatment of chlorinated ethenes in groundwater with ozone and hydrogen peroxide, *Environ. Prog.* 15 (1996) 187–193.
- [18] J.H. Kwong, J.H. Jung, H.D. Lee, Y.S. Park, D.W. Kim, Development of a hydrodynamic static mixer for mixing chemicals in ballast water treatment systems, *J. Water Process Eng.* 8 (2015) 209–220.
- [19] A. Cybulski, K. Werner, Static mixers—criteria for application and selection, *Int. Chem. Eng.* 26 (1986) 171–180.
- [20] J.P. Gingras, L. Fradette, P. Tanguy, J. Bousquet, Inline bitumen emulsification using static mixers, *Ind. Eng. Chem. Res.* 46 (2007) 2618–2627.
- [21] A.S. Klett, A.M. Payne, M.C. Thies, Continuous-flow process for the purification and fractionation of alkali and organosolv lignins, *ACS Sustain. Chem. Eng.* 4 (2016) 6689–6694.
- [22] M. Rauline, P.A. Tanguy, J.M. Le Blevec, J. Bousquet, Numerical investigation of the performance of several static mixers, *Can. J. Chem. Eng.* 76 (1998) 527–535.
- [23] E.B. Nauman, B.A. Buffham, Mixing in continuous flow systems, *Chem. Eng. Commun.* 29 (1983) 369–370.
- [24] I. Manas-Zloczower, Studies of mixing efficiency in batch and continuous mixers, *Rubber Chem. Technol.* 67 (1994) 504–528.
- [25] S. Shojaei, S.H. Hosseini, A. Rafati, G. Ahmadi, Prediction of the effective area in structured packings by computational fluid dynamics, *Ind. Eng. Chem. Res.* 50 (2011) 10833–10842.
- [26] S.H. Hosseini, S. Shojaei, G. Ahmadi, M. Zivdar, Computational fluid dynamics studies of dry and wet pressure drops in structured packings, *J. Ind. Eng. Chem.* 18 (2012) 1465–1473.
- [27] S. Liu, A.N. Hrymak, P.E. Wood, Laminar mixing of shear thinning fluids in a SMX static mixer, *Chem. Eng. Sci.* 61 (2006) 1753–1759.
- [28] A. Baumann, S.A.K. Jeelani, B. Holenstein, P. Stossel, E.J. Windhab, Flow regimes and drop break-up in SMX and packed bed static mixers, *Chem. Eng. Sci.* 73 (2012) 354–365.
- [29] J.M. Zalc, S.E. Szalai, F.J. Muzzio, S. Jaffer, Characterization of flow and mixing in an SMX static mixer, *AIChE J.* 48 (2002) 427–436.
- [30] J.M. Zalc, S.E. Szalai, F.J. Muzzio, Mixing dynamics in the SMX static mixer as a function of injection location and flow ratio, *Polym. Eng. Sci.* 43 (2003) 875–890.
- [31] D.M. Hobbs, P.D. Swanson, F.J. Muzzio, Numerical characterization of low Reynolds number flow in the Kenics static mixer, *Chem. Eng. Sci.* 53 (1998) 1565–1584.
- [32] O. Byrde, M.L. Sawley, Optimization of a Kenics static mixer for non-creeping flow conditions, *Chem. Eng. J.* 72 (1999) 163–169.
- [33] E. Saadtdjian, A.J.S. Rodrigo, J.P.B. Mota, On chaotic advection in a static mixer, *Chem. Eng. J.* 187 (2012) 289–298.
- [34] M. Regner, K. Östergren, C. Trägårdh, Effects of geometry and flow rate on secondary flow and the mixing process in static mixers—A numerical study, *Chem. Eng. Sci.* 61 (2006) 6133–6141.
- [35] H.S. Song, S.P. Han, A general correlation for pressure drop in a Kenics static mixer, *Chem. Eng. Sci.* 60 (2005) 5696–5704.
- [36] E. Fourcade, R. Wadley, H.C.J. Hoefsloot, A. Green, CFD calculation of laminar striation thinning in static mixer reactors, *Chem. Eng. Sci.* 56 (2001) 6729–6741.
- [37] P. Joshi, K.D.P. Nigam, E.B. Nauman, The Kenics static mixer: new data and proposed correlations, *Chem. Eng. J.* 59 (1995) 265–271.
- [38] M. Rafiee, S. Bakalis, P.J. Fryer, A. Ingram, Study of laminar mixing in kenics static mixer by using Positron Emission Particle Tracking (PEPT), *Procedia-Food Science.* 1 (2011) 678–684.
- [39] M.K. Singh, P.D. Anderson, H.E.H. Meijer, Understanding and optimizing the SMX static mixer, *Macromol. Rapid Commun.* 30 (2009) 362–376.
- [40] S.S. Soman, C.M.R. Madhuranthakam, Effects of internal geometry modifications on the dispersive and distributive mixing in static mixers, *Chem. Eng. Process.* 122 (2017) 31–43.
- [41] H.-B. Meng, M.-Y. Song, Y.-F. Yu, X.-H. Jiang, Z.-Y. Wang, J.-H. Wu, Enhancement of laminar flow and mixing performance in a lightnin static mixer, *Int. J. Chem. React. Eng.* 15 (2016) 20160112.

- [42] H. Meng, F. Wang, Y. Yu, M. Song, J. Wu, A numerical study of mixing performance of high-viscosity fluid in novel static mixers with multitwisted leaves, *Ind. Eng. Chem. Res.* 53 (2014) 4084–4095.
- [43] H. Meng, J. Zhu, Y. Yu, Z. Wang, J. Wu, The effect of symmetrical perforated holes on the turbulent heat transfer in the static mixer with modified Kenics segments, *Int. J. Heat Mass Transf.* 99 (2016) 647–659.
- [44] M. Zhou, D. Bai, Y. Zong, L. Zhao, J.N. Thornock, Numerical investigation of turbulent reactive mixing in a novel coaxial jet static mixer, *Chem. Eng. Process.* 122 (2017) 190–203.
- [45] S. Jegatheeswaran, F. Ein-Mozaffari, J. Wu, Process intensification in a chaotic SMX static mixer to achieve an energy-efficient mixing operation of non-newtonian fluids, *Chem. Eng. Proc.* 124 (2018) 1–10.
- [46] S. Jegatheeswaran, F. Ein-Mozaffari, J. Wu, Laminar mixing of non-Newtonian fluids in static mixers: process intensification perspective, *Rev. Chem. Eng.* (2019) <https://doi.org/10.1515/revce-2017-0104>.
- [47] O. Mihailova, D. O'Sullivan, A. Ingram, S. Bakalis, Velocity field characterization of Newtonian and non-Newtonian fluids in SMX mixers using PEPT, *Chem. Eng. Res. Des.* 108 (2016) 126–138.
- [48] Z. Jaworski, P. Pianko-Oprych, D.L. Marchisio, A.W. Nienow, CFD modelling of turbulent drop breakage in a Kenics static mixer and comparison with experimental data, *Chem. Eng. Res. Des.* 85 (2007) 753–759.
- [49] M.M. Haddadi, S.H. Hosseini, D. Rashtchian, G. Ahmadi, CFD modeling of immiscible liquids turbulent dispersion in Kenics static mixers: focusing on droplet behavior, *Chin J. Chem. Eng.* (2019) <https://doi.org/10.1016/j.cjche.2019.07.020>.
- [50] M. Al-Atabi, Design and assessment of a novel static mixer, *Can. J. Chem. Eng.* 89 (2011) 550–554.
- [51] J. Sir, Z. Lecjaks, Pressure drop and homogenization efficiency of a motionless mixer, *Chem. Eng. Commun.* 16 (1982) 325–334.
- [52] R.B. Bird, W.E. Stewart, E.N. Lightfoot, *Transport Phenomena*, John Wiley & Sons, New York, 2002.
- [53] M. Coroneo, G. Montante, A. Paglianti, Computational fluid dynamics modeling of corrugated static mixers for turbulent applications, *Ind. Eng. Chem. Res.* 51 (2012) 15986–15996.
- [54] V. Kumar, V. Shirke, K.D.P. Nigam, Performance of Kenics static mixer over a wide range of Reynolds number, *Chem. Eng. J.* 139 (2008) 284–295.
- [55] W.L. Wilkinson, M.J. Cliff, An Investigation into the Performance of a Static In-line Mixer, In *Second European Conference on Mixing*, 1977.
- [56] N.F. Shah, D.D. Kale, Two-phase gas-liquid flows in static mixers, *AIChE J.* 38 (1992) 308–310.
- [57] C.D. Grace, Static mixing and heat transfer, *Chem. Process. Eng.* 52 (1971) 57–59.
- [58] S.H. Hosseini, G. Ahmadi, M. Olazar, CFD simulation of cylindrical spouted beds by the kinetic theory of granular flow, *Powder Technol.* 246 (2013) 303–316.
- [59] C. Guenther, M. Syamlal, The effect of numerical diffusion on simulation of isolated bubbles in a gas-solid fluidized bed, *Powder Technol.* 116 (2001) 142–154.
- [60] M.D. Das, A.N. Hrymak, M.H.I. Baird, Laminar liquid-liquid dispersion in the SMX static mixer, *Chem. Eng. Sci.* 101 (2013) 329–344.