



Shahid Chamran
University of Ahvaz

Journal of Applied and Computational Mechanics



Research Paper

Experimental Study of the Heat Transfer Enhancement in Concentric Tubes With Spherical and Pyramidal Protrusions

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Received June 29 2019; Revised September 06 2019; Accepted for publication September 16 2019.

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Abstract. In the current research project, the thermal performance of a series of newly designed mixers has been investigated. Each mixer has two concentric cylinders comprising two annular slot flow channels around a solid cylindrical rod at the center. In each mixer, the first cylinder around the central solid rod has either spherical or pyramidal protrusions throughout the outer surface. It has been observed that with varying mass flow rate of cold and hot water (1 kg/m³-sec to 5 kg/m³-sec), 17% increase in rate of heat transfer for cold water & 73% for hot water has been observed with a variation in mass flow rate of 1-3 kg/m³-sec with all combination of angles of holes in spherical protrusions. In the case of pyramidal protrusions, the rate of heat transfer has been raised from 16% for cold water & 88% for hot water at varying a mass flow rate of 1-3 kg/m³-sec in all combinations of angles of the top vortex in each protrusion. The effect of imparting the centrifugal force has raised the rates of heat transfer in the range of 24-36% at varying rpm from 60-180 rpm of the central cylinder, with the highest with 120 rpm. A comparison of the heat transfer rates reveals that with increasing the mass flow rates, rpm, angle of the holes in spherical protrusions and angle of the traversed angle at the top corner of each pyramidal protrusion didn't contribute linearly in terms of rising in the rate of heat transfer.

Keywords: Static mixer, Flow rate, Rpm, Protrusions, Thermal performance.

1. Introduction

Mixers have an important role in the process industry. With the advent of new designs and the applications of the technological improvements in mixer's designs make them an essential choice in terms of maintenance-free inline equipment for the process industry. Mixers are employed in two shapes in the process industry. First, they either being used as inline equipment, facilitating the mixing in unidirectional flows without any reinjection from the outlet, secondly; they could be placed in a loop. The amount of energy needed to operate these types of mixers is low or virtually zero as they have no moving part plus they have a low maintenance cost. Mixers with dynamic or moving parts mostly used in the fluids which have high viscosity. They provide better mixing for dilution or homogenization at a more enhanced and better level with lower residence time. The reason for providing better performance is the creation of high shear among the fluid region which has been induced by sufficient circulation [1]. Most of the time, in two-fluid mixing setups, the mixing performance in terms of a numerical value has been given as volume percent, as in the present research project, the two fluids mixed with each other inside a stainless steel annular confinements with some reasonable pressure buildup inside these annular channels, therefore, the in-situ measurements to estimate the mixing performance



or sample extraction at any time for the measurements (wherein present study, both the fluids have the same type and nature with the only difference in their phases) of the mixing performance in terms of volume percentage is not feasible. However, in our setup, the extent of mixing has been measured in terms of the temperature of the mixture of hot and cold water collected at the outlet using temperature sensor 2 (as shown in Fig. 1.). Around 30 commercial designs of the static mixers are available for the industry till the date [2]. The static mixers contain elements, or inserts or some irregular body contours that have a sole purpose to distribute the one fluids into another. The distribution has been achieved by injecting one fluid into the other along the orthogonal or transverse direction to the flow of the second fluid. The performance of static mixers is the function of the residence time, aspect ratio and the number of irregular shaped body contours/protrusions/elements or inserts. Most processes in the process industry need homogenization via mixing, resulting in endothermic and exothermic phenomena, so the geometry of such equipment plays an important role in terms of controlling the mixing and or homogenization. Cited literature [3,4], regarding the classification of these mixers, is based on their geometries. Static mixers of the types used in turbulent miscible fluids use eddy diffusion for the best mixing in most industrial processes, yet the best mixing and hence the homogenization has been achieved at the cost of large pressure drop. Studies addressing these issues [5–8] in turbulent flows reveals that the homogenization via mixing is achieved by energy dissipation in boundary layers and fluid itself. In addition to it, Computational Fluid Dynamic (CFD) analysis of static-mixers [9], High Efficiency Vortex (HEV) Static Mixer [10], and Sulzer Mixer (SMX) Static Mixer [11], are among some good cited papers that shed enough light on performance and characteristics of these mixers, here in the current manuscript, we test newly designed mixers for their thermal performance evaluation using hot and cold water as flowing fluids. Cited literature like this and myriad other literary citations reveals the effectivity of the mixers in turbulent mixing of liquid-liquid systems. But before we go through all the rest of the details, literature which is based specifically on the use of static mixer for turbulent mixing is given as follows;

Dispersion of viscous liquids by the turbulent flow in a Kenics mixer has been investigated some 3 decades before [12], where a semi-empirical relation has been developed that relates the mean size data and collapse the Weber number results in inviscid limit. Along with this, the low viscosity mixing and mass transfer in gas-liquid systems have been investigated in Sulzer's SMV mixer [13]. Mixing between two gaseous phases has been studied [14] and improved mass transfer has been observed using HEV type mixer. Mixers of the types like Low-Pressure Drop (LPD), LLLPD & Interfacial Surface Generator (ISG) have been developed recently and successfully employed in blending oils, liquid-liquid dispersion and wastewater neutralization [15]. An inline mixer of series-45 has been employed to study the fast reactive flow mixing [16], whereas the effectivity and the range of application of these series-45 mixers have been ranging from polymers, petrochemicals, paper & pulp industries, and hydrocarbon refining systems. The relation between the average drop size with residence time has been investigated in Lightnin inline mixing elements. It has been found that the equilibrium drop size agrees well with the Kolmogoroff's theory for drop capture in turbulent flows [17]. Out of the 30 different types of mixers which have been cited in the cited literature [2], extensive research work has been done on the design evaluations for each newly designed mixer. The present two types of mixers designs (mixers with spherical and mixers with pyramidal protrusions) in terms of efficient mixing have been discussed in the present manuscript. The quality of these designs is the modifications that have been made inside the surface contours of these mixers (spherical and pyramidal protrusions). The effectivity of these modifications have been tested with both the static and dynamic tests in which the central annular channel for the hot water has been kept stationary as well as put into rotation with certain rpm (60-180). Such modifications, could be proved very useful for a number of engineering applications like the bitumen treatment where the density of the bitumen and water is comparable. Such type of investigations which could mock up the real conditions and tests the effectivity of the said systems just based on the surface modifications, for the improvement in the performance of the mixers have never been tested before, nor cited elsewhere in literature as best known to the authors of the present manuscript. Thus by finding the research gap, the issue has been addressed using the experimental study which has been discussed in details in the present manuscript. The details of experimental setup and experiments being performed, with the outcomes, have been presented and discussed in detail in the following sections.

2. Experimental Setup

The experimental setup is comprised of a mixer as shown in Fig. 1. Two major types of mixer designs have been discussed here. First; mixers with spherical protrusions and second mixers with pyramidal protrusions (as shown in Fig. 1). There is a total of 8 mixers (4 for each type) have been tested in the current project to investigate the thermal performance of the said designed mixers. The complete experimental plan has been shown in Table-01. The experimental setup is comprised of a mixer which has a solid rod at its center. The length of the static mixer is 60cm with the diameter of the solid rod placed at the center is 10cm. The thickness of the first annular channel above the sold rod is 2cm for the flow channel of the hot water. The thickness of the 2nd annular slot flow channel is 3cm with the 2cm is the main annular flow channel for the flow of the cold water and 1-0.5 cm is the range of the thickness of the channel in which spherical and pyramidal protrusions exist. In each type of the said mixer, the first cylinder around this solid cylinder has pyramidal and spherical shape (dome) protrusions on its surface with each type of surface protrusion has 4 holes inside it. The holes inside these spherical shape protrusions have been screwed through the dome at a varying angle from the axial axis of each spherical protrusion. These angles have been varied from 90 degrees to 60 degrees and then till 30 degrees as shown in Fig. 1. It should be noted that in case of 60 and 30-degree angles for the location of these holes inside the spherical protrusions, there are 4 holes made in all 4 directions in each spherical protrusion whereas, in

case of a 90-degree angle, 4 holes adjacent to each other in a square configuration have been made exactly at the top of the dome (spherical protrusion). The top angle traversed in each of the pyramidal shape protrusion has been varied from 30 degrees to 45 degrees and then further up till 60 degrees as shown in Fig. 1.

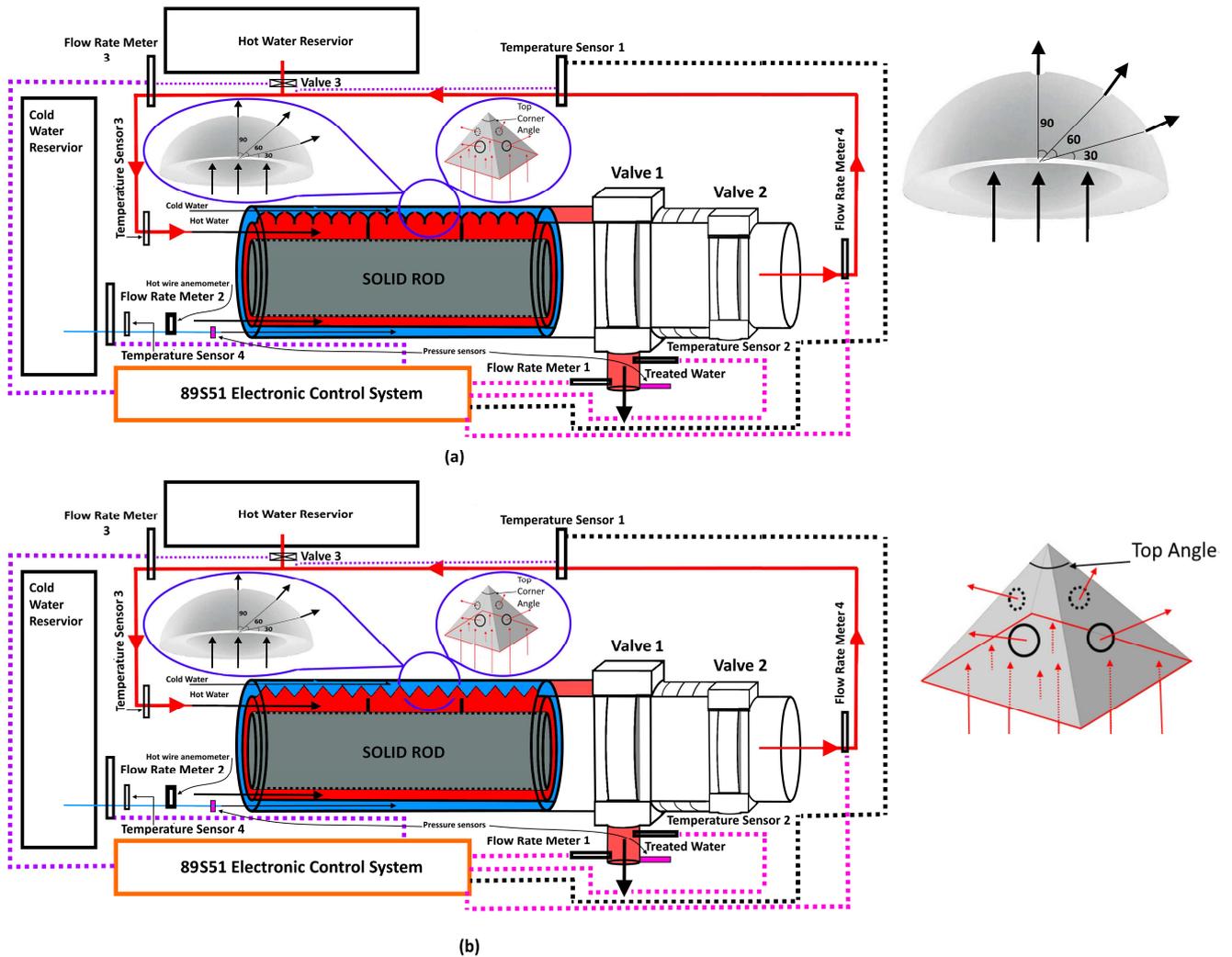


Fig. 1. (a) Mixer with spherical protrusions (b) Mixers with pyramidal protrusions.

In pyramidal protrusions, each protrusion has 4 holes inside it, which are made on each side of the pyramid. So in each type of these static mixers, a single central cylinder with either spherical shape or pyramidal shape protrusions on its outer surface lying towards the second annular channel. We have a total of 8 mixers varied in shape, angle of hole's locations in the spherical and angle traversed at top corner in pyramidal protrusions inside the central cylinder. The experimental setup has two annular regions around the solid rod, with the first annular region is just above the solid rod is the flow channel for the hot water and the second annular flow channel exists between the outermost enclosure and the central cylinder with having protrusions at its outer surface. The hot water at constant temperature has been injected inside the first annular region just above the solid rod with a varying mass flow rate of $1 \text{ kg/m}^3\text{-sec}$ to $5 \text{ kg/m}^3\text{-sec}$, whereas the annular region between the outer most enclosure and the central cylinder with protrusions have been injected with cold water at a flow rate varying from $1 \text{ kg/m}^3\text{-sec}$ to $5 \text{ kg/m}^3\text{-sec}$. Hot water has been injected at a temperature of 60°C and cold water has been injected at 20°C . The treated water has been collected using a "valve 1" diverting the mixture of cold and hot water in a downward direction, whereas the mass flow rate meter 1 and temperature sensor 2 has been installed at this end to control and monitor the temperature and flow rate at this outlet port. The hot water inside the first annular region will not be mixed with the cold water in the conditions when the flow rate of the hot water is less than the mass flow rate of the cold water. In such conditions, the temperature of the hot water inside the first annular channel will be reduced due to the mixing of the cold water from the annular channel 2. So instead of mixing of both hot and cold water inside the annular channel 2, this mixing will take place inside the annular channel 1. The temperature of the hot water will be regulated by injecting it back into the loop pipe through valve 2, which is flowing through the pipe has its joint with the hot water reservoir connection (showing by the joint with the hot water reservoir at the top of each Fig. in Fig. 1). Thus by using the hot water from the hot water reservoir, the temperature and the flow rate has been regulated using the mass flow rate meter 3, mass flow rate meter 4, the

temperature sensor 1 and valve 3 electronically. In order to get rid of this circulation, a provision has been provided through which a positive pressure gradient always be kept between these two annular channel flowing fluids by controlling the valve 2 electronically. This provision shuts the valve 2 in such a way that the hot water inside the first annular channel containing the hot water always injected inside the annular channel 2 through the holes inside the protrusions. Due to this provision, hot water mixing inside the 2nd annular channel (containing the cold water) has been made possible on a permanent basis.

Table 1. Experimental Plan outlook

Serial No:	Experimental Phase	Types of Mixer	Operating Conditions
01	Experimental Phase-01	Spherical protrusions with 90 degree opening	$M_{\text{hot-water}} = 5 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 1 \text{ kg/m}^3\text{-sec}$
02	Experimental Phase-02	Spherical protrusions with 60 degree opening	$M_{\text{hot-water}} = 3 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 3 \text{ kg/m}^3\text{-sec}$
03	Experimental Phase-03	Spherical protrusions with 30 degree opening	$M_{\text{hot-water}} = 1 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 5 \text{ kg/m}^3\text{-sec}$
04	Experimental Phase-04	Pyramidal protrusions with 30 degree top corner angle	$M_{\text{hot-water}} = 5 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 1 \text{ kg/m}^3\text{-sec}$
05	Experimental Phase-05	Pyramidal protrusions with 45 degree top corner angle	$M_{\text{hot-water}} = 3 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 3 \text{ kg/m}^3\text{-sec}$
06	Experimental Phase-06	Pyramidal protrusions with 60 degree top corner angle	$M_{\text{hot-water}} = 1 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 5 \text{ kg/m}^3\text{-sec}$
07	Experimental Phase-07	Spherical protrusions with 90-30 degree opening and rotated at a rotational speed of 60-180 rpm.	$M_{\text{hot-water}} = 1 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 5 \text{ kg/m}^3\text{-sec}$
08	Experimental Phase-08	Pyramidal protrusions with 90-30 degree opening and rotated at a rotational speed of 60-180 rpm.	$M_{\text{hot-water}} = 1 \text{ kg/m}^3\text{-sec}$, $M_{\text{cold-water}} = 5 \text{ kg/m}^3\text{-sec}$

It should be noted that the flow rate and the temperature have been monitored after valve 2 at the flow line for the hot water using the mass flow rate meter 4 and temperature sensor 1. Similarly, the mass flow rate of the cold water injection line has been monitored using the mass flow rate meter 2. The flow rate and temperature of the hot water after the injection of water from hot water reservoir has been monitored using the mass flow rate meter 3 and temperature sensor 3. In case of any loss in mass flow rate in hot and cold water lines, and loss of temperature in hot water line has been transmitted as a signal to the 89S51 microcontroller-based electronic control system, which regulates the flow rate of the cold and hot water electronically by increasing and decreasing the mass flow rate and hence temperature of the hot water in accordance with the situation. The four temperature sensors and 4 flow rate meter sensors have been operated and controlled independently using the 89S51 electronic control system. These sensors have been controlled through routines in micro-controller for controlling their operation. Their response has been judged by embedded code in microcontroller and their operations have been controlled after examining their response against the set criteria given as input into the electronic control system using user interface. The discussion on the drawn results has been presented in the following sections.

3. Results and Discussion

In the current research project, the thermal performance of a series of newly designed mixers has been investigated. The main theme is to investigate the effectiveness of the designed mixers for the turbulent mixing of the two miscible fluids i.e. two streams of water at different temperatures in terms of rate of heat transfer among them. The relation for the Reynold number calculation has been given by Eq. (1). as follows:

$$\text{Re} = \frac{\rho_f U_f L}{\mu} \quad (1)$$

In Eq. (1)., L is the length of the channel, which is equal to 60cm, ρ_f is the density of the cold water at the inlet at 20°C is equal to 998.2 kg/m³, U_f is the average velocity of the cold water at the inlet which has been measured using Hotwire anemometer [19] is equal to ~15.6-16 m/sec. μ is the dynamic viscosity which at 20°C is equal to 1.002×10^{-4} Pa.s. From Eq. (1)., the flow proved to be turbulent with $\text{Re} \sim 10.4\text{-}10.7 \times 10^6$. In addition to it, a physical inference that can be drawn related to this turbulent flow inside the channel 2. As the protrusions over the surface of the cylinder around the solid rod, have their faces towards the annular channel in which cold water is flowing. By considering a forced flow of the cold water inside the annular channel 2, the interaction of the cold water with the body of the protrusions resulted in the generation of eddies that will not leave the flow laminar. In addition to it, when the cold water flow has interacted with the hot water in an almost nearly perpendicular orientation, where the hot water has been injected through the holes in both type of protrusions, it will turn the flow into a more chaotic flow. Superimposed on this picture, further chaos will be induced by the perpendicular rotational movement of the protrusions which cast more disturbances inside the cold water flowing channel. Thus based on the physical inference, we can safely claim that the

flow inside the cold water channel will be turbulent. Pressure drop across this experimental setup has been measured from the mass flow rate meters 2 (for cold water) & 1 (for mixture of cold and hot water). The pressure drop ΔP has been dropped to around ~94% of the inlet pressure (for spherical protrusions) till ~96% of the inlet pressure (for pyramidal protrusions) (i.e. from ~0.94 to ~0.96 bars of gauge pressure) for the mass flow rate of 1 kg/m³-sec. For the mass flow rate of 3 kg/m³-sec, the pressure drop drops from 98% (spherical protrusion mixers) to 99% (pyramidal protrusion mixers) (i.e. from ~2.94 to ~2.97 bars of gauge pressure). For the mass flow rate of 5 kg/m³-sec, the pressure drop varies from 98% (spherical protrusions mixers) till 99.3% (pyramidal protrusions mixers) (i.e. from ~4.9 to ~4.975 bars of gauge pressure).

The whole system has been operated in a controlled environment which means that at a certain flow rate which has been retained using valves, i.e. valve 1, 2 & 3, whereas these valves have been controlled electronically using 89S51 Micro-controller system. The purpose of electronically controlled fluid mixing using these three valves is to keep a certain pressure inside the annular region filled with hot water in order to avoid the circulation as described before. Hot water will be mixed with the cold water under the effect of pressure exerted on it through a reduced mass flow rate of the valve 2, which helped us to retain a certain amount of pressure inside the mixing annular channel.

The setup comprised of 4 temperature sensors and 4 mass flow rate meters with three valves, whereas all these have been controlled electronically in almost an automatic configuration for estimating the extent of mixing using the electronic control system. The whole system is enclosed in the stainless steel enclosures i.e. cylinder with protrusions and outer cylinder, so due to the pressure under the effect of which the injection of hot water inside the cold water has been made possible, concerns related to the personal safety issues are inevitable. Whereas the setup itself is made from stainless steel, so the in-situ analysis is not possible. In addition to it, it is a continuous process involves pressure inside the annular channels which has been controlled by the temperature sensors, the mass flow rate meters and valves. Thus the only parameter that can ascertain the extent of mixing is the temperature of the water which has been collected from the outlet. We are not claiming that this setup is capable of perfect mixing, rather research has been done on the impact of the surface protrusions with and without rotation on the extent of mixing. The results drawn from these investigations have been presented as follows.

3.1. Effect of mass flow rates and angle of the holes on spherical protrusion mixers

The thermal performance of the newly designed mixers for the turbulent mixing of the two streams of hot and cold water has been investigated using specially designed mixers as shown in Fig. 1. In the 1st, 2nd and 3rd phases of experimentation, the variations in the rate of heat transfer have been measured with the help of the temperature differences using temperature sensor 2, 3 & temperature sensor 4 and mass flow rate meter 1, 2 and 3. It should be noted that LM35 temperature sensors have been used to measure the temperature at the specified positions as shown in Fig. 1. LM35 temperature sensors are precision temperature sensors having an accuracy of around 0.5°C at 25°C and having an operating temperature in the range of -55^o-150^oC and scale factor of 10 mV/^oC [24]. Mass flow rate meters have been used which have an operating range from 0.16-64 kg/m³-sec, with maximum error in flow rate up to 0.5% and on repeatability 0.1% [25]. The error bar that is based on the sensors own error in measurements and due to the repeatability of measurements has been calculated for each operating condition which is ~0.2-0.21 k-Watt, it has been shown by the top bracket on each bar. The relation used for the measurement of variations in the rate of heat transfer based on the mass flow rate and the temperature is given by Eq. (2):

$$Q = MC_p (T_i - T_o) \quad (2)$$

whereas:

T_i = Temperature measured from temperature sensor 4.

T_o = Temperature measured from temperature sensor 2.

M = Average of the mass flow rates measured by mass flow rate meter 2 and 3.

C_p = Specific heat of water = 4148 J/kg-K

The variations of the rate of heat transfer with variations in the mass flow rates of the hot and cold water inside the mixers having spherical protrusions are shown in Fig. 2.

It has been observed that with an increase in the mass flow rate of cold water from 1 kg/m³-sec to 3 kg/m³-sec, at hole angles of 90, 60 and 30 degrees, the rate of heat transfer has been raised from 8-17% at first, but then with a further increase up till 5 kg/m³-sec, the rate of heat transfer reduced to 4-6%. It should be noted that the decrease in the rate of heat transfer with an increase of mass flow rate of cold water to 5 kg/m³-sec (at mass flow rate of hot water equal to 5 kg/m³-sec) has been recorded when we compare the rate of heat transfer observed by each of the 3rd bar in comparison with the 2nd bar in the first patch of 3 bars on the top left side of Fig. 2. It's not depicting any increase as compared to the first bar in these 3 bars patch actually, as obviously in comparison with the first bar in the first patch of 3 bars on the left-hand side in Fig. 2, the overall rate of heat transfer increases. A possible reason for the initial increase and then decrease in the rate of heat transfer may be due to a considerable positive pressure gradient which is acting on the hot water at a mass flow rate of 5 kg/m³-sec and cold water at a mass flow rate of 3 kg/m³-sec. The pressure difference may be optimum for the present condition if keeping in view the holes orientation and the nature of the protrusions. Yet at

similar mass flow rates i.e. 5 kg/m³-sec each for hot and cold water, there is still a positive pressure gradient of ~0.5-0.7 bars which have been maintained via controlled flow through valve 2, but still may be a mass flow rate of 3 kg/m³-sec of cold water and 5 kg/m³-sec of hot water, these conditions have been proved as optimum condition for better mixing. It should be noted that the extent of mixing performance has been examined by the reading of the temperature sensor-2. Our criteria for the better mixing is to get the water at the temperature ~40°C±2°C. So at the operating conditions i.e. varying flow rates of the hot and cold water have been adjusted by the 89S51 Electronic Control System using this criteria. When the mixture of hot and cold water achieve this criteria, we starts collecting mixture of hot and cold water at these temperature ranges. On the basis of the angle of the holes in the spherical protrusions, under the effect of an increase in the mass flow rate of the cold water, the rate of heat transfer has the highest value at 60 degrees, but at 30 and 90 degrees, the rate of heat transfer is not so much considerable. A similar effect has been observed under the effect of an increase in the mass flow rate of the hot water from 1 kg/m³-sec to 3 kg/m³-sec, at 60 degrees of hole location in each spherical protrusion. Whereas, in the case of the 30 and 90 degrees of angles inside the spherical protrusions, the rate of heat transfer is not so much considerable. A possible reason for an increase in the rate of heat transfer at 60 degrees may be an increase in the rate of the dissipation of the energy of the hot water inside the main volume of cold water as compared to the dissipation of energy of the hot water at the inner walls of the inner cylinder body and the bodies of the respective protrusions. On the other hand, a gradual increase in the mass flow rate of the hot water from 1 kg/m³-sec to 3 kg/m³-sec, imparts proportional effect on the rate of heat transfer as depicted by the 2nd bar in each patch of the two bars on right hand side and the 3rd bar in each patch of the 3 bar patches on left hand side.

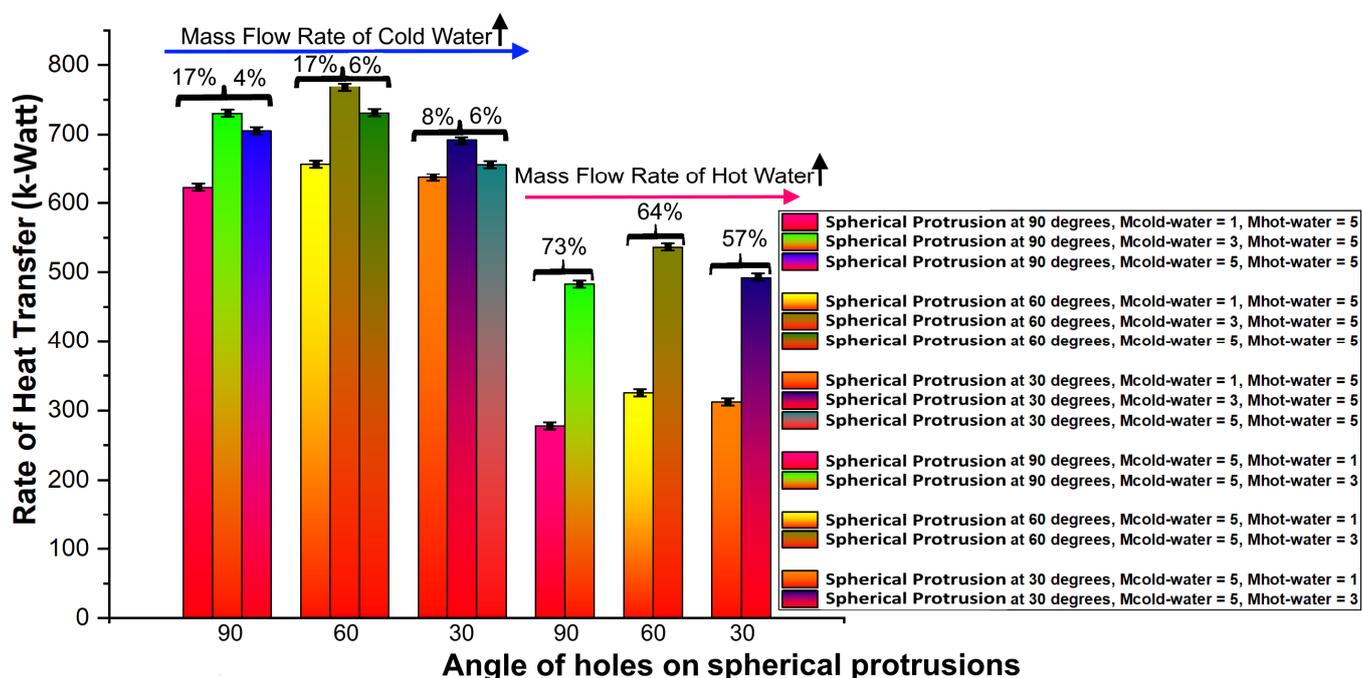


Fig. 2. Variation in rate of heat transfer with variations in mass flow rates of hot/cold water and angle of the holes on spherical protrusions

It has been observed that with an increase in the mass flow rate of the hot water from 1 kg/m³-sec to 3 kg/m³-sec, an increase in the rate of heat transfer of 57-73% has been observed whereas 32-43% increase in the rate of heat transfer has been observed when the mass flow rate of hot water has been raised from 3 kg/m³-sec to 5 kg/m³-sec.

3.2. Effect of mass flow rates and angle of the top corner angle on pyramidal protrusion mixers

In the 4th, 5th and 6th phases of the experimentation, the second type of mixers (mixers with pyramidal protrusions) have been used, whereas in these type of mixers the central cylinder has pyramidal protrusions on its outer surface. The angle traversed at the top corner of these protrusions varied from 30 to 60 degrees with a step increase of 15 degrees in each type of the mixer. Flow rates of the hot and cold water have been varied from 1 kg/m³-sec to 5kg/m³-sec with an increase of 2 kg/m³-sec in each step. The results drawn based on the above-mentioned variations in the flow rates and the shapes of the pyramidal protrusions have been shown in Fig. 3.

From Fig. 3, it has been observed that the effect of a rise in the mass flow rate of cold water imparts a positive effect on the rate of heat transfer from the hot water to the cold water. As shown by the first patch of three bars on the left-hand side, an increase of 16% has been observed in the 2nd bar as compared to the first bar which shows a positive effect imparted on the rate of heat transfer by increasing the mass flow rate of cold water from 1 kg/m³-sec to 3 kg/m³. A further rise in the mass flow rate of the water from 3 kg/m³-sec to 5 kg/m³ imparts a negative effect on the rate of heat transfer. We observed a decrease of 3% in the 3rd bar in the same patch as compared to the 2nd bar. Following the same trend in the rest of the two patches of 3 bars each, it has been observed that an increase in the mass flow rate of the cold

water from 1 kg/m³-sec to 3 kg/m³-sec in these mixers, having pyramidal protrusions with angles varying from 30 to 60 degrees, a total of 5-16% increase in the rate of heat transfer has been observed while rising the mass flow rate of cold water from 1 kg/m³-sec to 3 kg/m³-sec. Whereas, a further increase in the mass flow rate of cold water from 3 kg/m³-sec to 5 kg/m³-sec contributes to a rise in the rate of heat transfer from 3% to 5% only. Again it should be noted that the rate of heat transfer has shown an increasing trend in each 2nd bar of the first three patches on the left-hand side. This increase depicts a positive increase under the effect of an increase in the mass flow rate of cold water from 1 kg/m³-sec to 3 kg/m³-sec at a constant mass flow rate of hot water i.e. 5 kg/m³-sec. The decreasing trend in the 3rd bar in all the first 3 patches on the left-hand side depicts a decrease in comparison with each of the 2nd bar in each patch. A possible reason for the first increasing and then decreasing trend in the rate of heat transfers may be due to a considerable positive pressure gradient exerted on the hot water flowing inside the first annular channel through the valve 2, which plays a main role in proper mixing so at a mass flow rate of cold water i.e. 3 kg/m³-sec and a mass flow rate of hot water i.e. 5 kg/m³-sec appears to be optimum condition for proper mixing in the present setup. It should further be kept in mind that criteria we have for the better mixing are not to collect the water with high temperature, rather an average of the temperature of both streams of water i.e. ~40°C±2°C has been set as criteria for the better mixing.

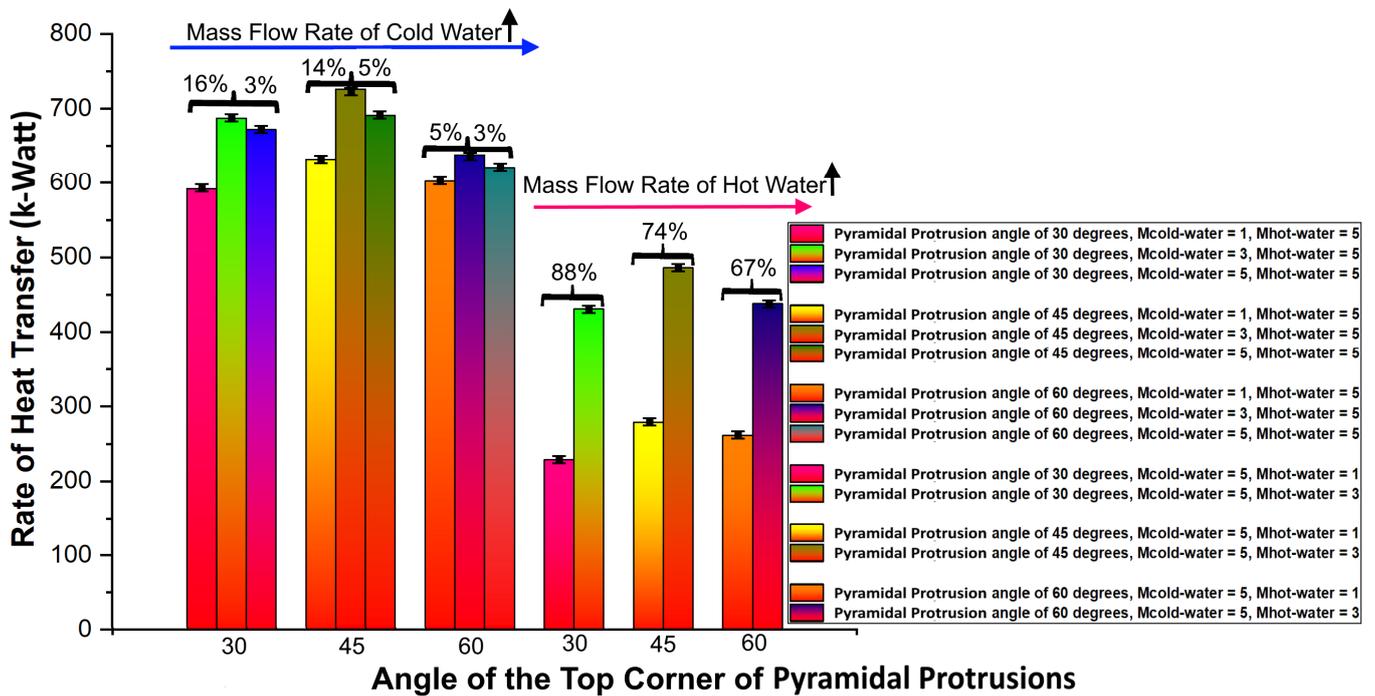


Fig. 3. Variation in rate of heat transfer with variations in mass flow rates of hot/cold water and angle of the top corner angle on pyramidal protrusions

An increase of mass flow rate of hot water from 1 kg/m³-sec to 3 kg/m³-sec against the maximum mass flow rate of cold water i.e. 5 kg/m³-sec depicts a rise in the rate of heat transfer which is ranging from 67-88%. Whereas with an increase in the mass flow rate of 3 kg/m³-sec to 5 kg/m³-sec, an increase in the rate of heat transfer ranging from 40-52% has been recorded. The effect of a rise in the angle of the pyramidal protrusions imparts an effect similar in nature as imparted by the rise in the mass flow rates of the hot and cold water in spherical protrusion mixers. With the rise in the angle of pyramidal protrusions from 30-45 degrees imparts a positive effect on the rate of heat transfer. Based on the maximum rate of heat transfer values depicted by the 2nd bar in the first three patches of bars on the left-hand side, an overall increase of 8% has been observed (comparison between 2 bar in the first patch and 2nd bar in the 2nd patch) at varying an angle from 30 to 45 degrees. A further increase in the angle from 45 to 60 degrees imparts a negative effect and a decrease of 14% has been observed (comparison of the 2nd bar in the second patch and 2nd bar in the third patch). This parabolic trend in the rate of heat transfer has been observed across the whole range of an increase in the mass flow rate of the cold water. In case of an increase in the mass flow rate of the hot water, the variation in angle from 30 to 45 first imparts a positive effect with an increase in the rate of heat transfer of 9% has been recorded, whereas a further increase in the angle from 45 to 60 degrees imparts a negative effect of around 8% on the rate of heat transfer from the hot to the cold water. A possible reason for this parabolic trend in the rate of heat transfer may be the facilitation that 45 degrees angle pyramidal protrusion offered in terms of dissipation of more energy from the hot water inside the cold water volume across the holes in pyramidal protrusions at this degree of angle (i.e. 45 degrees). Contrary to this, more energy may be dissipated within the hot water channel when the pyramidal protrusion has an angle equal to 30 degrees or 60 degrees.

3.3. Effect of mass flow rates and angle of the holes on spherical protrusion mixers with rotation

The effect of the variation in mass flow rates of the hot and cold water on the thermal performance of these mixer



has been investigated with varying angle of the location of the holes in the bodies of the spherical protrusions and with the variation of the angles of the top corner angle of the pyramidal protrusions. In the phase 7th of experimentation, the effect of the centrifugal force on the thermal performance of these newly designed mixers have been investigated. The central solid rod provides supports to the first cylinder through joints welded together at several places inside the first annular channel. The central solid rod along with the first cylinder around it that comprising the first annular channel has been rotated by rotating means using an electric motor which has been tuned at predefined rpm using a combination of transformer and regulator. Thus the first annular flow channel has been rotated at three different rpm (60-120-180) at varying the mass flow rate of the hot and cold water inside spherical protrusion surface mixers first. The results thus drawn for the spherical shape protrusion mixers is shown in Fig. 4.

From the bar chart shown in Fig.-04, It should be noted that the results have been drawn in increasing order with respect to rpm from left to right. The upward arrows showing the bar charts based on the results under the effect of increasing the mass flow rate of the cold water from 1 kg/m³-sec to 5 kg/m³-sec at a maximum mass flow rate of the hot water i.e. 5 kg/m³-sec. The downward arrows have been drawn across the bar charts based on the results under the effect of increasing the mass flow rate of the hot water from 1 kg/m³-sec to 5 kg/m³-sec at a maximum mass flow rate of the cold water i.e. 5 kg/m³-sec. It has been clear that with the increase in the rpm, the rate of heat transfer increases as well, but this trend remains dominant till 120 rpm, further increase in rpm till 180 didn't contribute too much in raising the rate of heat transfer till some appreciable values (as have been seen from the right-hand side of Fig.-04). In addition to these observations, it has also been observed that with an increase in the mass flow rate of the cold water from 1 kg/m³-sec to 5 kg/m³-sec at varying rpm (60-180) and varying angle of hole location on each of the spherical protrusions, the maximum rate of heat transfer has been observed at 60-degree angle of these holes in all conditions. A possible reason for the maximum value of heat transfer up till 120 degrees may be due to the additional energy which has been exerted in the radial direction on the hot water volume flowing inside the 1st annular channel to inject it through the central cylinder holes into the cold flowing volume of water.

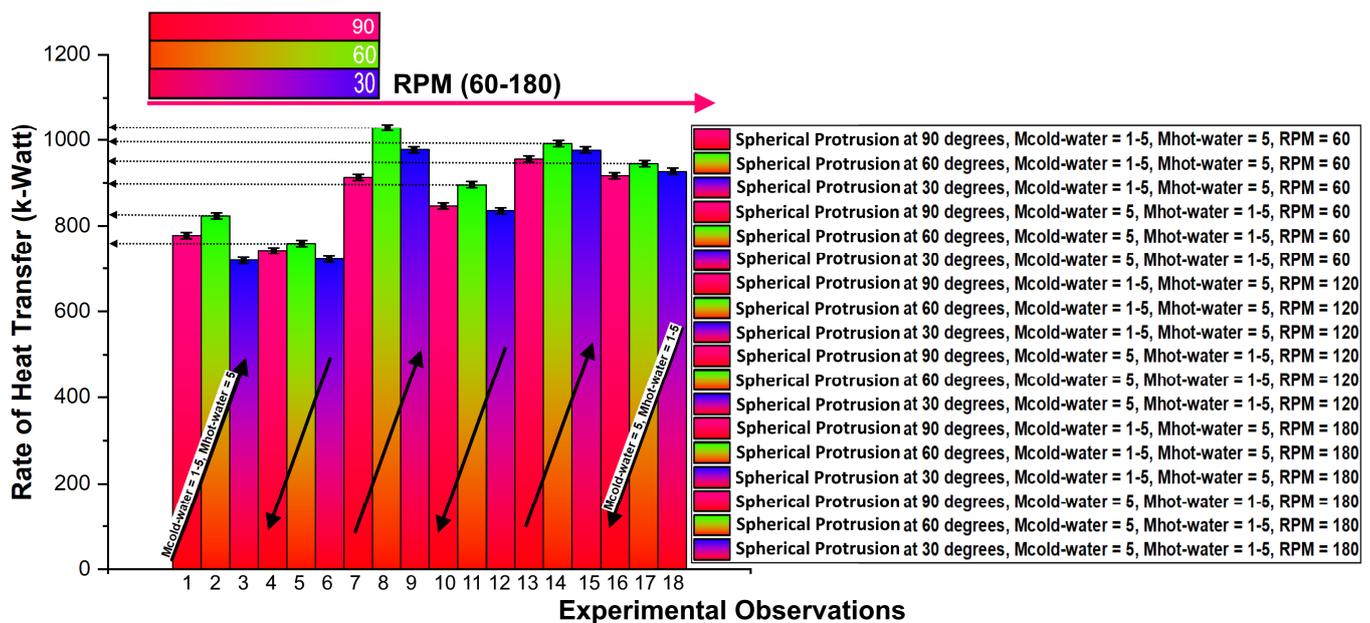


Fig. 4. Variation in rate of heat transfer with variations in mass flow rates of hot/cold water and angle of the holes on spherical protrusions with rotation

As the sizes of these holes are fixed, so at 180 degrees, there may be due to some throttling effect, the hot water may not inject inside the cold water volume through these holes, more than a limit even with increasing the rpm above 120. In line with this throttling effect, another reason supporting this observation may be the higher rate of the dissipation of the energy near the boundary walls of the inner and outer cylinder [5–8], thus even the higher rpm didn't contribute too much into an increase in the rate of heat transfer. Effect of rising in rpm from 60-120 degrees at 60 degrees of holes in spherical protrusion mixers at variation in the mass flow rate of cold water at a maximum mass flow rate of hot water has been transformed in an increase of 23% in the rate of heat transfer, whereas further increase in the angle from 120-180 degrees at same conditions imparts only an increase of 5% in the rate of heat transfer. On the other hand, under the effect of a rise in the mass flow rate of the hot water at a maximum mass flow rate of the cold water under the effect of variation of rpm from 60 to 120 imparts an effect on the rate of heat transfer up till 16%. Whereas further variation in the rpm from 120 to 180 rpm, the rate of heat transfer has been raised up till 5%.

3.4. Effect of mass flow rates and angle of the top corner on pyramidal protrusions with rotation

The effect of the variations in the rpm on the thermal performance of these designed mixers having flow channel

with pyramidal protrusions has also been investigated at varying mass flow rates of the hot and cold water at varying rpm. The results have been drawn in the form of bar charts as shown in Fig. 5.

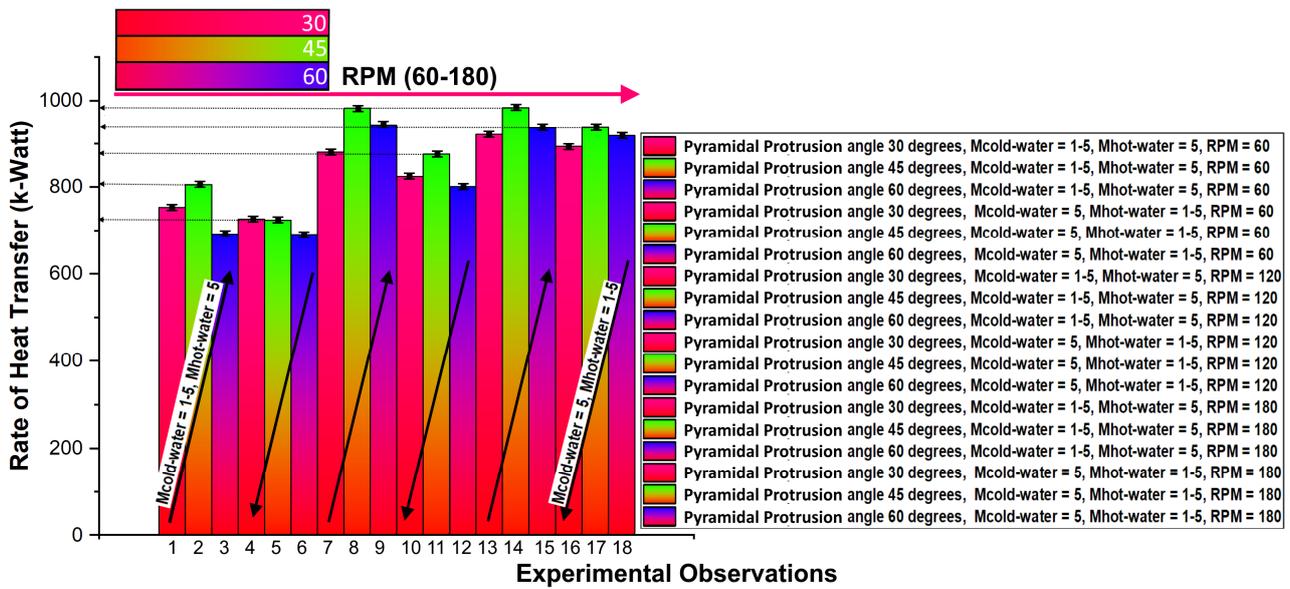


Fig. 5. Variation in rate of heat transfer with variations in mass flow rates of hot/cold water and angle of the top corner on pyramidal protrusions with rotation

From Fig. 5, it should be clear that the bar charts have been drawn with respect to an increasing order of rpm from left to right-hand side. In addition to it, the bar charts in a patch of three bars, with arrow in upward direction have shown an increase in the mass flow rate of cold water from 1 kg/m³-sec to 5 kg/m³-sec at maximum mass flow rate of the hot water i.e. 5 kg/m³-sec with varying angle of the pyramidal protrusion from 30 to 60 degrees. The patch of the 3 bars with downward directed arrow has shown the rate of heat transfer at varying mass flow rate of the hot water from 1 kg/m³-sec to 5 kg/m³-sec at maximum mass flow rate of the cold water i.e. 5 kg/m³-sec with varying angle of the pyramidal protrusion from 30 to 60 degrees. It has been observed that with an increase of mass flow rate of cold water at the maximum mass flow rate of hot water with 45 degrees of angle in each pyramidal protrusion at varying rpm from 60-120, an increase of 22% in the rate of heat transfer from the hot to the cold water has been observed. Further increase in the rpm from 120-180 at the same conditions brought no effect on the rate of heat transfer. In the case when we raise the mass flow rate of the hot water at the maximum mass flow rate of the cold water, with variation in the angle of the pyramidal protrusions from 30-45, at varying rpm from 60-120, 22% increase in the rate of heat transfer has been recorded whereas in the case of further variation in angle from 120-180 at varying rpm from 120-180, an increase of 7% has been recorded in the rate of heat transfer.

It is thus inferred from these results drawn for observing the effect of variation of the rpm, that even at smaller mass flow rate with a medium range of rpm, higher rates of heat transfer can be obtained from a specific design of mixer in industrial processes.

4. Comparison of the Thermal Performance under all Operating Conditions

In the current research project, the thermal performance of the newly designed mixers has been evaluated under different operating conditions and then the effect of the centrifugal force has been investigated on the thermal performance of these mixers. There is a total of 8 types of mixers which could be divided into two broad categories. Out of these two types, the first 4 mixers have spherical protrusions with the holes inside these protrusions. In the second category, lies those mixers which have pyramidal protrusions. Out of all the experimentation phases, as mentioned in the Table-01, there are certain operating conditions, under which higher rates of heat transfer has been observed.

In order to get an optimized view of the whole project, under all operating conditions, and their subsequent effect, the results have been plotted in the form of combined bar charts in Fig. 6. In order to find the best operating condition out of all, it has been observed that the mass flow rate of 3 kg/m³-sec for cold water, 5 kg/m³-sec for the hot water at 60 degrees of hole angle in spherical protrusions and 45 degrees of the angle in pyramidal protrusions yields the highest thermal performance in these mixers in static mode. In dynamic mode (i.e. when these mixers have been rotated with certain rpm) 120 rpm has been qualified for promising results. In addition to it, By comparing these results, we can get an optimized over-view for these mixers. It can be concluded that if we cannot exceed a mass flow rate of cold water above than 1 kg/m³-sec under certain conditions in static mode, a similar result or even better result for the thermal performance can be achieved in dynamic mode at rpm even lower than 60. Thus by comparing these results, we got an optimized pictured for the operating conditions of these newly designed mixers.

5. Concluding Discussion on Results

In the mixers used in the process industry, the dissipation of energy could be divided into two types, out of which the first type of energy is the one which has been dissipated near the inner boundary walls of the mixers and near the planes with which fluids interact, wherein the present case this purpose has been served by the spherical and pyramidal protrusions. The second type of energy which is initially contained by the mass of the hot water has been dissipated in the bulk volume of fluid i.e. cold water in the present case. The dissipation of the energy of the hot water inside the cold water volume in the present case plays an important role as it acts as a determining factor for the evaluation of the thermal performance of these newly designed mixers along with the other factors like pressure drop and extent of mixing. As the total dissipation energy has been divided into two types, so in the cases having higher thermal performance with higher values of the rate of heat transfer has more dominant second type of dissipation of energy as compared to the first type of dissipation of energy which could be observed from the results shown in Fig. 2, 3, 4 and 5. In the cases, where the high mass flow rate of the hot water didn't contribute up to a considerable limit in the value of the rate of heat transfer, in such conditions, energy dissipation near boundary walls and the surfaces of the protrusions is dominant. It has been observed unanimously that the rise in the mass flow rate of the cold water up till some limit imparts a considerable positive effect on the rate of heat transfer as shown in all results Figs. 2 to 5. Effect of the rpm and the location of the holes in spherical protrusion and angle of pyramidal protrusions have been neutralized which may be due to some throttling effect after some limiting value.

Acknowledgment

The author is thankful to the Faculty of Civil Engineering, Department for Management of Science and Technology Development, Ton Duc Thang University (TDTU), Ho Chi Minh City, Vietnam, for their support to this work.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship and publication of this article.

Funding

The author received no financial support for the research, authorship and publication of this article.

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