Turbulent Mixing of Two Immiscible Fluids

The emulsification process in a static mixer HEV (high-efficiency vortex) in turbulent flow is investigated. This new type of mixer generates coherent large-scale structures, enhancing momentum transfer in the bulk flow and hence providing favorable conditions for phase dispersion. We present a study of the single-phase flow that details the flow structure, based on LDV measurements, giving access on the scales of turbulence. In addition, we discuss the liquid-liquid dispersion of oil in water obtained at the exit of the mixer/emulsifier. The generation of the dispersion is characterized by the Sauter diameter and described via a size-distribution function. We are interested in a local turbulence analysis, particularly the spatial structure of the turbulence and the turbulence spectra, which give information about the turbulent dissipation rate. Finally, we discuss the emulsifier efficiency and compare the HEV performance with existing devices.

Keywords: Liquid-Liquid Dispersion, Turbulent Spectra, Static Mixer, Energetic Efficiency, Energy Dissipation Rate, High Efficiency Vortex (HEV), Longitudinal Vortices

1 Introduction

The global trend in chemical and manufacturing industries is towards improved energy efficiency, cleaner synthesis, reduced environmental impact, and smaller, safer, multifunctional process plants. Such concerns are the driving force for the intensification of batch processes, which are being replaced with continuous high-intensity in-line mass- and heat-transfer equipment. In this context the process-intensification (PI) approach, in which the fluid dynamics of the process is matched to the reaction in order to improve selectivity and minimize the by-products, takes on particular importance.

It is estimated that in a typical large chemical plant, between 5 and 45 million Euros are wasted every year through inefficiencies. In some cases it is estimated that optimizing reactor performance for maximum yield and selectivity would save between 0.4 and 0.8 million Euros per product per year. Overall, reactor-related problems are believed to account for between 0.5% and 3.0% of total turnover, which for European Union chemical industries amounts to 1.9 to 11.4 billion Euros per year [1].

Systems involving more than one component (or phase) contain interfaces between the components. Our ability to predict the performance of such systems is extremely limited. In addition, many multiphase processes are carried out in stirred-tank reactors. Poor flow patterns and low inhomogeneous mixing are characteristic of stirred-tank reactors and typically afford energy dissipation rates in the range 1–10 W kg⁻¹.

High selectivity requires high rates of micromixing, which need turbulent energy dissipations higher than 100 W kg⁻¹. Therefore, fast exothermic reactions when carried out in stirred tanks start before mixing is complete, leading to slow apparent rates of reaction and formation of by-products that must be separated further downline. The high-efficiency vortex (HEV) heat exchanger-reactor is selected for its capacity to generate large-scale vortex motions and enhance turbulent energy dissipation in the flow.

A typical potential application of this device in manufacturing processes is the "mixhead" of resin-injection-molding (RIM) machines. Mixing, often called the heart of RIM, is what differentiates it from other reaction-molding processes such as thermoset injection molding or sheet molding. Most mixhead designs were developed by trial and error. Even today, newly designed mixheads are mounted on a machine and a typical reaction is tried on them [2]; mixing quality is then judged by the visual appearance of the product. Therefore, understanding the basic physical phenomena underlying mixing in flows in manufacturing processes is fundamental to a predictive approach to these processes.

In this paper we give a global characterization of a special static mixer designed for use as a reactor-hear exchanger for process intensification in liquid-liquid mixing and reaction. Its design is based on curved baffles fixed on the tube walls that generate longitudinal vortices, substantially increasing transport phenomena over the simple pipe and even over some static mixers known for their high efficiency. The emulsification performance of this system, indicative of its mixing abilities, is presented in this study. Oil-in-water emulsions obtained with the static mixer are characterized by the granulometric distributions. The mean size, size distribution, and power consumption of the mixer are compared with those in some existing devices.

The turbulent characteristics of the flow in the mixer are studied extensively and the physical phenomena underlying the high efficiency of the mixer are addressed.

2 Experimental Setup and Methods

The Perspex HEV test section designed and constructed for this work (Fig. 1) is a straight tube of inner diameter 20 mm along which seven tab arrays are fixed. Each of the seven arrays consists of four trapezoidal tabs positioned at 90° to one another and fixed on the tube walls. The tabs are turbulence promoters and generate longitudinal vortical structures. The test section is 180 mm long and the distance between two successive tab arrays is 20 mm (one tube diameter).

The test section is connected to a preconditioner and postconditioner, which are 300 mm straight transparent tubes of circular inner cross section and 20 mm inner diameter. The preconditioner is used to provide a fully developed flow at the inlet of the test section, and the postconditioner to observe the effect of the test section on mixing quality.

A schematic diagram of the experimental setup is shown in Fig. 2. It consists of feed loops for oil and water. The flow rates are controlled by valves and measured with two flowmeters with overlapping ranges.
In Sec. 3, single-phase-flow results are given. The working fluid is water and flow patterns are visualized by the laser-induced fluorescence (LIF) technique. Mean and fluctuating velocity fields were measured by laser Doppler velocimetry (LDV) and particle image velocimetry (PIV). The local turbulent energy dissipation rates were hence obtained by the determination of the integral length scales. The pressure drop was measured by a differential manometer, and the temperature remained about the ambient 20°C±0.5. Experiments were run for Reynolds numbers ranging between 1500 and 15,000.

In Sec. 4, liquid-liquid phase dispersion is studied. The working fluids are water for the internal phase and an additive technical vaseline oil (Albelf ID 15) for the dispersed phase. The setup allows experiments corresponding to dispersed-phase mixing rates of up to 15%, with Reynolds numbers ranging from 7500 to 15,000. A microencapsulation, based on the isocyanate-amine polymerization reaction, is performed on the emulsion at the exit from the test section. Further details on the experimental setup and the microencapsulation technique are given by Lemenand et al. [3]. The physical properties of oil are given in Table 1.

A video-optic computer-assisted device was used for granulometric analysis (Pegase software). It was found that a sample of at least 600 droplets is needed to reach 5% precision in the Sauter diameter value. Figure 3 shows some photographs of various sampled dispersions.

### Table 1 Physical properties of oil loaded with 10% volume of encapsulation reactant

<table>
<thead>
<tr>
<th>Property (20°C)</th>
<th>Value</th>
<th>Measurement method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic viscosity</td>
<td>$3 \times 10^{-6}$ m² s⁻¹</td>
<td>Mettler™ RM180 rheometer</td>
</tr>
<tr>
<td>Density</td>
<td>0.85</td>
<td>Data Technical™ picnometer</td>
</tr>
<tr>
<td>Interfacial tension with water</td>
<td>$2 \times 10^{-3}$ N m⁻¹</td>
<td>Krüss™ tensiometer (K12) ring method</td>
</tr>
</tbody>
</table>

Fig. 1 Heat exchanger-reactor HEV

Fig. 2 Experimental setup

Fig. 3 Emulsion samples—optical microscopy

Fig. 4 Coherent structures at Re=1500

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still be observed. Figure 5 illustrates the axial mean velocity profiles 2 mm downstream of each tab array for flow Re=15,000 \(4\) along axis \(A\) (shown in Fig. 4). The same figure shows the velocity profile in the straight tube upstream of the first tab array. It can be seen that the first tab array has no significant effect on the mean velocity profile. However, the effect of the second tab array superposed on that of the first induces two minima behind the tabs in the mean velocity profile. This deformation of the velocity profile is due to the transfer of low-momentum fluid particles from the HEV wall vicinity to the core flow and is also visible downstream of the subsequent tabs.

Figure 6 shows turbulence kinetic energy (TKE) dissipation profiles 2 mm behind each tab array \(5\) for Reynolds number 10,000 along axis \(A\). The effect of the radial velocity component in the streamwise vortices is visible here: high turbulence patterns close to the wall are transferred towards the core region, so that the TKE dissipation in the HEV center is dramatically intensified compared with the empty tube.

The TKE dissipation rate \(e\) was computed using Batchelor’s energy-cascade model \(6\):

\[
e = C \frac{q^{3/2}}{l}
\]

where \(l\) is the Prandtl mixing length and \(q\) is the turbulent kinetic energy.

Assuming that the high-frequency fluctuations involved in the energy dissipation are locally isotropic, and also that the integral macroscale \(\Lambda\) can approximate the length scale \(l\), one can define the local turbulent energy dissipation by

\[
e = C \left(\frac{q^{3/2}}{\Lambda}\right)^{\frac{2}{3}}
\]

In the present work, the integral macroscale \(\Lambda\) is determined from the time macroscale using Taylor’s hypothesis:

\[\Lambda = U_{con} T\]

where \(U_{con}\) represents the convection velocity. This velocity was determined by using Van Doorn’s expression \(7\) for three-dimensional flows and simplified through the following hypotheses:

1. the axial mean velocity component is much larger than the tangential and radial components,
2. the velocity fluctuation field is locally isotropic.

This model predicts fairly well the turbulent energy dissipation in grid-generated turbulence with constant \(C=1.0\); however, the validity of the model for anisotropic turbulent flows may depend on the flow type \(8,9\). The numerical value of \(C\) must then be determined experimentally for specific cases.

In order to estimate the numerical value of \(C\), a series of experiments was carried out in a straight tube equipped with turbulence promoters (HEV) to measure \(u^2\) and \(\Lambda\). Then \(e/C\) was compared to the turbulence kinetic energy dissipation \(e\) obtained by Lawn \(10\) in a straight tube. This leads to a \(C\) value of 1.8, which is adopted in the latter equation.

The above description of the flow pattern allows a better understanding of the role of the tabs on the flow structure. As shown in Fig. 7, a high shear zone appears at the top of the tabs, which is the active mixing region in the device.
4 Liquid/Liquid Phase: Dispersion of Oil in an External Water Phase

HEV can be used successfully in the emulsification process. Here we focus on the granulometric characterization of oil-water emulsions obtained in a wide range of hydrodynamic conditions in the mixer. The droplets are sized using optical microscopy. The mean size, characterized by the Sauter diameter, is fitted to classical turbulent breakup models. The Sauter diameter and power consumption are compared with those in some existing devices.

4.1 Modeling Droplet Breakup in Turbulent Flow. A droplet subjected to mechanical stresses (pressure, velocity gradients, or turbulence forces) can burst into several smaller droplets. This phenomenon results from the competitive effects of the rheological and interfacial properties of the two phases, on the one hand, and mechanical forces via the flow conditions on the other. Application of the general breakup model to "noncoalesced" and inviscid systems, in homogeneous and isotropic turbulence, was tested here following the maximum drop size prediction in the Hinz-Kolmogorov theory, using a critical Weber number of order unity. Here we use the Hesketh et al. [11] presentation for this model:

\[
d_{\text{max}} = \left( \frac{Wc_{\text{c}10}}{2} \right)^{0.6} \left( \frac{\alpha^{1.5}}{\rho D_{\text{H}}^{2} \rho_{d}^{2}} \right)^{0.4} e^{-0.4} \tag{4}
\]

For a wide range of applications (stirred vessels, homogenizers, and the like), the breakup is fairly well predicted by a dimensionless Weber number, in formulas that may include the effect of the viscosity of the dispersed phase (the viscosity number). The dimensionless Shinnar [12] equation results from Eq. (4):

\[
d_{32}/D_{H} = C_{1} \ln \left( \frac{d_{32}}{D_{H}} \right) \tag{5}
\]

where the Weber number is defined as

\[
Wc = \frac{\rho_{d}U^{2}D_{H}}{\sigma} \tag{6}
\]

Some extensions of the basic model presented in Eq. (6) have been derived by different authors. Berkman and Calabrese [13] justified a corrective term for dilute emulsions to take into account the viscosity of the dispersed phase for a Kenics static mixer:

\[
\frac{d_{32}/D_{H}}{0.49} = 1.38N_{\text{Vij}} \left( \frac{d_{32}/D_{H}}{0.49} \right)^{1.3} \tag{7}
\]

with the viscosity number \(N_{\text{Vij}}\) defined by

\[
N_{\text{Vij}} = \frac{\mu_{d}U}{\sigma \left( \frac{\rho_{d}}{\rho_{l}} \right)^{0.5}} \tag{8}
\]

The value of the droplet mean diameter, and thus of the interfacial area, is nevertheless modified by the volume fraction of the dispersed phase from 15% to 30%. The linear corrective term found by Pacek et al. [14] takes into account the coalescence:

\[
\frac{d_{32}}{D_{H}} = C_{4}+C_{5} \sigma_{d} Wc_{\text{c}10}^{-0.6} \tag{9}
\]

4.2 Results and Discussion. Measurements were performed in the 0.1-0.25 l s⁻¹ flow rate range, for 0%-15% oil volume fraction, in order to investigate the effect of the Weber number on droplet distribution. All experiments were performed at room temperature (18-20°C).

4.2.1 Mean and Maximum Diameter. Proportionality between the Sauter mean diameter, \(d_{32}\), and the maximum diameter of the drops, \(d_{\text{max}}\), is the basic assumption of the turbulent breakup model [15,14]. Experimental results reveal that the diameters \(d_{32}\) and \(d_{\text{max}}\) are actually correlated according to the linear relation:

\[
d_{32} = C_{4} d_{\text{max}} \tag{10}
\]

where \(C_{4}=0.48\).

4.2.2 Sauter Diameter as a Function of Weber Number. The average droplet diameter strongly depends on the hydrodynamic conditions through the energy dissipation rate. The HEV measurements in Fig. 8 show fairly good agreement with this theoretical slope of \(-0.6(C_{4}=0.57)\), demonstrating that turbulent disruption governs the emulsification mechanism. The fit constant is smaller than 1 (usual value), suggesting that under similar conditions the Sauter diameter is smaller in the HEV than in classical static mixers. This feature will be investigated further by analyzing the energy consumption efficiency of this device.

4.2.3 Size Distribution Function. The method proposed by Schwarz and Bezemer [16] is applied to fit the present data. The cumulative volume \(V\%\) of the distribution function is modeled using a typical constant \(a\):

\[
\ln V\% = \ln 100 + \frac{a}{d_{\text{max}}} - \frac{a}{d_{\text{max}}} \tag{11}
\]

Figure 9 shows a plot for an emulsion of oil fraction 5% in which for each Reynolds number the Schwarz-Bezemer model represents the droplet size distribution in HEV, as far as the straight lines extrapolate to the same intercept.

The value of \(a/d_{\text{max}}\) is a constant (1.08) independent of the operating conditions, which is more convenient for scale-up operations than a classical log-normal distribution.

5 Local Turbulence Analysis

Previous results on the dispersion of oil in water under the combined action of mean and fluctuating velocity fields have raised the complex question of the turbulence parameters relevant in describing the ability of turbulence to split up the oil droplets. In fact, the local or mean turbulent dissipation rate measured on axis \(A\) cannot explain the low value of \(d_{\text{max}}\) given by Eq. (4). More precise turbulence measurements (on axis \(B\)) are essential to investigate the turbulent dispersion efficiency, which is related to the knowledge of its properties: first, is the turbulence in the HEV homogeneous and isotropic [Eqs. (2) and (3)], and, second, where in the device is the highest mixing efficiency concentrated?

5.1 Spatial Structure of Turbulence. The most significant effect of the tabs is to increase the turbulence energy along the tube axis. Figure 10 shows the radial profile of the turbulent rms velocity at three axial positions: \(x_{1}\), upstream of HEV; \(x_{2}\), downstream of the first tab, and finally \(x_{3}\), downstream of the seventh...
one.

If the distribution at \( x_u \) corresponds to an equilibrium turbulent flow with turbulence production at the wall, turbulence is completely redistributed inside the HEV for stations \( x_d1 \) and \( x_d7 \). A peak of turbulence production is observed at the top of the tabs \( (y=0.37 R) \) that splits the flow in two regions of approximately equal turbulent energy: the tube core and the wake of the tabs. Obviously the level of turbulence increases downstream, reaching a plateau level that Mokrani et al. [4] have shown to be located between the second and the third tabs.

The quality of the turbulent flow was analyzed by plotting (Fig. 11) the probability density functions (pdf’s) with respect to the normal law. Figure 11(a) shows that the pdf in the tube center does not deviate from the normal law either at \( x_u \) or at \( x_d7 \) and deviates only transitionally after the first tab. Thus in this region the turbulence is intensified by the action of the tabs, but the distribution is not affected. Figure 11(b) shows the more complex situation in the wake region; here the pdf exhibits high skewness and flatness at \( x_d1 \) and \( x_d7 \), indicating that the turbulence there cannot be considered homogeneous and isotropic.

A schematic description of the flow inside the HEV may require considering three zones: the turbulent core region with high mean...
and fluctuating velocities, the wake region with high fluctuating velocity but low mean motion, and the region of sharp shear flow between them. The following sections analyze the turbulence through its spectral energy distribution and its autocorrelation function.

5.2 Turbulence Spectrum. To visualize the frequency range of energetic eddies in the turbulence, Fig. 12 plots the premultiplied spectrum \( fE_{11} \), with \( f \) the frequency and \( E_{11} \) the power density spectrum of the axial velocity component. Then the area under the curve is proportional to the energy of the signal \( u'^2 \) and can be used to normalize them. Figure 12 compares the normalized spectra at the upstream position \( x_u \) with the \(- \frac{5}{3} \) power-law curve indicating the theoretical energy cascade in the inertial range.

All curves collapse together with the same integral time scale at the point where the spectra begin to follow the \(- \frac{5}{3} \) power law. The upstream turbulence inside the tube is quite homogeneous, with a simple diffusion of the turbulence energy from the wall to the center and only slight differentiation of the coherent large structures.

On the other hand, the spectra at the end of the HEV \( (x_d) \) fall into different types in comparison with the upstream turbulent spectrum (Fig. 13). The most energetic flow is obviously found at the top of the tabs \( y/R=0.37 \) (shear flow), where the turbulence energy is produced at higher frequency than in the upstream flow. The integral time scale is roughly ten times smaller than that of \( x_u \).

The spectrum at the center is bimodal: a large-scale peak similar to the upstream turbulence combines with a turbulent cascade at higher frequencies resulting from the radial diffusion of the shear zone. In the wake region the spectrum is more complex, with a quite large peak at roughly the same integral time scale. Thus, except in this wake region, the turbulence is well modeled by homogeneous and isotropic turbulence.

With the help of these spectra, the integral length scale is calculated by Eq. (3) and then the local turbulent dissipation rate \( \epsilon \) as computed with Eq. (2) is plotted in Fig. 14 versus \( y/R \) at the three axial positions [even though Eqs. (2) and (3) are not completely valid below \( y/R<0.37 \) ]. The highest energy dissipation rate \( \epsilon \) is found at the high-shear-velocity position at roughly the same radial position as the tab tip. This value will be used further to predict the mixing efficiency of this turbulence in the HEV.

6 Discussion

This section examines the breakup process and the dispersion performance in order to clarify whether the TKE dissipation rate effectively governs the maximum particle diameter and to determine the energy consumption required to achieve the oil dispersion.

6.1 Energy Cost. The energy consumed in this experiment is the external pumping power necessary to propel the fluids through the static mixer, which is mostly dissipated into heat through turbulent fluctuations. As shown in Fig. 15, a small part of this energy is devoted to the potential surface energy involved in the creation of new interfacial area during emulsification:

\[
E_s = \frac{\sigma A}{\rho} \tag{12}
\]

The mean energy dissipation rate is computed from the total power consumption for a unit mass of the processed fluid:

\[
\dot{E} = \frac{Q \Delta P}{\rho V} = \frac{U \Delta P}{\rho L} \text{ (W kg}^{-1}\text{)} \tag{13}
\]

Hence the specific energy obtained by integration over the residence time \( L/U \) is

\[
E = \frac{\Delta P}{\rho} \text{ (J kg}^{-1}\text{)} \tag{14}
\]
The pressure-drop values in the test section were measured and compared with the theoretical values for a simple smooth duct of equal hydraulic diameter. The $z$ factor, defined as the pressure-drop ratio between the HEV and the simple duct,

$$z = \frac{\Delta P_{\text{HEV}}}{\Delta P_{\text{Duct,0}}},$$  \hspace{1cm} (15)

shows that the vortex generators provide up to an eightfold increase in dissipative efficiency, independent of the flow rate (Table 2).

Moreover, the pressure-drop measurements show an important decrease by increasing the oil volume concentration, because of the damping of turbulence occurring near the contact surface between the two phases [3]. The damping factor (Fig. 16) is calculated with reference to the single-phase flow in the HEV.

6.2 Efficiency. To assess the efficiency of HEV as an emulsifier, its experimentally measured energy cost is compared with those of existing devices as reported by previous investigators. Figure 17 correlates the energy spent in phase dispersion with the interfacial area generated by each system [17]. The working zone of the HEV mixer is in the small-energy range (between 0.1 and 1 J kg$^{-1}$) for a typical interfacial area of 300–3000 m$^2$ m$^{-3}$. This shows a good efficiency for the dispersion of immiscible liquids: a decrease in energy consumption by a factor of up to 1000 for interfacial areas around 1000 m$^2$ m$^{-3}$.

6.3 Equilibrium Size. A large amount of laser Doppler velocimetry data was obtained and analyzed in the HEV in order to describe the turbulent energy dissipation distribution in the HEV geometry. Equation (2) was used to evaluate the energy dissipation.

The macroscale $\lambda$ was derived from the temporal autocorrelation function of the instantaneous velocity. An appropriate convection velocity was calculated by using a generalized Taylor hypothesis. Wu and Patterson [18] have already obtained satisfactory results using this method.

It is well established that in a given system, where some disruptions of the droplets occur, a maximum equilibrium droplet size is reached that can resist the turbulent forces. It is understandable that the successive divisions leading to this equilibrium size will need a “certain” time. If this time is longer than the residence time, the droplets obtained will be coarser than the predicted size, and thus the system can be optimized by increasing the residence time, for instance by adding another mixing element. The time scale proposed by some authors (Davies [19], Hesketh et al. [11]) suggests that the minimal residence time for optimal division is between 1.5 and 10 s (the characteristic time for droplet breakup is estimated at about 1 $\mu$s and a sufficient number of divisions must take place).

To analyze these features in the present system, Fig. 18 compares the experimental maximum drop size to that predicted by Eq. (4). The predicted maximum values with the mean turbulence dissipation rate are slightly higher than the measured values. This could mean that the equilibrium diameter has been reached and that the HEV mixer is long enough. Nevertheless, considering the local nature of the dissipation rate and recalling that the maximum “surviving” drop size in the flow is governed by the highest turbulence intensity, the maximum diameter was also computed from the maximum $\varepsilon$ value. Following this hypothesis, the equilibrium seems to have been achieved. In other words, it can be concluded from this plot that the actual drop size is controlled by a dissipation rate of the order of the maximum local value. The nonuniformity of the dissipation field may explain the discrepancy between various flow configurations, and consequently the large variety of constants $C$ in Eq. (2).

**Table 2**

<table>
<thead>
<tr>
<th>$\phi$ (%)</th>
<th>0</th>
<th>2.5</th>
<th>5</th>
<th>7.5</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
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<tbody>
<tr>
<td>$z$</td>
<td>7.87</td>
<td>7.68</td>
<td>7.21</td>
<td>6.31</td>
<td>5.23</td>
<td>4.49</td>
<td>2.93</td>
</tr>
</tbody>
</table>

**Fig. 15** Ratio of surface energy to available mechanical energy

**Fig. 16** Damping factor

**Fig. 17** Comparative energy cost of HEV
7 Conclusions

The formation of droplets in the turbulent flow of two immiscible fluids in a HEV mixer was studied. The mixing mechanism is the generation of a cascade of longitudinal vortices behind rows of tabs fixed in a straight tube of circular cross section. By generating extra shear in the flow, vortices increase the turbulent energy dissipation, which contributes directly to droplet breakup.

The very low energy level and the relatively high contact obtained without any surfactant show that HEV mixers have high potential for industrial applications.

Experiments carried out in low hold-up range (0%-15%) suggest that the Sauter mean diameter varies with the ~0.4 power of the TKE dissipation rate [Eq. (4)], demonstrating that the dominant mechanism of emulsification is turbulent disruption.

The size distribution of the droplets obtained with HEV was modeled according to the method proposed by Schwarz and Bezemer [16]. In a log-linear coordinate system the data showed a linear relation between the cumulative volume (in %) of droplet diameters and the inverse of the bounding diameter d, verifying that the Schwarz-Bezemer model applies here.

The overall energy cost of the HEV mixer was studied. Experimental pressure-drop measurements showed that the vortex generators increase the dissipative efficiency as much as eightfold, and that this increase is independent of the flow rate. The energy consumption for generation of interfacial area with the HEV mixer was compared with those of some common static mixers. In the range of interfacial area 1000 m$^{-2}$, it was shown that HEV is up to 1000 times more energy efficient than other mixers.

A striking conclusion of this study is that the droplet size is controlled by the maximum turbulent kinetic energy dissipation rather than the mean turbulent kinetic energy dissipation, as commonly believed.

Nomenclature

- $A$ = interfacial area, m$^2$
- $C, C_i$ = constants ($i=1$ to $4$)
- $D$ = reactor diameter, m
- $D_{H}$ = hydraulic diameter, m
- $E$ = specific energy, J kg$^{-1}$
- $E_i$ = potential surface energy, J kg$^{-1}$
- $L$ = static mixer length, m
- $N_{V_i}$ = Hinze’s viscosity group
- $Q$ = volume flow rate, m$^3$ s$^{-1}$
- $\Delta P$ = pressure drop, Pa
- $Re$ = Reynolds number
- $T$ = time macroscale, s
- $U = \text{mean velocity, m s}^{-1}$
- $V = \text{volume, m}^3$
- $V_\% = \text{cumulative volume, }\%$
- $We = \text{Weber number}$
- $a = \text{characteristic diameter, m}$
- $d = \text{diameter, m}$
- $d_{2} = \text{Sauter mean diameter, m}$
- $l = \text{Hinze’s viscosity group}$
- $q = \text{turbulent kinetic energy, m}^2\text{s}^{-2}$
- $u = \text{mean fluctuation velocity, m s}^{-1}$
- $x_u = \text{axial location upstream of the mixer}$
- $x_d = \text{axial location downstream of the first tab}$
- $x_{d7} = \text{axial location downstream of the seventh tab}$
- $z = \text{pressure ratio}$

Greek Symbols

- $\varepsilon = \text{energy dissipation rate, W kg}^{-1}$
- $\overline{\varepsilon} = \text{mean rate of energy dissipation, W kg}^{-1}$
- $\Phi = \text{concentration of dispersed phase, }\%$
- $\Lambda = \text{macro scale of turbulent fluctuations, m}$
- $\mu = \text{dynamic viscosity, Pa s}$
- $\rho = \text{density, kg m}^{-3}$
- $\sigma = \text{interfacial tension, N m}^{-1}$

Subscripts

- $c = \text{continuous phase}$
- $conv = \text{convective}$
- $crit = \text{critical}$
- $d = \text{dispersed phase}$
- $max = \text{maximum}$
- $0 = \Phi = 0\%$

Dimensionless Numbers

- $Re = \rho U D_{H}/\mu_c = \text{Reynolds number}$
- $We = \rho U^2 D_{H}/\sigma = \text{Weber number}$

References


[19] Davies, J. T., 1985, “Drop sizes of emulsions related to turbulent energy dis-