12. Duan, G., Chen, B., Koshizuka, S., Xiang, H. (2017). Stable multiphase moving particle semi-implicit method for incompressible interfacial flow. Computer Methods in Applied Mechanics and Engineering, 318, 636–666. doi: https://doi.org/10.1016/j.cma.2017.01.002
13. Kannan, A. S., Naserentin, V., Mark, A., Maggiolo, D., Sardina, G., Sasic, S., Ström, H. (2019). A continuum-based multiphase DNS method for studying the Brownian dynamics of soot particles in a rarefied gas. Chemical Engineering Science, 210, 115229. doi: https://doi.org/10.1016/j.ces.2019.115229

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ANALYSIS OF THE EFFECT OF STIRRER AND CONTAINER ROTATION DIRECTION ON MIXING INDEX (Ip)

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The paper discusses the effect of the stirrer and container rotation direction on the mixing index (Ip). The chaos theory is the result of an in-depth study of various problems that cannot be answered by the two previous major theories, namely quantum mechanics and the theory of relativity. Effective mixing of the flow area does not depend on rapid stirring.

This study uses a container with a double stirrer, camera, programmable logic controller, tachometer, 6 A adapter, and a computer. DC electric motor (25 V) for turning stirrers and housings. The diameter of the primary and secondary stirrers is Dp=38 mm and Ds=17 mm. The diameter of the container made of transparent plastic is Dw=160 mm and height is 170 mm. Primary stirrer rotation (np)=10 rpm, secondary stirrer rotation (ns)=22.3 rpm, and container rotation (nw)=13 rpm, the angular velocity of the container is Ωw=360° while the angular speed of the primary stirrer is Ωp=180°. The liquid consists of a mixture of water and paint (white). For dye, a mixture of water and paint (red) is used. For testing the Brookfield viscometer, the viscosity of the liquid and dye is used. The results showed that turning the stirrer in the opposite direction to the container, there will be stretching, bending, and folding around the stirrer, and the smallest mixing index was P2V-b (0.94). In addition, based on the mixing index value above, the highest mixing effectiveness level is obtained, namely: P2V-b, P2S-b, P2B-b, P2V-a, P2B-a, and finally P2S-a. The mixing index is inversely related to the effectiveness level. So the highest effectiveness level is given by the following treatment: variation rotation (between opposite rotating mixers); opposite rotation (stirrer rotation opposite direction to the container); unidirectional rotation (stirrer rotation in the direction of the container)

Keywords: mixing index, chaos, stirrer, container, mixing effectiveness, rotation direction

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1. Introduction

The chaos theory is the result of an in-depth study of various problems that cannot be answered by the two previous major theories, namely quantum mechanics and the theory of relativity. Chaos conditions have started to be mathematically modelled since the late 1800s by Henri Poincare. The development of this theory in the 20th century was not as fast as the theory of quantum mechanics and the theory of relativity [1].

The chaos flow-based numerical and mathematical approaches have recently been widely used in various fields of science, including social, economic, political, biotechnology, meteorology, mechanical engineering, even in the entertainment world. For robotics experts, chaos-based modelling is used to identify the evolutionary process of life, understand genetic algorithms, simulate artificial life for how the brain works, or create intelligent machines. In the entertainment world, many games have been developed from chaos research such as the computer game series SimAnt, SimLife, SimCity and so on. In the medical field, chaos theory is used for the mixing of medicinal substances [2].

The stirring process in laminar flow with low Reynolds numbers can produce a very complex flow pattern [3]. The complexity of the flow pattern consists of many particles (microstructures) whose changes are influenced by fluid flow [4]. This phenomenon is called advection. In this motion, the velocity of the particles is the same as the velocity of the fluid [5].

During chaotic motion, the fluid and particles are stretched, thereby expanding the contact area and reducing the diffusion distance between them [6]. The strain occurs exponentially with time, resulting in efficient stirring [7]. In the mixing process, efficient strain distribution is a major factor [8].

Homogenization of a mixture involves two events at once, namely stirring and mixing. Stirring is stretching of the fluid surface mechanically, while mixing is the diffusion of substances within the fluid surface [9].

Referring to the above statements, it can be seen that chaotic flow will result in high mixing efficiency if the graph pattern that is formed is exponential with time. [10] obtained a relationship between the expansion of mixing with time which forms a sigmoidal curve.

In this context, the study aims to evaluate the chaotic flow patterns caused by differences in the rotation direction of the stirrer and the container. Variation in the rotation direction of the chaotic stirrer is needed to determine which treatment is the most effective and produces a homogeneous stirring. The mixture of two fluids is formed due to a movement that causes the deformation of the particles. So that variations in direction and speed of fluid motion are necessary.

The difference in the stirrer and container rotation direction gives rise to the fluid mixing index. The mixing index is indicated by the percentage of the color distribution.

2. Literature review and problem statement

During chaotic motion, the fluid and particles are stretched, thereby expanding the contact area and reducing the diffusion distance between them [11]. The strain occurs exponentially with time, resulting in efficient stirring [12]. In the mixing process, efficient strain distribution is a major factor [13].

Chaos flow will produce high mixing efficiency if the graph pattern that is formed is exponential with time. In [14], it was found that the relationship between the expansion of mixing and time formed a sigmoidal curve. The results of research [15] showed a two-dimensional chaotic advection flow system in two concentric tubes that rotated periodically and a tracer was injected through a hole at the bottom of the tube.

The development of particles in a fluid element becomes a chaotic flow pattern due to the influence of the initial conditions [16]. The changes in the position of the particles that form the up and down paths are caused by the strain and folding mechanism that occurs in the flow. Mixing effectiveness of the flow area does not depend on high flow rates (fast stirring). So that the term «chaos» appears, which is an extraordinary condition from its initial condition. Chaos movement in a rotating flow (journal bearing flow). A very viscous liquid occupies the space between two eccentric cylinders which can rotate alternately. Chaos flow produces structural lines consisting of thousands of fibers of varying thickness [15].

The chaotic patterns are formed by the existence of repeated stretching, shortening, bending, folding and fracturing mechanisms. With this condition, it causes a small dot to spread out into an unpredictable pattern (chaos). [15] analyzed experimentally the mixing behavior of compressed fluids driven by a rotating cylinder in a closed channel. The purpose of this research is to study the vortex growth behind the cylinder and to analyze the effect of eccentricity on Strouhal number. The test liquid uses clear coconut oil. The cylinder is placed in a closed square container while a dye is injected from the bottom, middle and top of the cylinder which changes its eccentricity. The results showed that at $e=0.25$ there was a maximum folding and a strain mechanism was formed with a faster diffusion time.

The mixing with two eccentric cylinders is described as follows (Fig. 1). Color stretch occurs because the colors are on different flow lines and coincide. When a shear rate occurs, the flow line which is relatively closer to the shear plane will carry some of the colors further away than some of the colors that are in the flow line which are relatively further from the shear plane. The same color of the flow line shows the influence of shear rate in that area is dominant. The grading colors indicate a decrease in the shear rate from areas near the shear plane (darker colors) to farther areas (light colors).

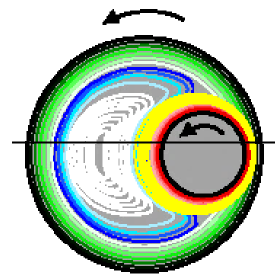

Fig. 1. Flow lines for eccentric cylinders [2]

The green color is the primary shear rate area of the container, the blue color is the secondary shear rate area of the container, the red color is the shear rate area of the stirrer, the white color shows the isolated mixing region. In the white line area, stretch and crease are minimal so mixing is difficult. The junction between the shear rate by the container and the stirrer is indicated by the yellow line. This meeting area is important because more chaos occurs in this area.

[7] studied the chaotic motion of viscous fluid between two rotating eccentric cylinders. From the research, it was found that the rotation of the inner cylinder and the outer cylinder was the same. It turns out that the chaos pattern occurs well in the mixture of flour and water which is diluted (500:875 ml), while for different amounts there is chaos in the mixture of flour and thick water.

Based on previous research, the discussion only revolves around concentricity and eccentricity. Meanwhile, research related to the direction of rotation of both the stirrer and the container with different eccentricity distances does not exist. Therefore, it is necessary to research mixing behavior related to the mixing index. It turns out that the mixing mechanism is independent of high flow rates. In this case, the author examines a mixing model to determine the most efficient mixing conditions, by applying the manipulation of the rotation direction and the eccentricity distance.

3. The aim and objectives of the study

The study aims to determine the effect of the stirrer and container rotation direction on the formation of chaotic flow and the effect of the stirrer and container rotation direction on the mixing index (*Ip*) in viscous fluid chaos flow.

To achieve this aim, the following objectives are accomplished:

– to make vary the stirrer and container rotation direction to the chaotic flow pattern;

– to make a graph of the mixing index (*Ip*) of the results of mixing paint with variations in the stirrer and container rotation direction.

4. Materials and methods

Fig. 2 shows the research scheme, the research uses a container with a double stirrer, camera, programmable logic controller (regulating the speed and direction of the motor), tachometer, 6 A adapter, and computer. DC electric motor (25 V) for turning the stirrer and container. The stirrer is made of polyvinyl chloride. The diameter of the primary and secondary stirrers is Dp=38 mm and Ds=17 mm. The diameter of the container made of transparent plastic is Dw=160 mm and height 170 mm. Primary stirrer rotation (np)=10 rpm, secondary stirrer rotation (ns)=22.3 rpm, and container rotation (nw)=13 rpm, the angular velocity of the container Ωw=360° while the angular speed of the primary stirrer is Ωp=180°.

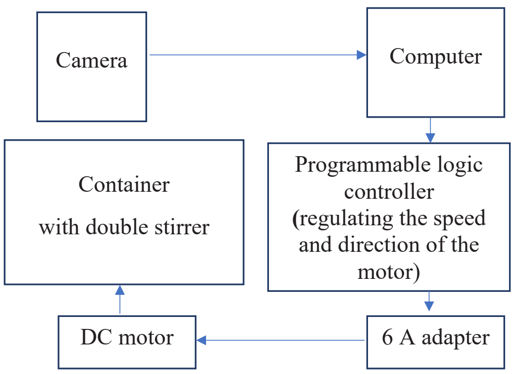

Fig. 2. Research scheme

The liquid consists of a mixture of water and paint (white) with a volume ratio of 1:1. For dye, a mixture of water and paint (red) with a volume ratio of 1:3 is used. For testing the Brookfield viscometer, the viscosity of the liquid and dye is used.

The design of this research uses variations in the stirrer and container rotation direction and the distance between the two stirrers. Variations in the rotation direction result in differences in the path and folds of the fluid flow. This is shown in Fig. 3.

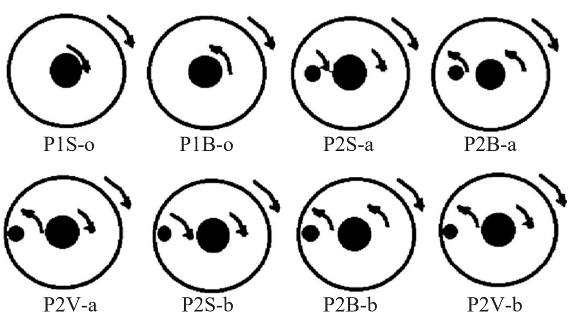

Fig. 3. Experimental designs

Fig. 3 shows the experimental design performed. The centre point of the container and the main stirrer is a point. The distance between the two stirrers is 40 mm. The research was carried out on the same rotation between the container with the two stirrers (P2S-a), one direction of rotation between the container and the two stirrers (P2B-a) and the direction of rotation between the container and one stirrer. Rotation varies between the container and the stirrer (P2V-a). In addition, for the distance of the two stirrers of 70 mm, the same treatment was also carried out, namely: P2S-b (unidirectional), P2B-b (opposite direction), and P2V-b (varying direction). The design is based on the container diameter Dw=160 mm, so that a distance of 40 mm is taken between the two stirrers and the other is 70 mm, to determine the effectiveness of stirring.

5. Results of the experiment

5. 1. Variation of rotation between the stirrer and the container

To find out more about the effect of variations in stirrer rotation with a container and the effect of eccentricity on chaotic behavior , Fig. 4–9 show the experimental results.

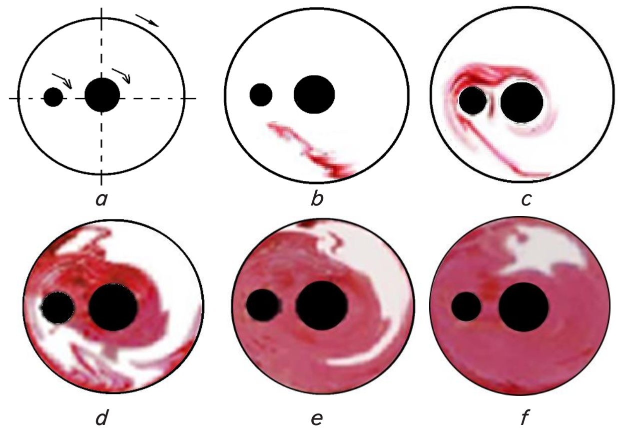

Fig. 4. Dye flow pattern for P2S-a, ε=0.30, ω=5, α=0.34: *a* – n=0; *b* – n=1; *c* – n=5; *d* – n=15; *e* – n=30; *f* – n=60

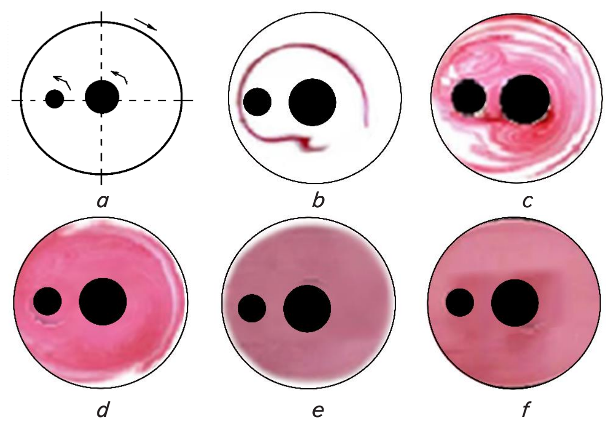

Fig. 5. Dye flow pattern for P2B-a, ε=0.30, ω=5, α=0.34: *a* – n=0; *b* – n=1; *c* – n=5; *d* – n=15; *e* – n=30; *f* – n=60

Fig. 4, 7 show the stirrer and container rotation where the stirrer rotation is in the same direction as the container. The results show that it only lengthens the stretch. Also, it makes the color layer thicker, so that the colors that are difficult to come out are wider. This is because it cannot create a divergent pathway (Fig. 10, *a*). This stable flow causes the flow layer to become thick, so it takes more time to break down the layer (Fig. 10, *b*).

Fig. 10 shows that in P2S-a with ε=0.30, N=5, the dye stream only rotates around the stirrer. Likewise, in P2S-b with ε=0.53, it appears to form a trajectory pattern, the flow is towards the stable point (steady-period trajectory). The stable trajectory pattern in the next period will give rise to the island phenomenon.

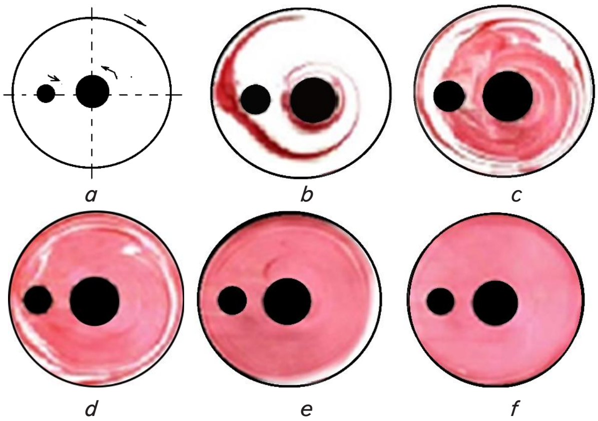

Fig. 6. Dye flow pattern for P2V-a, ε=0.30, ω=5, α=0.34: *a* – *n*=0; *b* – *n*=1; *c* – *n*=5; *d* – *n*=15; *e* – *n*=30; *f* – *n*=60

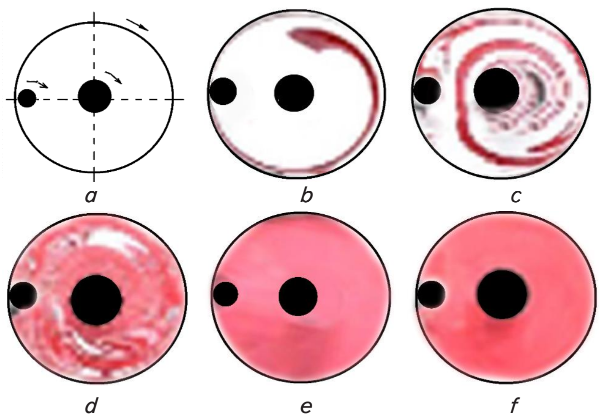

Fig. 7. Dye flow pattern for P2S-b, ε=0.53, ω=5, α=0.34: *a* – *n*=0; *b* – *n*=1; *c* – *n*=5; *d* – *n*=15; *e* – *n*=30; *f* – *n*=60

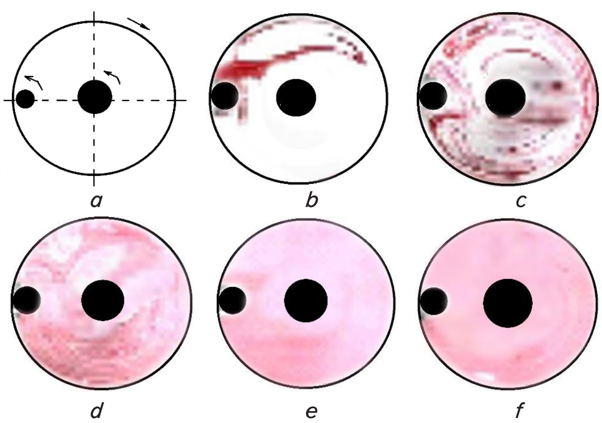

Fig. 8. Dye flow pattern for P2B-b, ε=0.53, ω=5, α=0.34: *a* – *n*=0; *b* – *n*=1; *c* – *n*=5; *d* – *n*=15; *e* – *n*=30; *f* – *n*=60

In the stirrer whose rotation direction is opposite to the container (Fig. 5, 8, *N*=1), the dye flow is stretched, then bending occurs, then the folding process occurs in the area around the stirrer.

Meanwhile, for the variation of the stirrer rotation with the container, the chaotic process occurs the fastest. Starting from stretching, contraction and folding to stable folds and unstable folds forming a sea of chaos.

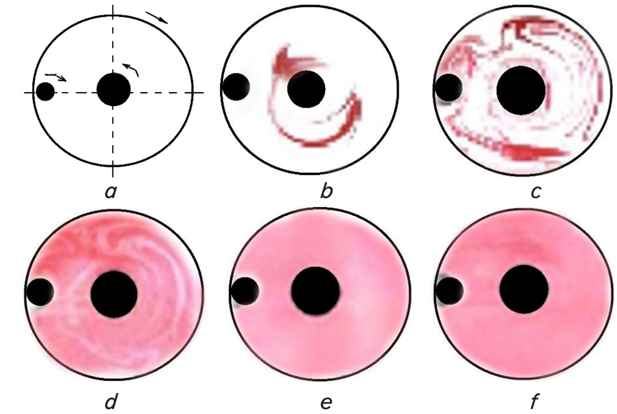

Fig. 9. Dye flow pattern for P2V-b, ε=0.53, ω=5, α=0.34: *a* – *n*=0; *b* – *n*=1; *c* – *n*=5; *d* – *n*=15; *e* – *n*=30; *f* – *n*=60

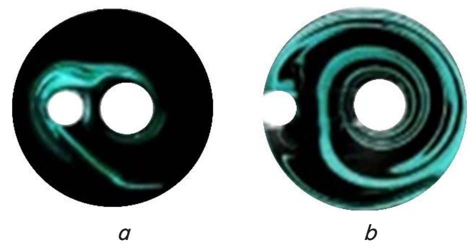

Fig. 10. Unidirectional stirrer flow pattern and rotating container in period 5: *a* – P2S-a, ε=0.30; *b* – P2S-b, ε=0.53

5. 2. Mixing efficiency (η) and mixing index (*Ip*)

According to [17], mixing efficiency is identical to strain efficiency (1). It is difficult to measure the range of colors in an experiment so that the percentage distribution of colors can be measured. So, mixing efficiency statistically can be seen from the percentage of color distribution.

Based on the measurement results of the color distribution during that period, the mixing efficiency can be determined from the fastest period until it reaches 100 % color distribution. It turns out that from the test results, the color distribution up to 100 % is achieved at *N*=27. Fig. 11 shows the mixing efficiency up to the period *N*=27.

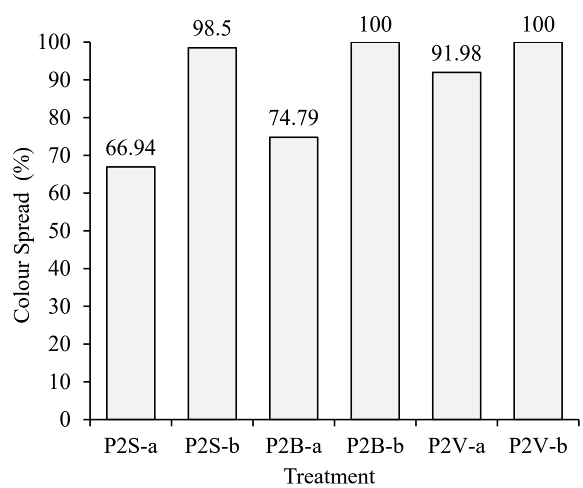

Fig. 11. Mixing efficiency up to period *N*=27

Fig. 11 shows that in the 27th period, there has been a 100 % color distribution, namely P2B-b and P2V-b, which indicates that both have the best mixing efficiency. The method as above is done by only looking at one condition, namely at the point that has reached 100 % as a measurement parameter. To determine the level of color distribution and mixing effectiveness up to period 60, the mixing index was used. The mixing index (*Ip*) is the standard deviation of the percentage level of the color distribution in the *N* period (1) [17],

$$Ip=\sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(\frac{S_n-\bar{S}}{\bar{S}}\right)^2}. \tag{1}$$

where $S_n=X_n-X_{(n-1)}$ is the level of color distribution in period N and is the average color percentage level up to period N. Mixing is said to be very effective if the mixing index is small (Table 1).

Table 1

Mixing index

Treatment	$I_{p\text{-}10}$	$I_{p\text{-}20}$	$I_{p\text{-}30}$	$I_{p\text{-}40}$	$I_{p\text{-}50}$	$I_{p\text{-}60}$
P2S-a	1.64	2.66	2.25	2.06	1.99	1.94
P2S-b	1.10	1.11	1.15	1.11	1.09	1.08
P2B-a	1.19	1.57	1.52	1.57	1.60	1.55
P2B-b	0.95	1.02	1.19	1.15	1.12	1.10
P2V-a	1.04	1.41	1.26	1.21	1.17	1.14
P2V-b	0.94	0.83	0.88	0.91	0.93	0.94

Table 1 shows that until $N=60$, the smallest mixing index is P2V-b (0.94). Thus, based on the mixing index value above, the highest mixing effectiveness level is obtained, namely: P2V-b, P2S-b, P2B-b, P2V-a, P2B-a, and finally P2S-a. While the chaos flow mechanism using two stirrers can be seen in Fig. 12.

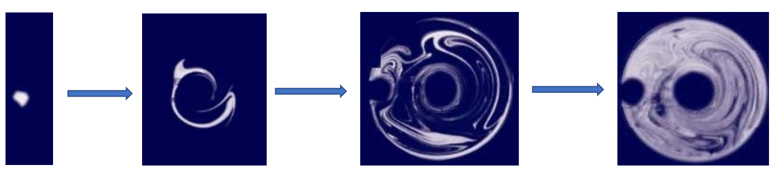

Fig. 12. Chaos flow mechanism using two stirrers

Fig. 12 shows the mechanism of chaotic flow behavior starting from the initial droplet formation. Starting from the initial drop, it forms a horseshoe map. The horseshoe area that is formed in a short time shows chaos, in this condition, there is stretching, contraction and folding. Periodically, this mechanism forms a combined pattern of stable folds and unstable folds connecting each other to become a sea of chaos. After the sea of chaos formed, the dye quickly stretched, broke, and spread into a thin river layer. Chaotic behavior occurs continuously with the times.

6. Discussion of the experiment

6. 1. Effect of rotation between the stirrer and the container

The direction of rotation between the stirrer and the container will determine the chaotic flow pattern. This chaotic flow will produce a layer structure consisting of thousands of lines that have a wide thickness distribution. The flow tracker rapidly stretches into the system layer continuously as the period increases. The layer becomes thinner and thinner because of a complex repeating process of stretching, spreading and folding mechanisms.

The study of chaotic flow patterns gives the same results as trends in color distribution, flow patterns, location of fold formation, location, movement and symmetry of isolated areas, and the rate of color stretching. The wider the distribution of colors, the greater the percentage of the resulting mixture. In chaotic conditions, the percentage of color mixing increases sharply which shows a stretch, followed by a decrease in the percentage of colors which shows a shortening and folding mechanism.

Chaotic behavior is formed quickly if it occurs in a periodic (intermittent) flow area. The mixing of two fluids is formed due to movement (advection), which results in particle deformation. The stirrer and container rotation shown in Fig. 4, 7 can be seen in the treatment where the stirrer rotation is in the same direction as the container, which tends to only lengthen the stretch and create a thick layer of color so that the color is difficult to get out of the wider path. This is because the flow between two unidirectional cylinders will result in the trajectory of the flow line towards the balance point (fixed point) or stable manifold so that the dye fluid elements are not able to make divergent trajectories. So, the breakdown of this particle layer takes a long time.

In the mixer with the direction of rotation opposite to the container (Fig. 5, 8), the dye flow line undergoes a stretching process, then the bending process is followed by a folding process around the stirrer. Whereas the mixer with various rotations in Fig. 6, 9 with the container, the fastest to form a chaotic region. In the stirring process with varying directions between the two stirrers and the container, the mixing mechanism is fast.

6. 2. Mixing efficiency (η) and mixing index (*Ip*)

Fig. 11 shows that the mixing efficiency is affected by the stirrer and container rotation direction and the eccentricity distance between the stirrers. It can be seen that P2B-b and P2V-b, the rotation of the stirrer with the container opposite the large eccentricity distance.

Table 1 shows the mixing index treatment which has a small *Ip*, the tendency of color distribution to form a low kurtosis as well. The mixing index is inversely related to the level of effectiveness. So, the highest effectiveness level is given by the following treatment: variation rotation (between opposite rotating mixers); opposite rotation (stirrer rotation opposite direction to the container); unidirectional rotation (rotation of the stirrer in the direction of the container).

The chaotic flow pattern is determined by the direction of flow due to the container and stirrer rotation. Chaotic flow produces layered structures with thousands of lines forming a flow pattern and continuously occurs. The layers become thinner for repeated stretching, spreading, and folding mechanisms.

P2S-a treatment began to appear island and there are isolated areas that still cannot be lost. In addition, P2B-a also still leaves poorly mixing areas, up to $N=27$. In addition, it can be seen that the double stirrer with smaller eccentricity results in ineffective mixing. Therefore, increasing the distance between stirrers (d=70 mm) can eliminate isolated areas as well as areas that are poor mixtures. Isolated areas or poor mixtures should be avoided especially in mixing processes that require a homogeneous mixture (such as chemical, pharmaceutical mixing processes, etc.).

7. Conclusions

1. Turning the stirrer towards the container will extend the stretch and allow the tough layer to escape the wider line. Turning the stirrer in the opposite direction to the container, there will be stretching, bending, and folding around the stirrer. For various cycles of mixing the container, the flow form is most rapidly chaotic.

2. The smallest mixing index is P2V-b (0.94). In addition, based on the mixing index value above, the highest mixing effectiveness level is obtained, namely: P2V-b, P2S-b, P2B-b, P2V-a, P2B-a, and finally P2S-a.

Acknowledgments

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Reference

1. McHarris, W. C. (2006). On the Possibility of Nonlinearities and Chaos Underlying Quantum Mechanics. arXiv.org. Available at: https://arxiv.org/ftp/quant-ph/papers/0610/0610234.pdf
2. Gouillart, E. (2007). Chaotic mixing by rod-stirring devices in open and closed flows. Fluid Dynamics. Université Pierre et Marie Curie – Paris VI.
3. Susilo, S. H., Asrori, A. (2021). Analysis of position and rotation direction of double stirrer on chaotic advection behavior. EUREKA: Physics and Engineering, 2, 78–86. doi: https://doi.org/10.21303/2461-4262.2021.001707
4. Abdillah, L. H., Winardi, S., Sumarno, S., Nurtono, T. (2018). Effect of Mixing Time to Homogeneity of Propellant Slurry. IPTEK Journal of Proceedings Series, 4 (1), 94. doi: https://doi.org/10.12962/j23546026.y2018i1.3515
5. Kumar, S., Gonzalez, B., Probst, O. (2011). Flow past two rotating cylinders. Physics of Fluids, 23 (1), 014102. doi: https://doi.org/10.1063/1.3528260
6. Zade, S. (2019). Experimental studies of large particles in Newtonian and non-Newtonian fluids. Stockholm. Available at: https://www.diva-portal.org/smash/get/diva2:1347711/FULLTEXT01.pdf
7. Cao, L., Shi, P.-J., Li, L., Chen, G. (2019). A New Flexible Sigmoidal Growth Model. Symmetry, 11 (2), 204. doi: https://doi.org/10.3390/sym11020204
8. Rice, M., Hall, J., Papadakis, G., Yianneskis, M. (2006). Investigation of laminar flow in a stirred vessel at low Reynolds numbers. Chemical Engineering Science, 61 (9), 2762–2770. doi: https://doi.org/10.1016/j.ces.2005.10.074
9. Tjørve, E., Tjørve, K. M. C. (2010). A unified approach to the Richards-model family for use in growth analyses: Why we need only two model forms. Journal of Theoretical Biology, 267 (3), 417–425. doi: https://doi.org/10.1016/j.jtbi.2010.09.008
10. Krolczyk, J. B. (2016). The Effect of Mixing Time on the Homogeneity of Multi-Component Granular Systems. Transactions of Famena, 40 (1), 45–56. Available at: https://hrcak.srce.hr/index.php?show=clanak&id_clanak_jezik=229037
11. Ayegba, P. O., Edomwonyi-Otu, L. C. (2020). Turbulence statistics and flow structure in fluid flow using particle image velocimetry technique: A review. Engineering Reports, 2 (3). doi: https://doi.org/10.1002/eng2.12138
12. Ascanio, G. (2015). Mixing time in stirred vessels: A review of experimental techniques. Chinese Journal of Chemical Engineering, 23 (7), 1065–1076. doi: https://doi.org/10.1016/j.cjche.2014.10.022
13. Turner, M. R., Berger, M. A. (2011). A study of mixing in coherent vortices using braiding factors. Fluid Dynamics Research, 43 (3), 035501. doi: https://doi.org/10.1088/0169-5983/43/3/035501
14. Turuban, R., Lester, D. R., Heyman, J., Borgne, T. L., Méheust, Y. (2019). Chaotic mixing in crystalline granular media. Journal of Fluid Mechanics, 871, 562–594. doi: https://doi.org/10.1017/jfm.2019.245
15. Fiordilino, E. (2020). The Emergence of Chaos in Quantum Mechanics. Symmetry, 12 (5), 785. doi: https://doi.org/10.3390/sym12050785
16. Susilo, S. H., Suparman, S., Mardiana, D., Hamidi, N. (2016). The Effect of Velocity Ratio Study on Microchannel Hydrodynamics Focused of Mixing Glycerol Nitration Reaction. Periodica Polytechnica Mechanical Engineering, 60 (4), 228–232. doi: https://doi.org/10.3311/ppme.8894
17. Rugh, S. E. (1994). Chaos in the Einstein equations. Chaos, Solitons & Fractals, 4 (3), 471–493. doi: https://doi.org/10.1016/0960-0779(94)90059-0