VOL. 17, NO. 3, FEBRUARY 2022 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

DEVELOPMENT OF STATIC MIXER FOR WATER TREATMENT AND INVESTIGATION OF EFFECT OF GEOMETRICAL PARAMETERS ON MIXING EFFECTIVENESS

Ashwin Denny[1], D. S. Robinson Smart[2], Denny C. Kurissingal[3], J. Pradeep Kumar[2] and Joses Jenish Smart[4]
[1]Department of Mechanical Engineering and Management, University of Leicester, United Kingdom
[2]Department of Mechanical Engineering, Karunya Institute of Technology and Sciences, Coimbatore, India
[3]UTE Desaladora Chennai Operation Y. Mantenimiento, Chennai, India
[4]Manufacturing Engineering, ResMed Corp, United States of America
E-Mail: smart@karuya.edu

ABSTRACT

The mixing of liquids and fluids is one of the most significant industrial processes. Static mixers are also known as mixers which are having fewer moving components and are known as motionless mixers. These kinds of mixers are very efficient devices that are very effective and efficient used for mixing both multiphase and single-phase fluids. One of the objectives in using the static mixers is less energy consumption by avoiding complicated and expensive processes. The conventional mixers which are having moving parts such as impellers are subjected to frequent failure due to corrosion and fatigue failures. Hence in this research work, a motionless type static mixing nozzle has been developed. The developed static mixing nozzle consists of Convergent and divergent sections and a spraying nozzle is inserted into the convergent portion to spray the water to be treated. With a gradual increase in the utilization of static mixers in several industrial operations, it is necessary to accomplish higher mixing efficiency. Mixing performance has been enhanced by designing and developing a new type of static mixing nozzle. For investigations purpose, the internal geometry such as convergent angle, throat length, and distance between the spray nozzle potions to the entrance of the throat is kept variable. The spray nozzle position can be adjusted concerning the entrance of the throat by using a threaded portion connected to the convergent nozzle. The main objective of this research is to improve the mixing performance of static mixers by incorporating design modification to the internal geometry. Various geometry of mixing nozzle was selected and the experiments were conducted by varying the position of spraying nozzle from 50 mm to 70 mm, convergent angle (Cone angle) as 20°C to 25°C, and the throat length from 147 mm to 174 mm. During the experiments, the pH value, turbidity, conductivity, and concentration of mixed fluid were measured and analysed. The results of the experiments revealed that the static mixer geometry such as cone angle, throat length, position of spay nozzle can enhance the mixing effectiveness and can be used in water treatment plants.

Keywords: mixing nozzle, convergent angle, throat length, static mixer.

1. INTRODUCTION

Purification and desalination of water is an important activity in the area of water treatment. In the water treatment plants, fluids are to be mixed for purifying and filtering the water. There are different mixing systems are available such as impeller, nozzle mixing, stirrer tank, and static mixer [1, 2]. Many mixers of static types are extensively used in various homogenization processes in industrial operations for example cosmetics, food processing, polymer blending, heat transfer, chemical reaction, pharmaceutics, and also in wastewater treatment. They are mostly used in disposable applications, like in situ mixings of two components epoxy adhesive and sealants [3].

The stirred vessel mixing system is used in process industries and different types of impellers are used to mix the liquid by dynamic motion. The impeller creates a circulation of fluid and shear of fluid, which is necessary for mixing the liquids. In stirred tank liquids can only be mixed in batches [4]. The stirred tank usually operates in batch or semi-batch mode and has large inventories and fluctuations in turbulent dissipation energies.

The impeller and other mixing components are subjected to various dynamics forces, which leads to frequent failure of the system. Hence this research work focused on design, development, experimental analysis to investigate and to study the effect of geometrical variation of mixing nozzle on mixing effectiveness [5]. Static inline mixers are used to mix the liquids continuously in a flow line itself. The incline static mixers are effective answers to the end-users mixing requirements, which consists of no moving parts and only the mixing inserts, will be provided inside the mixer to create vorticity of liquids. Fluids that are to be mixed are pumped into a pipeline, which assists some mixing inserts and uses a separate pump. When the liquid flows into the mixer flow, the stream is subdivided and mixed when both the streams are recombined. The major disadvantage of the system is pressure drop across the mixing inserts and energy spends for mixing is more. The inline mixer consists of a rotating impeller connected to the processing pipeline. The liquid which is to be mixed passes through the pipe [6].

This research work deals with the development of a static mixing nozzle with three different configurations named static mixers 1, 2 & 3. The mixing nozzle has been designed and developed to convert the seawater into potable water. The mixing nozzle mixes the seawater and additives effectively. The mixing nozzle consists of a convergent nozzle and a throat. The convergent angle of the convergent nozzle was provided as 20, 23 & 25°. The spring nozzle position from the entrance of the throat can be varied as 50, 60, and 70 mm for experimental purposes. The primary liquid will be directed to the convergent nozzle through the spraying nozzle and the additives will be added. Additives such as ferric chloride, hypochlorite, and sulphuric acid are mixed at the convergent nozzle. As the convergent nozzle increases the velocity of liquids flow, there will be mixing taking place. Further the mixed liquids will flow through the throat and the mixing will be enhanced as the flow path is increased. The throat lengths have been varied as 147, 161 & 174 mm. The mixing has been quantified by the measured parameters such as mixed liquid pH value, conductivity, and turbidity. Investigations have been carried out by varying the convergent angle, throat length of the mixing nozzle, and the position of the spraying nozzle as mentioned above. The pH value, conductivity, and turbidity of mixed liquid have been measured to evaluate the quality of mixing.

2. LITERATURE REVIEW

Charbel Habchi *et al* [7] clearly explained that flow is deeply laminar and the fluid is highly viscous, the 3D-Flow configuration shows little mixing enhancement concerning plain pipe flow and generates a higher pressure drop. The flux recombination mixers, however, show an interesting rapid decrease in scalar concentration gradients. Sarah Armbrustera *et al* [8] have investigated aerating Static mixers that prevent fouling. All fouling countermeasures were successful in terms of fouling mitigation. Air sparging alone already decreased the rise in resistance. Filipp Gobel *et al* [9] studied the simulation of granular mixing in a static mixer by the discrete element and it has been pointed out that, the larger tube diameter value (smaller d/D) leads to the better performance of static mixers. By comparing the mixing efficiencies and flow rates of static mixers with different geometries, it was concluded that the kenics mixer with four elements at a twist angle of 180°. Noureddine Lebaz *et al* [10] studied the population balance model for the prediction of breakage of emulsion droplets in SMX+ static mixers that were analyzed. The studies revealed that the model predictions were found to be in good agreement with the experimental data for all the parameters which are investigated even there is a drastic difference on the DSD were indicated as in the case of viscosity and rate of volume-average energy dissipation. The ability of the model to capture accurately the full DSD makes it a valuable tool for studying emulsification using static mixers. Sudhanshu S. Somana [11] have carried out the research on the effect of modifications in the internal geometries on the dispersive and distributive mixing in static mixers. The study reveals that, the overall mixing performance of the SM reduced and which leads to a higher pressure drop than the standard SMX mixer.

Few researchers have carried out the near-field flow characteristics of coaxial circular jets. The changes in the primary and secondary jet velocities, jet exit velocities, nozzle dimensions, and geometry have a profound effect on the mixing [12]. This work clearly shows the current stage of knowledge on coaxial jet flows. Based on these studies it is confirmed that several regions in the mixing field are identified in which the inner mixing layer is either governed by shear or wake instabilities and enhances the mixing. The studies indicate that the effect of nozzle geometry can enhance the mixing and has to be investigated in detail.

An evaluation of an ejector entraining two secondary jets which are coaxial with the motive stream has been studied [13]. The ejector for evaluation consists of a cylindrical-type mixing section and a throat for mixing fluids. There is a mechanism to change the length of its cylindrical section. Pressure variations in the mixing chamber were recorded, and these values were used to decide on the effect of the cylindrical length-to-diameter ratios. Results indicate the influence of the supply of primary fluid, the cylindrical length-to-diameter ratio on the jet entertainment influences efficiency of the nozzle.

3. METHODS

The word mixing is used to operate, which leads to reduction of non-uniformities or variation in temperature, properties, or composition of the material in bulk. The mixing nozzle works on the principle of the jet pump and convergent-Divergent nozzle (CD Nozzle). The CD nozzle also consists of a driving nozzle inserted at the entrance of the CD nozzle. The convergent-divergent nozzle mainly consists of three major parts, they are the suction area, the throat, and the divergent area. On the suction area, there are four inlets provided for the entry of the secondary fluid to the mixing chamber. The pump supplies the primary fluid at very high pressure to the driving nozzle. A high-pressure stream of liquid is forced into a nozzle which has been designed to create the highest possible velocity. As the fluid is directed through this nozzle, as the pressure is reduced due to the Convergent portion, a higher velocity jet is created and the additives or secondary fluid or chemical will be sucked inside the nozzle due to the creation of a vacuum. As the additives and primary liquid are flowing in the nozzle due to the turbulence, the chemical and fluids will be mixed to gather and the water will be treated.

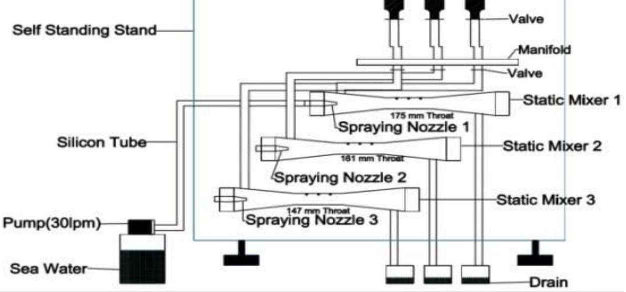

Figure-1(a). Static mixer experimental set-up.

Figure-1(b). Static mixer experimental set-up.

Figure-1 (a) shows the developed experimental set-up of the static mixing nozzle. The seawater to be converted as portable drinking water is pumped by a 0.5 hp pump. The delivery of the pump is adjusted to 30 liters per minute. The outlet of the pump is connected to a spraying nozzle which has been provided inside a convergent nozzle. The spraying nozzle consists of thread at the peripheral. The spraying nozzle consists of 12 spraying jets at the outlet. The position of the spraying nozzle concerning the entrance of the throat can be varied as 50, 60, and 70 mm. The convergent nozzle is connected to a throat by using flanges with bolts and nuts. Additives such as ferric chloride, hypochlorite, and sulphuric acid are mixed at the manifold and directed to a convergent nozzle for mixing with seawater. There is a convergent section having fabricated with various cone angles 20°C, 23°C, and 25°C Also three throat sections having the various length as 174 mm, 161 mm, 147 mm are fabricated. As the seawater passes through the spraying nozzle velocity found to be increased due to the convergent section. Manifold supplies the required quantity of additives and is being dosed with the seawater at the convergent nozzle. As the additives and seawater pass through the convergent section, throat section due to turbulence and vorticity created by spraying nozzle and convergent section, mixing will be enhanced. The coefficient of variation is the difference in density or pH value or conductivity or turbidity of the mixed fluid in randomly selected points in the mixing chamber or mixing nozzle. The reduction in the coefficient of variation corresponding to the mixing length will be used to decide the quality of the mixing. This reduction in the coefficient variation concerning the length of the mixing chamber or throat is evidence of chaotic mixing in the mixer [14,15].

As the seawater is salinity in nature and it is consisting of many dissolved salts. Usually, the seawater pH value will be between 7.5 and 8.4. This level of pH value is not suitable for potable drinking water and the seawater has to be treated to reduce the pH value. The seawater pH and its nature majorly contribute and plays an important role in the ocean's carbon cycle, also it proves that the carbon dioxide emissions causing on-going ocean acidification. Hence it is very important for pH measurement in water treatment plants. However, due to the seawater's chemical properties and various pH scales in chemical oceanography, the pH measurement becomes complicated. There are various methods involved in the measurement of pH values. The pH can be measured by using a concentration cell with transference. This can be obtained by measuring the potential difference between a hydrogen electrode and a standard electrode such as the electrode which has been coated with silver chloride. A colour-changing indicator or a glass electrode or pH meter has been used to measure the pH value of seawater, salty water, and other aqueous solutions. Measurements of pH are very important in many applications such as wastewater treatment, chemistry, desalination, medicine, and agronomy as the products which are being produced in the above-said fields are used in human health-related areas.

Reducing turbidity as per the requirement is another challenge in the water treatment plant. Turbidity is the cloudiness or haziness of a mixed fluid composed caused by enormous numbers of distinct particles which are normally indistinguishable to the naked eye, similar to smoke in the air. The settling or decanting or filtration process is generally used to treat turbidity. Depending on the requirement and application, the additive, chemical reagents are to be injected or dosed into the stream of wastewater to enhance the efficiency and effectiveness of the filtration or settling process. Along with the advanced methods for removing the turbidity, sand filtration or settling tanks or clarifiers and other techniques are also being used in the water treatment plant, desalination plants, and municipal wastewater plants to remove turbidity. Testing and measuring turbidity is a key activity that is conducted to ensure water quality. The water or any fluids can contain dissolved and suspended solid particles of various sizes. Sometimes it may not be visible to the naked eye and leads to contaminated water. There may be some suspended particles that will be more enough and heavy enough to settle quickly to the bottommost of the container if a liquid sample is kept long to stand. But it was observed that very small particles were found settling very slowly or not settling if the sample is frequently agitated or the particles are colloidal. So due to the small solid particles, turbidity could be observed in the mixer during the mixing process.

Turbidity or cloud-like mixed fluid is appearing and also applied to translucent solids such as plastic or glass. In many experiments and applications turbidity meter is being used to measure the turbidity including this research work. The scattered light concept is used in the turbidity meter to measure the turbidity. The scattered light is apprehended by a photodiode, which creates an electronic signal and that is rehabilitated to turbidity.

The samples of mixed fluids are withdrawn at the throat by using a syringe arrangement. The samples are tested for their turbidity, conductivity, and pH values. The above experiments are repeated by changing the cone angle to 20°C (Static Mixer 1), 23°C (Static Mixer 2), and 25°C (Static Mixer 3) and the throat length as 175 mm, 161 mm, and 147 mm. The evaluated values of turbidity, conductivity, and pH are tabulated.

4. RESULTS AND DISCUSSIONS

4.1 Effect of Spraying Nozzle Position on Mixing Efficiency

Experiments were conducted by changing the spraying nozzle position to 50, 60, and 70 mm away from the entry of the throat. It was observed that from Table-3 and Figures 2 to 4 that, as the spraying nozzle position increases from 50 mm to 60 mm, the mixing efficiency in increasing and reaches 100% as the spraying of seawater taking place near the entrance of additives, the interaction between the fluids found to be better. As the spraying nozzle position increases from 60 to 70, there is less interaction between the fluids due to the increase in the distance between the additives entry and to spraying locations.

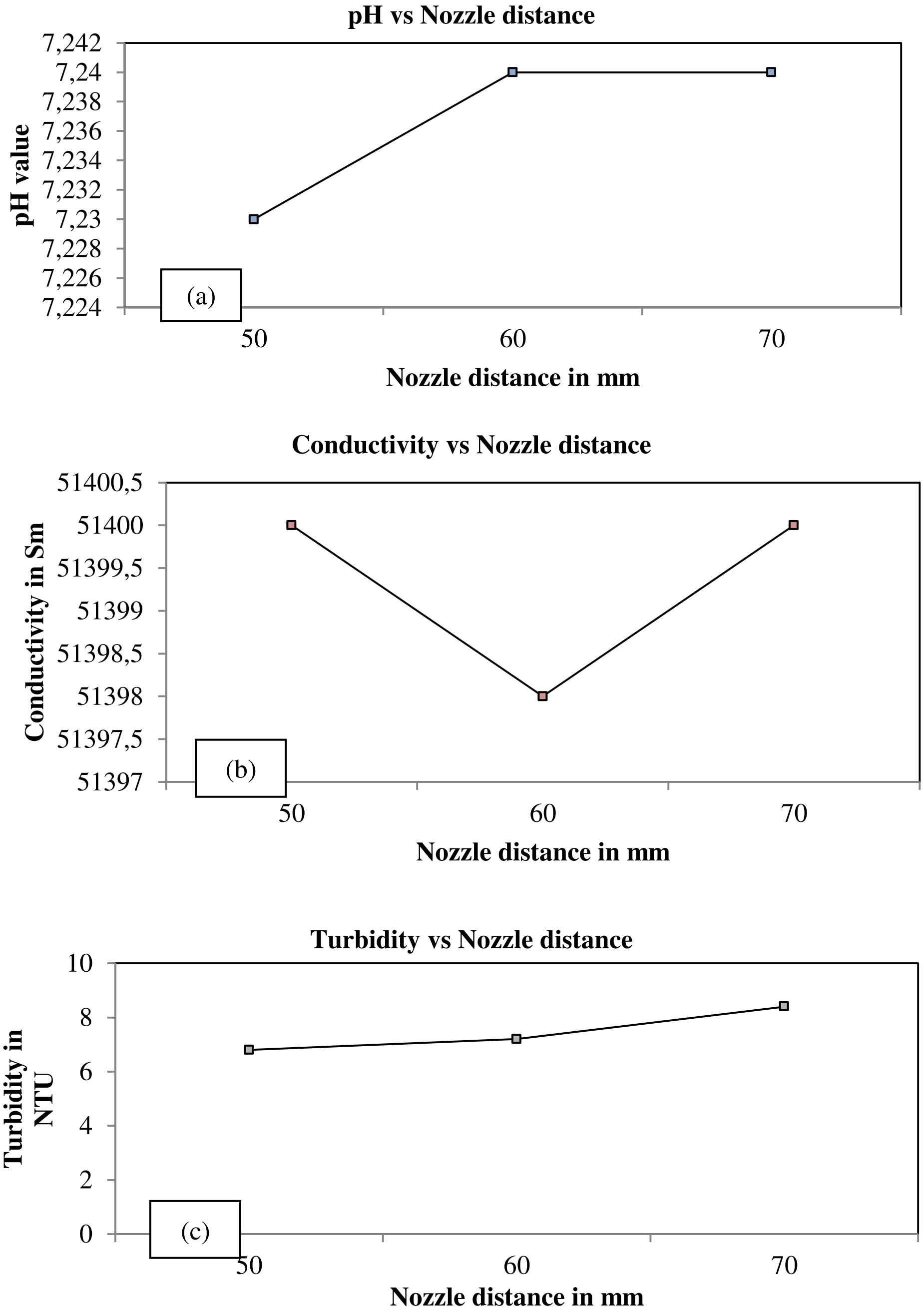

Figure-2. Static mixer 1 (a) pH vs spraying nozzle position (b) Conductivity vs spraying nozzle position (c) Turbidity vs spraying nozzle position.

4.2 Effect of Convergent nozzle Angle on Mixing Efficiency

The decrease in convergent nozzle angle from 25° to 20° leads to more kinetic energy, vorticity, and turbulence. Tables 3 to 5 reveal that the decreases in cone angle increase the mixing efficiency. The convergent angles 20° and 23° provide 100% mixing efficiency than the 25° when the nozzle position is in-between 50 to 60 mm.

4.3 Effect of Throat Length on Mixing Efficiency

Experiments were conducted to evaluate the mixing efficiency when the throat length varies to 147, 161, 174 mm. The longer throat length facilitates more mixing length, increase in the flow path and it was observed that 174 mm throat length gives higher mixing efficiency than the 161 mm and 147 mm as shown in Table-1.

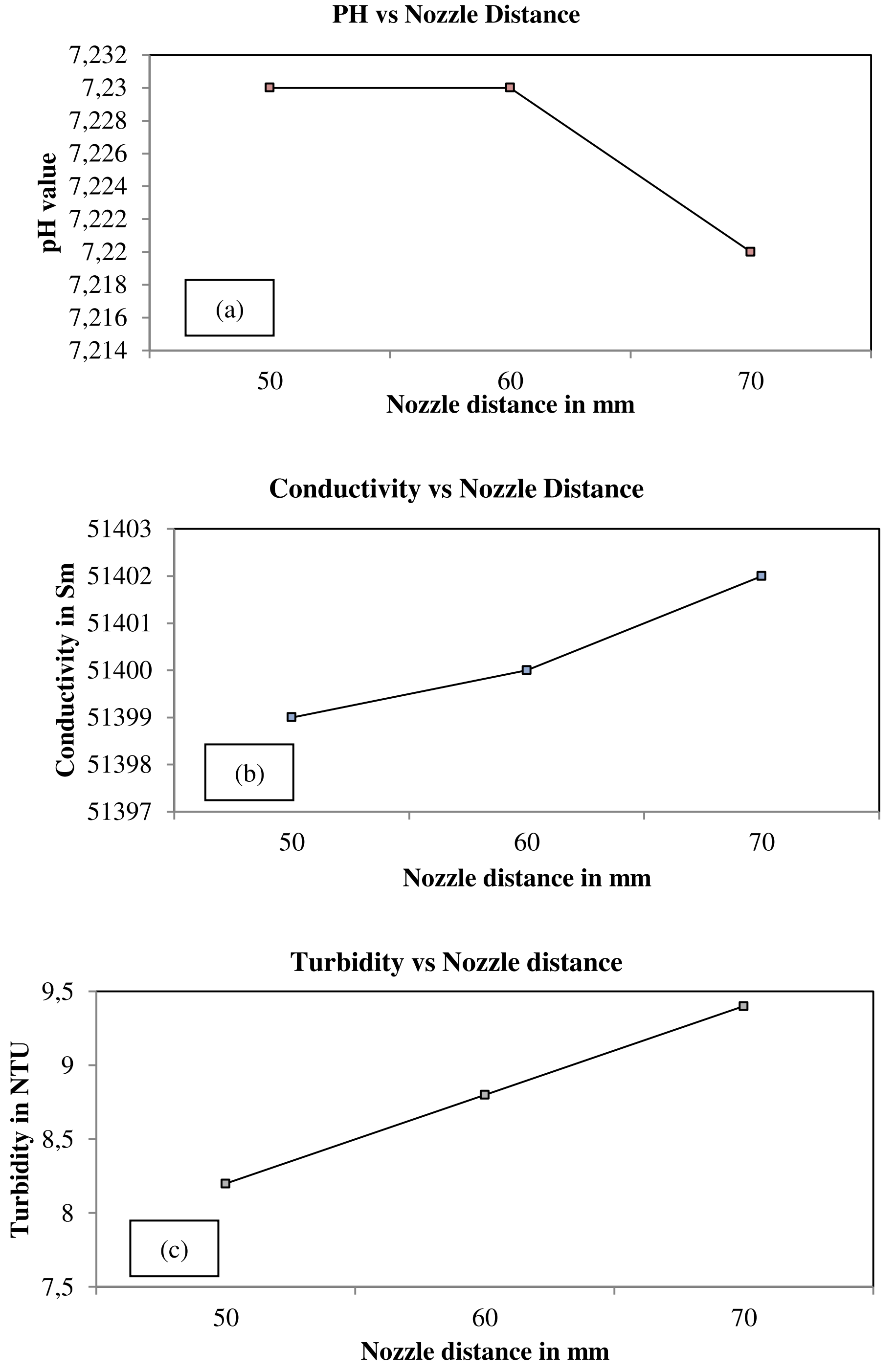

Figure-3. Static mixer 2 (a) pH vs spraying nozzle position (b) Conductivity vs spraying nozzle position (c) Turbidity vs spraying nozzle position.

4.4 Effect of Throat Length on Mixing Efficiency

Figures 2-4 reveals that, the mixing effectiveness increases when the pH value of mixed fluid is in the range of 7.23 - 7.24, conductivity reaches 51400 S_m, turbidity is 6.8 to 7, the position of spraying nozzle is 50 mm, 60 mm, and convergent nozzle angle is in-between 20° and 23°C. This condition leads to higher efficiency. Hence the position of the spraying nozzle can be 50 to 60 and convergent angle 20° to 23°C for better mixing and higher efficiency. In other cases for mixer 2 & 3, the values of pH, conductivity, turbidity are found to be increasing, which leads to a reduction in mixing efficiency.

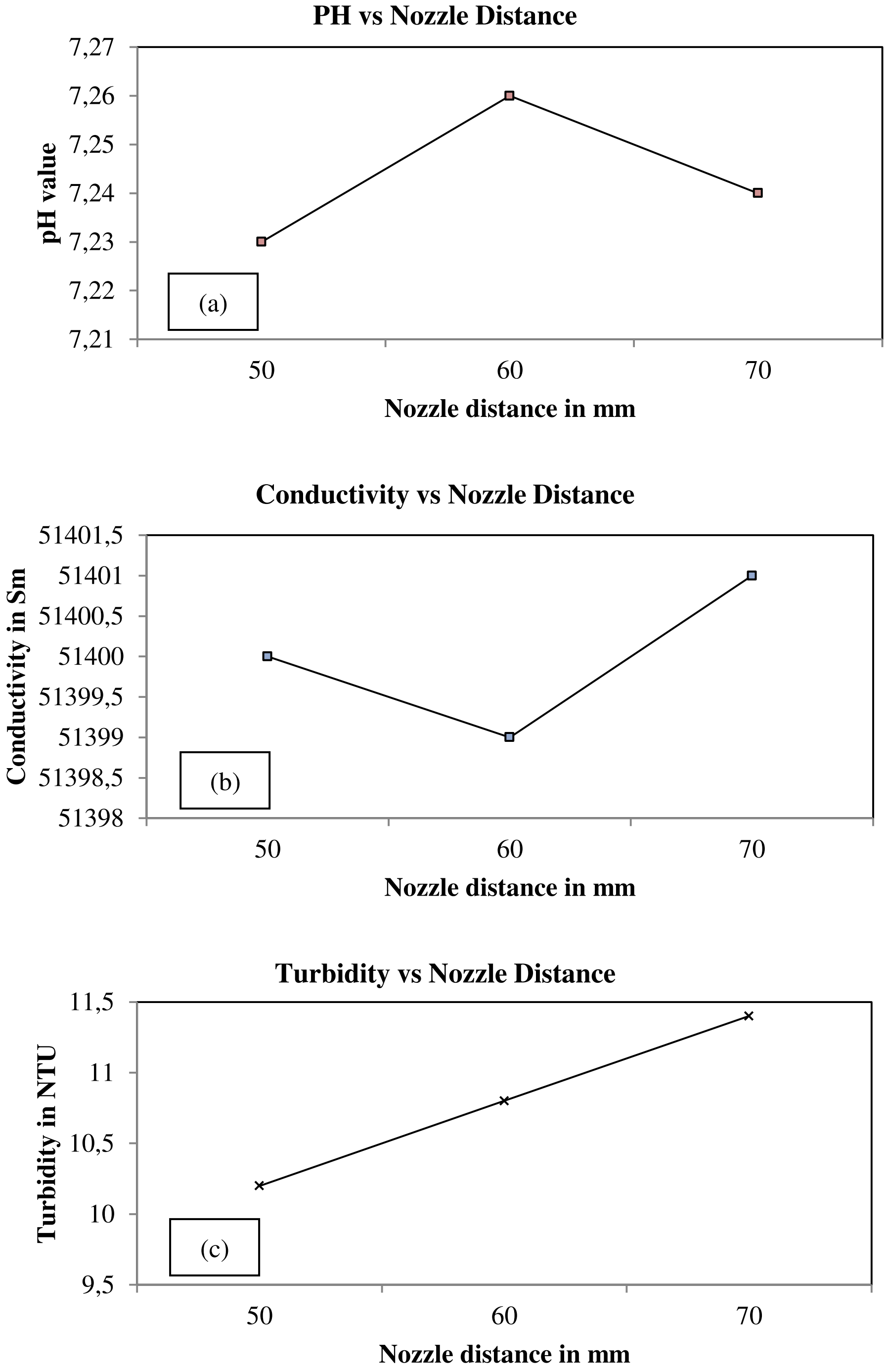

Figure-4. Static mixer 3 (a) pH vs spraying nozzle position (b) Conductivity vs spraying nozzle position (c) Turbidity vs spraying nozzle position.

4.5 Effect of Throat Length on Mixing Efficiency

Turbidity is a very important mixing parameter that decides the mixing efficiency. Tables 1 to 5 and Figures 2-3 shows that the spraying nozzle position varies from 50 to 70 mm, the turbidity increase from 6.8 to 8.4 in the case of nozzle 1 which has a larger throat of 174 mm. As the spraying nozzle position moves from additives spraying location there will be lesser mixing and turbidity found to be higher. This shows that spraying nozzle position 50 mm and throat length 174 mm enhances the mixing efficiency with a decrease in turbidity to 6.8. As the throat length and spraying nozzle position decrease to 160 mm, 147 mm, and 60 to 70 mm respectively, turbidity increase from 7.22 to 11.4, this decreases the mixing effect.

Table-1. Mixing of chemical and seawater using spraying nozzles 1, 2 & 3.

Static Mixer	**1**	**Raw Water**	**Sea Water**
Throat	174 mm	pH	8.1
Chemical dozing	Sulphuric acid - 10 ppm Hypochlorite - 2.0 ppm Ferric chloride - 0.75 ppm	Conductivity (S_m)	51400
Feed flow	30 LPM	Turbidity (NTU)	12.6
Nozzle distance (mm)	pH	Conductivity	Turbidity
50	7.23	51400	6.8
60	7.24	51398	7.2
70	7.24	51400	8.4
Static mixer	**2**	**Raw water**	**Sea water**
Throat	161 mm	pH	8.1
Chemical dozing	Sulphuric Acid - 10 ppm Hypochlorite - 2.0 ppm Ferric chloride - 0.75 ppm	Conductivity (S_m)	51400
Feed flow	30 LPM	Turbidity (NTU)	12.6
Nozzle distance (mm)	pH	Conductivity	Turbidity
50	7.23	51399	8.2
60	7.23	51400	8.8
70	7.22	51402	9.4
Static mixer	**3**	Raw water	Sea water
Throat	147 mm	pH	8.1
Chemical dozing	Sulphuric Acid - 10 ppm Hypochlorite - 2.0ppm Ferric chloride - 0.75ppm	Conductivity (S_m)	51400
Feed flow	30 LPM	Turbidity (NTU)	12.6
Nozzle distance (mm)	pH	Conductivity	Turbidity
50	7.23	51400	10.2
60	7.26	51399	10.8
70	7.24	51401	11.4

Table-2. Mixing of chemicals and seawater without spraying nozzle.

Container	**30 Litres Capacity**	**Raw Water**	**Seawater**
Function	Stirring with a glass rod for 60 sec	pH	8.1
Chemical dozing	Sulphuric Acid - 10 ppm Hypochlorite - 2.0 ppm Ferric chloride - 0.75 ppm	Conductivity (S_m)	51400
		Turbidity (NTU)	12.6
Mixing time	pH	Conductivity	Turbidity

10 mins	7.23	51400	10.1
20 mins	7.23	51400	9.9

4.6 Test for Conductivity

4.6.1 Static mixer 1

Table-3. Experimental result of conductivity of mixed fluid for mixer 1, if convergent angle 20, throat length 174 mm and standard conductivity value (S_m) 51400.

Test No	Nozzle position (mm)	Standard conductivity value (S_m)	Experimental conductivity value (S_m)	Ɛ = Standard Value/Experimental Value ×100
1	50	51400	51400	100%
2	60	51400	51398	100%
3	70	51400	51400	100%

4.6.2 Static mixer 2

Table-4. Experimental result of conductivity of mixed fluid for mixer 2, if convergent angle 23, throat length 161 mm and standard conductivity value (S_m) 51400.

Test No	Nozzle position (mm)	Standard conductivity value (S_m)	Experimental conductivity value (S_m)	Ɛ = (Standard Value/Experimental Value) ×100
1	50	51400	51399	100%
2	60	51400	51400	100%
3	70	51400	51402	99.9%

4.6.3 Static mixer 3

Table-5. Experimental result of conductivity of mixed fluid for mixer 2, if convergent angle 25, throat length 147 mm and standard conductivity value (S_m) 51400.

Test no	Nozzle position (mm)	Standard conductivity value (S_m)	Experimental conductivity value (S_m)	Ɛ = (Standard Value/Experimental Value) ×100
1	50	51400	51400	100%
2	60	51400	51399	99.9%
3	70	51400	51401	99.9%

4.7 Effect of Spraying Nozzle Position on Turbidity

With a feed flow of 30 lpm of seawater having turbidity of 12.6 NTU is mixed with chemicals through the respective nozzle. Following are the chemicals used and few important nozzle specifications:

a) Sulphuric acid H_2SO_4
b) Hypochlorite HOCL
c) Ferric chloride $FECL_3$

Experiments were conducted by changing the mixing nozzle 1, 2 & 3, nozzle throat length as 174, 161 & 147 mm distance between the exit of spraying nozzle and the entrance of throat as 50, 60, and 70 mm. Turbidity for each case has been measured and tabulated in Tables 1,3 to 5. Table-3 shows the mixed fluid turbidity without using a mixer and found to be a higher value between 8.1 to 12.6.

First, the mixing was done by using the Nozzle/Mixer 1 keeping the throat length as 174 mm and the distance between the exit of the spraying nozzle and the entrance of the throat as 50 mm. After mixing turbidity was measured using the turbidity meter. The same experiments were repeated by changing the distance between the exit of the spraying nozzle and the entrance of the throat as 60 mm and 70 mm. The results have shown in Figure-5. The experiments revealed that as the distance between the exit of the spraying nozzle and the entrance of the throat decreasing was from 70 mm to 50 mm the turbidity was decreasing from 8.4 to 6.8 and there is an increase in the mixing effect as shown in Table-1.

The same experiments were repeated by using Mixer 2 & 3 with the throat lengths 161 & 147 mm. The results of these experiments have been shown in Figures 6 & 7. The results show that in mixer 2, as the distance between the exit of the spraying nozzle and the entrance of the throat decreasing was from 70mm to 50 mm the turbidity was decreasing from 9.4 to 8.2 and there is an increase in mixing effect. When mixer 3 was used, it was observed that, as the distance between the exit of the spraying nozzle and the entrance of the throat decreasing was from 70 mm to 50 mm the turbidity was decreasing from 11.4 to 10.2 and there is an increase in mixing effect,

So the above experiments and analysis clearly show that mixer 1 only can provide more mixing effect as the turbidity is 6.8 which are lesser than other mixers.

To know the effectiveness of the mixing, first, the fluids and chemicals were taken in a beaker and mixed manually for 10 & 20 mins. Then the mixed liquid was measured (the values are considered as standard values) and compared with the mixers 1, 2 & 3. The results of turbidity have been shown in Tables 6, 7 & 8 and Figures 5, 6 & 7 for the throat length 175 mm, 161 mm, and 147 mm respectively.

The turbidity results are as shown below.

Table-6. Turbidity for standard experiment and when the Nozzle throat length is 175mm.

Turbidity (Ntu)		
Nozzle - 175 mm throat	**Stirred 10 min**	**Stirred 20 min**
7.6	10.1	9.2

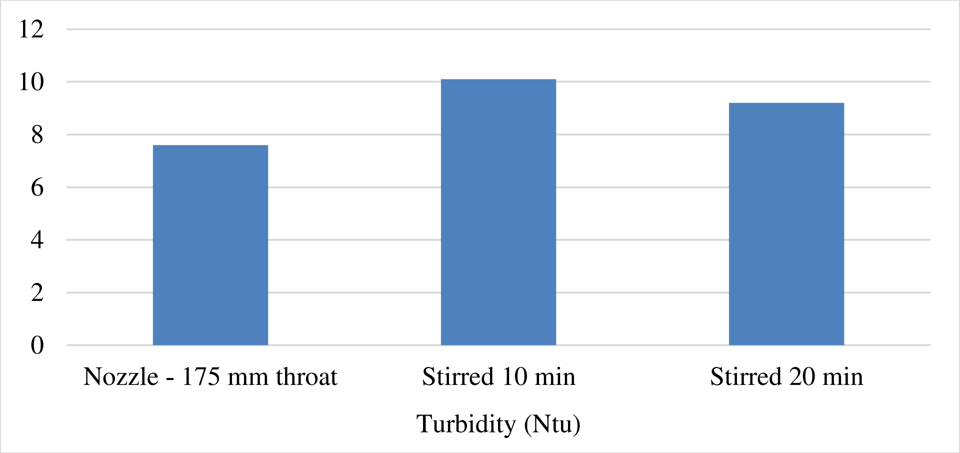

Figure-5. Turbidity for standard experiment and when the Nozzle throat length is 175mm

Table-7. Turbidity for standard experiment and when the Nozzle throat length is 161mm.

Turbidity (Ntu)		
Nozzle - 161 mm throat	**Stirred 10 min**	**Stirred 20 min**
8.5	10.1	9.2

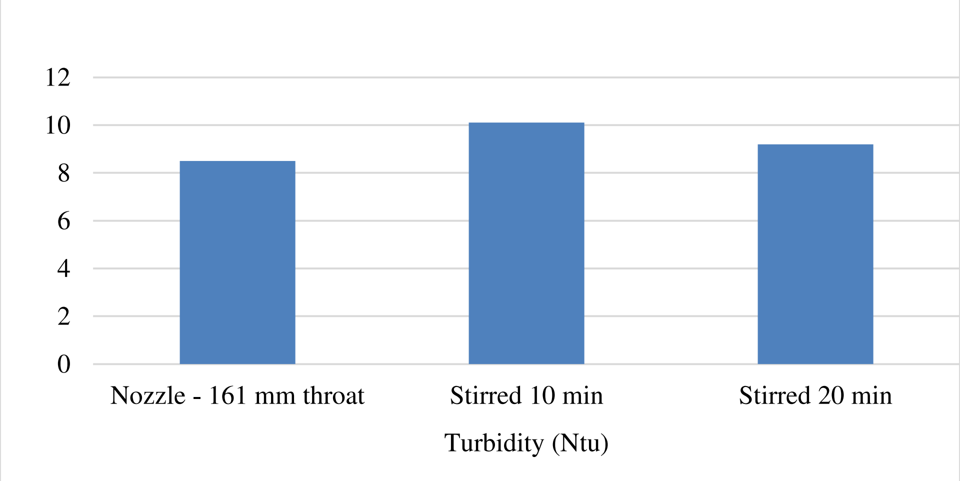

Figure-6. Turbidity for standard experiment and when the Nozzle throat length is 161mm.

Table-8. Turbidity for standard experiment and when the Nozzle throat length is 147mm.

Turbidity (Ntu)		
Nozzle - 147 mm throat	**Stirred 10 min**	**Stirred 20 min**
10.5	10.1	9.2

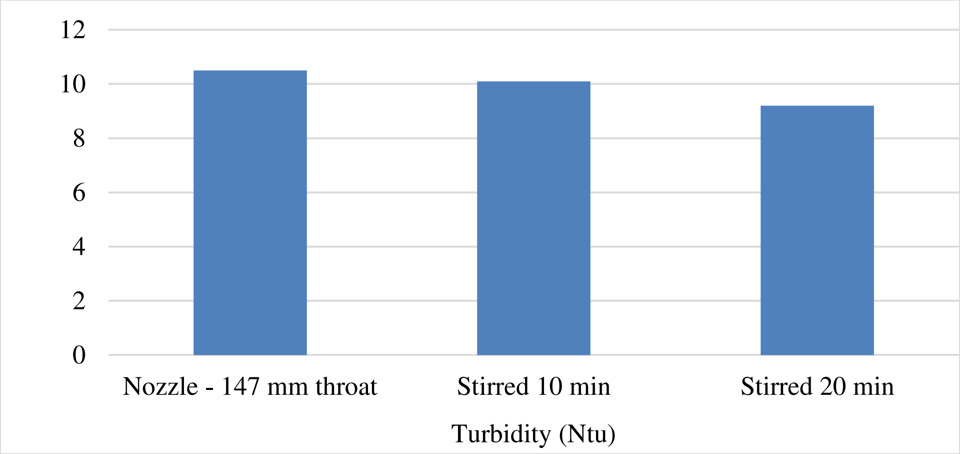

Figure-7. Turbidity for standard experiment and when the Nozzle throat length is 147mm.

5. CONCLUSIONS

The design, fabrication, experiment, and performance evaluation of static mixer using spraying nozzle have been carried out successfully. Experiments were conducted by varying various parameters like the position of the spraying nozzle, distance of the driving nozzle from the throat. These variations help to find pH, conductivity, turbidity at various points. The need to optimize the Static mixer is that many industries require mixing different fluids properly. A detailed experiment was carried out for recording various parameters concerning the chemicals and size of the static mixer. The readings such as pH, conductivity, and turbidity were tabulated. The experimental results reveal that the mixing efficiency can be increased when the spraying nozzle position is 50 mm, the convergent angle is 20° to 25°, and the throat length is 147 mm to 161 mm are maintained. The turbidity analysis clearly shows that when the position of the spraying nozzle is reduced from 70 mm to 50 mm and nozzle 1 was selected, the turbidity is decreased from 11.4 to 6.4 and further this fluid will be processed to make it potable. Hence, the overall experimental analysis shows that, in a spraying nozzle mixing system, the spraying nozzle position is 50 mm, the convergent angle is 20° to 25° and throat length is 147 mm to 161 mm are maintained, the results are more efficient than in a standard mixing system.

REFERENCES

[1] D. Rauline, J. M. Le Blévec, J. Bousquet, P. A. Tanguy. 2000. A comparative assessment of the performance of the Kenics and SMX static mixers, Chem. Eng. Res. Des. 78: 389-396. https://doi.org/10.1205/026387600527284.

[2] P. F. Linden, J. E. Simpson. 1986. Gravity-driven flows in a turbulent fluid, J. Fluid Mech. 172: 481-497. https://doi.org/10.1017/S0022112086001829.

[3] D. Rauline, P. A. Tanguy, J. M. Le Blévec, J. Bousquet. 1998. Numerical investigation of the performance of several static mixers, Can. J. Chem. Eng. 76: 527-535. https://doi.org/10.1002/cjce.5450760325.

[4] F. J. Muzzio, P. D. Swanson, J. M. Ottino. 1991. The statistics of stretching and stirring in chaotic flows, Phys. Fluids A. 3: 822-834. https://doi.org/10.1063/1.858013.

[5] O. Wünsch, G. Böhme. 2000. Numerical simulation of 3d viscous fluid flow and convective mixing in a static mixer, Arch. Appl. Mech. 70: 91-102. https://doi.org/10.1007/s004199900042.

[6] J. M. Zalc, E. S. Szalai, F. J. Muzzio, S. Jaffer. 2002. Characterization of flow and mixing in an SMX static mixer, AIChE J. 48: 427-436. https://doi.org/10.1002/aic.690480303.

[7] C. Habchi, A. Ghanem, T. Lemenand, D. Della Valle, H. Peerhossaini. 2019. Mixing performance in Split-And-Recombine Milli-Static Mixers-A numerical analysis, Chem. Eng. Res. Des. 142: 298-306. https://doi.org/10.1016/j.cherd.2018.12.010.

[8] S. Armbruster, A. Brochard, J. Lölsberg, S. Yüce, M. Wessling. 2019. Aerating static mixers prevent fouling, J. Memb. Sci. 570-571: 537–546. https://doi.org/10.1016/j.memsci.2018.10.039.

[9] F. Göbel, S. Golshan, H. R. Norouzi, R. Zarghami, N. Mostoufi. 2019. Simulation of granular mixing in a static mixer by the discrete element method, Powder Technol. 346: 171-179. https://doi.org/10.1016/j.powtec.2019.02.014.

[10] N. Lebaz, N. Sheibat-Othman. 2019. A population balance model for the prediction of breakage of emulsion droplets in SMX+ static mixers, Chem. Eng. J. 361: 625-634. https://doi.org/10.1016/j.cej.2018.12.090.

[11] S. S. Soman, C. M. R. Madhuranthakam. 2017. Effects of internal geometry modifications on the dispersive and distributive mixing in static mixers, Chem. Eng. Process. Process Intensif. 122: 31-43. https://doi.org/10.1016/j.cep.2017.10.001.

[12] R. van Hout, S. Murugan, A. Mitra, B. Cukurel. 2021. Coaxial circular jets-a review, Fluids. 6: 1-22. https://doi.org/10.3390/fluids6040147.

[13] W. A. Aissa. 2014. Effect of throat length on the performance of an air ejector.

[14] J. M. Zalc, E. S. Szalai, F. J. Muzzio. 2003. Mixing Dynamics in the SMX Static Mixer as a Function of Injection Location and Flow Ratio, Polym. Eng. Sci. 43: 875-890. https://doi.org/10.1002/pen.10072.

[15] H. E. H. Meijer, M. K. Singh, P. D. Anderson. 2012. On the performance of static mixers: A quantitative comparison, Prog. Polym. Sci. 37: 1333-1349. https://doi.org/10.1016/j.progpolymsci.2011.12.004.