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Mixing Characteristics of Motionless Mixers

Yang, H. C.*

* School of Mechanical and Automotive Eng., Chonnam National University, 96-1 Dunduck-dong,
Yeosu, Chonnam 550-747, Korea. E-mail: hcyang@chonnam.ac.kr

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Abstract : Motionless mixers have found a large range of applications, including blending, reaction, dispersion, heat transfer and mass transfer. Understanding the mixing processes that occur in these diverse systems is essential for predicting many aspects of practical importance. The objective of this study is to perform the experimental investigations of mixing characteristics for three different motionless mixers. The red color dye tracer was mixed in the main stream of green hair styling gel, and then the mixing efficiency was quantified by calculating the percentage area concentration of red color at the outlet cross section using a digital image processing technique. In the Sulzer SMX and YHC mixer, a single element mixes the fluid nearly in two dimensions, and three-dimensional mixing is accomplished by the next elements aligned at 90° to their former one. In the Sulzer SMX mixer, the flow appears to be globally well mixed after 5 elements, while in the YHC and YNU mixers, it is necessary to globally well mix more than 1 and 2 elements.

Keywords : Motionless Mixer, Mixing Element, Mixing Characteristics, Visualization, Digital Image Processing Technique.

1. Introduction

Mixing of viscous fluids is ubiquitous and essential in a variety of industrial applications including chemical process, biomedical process, food engineering, and so on. Mixing can be performed in mechanical agitators or in motionless (also called static or inline) mixers. Longitudinal and transverse distribution of materials to be mixed can be obtained in the mechanical agitators by means of moving blades. Mixing in motionless mixers is achieved by the continuous splitting, extension and transposition of the fluids by means of motionless elements. Motionless mixers are increasingly finding use in a variety of industries due to their advantages such as low energy consumption, modest space requirements and almost total freedom from wear and maintenance. Also, low investment and operating costs are reasons for their use in many process industries for mixing and reaction. The shear forces imposed are generally low, so that during the processing the product is not damaged (Bauman, 2001; Hobbs, 1997; Junker et al., 1994).

A limited number of experimental methods are available for a limited range of operating conditions and applications, based mainly on qualitative analysis. The parameters of mixing performance have traditionally been introduced based on the residence time distribution, the pattern of striation, the mixing index and the variance of concentration. Residence time distributions for the Kenics mixer have been determined experimentally (Pustelnik, 1986) and numerically (Kemblowski and Pustelnik, 1988; Naumann, 1991). A concept that has been applied as a measure of mixing performance for motionless mixers is reduction of striation thickness and increase of striation length during the blending of two initially segregated fluids. For the Kenics mixer, based on the simplified analysis of the flow, the correlations for the striation thickness and for the number of striations have been reported (Middleman, 1977; Boss and Czastkiewicz, 1982). The mixture quality has often been quantified in terms of a mixing index that describes the degree of homogeneity of the mixture. The mixture homogeneity is evaluated based on a statistical analysis of samples from the mixture, with the mixing index expressed as a function of the standard deviation(σ) or variance(σ^2) of the mixture samples. The mixture variance is defined as:

$$\sigma^2 = \frac{\sum_{i=I}^{n}\left(C_i - \overline{C}\right)^2}{n-I}$$

where C_i is the concentration of the ith sample, $\overline{C}$ is the mean value of concentration, and n is the number of sample. Study by Pahl and Muschelknautz (1982) presented data for mixture quality in terms of the variation coefficient in a number of different motionless mixers including the Kenics mixer. Unfortunately, non-intrusive flow visualization is often difficult as a result of their complex geometry. Recently, one intrusive optical method developed for motionless mixer was based on flowing a suspension of particles through the mixer, which were then illuminated by a laser beam and photographed at the exit (Jaffer and Wood, 1998). Mixing performance was quantified by measurement of the striation thickness, variance of striation widths and interfacial area.

Because of the complexity of the mixing phenomena, only very limited data have been appeared in the study of motionless mixers. Especially, a deep understanding of the mixing characteristics is still lacking when geometrically complex elements are involved. The objective of this study is to perform the experimental investigation of mixing characteristics for three different motionless mixers in order to evaluate the mixing efficiency.

2. Experimental Apparatus and Method

2.1 Motionless Mixer Element

Motionless mixing means homogenization without the use of moving parts. The need for motors and electrical wiring is eliminated, resulting in comparatively low investment costs. Also, sealing problems are eliminated. One of the most widely used motionless mixers for viscous, low Reynolds number applications is Sulzer type mixer. The mixing element of Sulzer SMX one is made of intersecting bars or sheets welded together to form open channels. The purpose of Sulzer SMX type of lamellar mixing elements is to split the material into individual streams that meet other streams as they flow transversely through the elements. Therefore, mixing in the Sulzer SMX mixer is not random but follows a geometric pattern (Bauman, 2001).

Fig. 1. Geometry of 4-element Sulzer SMX, YHC and YNU elements.

Figure 1 shows four-element Sulzer SMX, YHC and YNU mixing elements made of stainless steel. Each unit element has a diameter of 40 mm and a length-to-diameter ratio (L/D) equal to one. The thickness of intersecting bars and elliptic plates is 2 mm. The YHC and YNU elements are the new ones designed in this study. Each unit element of the YHC and YNU types is aligned at 90° to their neighbor as the Sulzer SMX one. In general, the narrower the passageways and the larger the fraction of cross section occupied by elements, the higher the pressure drop. Because the element of Sulzer SMX mixer is relatively complicated in construction and the fraction of cross section occupied by the elements is large, the mixing efficiency is better than others, while the pressure drop is larger than others. The new ones were designed to decrease the pressure drop and to minimize the decrease of the mixing efficiency compared with the Sulzer SMX one. The YHC element is similar to the Sulzer SMX one except that holes bored through each intersecting bar provide the flow pathways. The unit YNU element is made of orthogonally intersecting elliptic plates as shown in Fig. 1. In the YNU mixer, it has been intended that mixing fluid flow through 3 mm diameter dividing holes having about 27 % cross-sectional areas per unit elliptic plate.

2.2 Experimental Apparatus and Method

In this study, to examine the mixing characteristics of two similar fluids, one stream is dyed red and the other green. The green hair styling gel was used as bulk mixing fluid and dye tracer was prepared by mixing red color into the pure hair styling gel. The green gel and the red dye tracer were non-Newtonian fluids. The rheological properties of the test fluids were measured over the shear rate range of 50 to 650s^{-1}. There was no change of rheological properties before and after the test fluid was flowed through a motionless mixer assembly. Shear stress, τ , and shear rate, $\dot{\gamma}$, data for the green gel and the red dye tracer were fitted by power-law model(Shah and Kale, 1991). For non-Newtonian fluids:

$$\tau = \eta\dot{\gamma}$$

In this case, the apparent viscosity could be described as:

$$\eta = K\dot{\gamma}^{n-1}$$

we had to determine K and n from the experimental data. Where K is the consistency index, n is a measure of deviation of the fluid from Newtonian. From the final empirical correlation, we could get $K = 73.5575$, and $n = 0.2794$. Where $n < 1$ indicated shearing-thinning or pseudo-plastics fluid. The volumetric flow rate and the density of test fluids were 1.1×10^{-5} m^3/s and 1030 kg/m^3.

Initially, the interface between the two fluids, the inter-fluid contact area, occurs at the circumference of 11 mm diameter from the center of the mixer as shown in Fig. 2. Figure 2 shows a schematic diagram of motionless mixer experimental set-up. The basis of the experimental set-up is a 40 mm diameter transparent acrylic tube in which the mixing elements are fixed. A liquid distributor system of two concentric tubes (500 mm length) equipped with a piston assembly was used to feed fluids into the mixing region. The visualization experiment was performed as follows. First, the annulus of the outer concentric tube of the liquid distributor system was filled with the green hair styling gel and the inner tube (11 mm inner diameter) of the liquid distributor system was filled with the dye tracer. Second, the liquid distributor system was inserted into the mixer housing. And then the piston assembly was used to feed simultaneously the fluids through the mixing elements until the mixture was flowed through the outlet section. The resulting mixing patterns were recorded photographically using a digital camera.

A digital image processing technique (Media Cybenetics, 1999) was used to analyze the visualized images quantitatively. This package allows measurement of points, lines and areas over a stored image. The percent area utility of the tool computes the percentage area of foreground pixels defined by a threshold. The threshold allows defining the foreground of the image by selecting a range of gray values or colors, whereas all other values are regarded as background. We can set up to five thresholds and compute the percentage area for them simultaneously. The thresholds can be shown on the images and the information about all the thresholds is included in exported data. Figure 3 shows an example of the quantification process of a visualized image using the percent area utility of the tool. The image on the first is the original having red and green colors. The second and third images show the results of red and green color thresholds. The last shows the results of all thresholds simultaneously. There can be the over- and/or non-selected regions. Therefore, after the modification, the percentage area data are appeared immediately in the data table. We could get the 99 % accuracy of the image analysis through the modification.

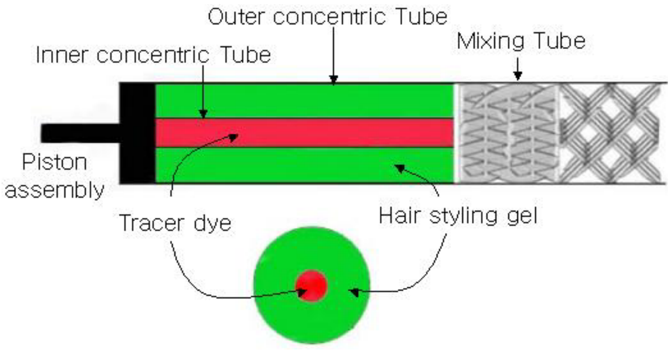


Fig. 2. Schematic diagram of experimental set-up.

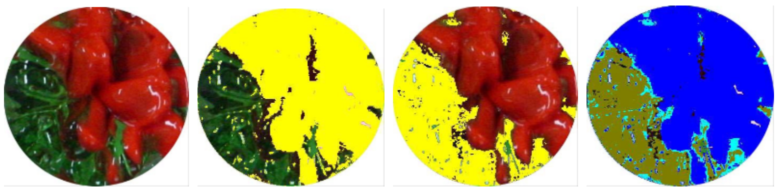


Fig. 3. Examples of quantification process of a visualized image.

3. Results and Discussions

In motionless mixers, efficient mixing of viscous fluids is produced by flows that redistribute fluid elements throughout space due to the combination of mechanisms: splitting or division, stretching, folding or re-combining and diffusion. Splitting and stretching transform portions of fluid into elongated striation, increasing the amount of inter-fluid contact area. Folding or re-combining reorients fluid elements with respect to the principal directions of deformation. Diffusion, which results from kinetic transport of individual molecules, induces uniformity at small scales. Diffusion and stretching are intimately coupled; as fluid elements are stretched by the flow, the rate of transport by diffusion is increased due to both an increase of the area available for transport and also a reduction of the diffusion length scale.

The aim of this study of mixing characteristics is to evaluate the effect of mixer types on the mixing efficiency or homogenization using visualization. Visual representations of mixing are particularly useful in understanding mixing phenomena. The mixing performance of motionless mixer is evaluated by several parameters as mentioned in the introduction. In this study the red color dye tracer was mixed in the main stream of green hair styling gel, and then the mixing efficiency was quantified by calculating the percentage area concentration of red color at the outlet cross section using a digital image processing technique as presented in Fig. 3.

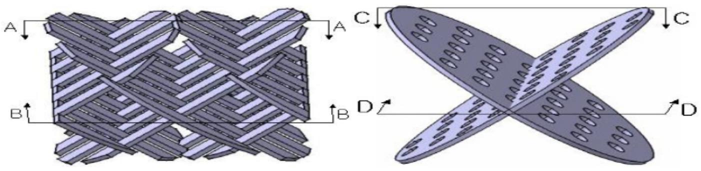
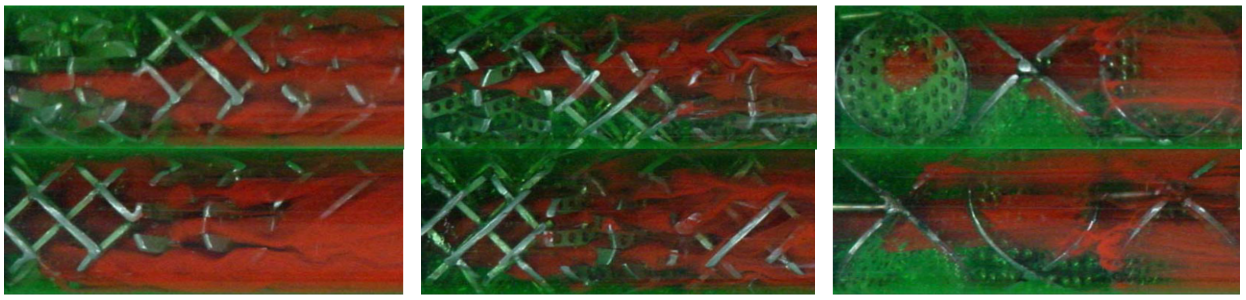


Fig. 4. Directional view of the first element of Sulzer type and YNU mixer for the visualization of axial mixing patterns.

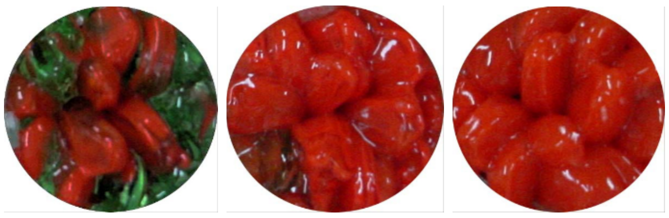
Figure 5 shows the axial views of mixing pattern in 3-element Sulzer SMX, YHC and YNU mixer. For the Sulzer SMX and YHC mixers, the upper and lower images show the axial mixing patterns visualized at the direction of A-A and B-B, and for the YNU one, the upper and lower ones show that visualized at the direction of C-C and D-D respectively as shown in Fig. 4. The Sulzer SMX and YHC elements of the lattice structure of intermeshing and intersecting bars, positioned at an angle to the mixing tube axis, repeatedly divide the fluid into striations and spread them over the tube cross-section. In the Sulzer SMX and YHC mixer, as the fluid moves downward through the first element, the splitting striations of the flow are formed principally in the direction of A-A as shown in the upper images of Figs. 5(a) and (b). Therefore, it can be found that a single element mixes the fluid nearly in two dimensions, and three-dimensional mixing is accomplished by the next elements aligned at 90° to their former ones. With increasing the number of mixing elements, each turned 90° relative to the former, the number of striations formed increases while their thickness diminishes. However, the number of splitting striations formed is not easy to verify visually and the striation formation laws are not verifiable. In the YNU mixer, the fluid is not drawn into elongated striations because the fluid flows through the dividing holes of 3 mm diameter without the splitting and directional change as shown in Fig. 5(c). It can be found that for the YNU mixer the combination of mixing mechanisms is less effective, because the YNU elements do not provide enough obstacles (for example, intersecting bars) in the flow path to induce mixing.



(a) Sulzer SMX mixer (b) YHC mixer (c) YNU mixer

Fig. 5. Axial mixing patterns in 3-element Sulzer SMX, YHC and YNU mixers (axial distance X = 3L(120 mm), radial distance Y = D(40 mm)).

Figure 6 shows the outlet cross-sections after 1, 3 and 5 elements. Mixing of different fluids is achieved by increasing the contact area between the fluid components. The deformation and folding of the interface can be related to its length increase or stretching. The splitting striation or stretching field, which describes the amount of interfacial area in each region of flow, measures local mixing intensities. In the Sulzer SMX and YHC mixer made of intersecting bars, mixing occurs through a combination of flow splitting and folding within an element and a re-combining and re-splitting mechanism at the junctions of successive element. After passing through an element, the red dye stream is stretched and extended toward the mixer tube wall, and the stretched and extended streams is folded and invaded the green gel stream. As mentioned in Fig. 5, it can be found that the splitting striations of the flow through the first element are formed principally in the direction of A-A as shown in the first element outlet of Figs. 6(a) and (b). Due to the strong combination of splitting, stretching, folding and re-splitting mechanisms, a relatively good mixing of the fluids is achieved after only three mixing elements in the Sulzer SMX and YHC mixer. In the YNU mixer made of orthogonally intersecting elliptic plates, the flow of red color through the first element exhibits more rounded cross-sectional features due to the weak combination of mixing mechanisms. Of course, this kind of visual evaluation is only qualitative, but it gives clear indications of the motionless mixer behavior: the mixing efficiency of the motionless mixer made of intersecting bars seems better than the mixer made of orthogonally intersecting elliptic plates with dividing holes.



(a) Sulzer SMX mixer

(b) YHC mixer

(c) YNU mixer

Fig. 6. Cross-sectional mixing patterns in the Sulzer SMX, YHC and YNU mixers at the outlet of 1, 3 and 5 elements.

Figure 7 shows the percentage area concentration of the red color dye tracer as a function of the number of mixing elements. The mixing efficiency was evaluated on the basis of the percentage area concentration for the dye tracer as presented in Fig. 3. The necessary number of mixing elements for a particular homogeneity requirement can be determined from the result. After 1 element, the percentage area concentration of the sulzer SMX and YHC mixer is more than 60 %, while that of the YNU mixer is less than 50 %. After 1 and 2 elements, the percentage area concentration of the YHC mixer is somewhat high than that of the Sulzer SMX mixer. In the Sulzer SMX mixer, the flow appears to be globally well mixed after 5 elements, while in the YHC and YNU mixers, it is necessary to globally well mix more than 1 and 2 elements. In general, the more divisions, the better the mixing efficiency. However, the narrower the passageways and the larger the fraction of cross section occupied by elements, the higher the pressure drop. The fact clearly indicates that the mixing mechanism is highly influenced by the mixer type or the mixing mode. However, it may not conclude that which one is far superior to, because it is necessary to consider the hardness and the cost of manufacturing of the element and the cleaning of elements in time of breakdown. Therefore, in order to consider these facts, more careful parametric experiments or analysis are required in the near future.

4. Conclusion

The mixing characteristics of three different motionless mixers were investigated experimentally to evaluate the effect of mixer types on the mixing efficiency using a digital image processing technique.

In the Sulzer SMX and YHC mixer, mixing occurs through a combination of flow splitting and folding within an element and a re-combining and re-splitting mechanism at the junctions of successive element. In the YNU mixer, the flow of red color through the first element exhibits more rounded cross-sectional features due to the weak combination of mixing mechanisms. In the Sulzer SMX mixer, the flow appears to be globally well mixed after 5 elements, while in the YHC and YNU mixers, it is necessary to globally well mix more than 1 and 2 elements.

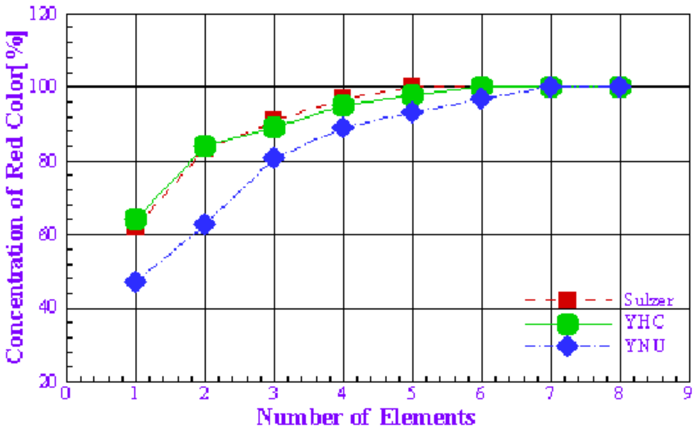


Fig. 7. Concentration of red color as a function of element number.

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Author Profile

Hei-Cheon Yang: He received his Ph.D (Eng) degree in Mechanical Engineering in 1994 from Chungang University in Seoul. He has been working as an associate professor in Chonnam National University, School of Mechanical and Automotive Engineering since 1997. His research interests are quantitative visualization, design and performance test of motionless mixers and thermal reactor, computational fluid dynamics.