Analysis Of Fluid Flow And Heat Transfer Characreistics in Sharp Edge Wavy Channels With Horizontal Pitch On Both EDGES

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1 ABSTRAT

Heat transfer enhancement using a trapezoidal channel with sharp edged wavy plate has been investigated by experimental work. The experiments were done for the Reynolds number in the range of 17037.1, 19799.9, and 26246.3 by varying heat flux. The results shows that the trapezoidal plate without wavy plate enhances the average Nusselt number by 35-60% at different heat flux and Reynolds numbers, but if a wavy plate introduced then the average Nusselt number was enhanced by 40-85%

KEYWORD: Heat exchanger, Temperature Indictor, Reynolds Number, Nusselt number,fins etc.

2 INTRODUCTION TO COMPACT HEAT EXCHANGER

Enhancement of heat transfer surface has developed over the years and is the main focus in the heat exchanger industry. Enhanced surface yield higher heat transfer coefficient when compared to un-enhanced surfaces. A surface can basically be enhanced in two ways, either active enhancement which requires deployment of external power which is obviously high in operational and capital cost thus commercially unviable, and passive enhancement which involves adding extended surface (e.g. fins), or employing interrupted surface (e.g. corrugations). Compact heat exchanger can be classified in two ways, plate types or primary surface heat exchanger. The hydraulic diameters for most heat exchangers are very small and often located in the range of 1 mm to 10 mm. Some advantages are observed in compact heat exchangers compared to the traditional shell and tube heat exchanger, such as high thermo-hydraulic performance, small size and compact volume. These advantages make compact heat exchangers very attractive in various industrial applications. Compact heat exchanger has wide applications in power, process, automotive and aerospace industries. Some examples of such enhanced compact cores include louvered fin, rectangular, triangular and corrugated or wavy fins.

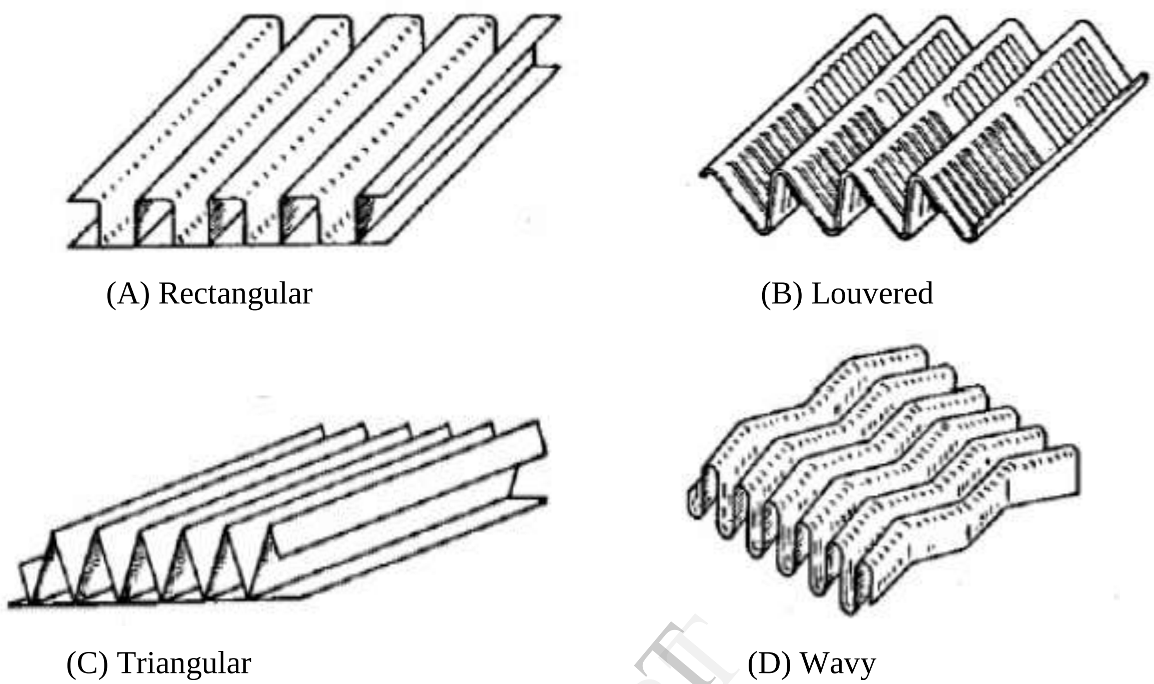


Fig. 1.Surface geometries of plate-fin exchanger: (A) plain rectangular fins, (B) louvered fins (C) Triangular fins (D) Wavy fins.

Special channel shapes, such as wavy channel in current study, which provides mixing due to secondary flows due periodic boundary layer modulation, separation or disruption. In such channels waviness causes the flow directions to change periodically. These wavy channel surfaces are particularly attractive for their simplicity of manufacturer, potential for enhanced thermal performance and easy to usage in both plate and tube type exchangers. Consequently, the boundary layer separates and reattaches periodically around the trough regions to permute enhanced heat transfer, increased pressure drop penalty is also accompanied.

3. PLATE HEAT EXCHANGER

The plate heat exchanger is widely recognized today as the most economical and efficient type of heat exchanger on the market. With its low cost, flexibility, easy maintenance, and high thermal efficiency, it is unmatched by any type of heat exchanger. The key to the plat heat exchanger's efficiency lies in its plates. With corrugation patterns that induce turbulent flows, it not only achieves unmatched efficiency, it also creates a self-cleaning effect thereby reducing fouling. The most common surface pattern used is the wavy channel design.

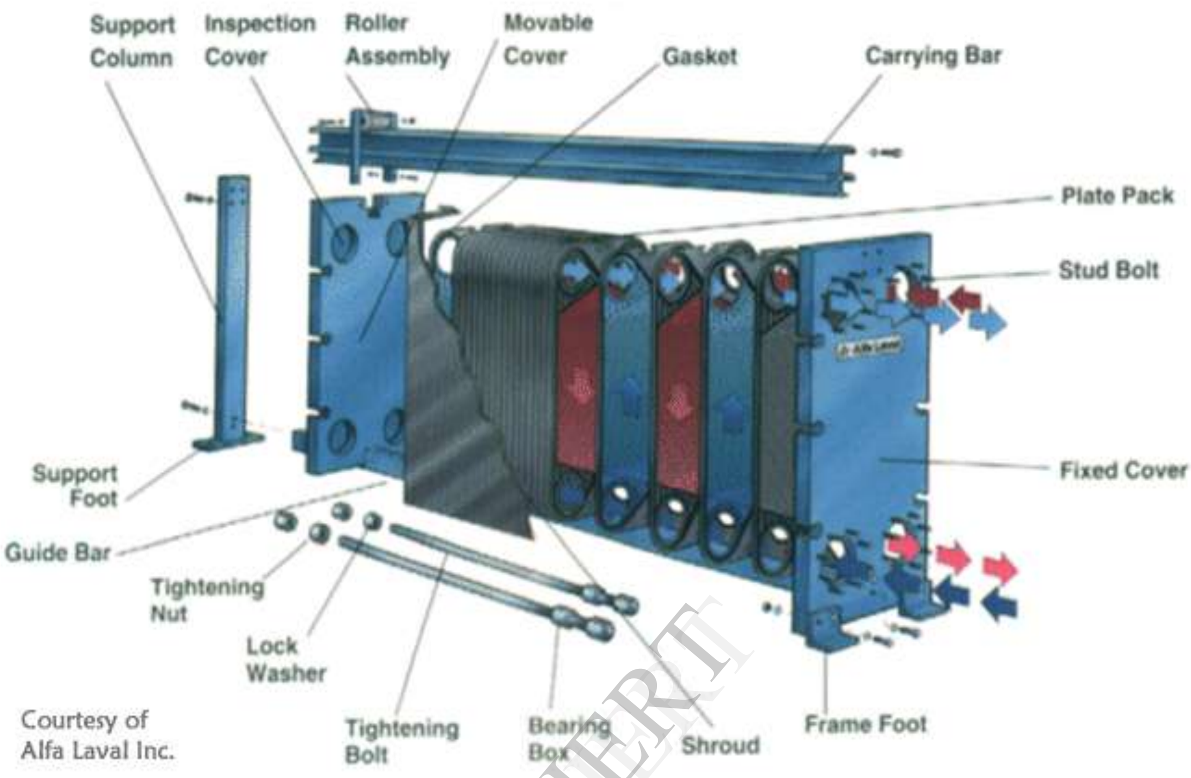


Fig.2. An exploded view of a plate heat exchanger

Heat transfer enhancement is an extremely significant issue in many engineering applications. Especially those using compact hear exchangers. Several publications have been dedicated to the study of innovative ways of increasing the heat transfer rate in compact heat exchangers. One of several devices utilized for enhancing heat and mass transfer efficiency is the symmetrical corrugated or wavy-walled channel. Of particular interest for a wide spectrum of uses in food, pharmaceutical, and chemical processing is the plate heat exchanger. The corrugation patterns on the plate surfaces essentially promote enhanced heat transfer in their interpolate channels, thus something the progress of small-approach-temperature operation with a more compact heat exchanger. The various applications considered in this work in compass wavy-plate-fin cores. And dialysis devices and membrane oxygenators.

4 Detailed Model of Experimental Setup

The experimental set up for the present study is presented in Figure 4.1. The experimental apparatus consist of a rectangular duct which was made up of plywood. The total length of the duct is 1750 mm. the apparatus consist of four parts, first part is the inlet section having length of 500 mm, width 200 mm, height 120 mm. A straightener is used in the inlet section up to a length of 200 mm to minimize the turbulence in the air and to keep a uniform air flow before entering the test section. A port is made in the top part of the inlet section for the measurement of velocity by hot wire anemometer. Second part of the duct is the test section having the overall length of 600 mm, width 200 mm, height 120 mm. Test section consist of a rectangular plate made up of aluminum , having dimension of 300x150x6 mm.

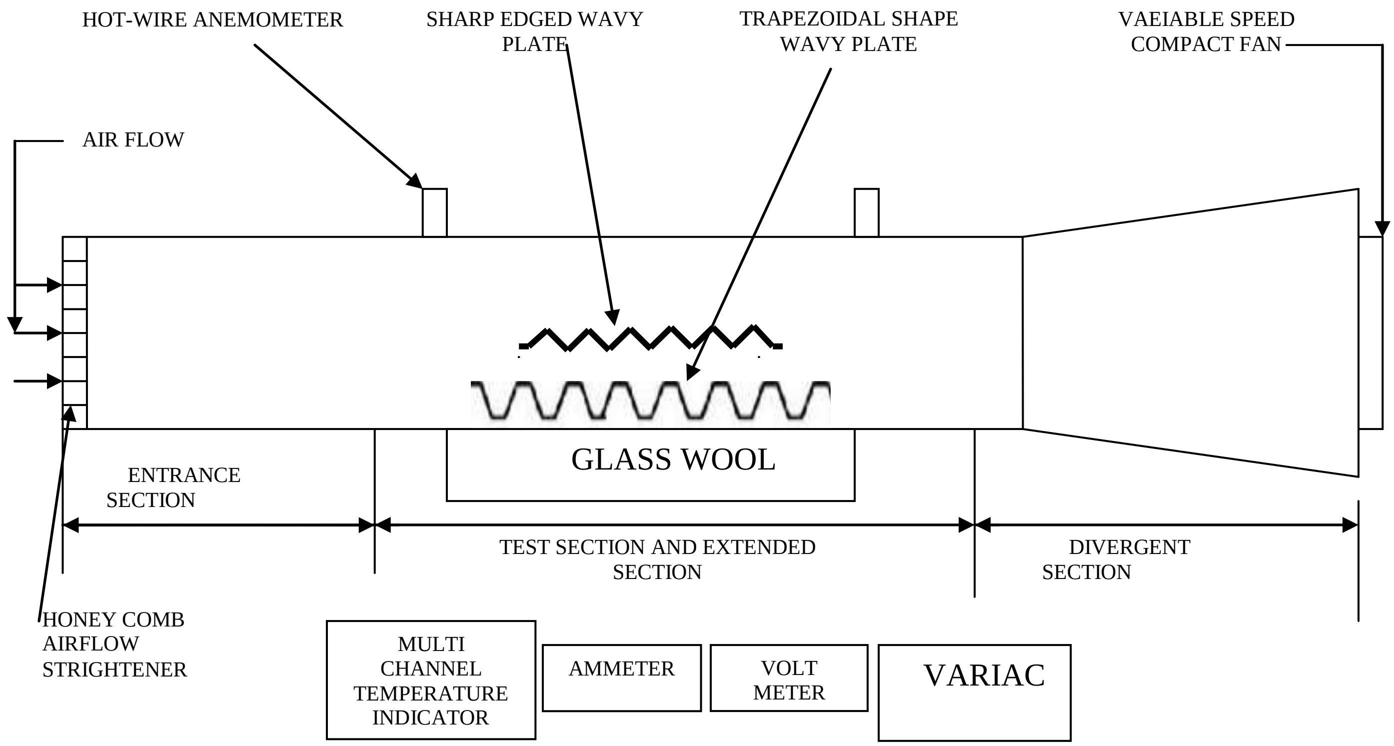


Fig.3: Schematic Diagram of Experimental Apparatus

5. LITERATURE REVIEW

The aim of present study is to enhance the heat transfer in heat exchangers. With this intent we would like to study different investigation related to the enhancement of heat transfer suitable for the application mentioned above

Stone and Vanka [1] studied developing flow and heat transfer in wavy passages. Calculations were presented for two different wavy channels, each consisting of 14 waves. It was observed that the flow was steady in part of the channel and unsteady in the rest of the channel. As the Reynolds number was progressively increased, the unsteadiness was onset at a much earlier location, leading to increased heat transfer rates. Varying the channel spacing alters the heat transfer and pressure drop characteristics, as well as the transition Reynolds number. **Rush, Newell and Jacobi [2]** experimentally investigated the local heat transfer and flow behavior for laminar and turbulent flows in sinusoidal wavy passages. Using visualization methods, the flow field was characterized as steady or unsteady, with special attention directed towards detecting the onset of macroscopic mixing in the flow. The location of the onset mixing was found to depend on the Reynolds number and channel geometry. Instabilities were manifest near the channel exit at low Reynolds number (Re = 200) and move towards the channel entrance as the Reynolds number was increased, the entire channel exhibits unsteady, macroscopic mixing at moderate Reynolds numbers (Re = 800). The onset of macroscopic mixing was directly linked to significant increase in local heat transfer. The heat transfer experiment confirmed that instabilities observed in the flow visualization experiments cause a heat transfer enhancement in the wavy channels. **Negny, Meye and Prevost [3]** studied numerically flow pattern and heat and mass transfer characteristics for a film flowing over a vertical wavy column in a laminar flow regime. In this approach, the heat and mass transfer coefficients were avoided in order to include hydrodynamics directly in the heat and mass transfer rates. As a consequence the numerical model was decomposed into two steps. Firstly, the flow pattern for a film with a free interface was developed. Secondly, heat and mass transfer were investigated with the incorporation of velocity fields. The heat and mass transfer coefficients increase in laminar flow. **Niceno and Nobile et al. [4]** investigated a two-dimensional steady and time dependent fluid flow and heat transfer through periodic, wavy channels with a prandtl number of 0.7, by means of an unstructured co-volume method. The two geometric configurations considered, a sinusoidal channel and an arc-shaped channel, was shown to provide little or no heat transfer augmentation, in comparison to a parallel-plate channel, in steady flow regimes at lower values of the Reynolds number. In addition, they both have higher pressure drop than that of the parallel-plate channel under fully developed flow conditions. For the unsteady regimes, reached at about Re =175-200 for the sinusoidal channel, and Re = 60-80 for the arc-shaped channel, both geometries exhibit a significant increase in the heat transfer rate, up to three times for the higher Reynolds number investigated. This increase was higher for the arc-shaped flow passage, but accompanied by a higher friction factor than that of the sinusoidal channel. For example for the arc-shaped channel at Re = 103, the nusselt number is Nu 13.6, a value obtained, for the sine-shaped channel, at higher Reynolds number, approximately Re = 263. it means that the arc-shaped channel provides higher increase of the heat transfer rate in unsteady flow regimes than sinusoidal channel, through with the penalty of higher friction factor. **Hossain and Islam [5]** investigated fluid flow and heat transfer in periodic, corrugated channel at unsteady flow conditions using FVM for a fluid with prandtl number 0.7, representative value for air. Periodic boundary conditions were used to attain the fully developed flow condition. Two different types of wavy geometry, sinusoidal and triangular, were considered. Effect of aspect ratio has been studied by changing the Hmin only. The flow in channel has been observed to be steady up to a critical Reynolds number. Beyond the critical Reynolds number the flow becomes unstable with a self-sustained oscillation and thereby increase heat transfer rate. For sinusoidal channel the critical Reynolds number increases with the increase of Hmin, but decrease in case of triangular channel. . **Alawadhi et al [6]** explained heat transfer enhancement using a wavy plate in a channel containing heated blocks. The blocks simulate an electronic package with a high thermal dissipation rate. The considered assembly consisting of a channel formed by two plates with heated blocks attached to both internal walls and a wavy plate installed at the centerline of the channel. The wavy plate enhances heat transfer from the blocks through the modification of the flow pattern in the channel. The effect of the Reynolds number, waviness of the plate, and blocks spacing on the nusselt number and maximum temperature of the blocks was investigated. Heat transfer enhancement of the blocks with a wavy plate was evaluated by comparing their thermal characteristics to blocks with a zero waviness plate. The results show that the wavy plate enhances heat flow out of the blocks and reduces their temperature up to 23%. The temperature of the blocks decreases when increases the waviness of the wavy plate and Reynolds number. **Bahaidarah and Anand [7]** numerically investigated a two-dimensional steady developing fluid flow and heat transfer through periodic wavy passage and compared to flow through a corresponding straight channel. In this work, sinusoidal and arc-shaped configurations were studied for a range of geometric parameters. The effects of the Reynolds number (Re), length ratio (L/a), and height ratio (Hmin/Hmax) on the developing velocity profiles, streamlines, isotherm, pressure drops, and Nusselt number were examined. At low Reynolds number, the two geometric configurations showed little or no heat transfer augmentation in comparison with a straight channel. In some cases heat transfer enhancement ratio were as high as 80% at higher Reynolds number. The recirculation flow covers the smaller portion of the domain at lower Re values, and it completely covers the concave area at higher Reynolds numbers. An increase either in the height ratio or length ratio for both configurations resulted in a decrease in the recirculation size and strength. **Bahaidarah et al [8]** studied numerically a two-dimensional developing fluid flow and heat transfer through a periodic wavy channel with staggered walls and compared flow through the corresponding wavy channel with non-staggered walls. The lower wall was displaced relative to the upper wall by one-fourth, one-half, and three-fourths of the total one-module length. In this work, sinusoidal and arc-shaped configurations were studied for a fixed set of geometric parameters. Sinusoidal channel with one-half displacement provide lower normalized pressure drop value when compared to all other channels (staggered and non-staggered) considered in this study. The module average nusselt number increases monotonically with Reynolds number, moreover, the heat transfer enhancement ratio for arc-shaped channels with three-fourth displacement was as high as 5.7%. **Naphon and Kirati [9]** analysed on the heat transfer and flow developments in the channel one side corrugated plate under constant heat flux conditions. The corrugated plate with the corrugated tile angels of 40 is simulated with the channel height of 7.5 mm. the flow and heat transfer development were simulated by the k-є standard turbulent model. A finite volume method with the structured uniform grid system was employed for solving the model. Effects of relevant parameters on the heat transfer and flow developments were considered. Breaking and destabilizing in the thermal boundary layer were promoted as fluid flowing through the corrugated surface. Therefore, the corrugated surface has significant effect on the enhancement of heat transfer. **Guzman, Cardenas, Urzua and Araya [10]** investigated enhancement characteristics of heat transfer, through a transition scenario of flow bifurcations, in asymmetric wavy wall channels by direct numerical simulations of the mass, momentum and energy equations, using the spectral element method. The heat transfer characteristics, flow bifurcation and transition scenarios were determined by increasing the Reynolds numbers for three geometrical aspect ratios $r = 0.25$, 0.375, and 0.5, and Prandtl numbers 1.0 and 9.4. The transition scenarios to transitional flow regimes depend on the aspect ratio. For the aspect ratios $r = 0.25$ and 0.5, the transition scenario was characterized by one Hopf flow bifurcation. For the aspect ratio $r = 0.375$, the transition scenario was characterized by a first Hopf flow bifurcation from a laminar to a periodic flow, and a second Hopf flow bifurcation from a periodic to quasi-periodic flow. The periodic and quasi-periodic flows were characterized by fundamental frequencies ω_1, and ω_1 and ω_2, respectively. For all the aspect ratios and Prandtl numbers, the time-average mean Nusselt number and heat transfer enhancement increased with the Reynolds number as the flow evolves from a laminar to a transitional regime. For both Prandtl numbers, the highest increase in the Nusselt number occurs for the aspect ratio $r = 0.5$; whereas, the lowest increases happen to $r = 0.25$... Significant heat transfer enhancements were obtained when the asymmetric wavy channel was operated in the appropriate transitional Reynolds number range **Bahaidarah et al. [11]** studied numerically a two-dimensional steady developing fluid flow and heat transfer through a periodic wavy passage (sharp edge-shaped configurations) for a fluid of prandlt number 0.7, with and without horizontal pitch. In this work four different types of wavy geometry, triangular without horizontal pitch (l/L = 0) and triangular horizontal pitch (l/L = 0.1, ¼, and ½) were considered. Triangular wavy channel without horizontal pitch (l/L = 0) provide lower normalized pressure drop values when compared to triangular wavy channel with horizontal pitch and it keep increasing as the (l/L) increases. The module average nusselt number increases monotonically with Reynolds number increases. However, it shows lower profile in case of triangular wavy channel with horizontal pitch, and it keeping decreasing as the (l/L) increases, when compared to triangular wavy channel without horizontal pitch. **Castelloes**, **Quaresma and Cotta [12]** studied convective heat transfer enhancement in low Reynolds number flows and channel with wall corrugation and the corresponding thermal exchange intensification achieved. The proposed model involves axial heat diffusion along the fluid and adiabatic regions both upstream and downstream to the corrugated heat transfer section, in light of the lower values of Reynolds numbers that can be encountered in this work. A hybrid numerical-analytical solution methodology for the energy equation was proposed, based on the Generalized Integral Transform Technique (GITT) in partial transformation mode for a transient formulation. The hybrid approach was first demonstrated for the case of a smooth parallel-plates channels situation, and the importance of axial heat conduction along the fluid is then illustrated. Heat transfer enhancement was analyzed in terms of the local Nusselt number and dimensionless bulk temperature along the heat transfer section. An illustrative sinusoidal corrugation shape was adopted and the influence of Reynolds number and corrugation geometric parameters was then discussed. *The above literature survey shows that the numerous experimental and theoretical studies have been done to enhance heat transfer in the wavy channels; however there is still a room to discus.*

6 RESULT AND DISCUSSION

6.1 Introduction

In this experimental study the observations were carried out in an open type wind tunnel of cross-section 200×120mm and length 1750mm for various test specimens (configurations). The test specimens were placed in a test section one by one to analyze the heat transfer enhancement under various heat flux and flow conditions and then observations were carried out by varying the heat flux i.e. (10.88, 25, 44.16, 68.8watt) and Reynolds number (17037.1, 19799.9, and 26246.3) for plane plate. After completing over plane plate it was replaced by the trapezoidal plate having 11mm grooves on 17 mm plane plate (Aluminium). The observations regarding heat transfer and pressure drop were carried out over trapezoidal plate on same conditions of heat flux and Reynolds number. And then a sharp edged wavy plate was placed over trapezoidal plate in centre at 15mm height. The variation in the heat transfer characteristics is compared with all type of channel configurations that were studied in this chapter.

6.2 Validation of Plane Plate

Experimental results for the plane plate have been made by placing it in the test section of open type wind tunnel. From fig 6.2 it has been observed that the Nusselt number increases with increase in Reynolds number. It is also clear from fig 6.1 the variation of Nusselt number obtained from the present work with the correlation i.e. $\mathbf{Nu=0.036Re^{0.8}\,Pr^{0.333}}$ recommended by the Nusselt himself for turbulent flow through non circular pipes. The experimental results agree well within ±15% for Nusselt number with plane plate.

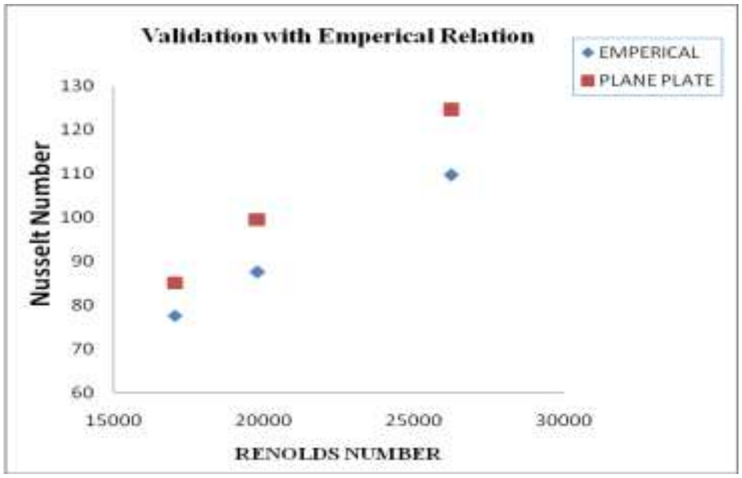
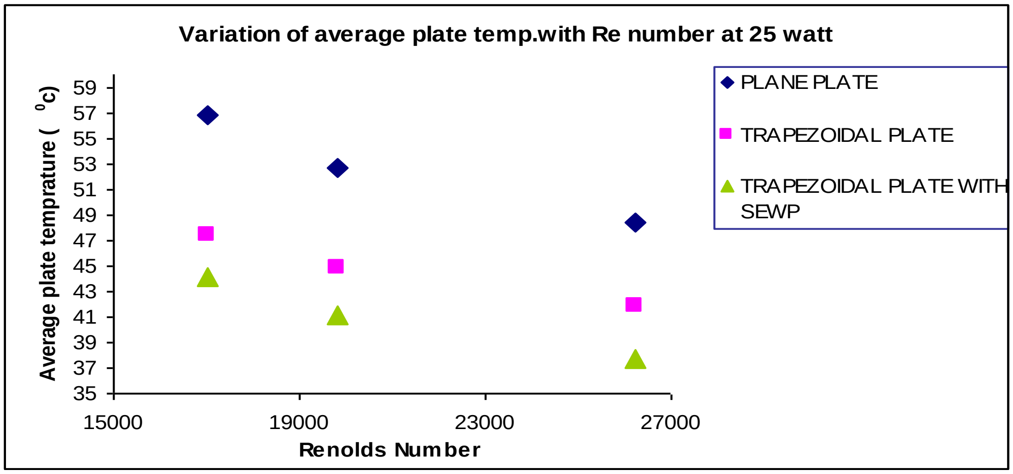
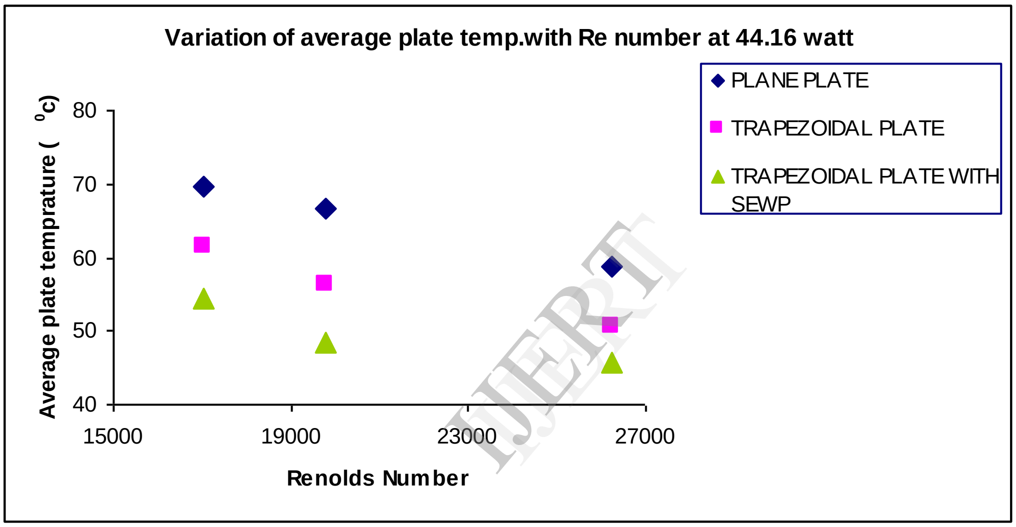


Fig 6.2 Validation of Nu with Re for Plane Plate

6.3 Variation of Average Plate Temperature with Reynolds Number at Different Heat Flux

Fig 6.3 (a-d) shows the variation of average plate temperature with Reynolds number, at different heat flux conditions and it also shows the comparison of average plate temperature between plane plate, trapezoidal plate and trapezoidal plate with sharp edged wavy plate. From fig 6.3 (a-d) it has been observed, that as the heat flux is increased, the average plate temperture increases for all the three cases, this is due to the increase in power dissipation with increase of heat flux. From fig 6.3 (a-d) it is observed at particular heat flux and Reynolds number the average plate temperature for trapezoidal plate is lower as compare to plane plate. But if we introduced a sharp edged wavy plate over trapezoidal plate then the average plate temprature of that channel will be lowest then other two cases shown in fig 6.3 (a-d). Due to the presence of wavy surface causes disturbance, induced breaking and destabilizing, recirculation, swirl flow as air flows through such surfaces in the main flow and hence the thinning of thermal boundary layer which leads to the enhancement in cooling of the plate and decreases the average plate temperature. It is clear from fig 6.3 that the average plate temperature decreases with increase in Reynolds number in all three cases,due to cooling effect produced by the increase mass flow rate of air.





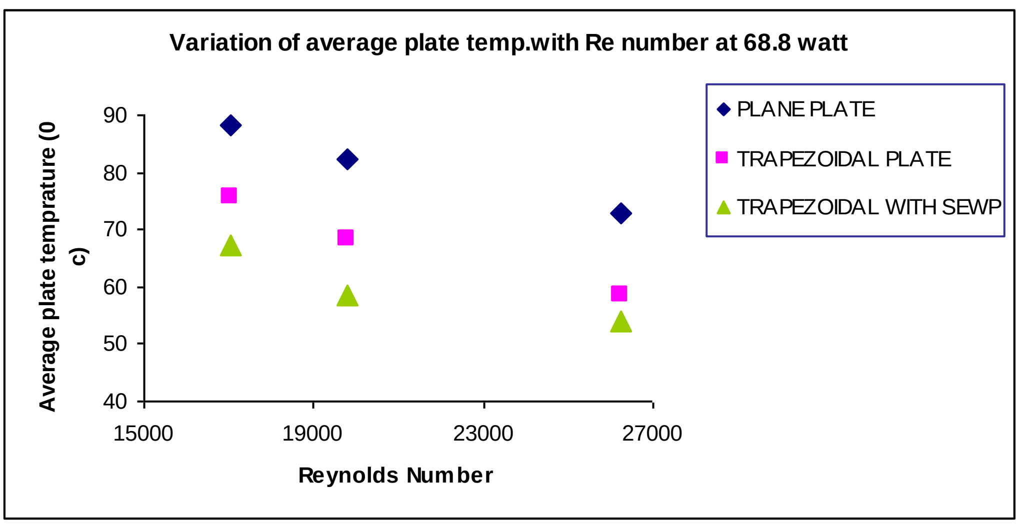


Fig 6.3 (a-d) Variation of Average Plate Temperature with Re for different heat flux

6.4 Variation of Outlet Air Temperature with Reynolds Number at Different Heat Flux and

Fig 6.4(a-d) shows the variation of outlet air temperature with Reynolds number at different heat flux and comparison between three cases also discussed in the given fig. In fig 6.4 it is observed that the outlet air temperature decreases with increase in Reynolds number due, to the turbulence and recirculation effect are permitted in the air flow with increase of Reynolds number. In the fig it is clear that the outlet air temperature for trapezoidal plate is more than plane plate, but for trapezoidal plate with SEWP outlet air temperature is highest than in other two cases. Due to the presence of turbulence in such channels causes, re-circulation as air flows through such surfaces in the main flow and hence leads to the enhancement in heat transfer rate and increases the surface temperature of plate. As the heat flux increases the outlet air temperature increases for particular Reynolds number, because with increase in heat flux the surface temperature of plate further increases which rises the outlet temperature of air.

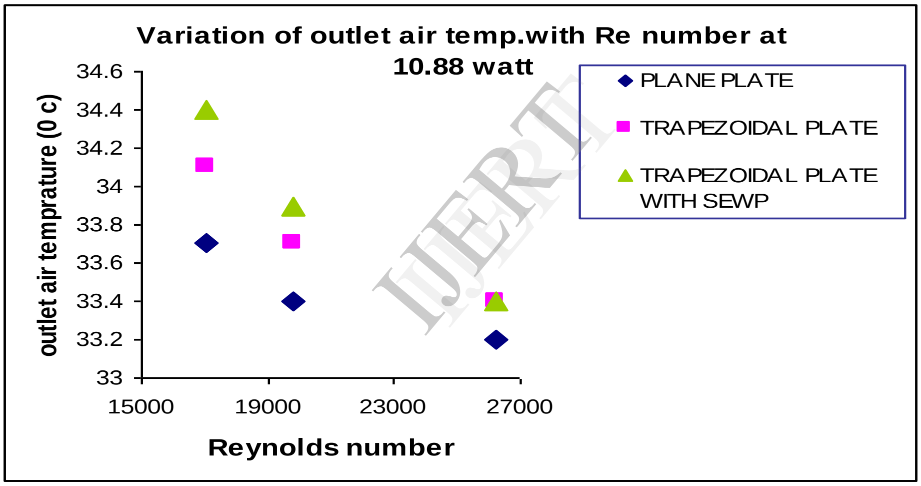
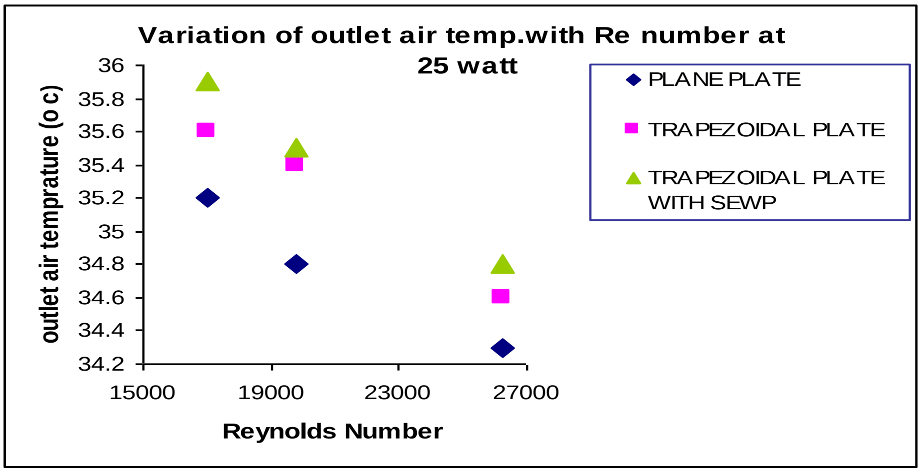


Fig 6.4 (a)



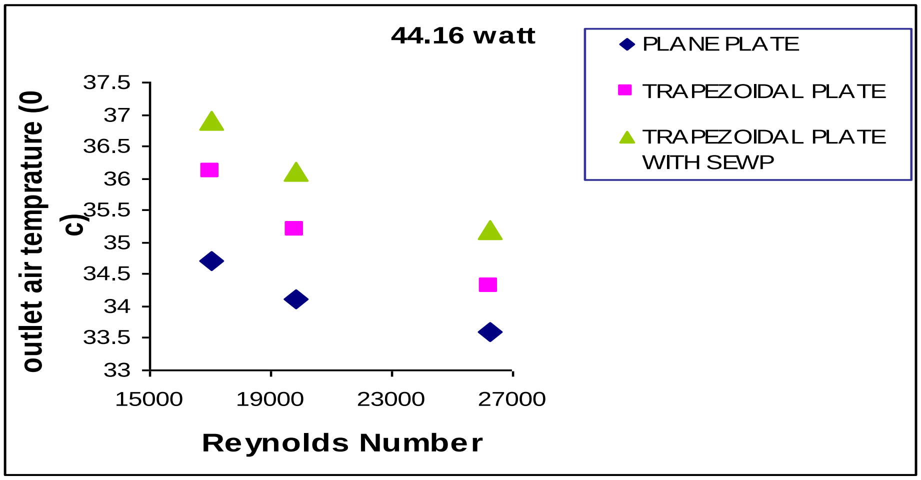


Fig 6.4 (b)

Fig 6.4 (c)

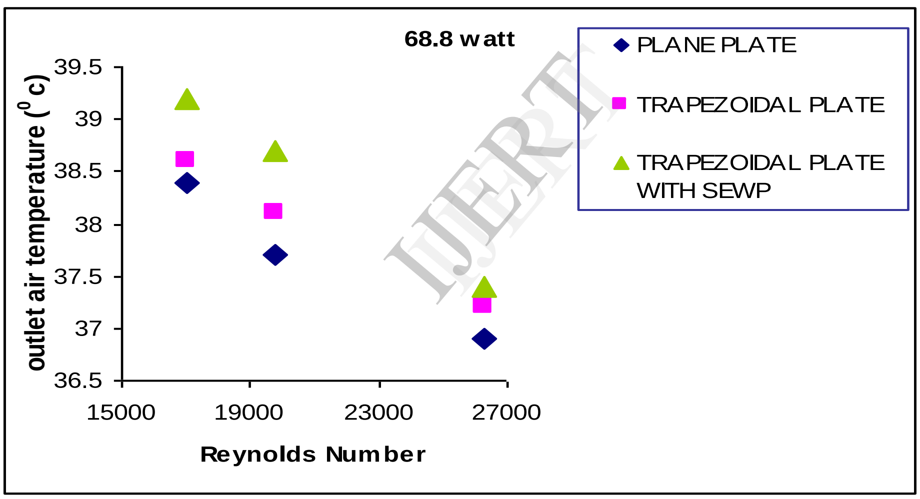


Fig 6.4 (d)

Fig 6.4 (a-d) Variation of Outlet air Temperature with Re for different heat flux

6.5 Variation of Nusselt Number with Reynolds Number at Different Heat Flux and Comparison between the Three Cases under Study:-

Fig 6.5 (a-d) shows the variation of Nu/Nu_o with Reynolds number. Nu/Nu_o is the Nusselt number ratio, which is defined as the ratio of augmented Nusselt number to Nusselt number of plane plate. And the Comparison between plane plate, trapezoidal plate and trapezoidal plate with SEWP has been performed. From fig 6.5 it has been observed that the Nu for trapezoidal plate at different heat flux was enhanced by 40-55% at 10.88 watt, 45-65% at 25 watt, 30-45% at 44.16 watt, and 25-35 % at 68.8 watt in the Reynolds number range of present study. Due to the presence of waviness causes disturbance, induced breaking and destabilizing, recirculation as air flows through such surfaces in the main flow and hence the thinning of thermal boundary layer which leads to the enhancement in the Nusselt number. In this way traprzoidal plate is the suitable method for augmentation in heat transfer. Fig also shows that the Nusselt number increases with increase in Reynolds number, but with increase in heat flux above 25 watt Nusselt number decreases continuously because increase in power dissipation with increase of heat flux as shown in fig. If we introduced a sharp edged wavy plate over trapezoidal plate at the hieght of 15 mm from the base plate then the Nu number for such channel was enhanced by 70-85% at 10.88 watt, 65-80% at 25 watt, 50-65% at 44.16 watt, and 35-50% at 68.8 watt in the Reynolds number range of present study. It has been found out according to literature survey that the presence of converging and diverging type of wavy channel accelerate and decelerate the air flow over the trapezoidal plate along the length of duct and disturb the flow, generates vortex shedding effect and act as turbulence promoter in the flow, so with increase of Reynolds number the size and strength of re-circulation zones, swirl flow also increases which leads to heat transfer enhancement i.e. increase in Nu number.

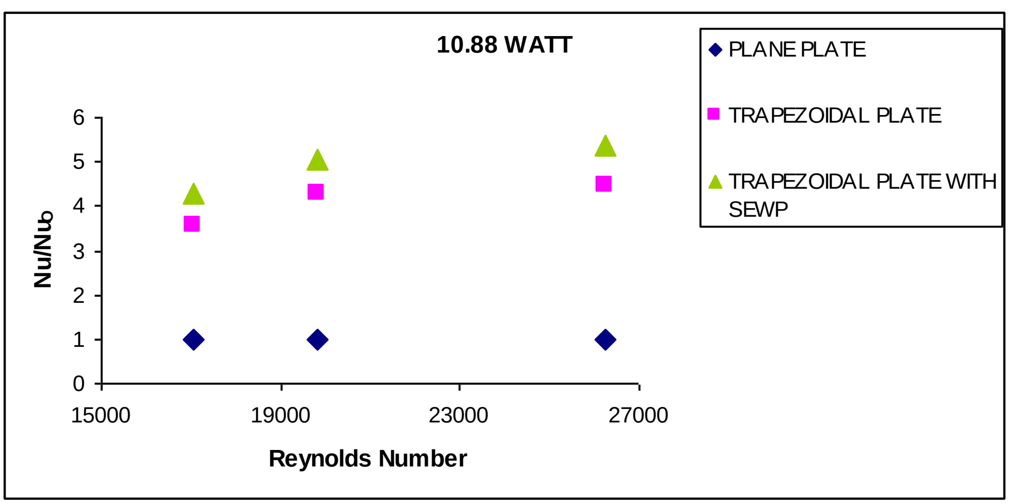


Fig (a)

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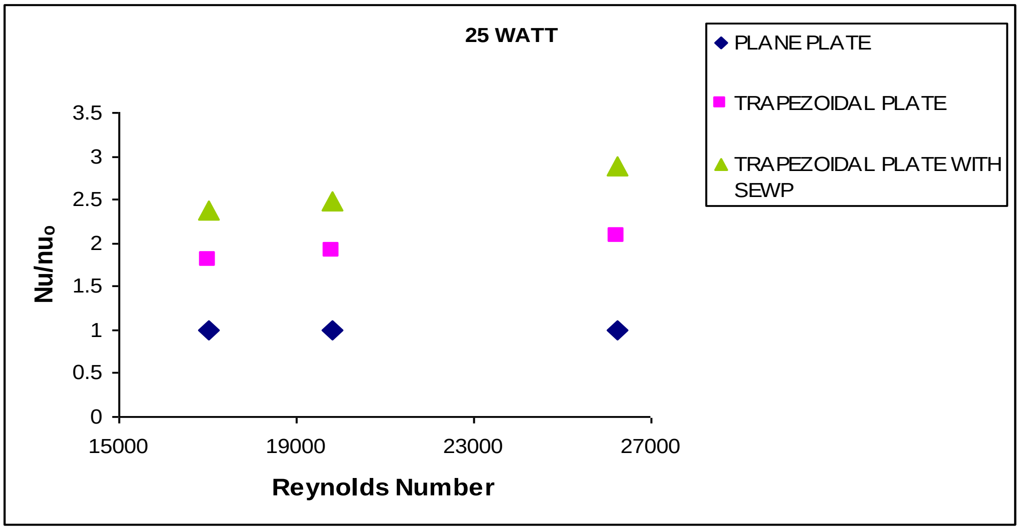


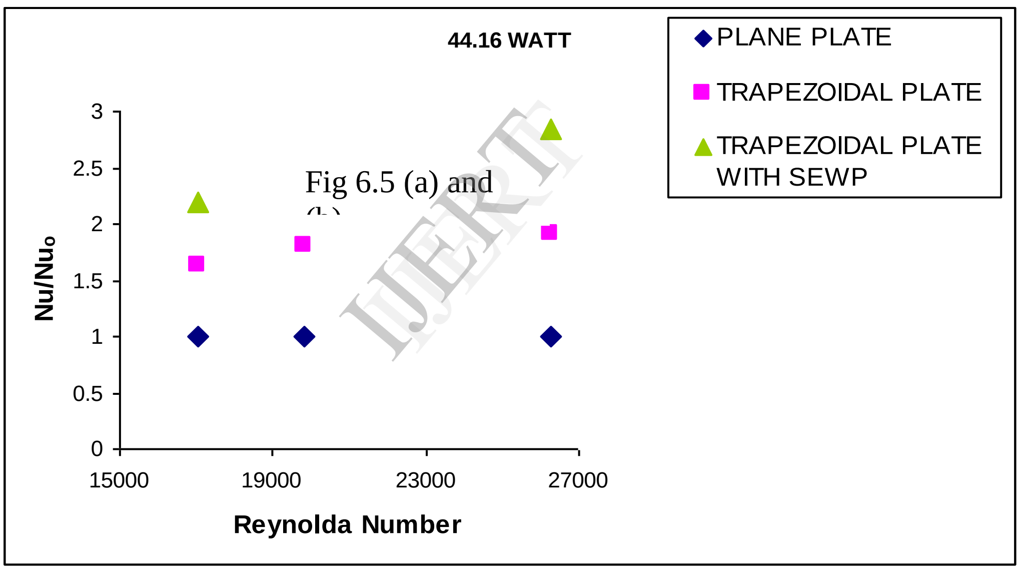
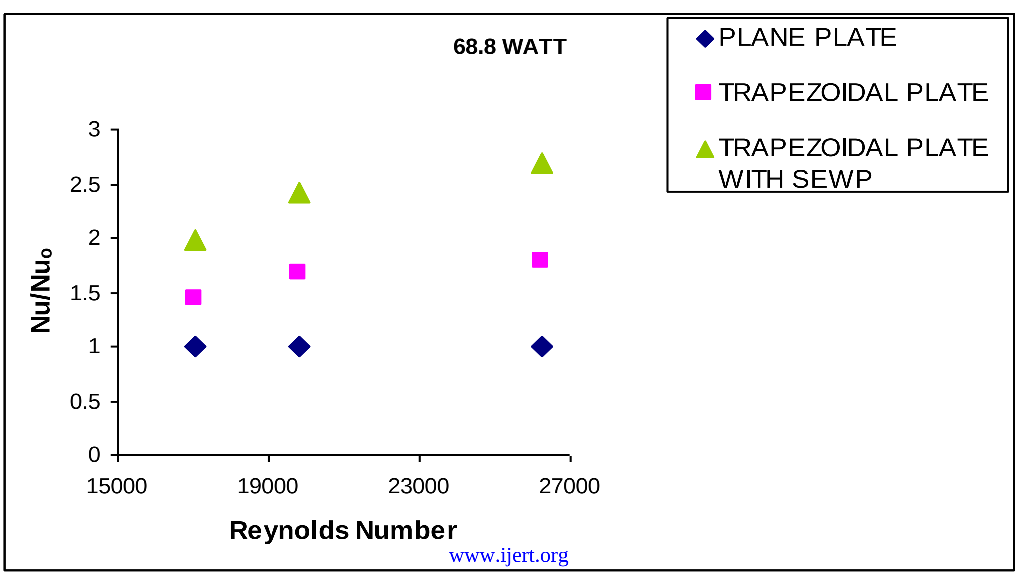


Fig 6.5 (a) and

Fig 6.5



6.6 Validation of Pressure Drop with Empirical Relation

Figure 6.6 shows the variation of pressure drop across the test section with plane plate, the pressure drop calculated by using Correlation of Blasius i.e. $\mathbf{f = 0.316Re^{-0.25}}$ for turbulent flow $\mathbf{Re<10^5}$. In this study the obtained pressure drop is reasonably agree well within ± 25% of pressure drop which is calculated by using above relation. As shown in Figure the pressured drop increases with increase in Reynolds number, due to the turbulence effect in the air flow increases which leads to increase in pressure drop

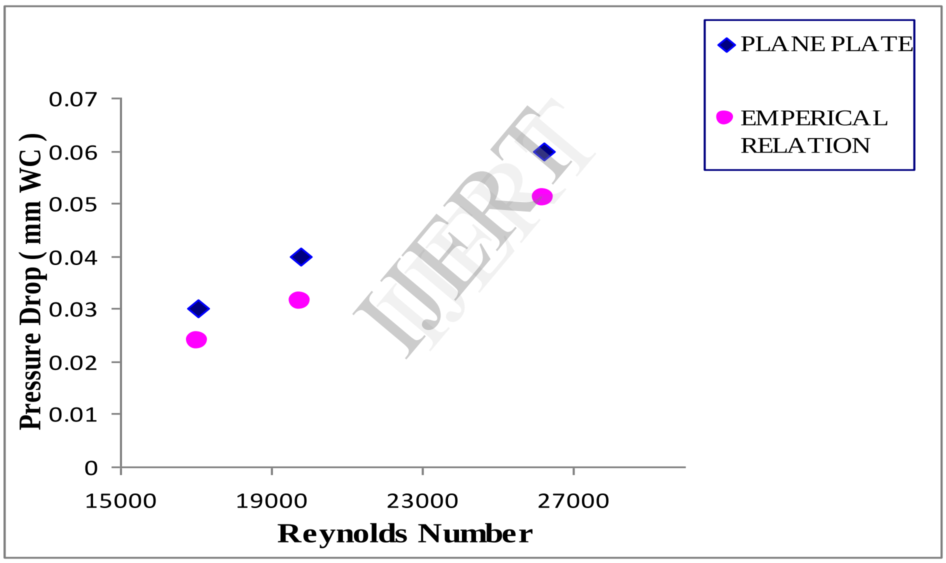
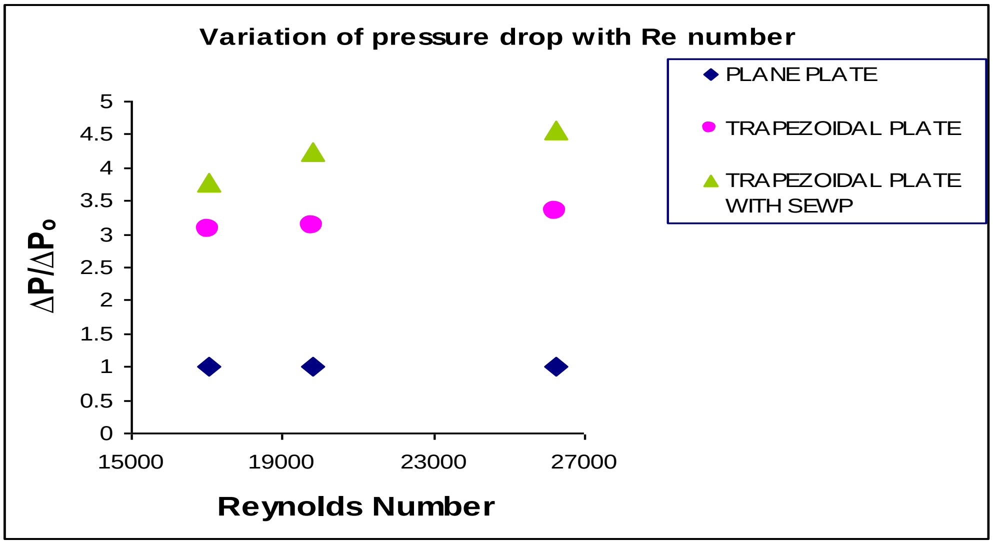


Fig.6.6 Validation of Pressure Drop for Plane Plate

6.7 Variation of Pressure Drop with Reynolds Number

Figure 6.7 shows the variation of pressure drop with Reynolds number for plane plate, trapezoidal plate and trapezoidal plate with SEWP. Due to the presence of waviness in trapezoidal plate causes disturbance, induced breaking and destabilizing, recirculation as air flows through such surfaces in the main flow, the pressure drop is 75-90% more as compared to plane plate. From fig it is observed that the pressure drop continues to increase with Reynolds number. Fig 6.7 also shows maximum increase in pressure drop with SEWP as compared to rest of the two in this study.



7.1 Conclusions and Future work

In the present experimental work, experiments were performed on three different test plates, first one was plane plate, second trapezoidal plate and third trapezoidal plate with SEWP. The comparison of heat transfer enhancement between these plates has been done in this experimental study.

On the basis of the results obtained the following conclusions are made:

1. Due to the presence of waviness in trapezoidal plate significantly enhances the heat transfer from the plate. Nusselt number for the trapezoidal plate is enhanced by 40-55% at 10.88 watt, 45-65% at 25 watt, 30-45% at 44.16 watt, and 25-35 % at 68.8 watt in the Reynolds number range of present study.
2. The Nusselt number increases with increase in Reynolds number and the air outlet temperature decreases with Reynolds number in spite of increase in heat transfer.
3. The enhancement in heat transfer for trapezoidal plate reduces the plate temperature by 7-10 % as compare to plane plate.

4. By introducing a SEWP over the trapezoidal plate further enhances the heat transfer. The Nusselt number for such plate is enhanced by 70-85% at 10.88 watt, 65-80% at 25 watt, 50-65% at 44.16 watt, and 35-50% at 68.8 watt in the Reynolds number range of present study, in this way trapezoidal plate with SEWP has found better heat transfer characteristics.
5. The average plate temperature with SEWP is low as compare to plane plate. This is because of augmentation in Nusselt number.

6. The enhancement of heat transfer achieved by using a SEWP over trapezoidal plate is associated with an increase in pressure loss and also pressure drop increases with increase in Reynolds number.

7.2 Scope for Future Work

The results of this work reveal that the trapezoidal plate with a sharp edged wavy plat as a generation of various effects such as turbulence augmentation and recirculation of flow is a useful device for improving heat transfer in heat exchangers. Here the computations have been done assuming flow regime to be turbulent.

The present problem can be extended in future in the following ways:

1. Further extension of present study can be made by changing the length of horizontal pitch on both sharp edges of wavy channel.
2. By changing the height of wavy plate over trapezoidal plate, this experimental study can be further extended.
3. The present experimental study can be extended by decreasing the cross-sectional area of rectangular duct.
4. Numerical simulation can be made of the present work and comparison can be done with experimental study.

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