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Analysis of Mixing Effectiveness of Perforated Plate for Inline Static Mixer

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Abstract: Inline static mixer can be used in a wide range with a different application such as mixing liquids, chemical processing and biodiesel blending. Currently, an issue in producing more effective static mixer for mixing liquids by introducing circle grids fractal plate drew the attention of the researchers. Therefore, this research is focusing on implementing a circle fractal plate as a mixing element for inline static mixer to increase a mixing effectiveness. Furthermore, it was assumed that the new type of circle grids fractal is simple to install and easy to manufacture. Besides that, pressure drop shows a significant effect in producing a better static mixer. This study will have conducted experimentally to analyze the effect of pressure drop on mixing effectiveness by using different perforated plate with different porosity which are NEL plate with 47.5% porosity, fractal perforated plate, 51.85% porosity and unchamfered plate, 62.85% porosity. For data collection, pressure value at upstream and downstream are recorded for analysis with different six openings of the discharge ball valve. The results shoes that the unchamfered plate produced higher mixing effectiveness. This statement was strengthened by the images of flow visualization and pressure drops table gained from the experiment. This finding can be useful for a future economic static mixer with the best performance for industrial needs.

Keywords: Mixing effectiveness, perforated plate, static mixer

1. Introduction

The static mixer usually used to mix the fluid. Normally fluid used to be mixed in liquid but there is also static mixer that used to mix gases. Static mixers consist of mixer elements consists of a series of baffles made either by metal or plastic and it is widely used in industries nowadays. For instance, in oil and gas industries static mixer can be used to mix additives into fuel oil or gasoline. Another application for the static mixer is to mix flavour in food industries [1]. The research and development of mixing technology is an active field of investigation in chemical engineering due to its growing importance in numerous industries [2,3]. Mixing can be achieved either by the batch and semi-batch operation with conventional mechanical agitators or increasingly by continuous operation. In the latter case, static mixers are usually selected. A typical static mixer consists of the stationary mixing elements, aligned in series and turned around their main axis by 90^{o} against their neighbours [4]. They split the fluid flow into several partial flows. These partial flows are then redirected and recombined in such manner that a mixture is obtained which is macroscopically homogeneous with respect to concentration and/or temperature. There are numerous kinds of static mixers used in practice, certainly more than thirty. The kind of static mixers used plays an important role in the mixing mechanism [5-7].

Static mixers, also known as motionless or in-line mixers, constitute a low-cost option for mixing in the chemical process industry. Static mixers offer attractive features such as closed-loop operation and no moving parts. The static mixer is a collection of blades which fits

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inside a pipe carrying the fluids to be blended. The two liquids to be mixed (typically a polymer melt and an additive) are forced through the mixer under high pressure, and they are cut and folded repeatedly as they negotiate the bends and openings within the mixer [8-10]. The use of static mixers has been advocated for a wide range of applications, such as continuous mixing, blending, heat and mass transfer processes and chemical reactions. The main design factors that motivate the selection of a static mixer for a given application imply that the mixer will achieve the desired degree of homogeneity, and satisfy the performance criteria of tolerable power consumption due to the fluid pressure drop and short residence time [11]. Table 1 shows the comparison on certain available static mixer available in the market.

Table 1 - Comparison of SMX, Kenics and Ross LPD static mixers

	SMX	Kenics	Ross LPD
Structure	Heavy	Light	Light
Pressure drop	High	Low	Low
Flow regime	Laminar	Turbulent	Turbulent
Efficiency	Good	Poor	-
Compactness performances	Good	Poor	Poor

There are many advantages of a static mixer such as reduce space. So, the unused space can be used for another usage like inventory storage or even by adding the numbers of a static mixer. In addition, the static mixer also can eliminate inspection costs and failures. Static mixer can be fabricated by common hardware materials thus there is no need to have a special inspection and permits. However, the disadvantage of the existing static mixers is high cost. The increase in cost is caused by the mixing element in the static mixer. The mixing element in existing static mixer has a complex shape and taking up space because of its length [12,13]. So, a new way to mix fluid but with the lowest cost as possible is by inserting a fractal plate as mixing element with optimal shape into the static mixers thus give the desired mixing but economic.

Therefore, the aim of this study is to investigate the mixing effectiveness of circle grids fractal plate for inline static mixer by determining the pressure drop, ΔP for mixing fluids using a different kind of perforated plate with different porosity and made an observation through flow visualization.

2. Previous Studies

There are a lot of previous researches including many factors had been done to enhance mixing of fluid. Different types of approach are done either by simulation or experiment. Perforated plate as a mixing element are based on numerous experiment and simulation by previous researcher in aiming the best perforated plate shape for top performance mixer in the future. Other than that, it also can reduce industrial cost as perforated plate is far cheaper and easy to manufacture but gives a great advantage in industry production. Besides, research related to in-line static mixer are also been investigate here to get better understanding regarding the achievement of commercially static mixer nowadays.

2.1 Perforated plate

One of the fundamental investigation of the flow forced through a perforated plate was by Queiros-Conde and Vassilicos [14] who investigated experimentally the scaling properties of the turbulent wake after different three-dimensional fractal grids in a wind tunnel. Moreover, the study shows that the turbulent wake is longer than the classical body turbulent wake. This may be explained by the increase of the turbulent intensity behind the grid. Followed by the research, there are some problem was solved numerically by introducing a shell-model to study a turbulent flow for objects of different perforated plate dimensions [15]. It was found that the power of the shell-model fractal forcing is an increasing function of the fractal dimension of the fractal object. Later, Staicu *et al*. investigated experimentally the effect of scaling properties of objects having a fractal-shaped and self-similar structure, on the turbulence generated in a wind tunnel [16]. From the study, the scaling properties of the turbulence intensity depend on the orientation and the position of the perforated plate relative to the velocity sensor.

Simulation conducted by Coffey *et al*. [12] in investigating the mixing effectiveness of fractal grids for inline static mixer regarding the mixing and drag performances of two slightly different perforated plate and two optimized pattern-enhanced fractal grid have been compared with a commercially available top-performance industrial mixing element (referred as CSM for Current Standard of Mixing) and a regular turbulence-generating grid. Overall, they concluded that the fractal grid is the best mixer compared to CSM and regular grid in term of Coefficient of Variance (*CoV*), concentration fields and drag. Also, the combination of PEFG and CSM gives an extraordinary result in mixing efficiency when perforated plate is placed upstream of CSM.

Recent research on experimental work in investigating the pressure losses through perforated plate by S. Malavasi *et al.* shows that pressure loss coefficient is independent of the Reynolds number as long as the parameters stays in the self-similarity range [17]. A

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reduction of the equivalent diameter ratio, β also affecting the pressure losses by causing the pressure loss coefficient to increase. Thickness plays an equal role on the pressure loss coefficient. It can be found that pressure loss coefficient decrease as thickness increases. Besides that, pressure losses are influenced by number and dissipation of holes.

Overall, from all the research mentioned above, we can say that scaling properties, fractal dimension, orientation and positions, coefficient of variance (*CoV*), concentration fields, drag, space-filling pattern, turbulence decay, diameter ratio, β, thickness, number and dissipation of holes, and pressure drop are vital factors and have to make in consideration for making the best fractal plate shape as the top performance mixer compared to existing mixer nowadays.

2.2 Static mixer

Research regarding static mixer had been conducted and the most popular static mixer that include in previous research are SMX static mixer and Kenics static mixer as many experimental methods used with the Kenics are relevant to the study of the SMX since they are strongly related to each other. An experimental related to pressure drop across a Sulzer SMX sixer with both Newtonian and non-Newtonian fluids had been conducted [9-11]. The extensive experiments were performed under varying operating conditions. The results shown that the pressure drop, ΔP increases with the number of mixing element N as well as the level of the fluid viscosity. On the other hand, the pressure drop, ΔP decreases with the fluid temperature when the wall of the static mixer is heated.

Another experimental work determined the relevant elements number of Kenics mixer for complete homogenization of two liquids of differing viscosities (glycerol and tap water) via iodometric decolorization [10]. Laser induced fluorescent and image analysis were used to quantify laminar mixing by measuring the average striation thickness, variance of striation widths, and interfacial area. They used miscible fluids which contain water with Rhodamine dye and operated in the turbulent regime. Their results showed that the velocity ratio between the two streams influences the radial mixing.

From the previous research regarding static mixer, it can be summarized that the pressure drop, number of element, velocity ratio, crossing angle, Reynolds numbers, and striation thinning are some of the parameters for making the best static mixer. Many other parameters can be investigated to improving commercially static mixer. Previous research on static mixer are done to gain information on what are the aspect must be emphasized in making much better static mixer in the future.

3. Methodology

3.1 Experimental test rig and procedure

This experiment is focused on mixing effectiveness of circle grids fractal for an inline static mixer. From the storage water tank, the water that is used as working fluid will flow through a cylindrical 50 mm clear pipe as flow medium in the vertical position and go to the ball valve via 90º elbow PVC pipe. A ball valve is used to block and to control the flow rate of the water before entering the test section. Then, the flow will pass through the circle grids fractal plate that had been fit in by installing flange. In the test section, observation through flow visualization on the mixing area which involves dye injection, UV lamp and camera is made to gain a better understanding of what happening to the mixing area. Next, the flow will meet the second ball valve that functions to control the flow rate of the water to the discharge tank. The schematic diagram of the experimental rig is shown in Fig. 1.

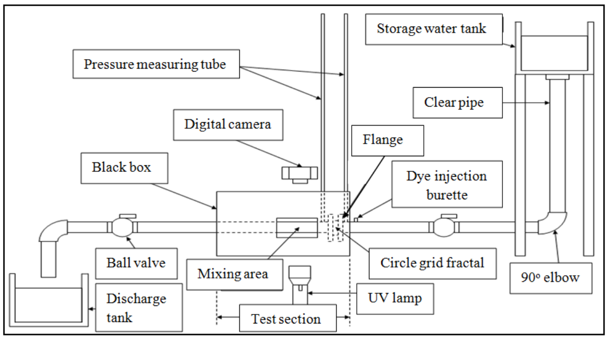

Fig. 1 - Schematic diagram of experimental rig

During the experimental work, the dye injection burette is fit tightly to the pipe to prevent any leakage occurrence. The perforated plate located between two flanges next to the dye injection burette and the test section is then covered up by the black box. The ultraviolet light is illuminated at the side of the black box in order to show a clear visualization of the mixing flow. At the top, a camera is on standby to capture the picture of the mixing liquid at the mixing area right after the flow pass through the fractal plate for observation purpose. The discharged tank is marked to get flowrate data. This experiment is tested by using three different kinds of circle grids fractal plate as shown in Fig. 2 with different porosity as mixing element to determining the pressure drop of each circle grids fractal plate.

(a) (b) (c)

Fig. 2 – Perforated plate with different porosities; (a) NEL (47.5% porosity), (b) Fractal (51.85% porosity) and (c) Unchamfered (62.85% porosity)

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3.2 Data analysis

By determining the pressure drop, we can determine the parameter that can be used to analyze an effectiveness of the perforated in static inline mixer. Based on this case, the plate tested will determine the pressure drop, ΔP. So, from the value of pressure drop collected, we can find out which plate is the best as mixing device. Another important parameter that will be analyze is the mass flow rate.

To gain the pressure difference, a basic equation will be use which is by multiply the density, ρ, gravity acceleration, g, and the height difference between two points measured, h. The different pressure,

$$\Delta P = \rho g h \,, \quad (1)$$

The mass flow rate, $\dot{m}$ can be determine by using the following equation which is the volume of the water, v divide by the time, t.

$$\dot{m} = v/t \,, \quad (2)$$

4. Results and Discussion

4.1 Mass flow rate

NEL Plate has the smallest porosity with porosity value of 47.5%. Small porosity will take the longest time to fill the discharge tank with a certain amount of water. At the 1st opening of the discharge ball valve, it only open 15° which allows the flow to be exposed with a little space thus creates the longest time that is 17.5 seconds. The time recorded decreasing as the larger the openings, the larger the space thus allow the flow to pass through more quick than the previous opening. This shows by the results obtained where for 2nd opening it decreasing to 7.9 seconds, 3rd and 4th opening with 4.7 seconds and 3.8 seconds respectively until the 6th opening with the smallest time recorded with 3.0 seconds.

Fractal perforated plate with a moderate porosity of 51.85%, the discharge tank for the first opening is 16.3 seconds. The time recorded for 1st opening in Fractal perforated late is lower than NEL Plate. This proves that as the porosity increase, the time taken decreasing. The time decrease rapidly more than half of the time in the 1st opening to 6.8 seconds for 2nd opening. The time keeps on decreasing until the 6th opening with 2.5 seconds.

Unchamfered plate is the highest porosity in this study with 62.85% porosity. Since higher porosity value is used, the time recorded will be affected as it will be become shorter than previous two types of plate. For the 1st opening, the time starts with 13.1 seconds and continues to decrease to 6.1 seconds and 3.3 seconds for 2nd and 3rd opening respectively until the last opening with the shortest time recorded of 2.1 seconds. The results for the mass flow rate at last opening was summarize as in Table 2.

Table 2 – Mass flow rate comparison for the tested perforated plate static mixer

Perforated plate	Mass flow rate kg/s
NEL Plate	2.85
Fractal plate	3.43
Unchampered plate	4.18

4.2 Pressure drop analysis

Pressure drop of flow inside a pipe is influenced mainly by the appearance of disturbances the flow encounter as it flows through the pipe. Based on graph plotted in Fig. 3, it depicts the relationship of Reynolds number and pressure drop of flow through all types of plate that had been studied. Based on the graph obtained, it clearly shows that all types of plate create an ascending pattern where it gives a positive reaction which increases simultaneously with different porosities for each plate.

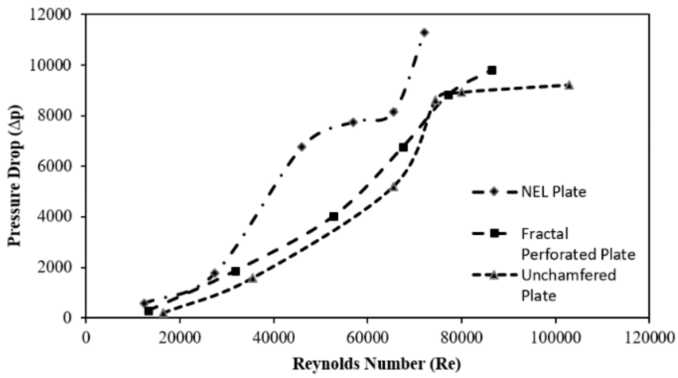

Fig. 3 – Pressure drops vs Reynolds number

NEL Plate is showed to be the steepest line starting with the Reynolds number of 12345.31 for the 1st opening which having 588.60 Pa of pressure drop and increasing gradually to the highest value of 72005.99 at the 6th opening with the value of pressure drop reaching 11281.50 Pa. Followed by Fractal Perforated Plate as the middle line, the graph shows a quite smooth data which starts with Reynolds number and pressure drop of 13253.49 and 294.30 Pa respectively. As opening of discharge valve increasing, the value of both Reynolds number and pressure drop also increase proportionally with the maximum Reynold number value of 86407.19 and pressure drop of 9810.00 Pa. The most declivous graph line is showed by unchamfered plate by having the starting pressure drop of 196.20 Pa and Reynolds number of 16492.02. The value keeps rising considerably until 3rd opening and it starts rise steeply to 4th opening as the results of high Reynolds number of 65459.08 and 74486.03 with pressure drop 5199.30 Pa and 8632.80 Pa and again slowly increase until 6th opening.

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4.3 Flow visualization analysis

The main concern of this analysis is to observe the condition of mixing in the flow inside a circular pipe with the all type of plate tested. This experiment use fluorescent dye injection to enhance the visualization. The flow images captured over 1 second's gaps for each image. The sequence images time is label as t_1 and continues consecutively. Fig. 4 shows the flow condition through all plates for 1st downstream/discharge valve openings with fluorescent dye injected into the flow.

For NEL plate, we can see the fluorescent dye solution slowly mixed with the flowing water. At certain time both fluids mixed well and flow out from the pipe. As the discharge valve openings are too small, the mixing process occurs slowly but it still achieved a fine mixing efficiency. For Fractal plate, it also shows almost the same results as NEL plate Compared to the previous two plate analyze, unchamfered plate showed a hardly seen of dye solution.

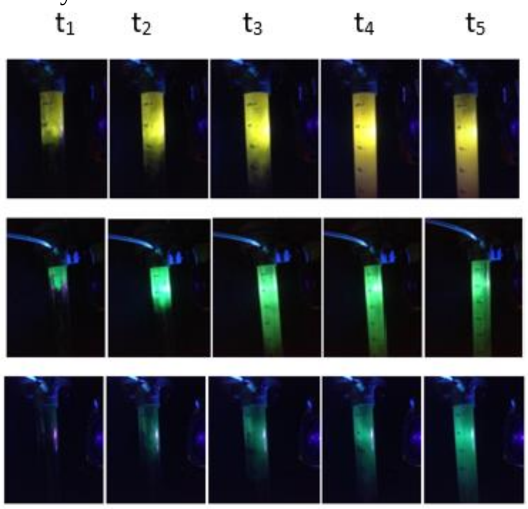

Fig. 4 – Visualization for 1st discharge valve opening for NEL Plate (1st row), Fractal Plate (2nd row) and Unchamfered Plate (3rd row)

Fig. 5 depicts the mixing of all types of plate or 2nd discharge valve opening. As flowing space increase, it will lead to fast mixing. For NEL plate, we can see both fluid mixes entirely start from t_3. Next, as fluorescent dye was injected, the solution fast mix at t_2 for Fractal plate. Same goes to unchamfered plate where it mixes very fast and cause the dye solution too hard to capture.

For 3rd discharge valve opening as shown in Fig. 6, we can see that the mixing occurs more fast than the first two discharge valve openings. For NEL plate, it already shows reaction to mix at t_1 where the purple color is the mixing of both fluid but still incomplete. This also occur for Fractal plate which shows purple color that indicate the mix occur but incomplete until t_2 where the solution starts to mix wholly. Since the opening increase, the flow velocity also increase thus results in high mixing efficiency as shown by unchamfered plate. Both solution mixes very fast so it is hard to see the mix solution.

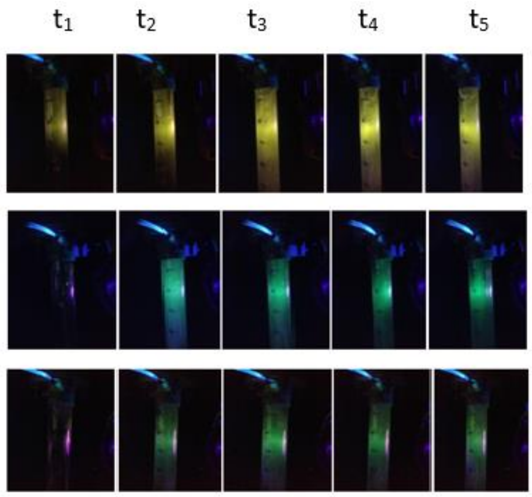

Fig. 5 – Visualization for 2nd discharge valve opening for NEL Plate (1st row), Fractal Plate (2nd row) and Unchamfered Plate (3rd row)

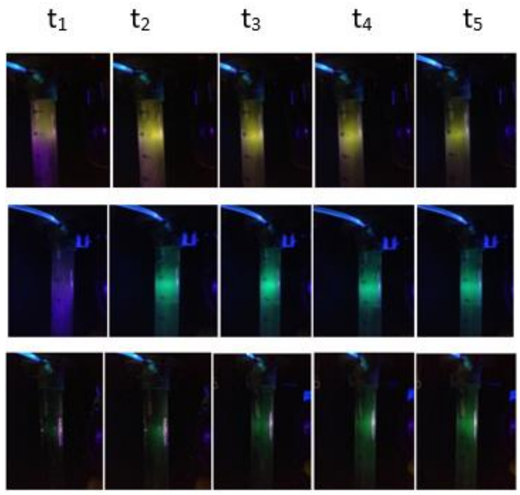

Fig. 6 – Visualization for 3rd discharge valve opening for NEL Plate (1st row), Fractal Plate (2nd row) and Unchamfered Plate (3rd row)

Based on the first three discharge valve opening, we can know the trend of the mixture which is the increasing in porosity will excite the mixing to become more effective. Thus, bigger discharge valve opening leads to higher mixing efficiency.

5. Conclusion

According to the experiment objectives, by satisfying three variables that have been completed in this study which is investigating the pressure drop in a circular pipe with three different kinds of circle grids fractal, comparing the resulting gain from each fractal plate porosity and identify the best parameter has to lead in achieving high efficiency of flow mixing in a circular pipe. Completion of all objectives was done by doing an experiment on mass flow rate, pressure drop and flow visualization.

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Based on the plotted graph of all types of plate and data of each plate showed that turbulent state flow was created by all the three types of a plate with various pressure drops, mass flowrates and velocity rates. All types of plate produce a turbulent flow state even at the first opening. The bigger the plate porosity and the opening of the discharge valve, it will result in higher Reynolds number value and vice versa. From the resulting gain, it can be said that smaller porosity creates a lower Reynolds number compared to bigger porosity where it creates a higher Reynolds number.

To summarize all three plate results from the flow visualization, it was proved that the porosity plate and the flowing area in response to enhance the fluid mixing properties. The flow velocity will increase as the result of increasing flow area thus exciting the flow so the flow will become turbulent directly increase the flow mixing efficiency. Based on results obtained, unchamfered plate is chosen to be the best circle grids fractal plate as it shows the lowest pressure drop and good mixing properties compared to the other two plates.

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