

Numerical Analysis of Compact Heat Exchanger for Flow Distribution

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Abstract

Background/Objectives: The common assumption made in basic heat exchanger design is that the fluid to be distributed uniformly at the inlet of the exchanger on each fluid side and throughout the core. But in actual practice it doesn't happen. Thus the main objective of this paper is to reduce the non uniformity in the flow of fluid in compact heat exchanger from the header tube to the lateral tube. **Methods/Statistical Analysis:** In this work, the flow mal-distribution of heat exchanger at different cross-sectional headers like circular, rectangular, square and triangular header with various flow rates ranging from Re 1000 to 20000 is analyzed. Numerical models and boundary conditions used in the analyses are validated against experimental data. Following the validated procedure, three-dimensional CFD analyses are carried out to study the effect of geometrical variation of headers on flow distribution. For each geometrical variation, analysis is continued till the trend of behavior of flow distribution is completely understood. The results are analyzed to reach the optimum configuration with each variation. **Findings:** For all the four types of header cross section and for various inlet mass flow rates, the triangular header produces more uniform distribution. With low pressure drop in triangular cross section, the velocity distribution is uniform. Because of uniform velocity distribution in the header the flow maldistribution is minimum in heat exchanger with triangular cross sectional header. Triangular header shows 77%, 45%, and 70% less flow maldistribution when compared to circular, square and rectangular headers respectively. **Application/Improvements:** Development in the field of renewable energy had made a great revolution in the usage of solar flat plate water heater in each and every home. Implement of this triangular shaped header cross in the core tube of flat plate collector, would increase the efficiency of solar flat plate water heater, which would ultimately improve its usage among the people.

Keywords: CFD, Fluent, Flow Maldistribution, Heat Exchanger

1. Introduction

A heat exchanger is a device used to transfer heat between two or more fluids. The fluids can be single or two phase and, depending on the exchanger type, may be separated or in direct contact. One of the common assumptions in basic heat exchanger design is that fluid to be distributed uniformly at the inlet of the exchanger on each fluid side and throughout the core. Mal-distribution of flow in heat exchangers is known to significantly affect their performance. Mal-distribution of flow in the header is influenced by the geometry of the header and inlet flow velocity. Flow distribution from a header into parallel channels applicable to heat exchangers is frequently encountered

in heat transfer equipments, such as condensers, evaporators, boilers, solar energy flat-plate collectors, and cooling system of nuclear reactor. Apparently, the flow rates of single-phase distribution through the parallel channels are often not uniform which could greatly affect the heat transfer performance, these heat transfer devices may suffer from significant performance drop subject to mal-distribution. Therefore, the issue of uniform flow distribution has recently received growing attentions for the heat exchanger design.

¹Santhoshsekar et al. predicted the pressure drop in cross flow heat exchanger using artificial neural network. Set of data obtained from numerical simulation were used in training a back propagation based neural network to

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predict the pressure drop. ²Yogesh et al. experimentally investigated the performance of cross-flow heat exchanger with corrugated copper fin. As the surface area, number of fins are increased the heat transfer rate is increased constantly. ³Jafar et al. investigated the flow of fluid in a heat exchanger by a uniform and a non uniform cross section header. And found that header with taper cross section showed improved efficiency when compared to the header with circular cross section. ⁴Rao et al. made a heat transfer analysis for shell and tube type heat exchanger. A program was written to evaluate the heat transfer parameter. ⁵Numerically studied the effect of area ratio on the flow distribution in parallel flow manifolds used in liquid cooling module for electronic packaging. The manifold was rectangular in shape, and a Reynolds no of 50 was used because of the laminar flow. Three area ratio 4, 8, and 16 was taken for the investigation. The results showed that the flow distribution was more uniform for the parallel flow manifold of area ratio 4. The static pressure difference between the dividing and combining flow headers had a direct consequence for the non uniform flow of fluid. And the major factor that controls the pressure variation is friction and momentum. The effect of friction and momentum for area ratio 4, 8, 12 was explained with the variation in pressure due to their effect. ⁶Investigated the effect of rectangular, triangular and trapezoidal header shapes for Reynolds number 50, 100 and 300 on flow distribution. From the work it was found that when the header shape is changed from rectangular to, triangular the flow mal-distribution was reduced. And also found that with increase in Reynolds number the percent flow in the last channel also increases, while the percent flow rates in other channels decrease. The higher the Reynolds number, the more non uniform is the flow distribution. ⁷Numerically examined the influence of inlet location on the performance of parallel-channel cold-plate. Totally a five different configuration was investigated and the result showed that there is no flow recirculation for U-type arrangement and comparatively they showed more uniform flow distribution, whereas for Z-type arrangement the heat transfer performance was low, due to the flow recirculation and mal-distribution. ⁸Made both experimental and analytical investigation on flow distribution in heat exchanger. They took three parameter like the relative velocity of flow in the branch tube as compared with the velocity of flow in the header, second is diameter ratio and the third is number of outlets or inlets in one cross section of the header (denoted by symbol M) was taken

into consideration. ⁹Investigated with eight different strategies to identify the most effective one for the attainment uniform flow distribution. The strategies taken for investigation were, a) enlargement of the cross-sectional area of the distribution manifold, b) linear tapering of the cross-sectional area of the distribution manifold, c) several non-tapering of the cross sectional area of the distribution manifold, d) tapering of the cross-sectional areas of both the distribution and collection manifolds, e) variation of the cross sectional areas of the channels which interconnect the distribution and collection manifolds, f) tailoring of the ducting that delivers fluid to the distribution manifold, and h) contouring of the shapes of the inlets of the interconnecting channels. Among this strategies the most effective one was enlargement of the cross sectional area of the distribution manifold, which clearly tells that the for smaller value of area ratio, the flow obtained is much uniform. ¹⁰Evaluated a tapered header configuration to reduce the flow mal-distribution. It was found that the flow mal-distribution is quite severe with constant cross-sectional headers. The simulation was done using a commercial CFD software FLUENT. A constant cross-sectional circular header with a diameter of 0.7 mm and 0.1 mm was investigated and found that pressure along the inlet header was increasing and that along the outlet header was decreasing which resulted in flow mal-distribution. Simultaneously, a taper cross section header with same hydraulic diameter was investigated. The pressures along the inlet as well as the outlet were found to be decreasing which resulted in a better flow distribution through the channels.

Though many works have been carried out in the field of heat exchanger to increase its efficiency by reducing the flow mal distribution, still a lot of work has to be carried out in this area to further increase its efficiency.

2. Objective and Methodology

The mal-distribution of the fluid flow in the heat exchanger is a serious problem which affects the performance of heat exchanger. The objective of this work is to analyze the heat exchanger numerically and to investigate the flow distribution in the heat exchangers. In this work, the fluid flow is investigated by varying different parameters like, header cross section, and area ratio and flow rate. The significance would be the performance of the heat exchanger, which will be highly effective when the flow mal-distribution of the fluid flow in the heat exchanger is

reduced. Thus the main focus of this work is to determine the condition at which uniform fluid flow can be obtained. Also to develop a co-relation from the investigated result, so that the co-relation formulated can be used to calculate the non-uniformity of the fluid flow in the heat exchanger directly. The significance of the co-relation is, the reduction in time for finding the non-uniformity.

Numerical models and boundary conditions used in the analyses are validated against experimental data. Following the validated procedure, three-dimensional CFD analyses are carried out to study the effect of geometrical variation of headers on flow distribution. For each geometrical variation, analysis is continued till the trend of behavior of flow distribution is completely understood. The results are analyzed to reach the optimum configuration with each variation. These configuration details are used to generate guidelines for inlet header design.

2.1 Validation

For any numerical analysis the procedure that is followed must be validated. In this analysis the work is validated as per¹¹ IngYoun Chen et.al. For validation purpose the geometrical model of the heat exchanger is created as per the dimension of the heat exchanger used in the experimental set up.

The model consists of a distribution inlet header, 9 parallel tubes and an outlet header. The geometric sizes of the test sections are, lengths of the parallel tubes are 400mm for 3 mm inner diameters with a pitch of 10 mm and header sizes with square cross section of 7 mm X 7 mm. The heat exchanger is operated at Z-type configuration. The Figure 1 shows the relation between discharge and non uniformity, at various inlet flow conditions. Both the CFD results and the experimental results are compared,

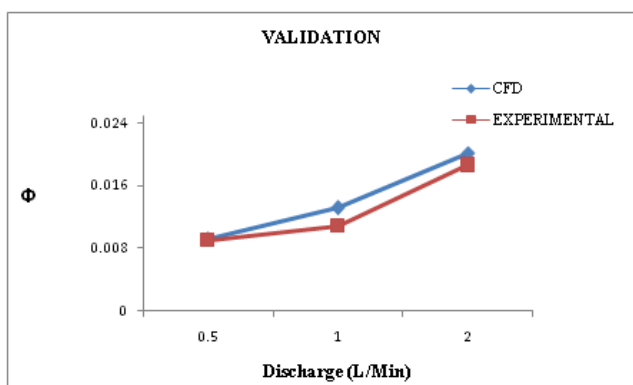


Figure 1. Discharge and Non Uniformity.

for a discharge of 0.5L/min, the error percentage between the CFD and the experimental value is 1.85%, for a discharge of 1L/min the error percentage between the CFD and the experimental value is 16.9%, for a discharge of 2L/min the error percentage between the CFD and the experimental value is 7.8%. From this result it is concluded that the procedure followed to analyze the flow distribution in heat exchanger using CFD software is validated.

2.2 Problem Definition

In this work, the flow mal-distribution of heat exchanger at different cross-sectional headers like circular, rectangular, square and triangular header with various flow rates ranging from Re 1000 to 20000 is analyzed. The model consists of a distribution inlet header, 9 parallel tubes and an outlet header.

The lengths of the parallel tubes are 400mm for 3 mm inner diameters with a pitch of 10 mm, and header sizes with a hydraulic diameter of 12mm are analyzed. The Figure 2 shows the geometrical dimensions of the heat exchanger. The header shapes are modified as square, circular, rectangular & triangular cross sections. The hydraulic diameter of all the four different shape of headers is same. The hydraulic diameters for various headers are calculated using the formula

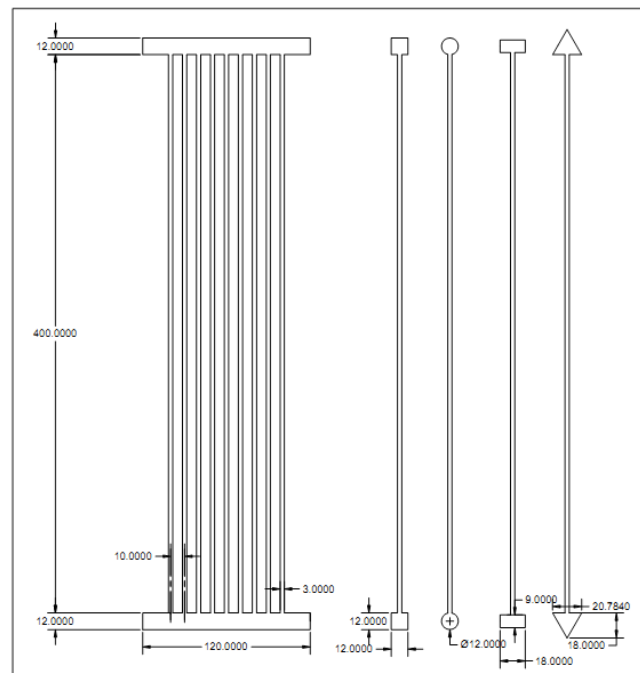


Figure 2. Geometrical Cross Section of Heat Exchanger & Its Various Header's.

$$\text{Hydraulic Diameter} = \frac{4 * A}{P} \quad (1)$$

The hydraulic diameter of header and lateral tube diameter for different area ratio are given in Table 1.

3. Results and Discussions

For calculating the flow distribution among the parallel tubes, the dimensionless parameters, β_i , β and ϕ are used for evaluating the flow distribution. Their definition are given as following:

$$\beta_i = \left(\frac{Q_i}{Q} \right) \quad (2)$$

Where β_i denotes the flow ratio for i^{th} tube, Q_i represents volume flow rate for i^{th} tube (m^3/s), and Q is total volume flow rate (m^3/s). To characterize used by the concept of standard deviation to define the mal-distribution, ϕ is:

$$\phi = \sqrt{\frac{\sum_{i=1}^N (\beta_i - \beta)^2}{N}} \quad (3)$$

Where N is the number of total tubes in the parallel flow heat exchanger and β is the average flow ratio for the total tubes. The larger value of ϕ indicates the higher mal-distribution.

3.1 Flow Ratio Variation in each of the Lateral Tubes for Area Ratio 0.4417

The results of flow distribution as a function of the Reynolds number are represented. As the Reynolds number increases, the percent flow rate in the last channel also increases, while the percent flow rates in other channels decrease. The higher the Reynolds number, the more non-uniform the flow distribution becomes. It shows that the Reynolds number effect on flow mal-distribution is more significant in the rectangular, circular and square header than in the triangular header. The first three pipes are considered as the front end of the header, the next three

as the mid-end of the header, and the last three pipes are taken as the rear end of the header.

3.1.1 Effect of Circular Header on Flow Distribution

The Figure 3 depicts the flow rate at different lateral pipe numbering from one to nine. In the circular cross-sectional header for different flow rate it has been found that for lower Reynolds number the flow ratio at the first tube is high and it decreases at the tubes at the rear end of the header. When the Reynolds Number is increased the flow ratio at the first tube decreases and it increases at the tubes at the rear end of the header.

3.1.2 Effect of Rectangular Header on Flow Distribution

The Figure 4 depicts the relation between the flow ratios at different lateral tube ranging from 1-9 for the rectangular cross sectional header. From the analysis it has been found that for various Reynolds Number ranging from 1000 to 20000 the flow ratio is minimum at the front part of the header and it is maximum at the rear part of the header. There is a slight decrease in the flow ratio at the initial tubes when the Reynolds Number is increased.

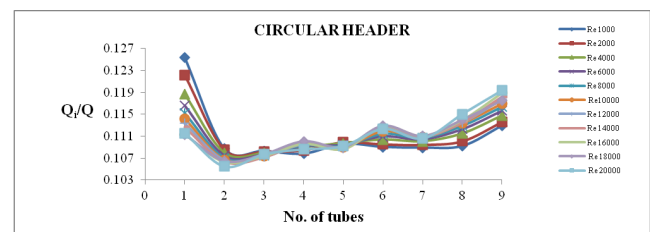


Figure 3. Flow Ratio and No. of Tubes for circular header for area ratio 0.4417.

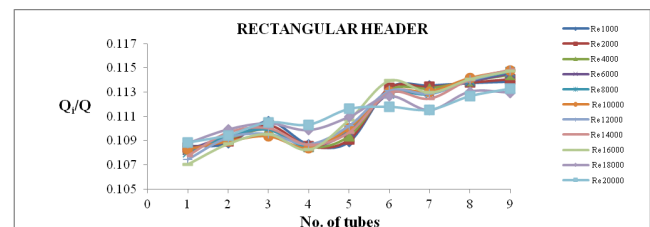


Figure 4. Flow Ratio and No. of Tubes for rectangular header for area ratio 0.4417.

Table 1. Area ratios

Sl. No	Hydraulic diameter (mm)	Lateral tube diameter (mm)	Area Ratio
1	12	3	0.4417
2	12	4	0.7851
3	12	5	1.221

3.1.3 Effect of Square Header on Flow Distribution

The Figure 5 gives the relation between the flow ratios at different lateral tubes ranging from 1-9 for square cross sectional header. The analysis of flow distribution in square cross sectional header is almost similar to that of flow distribution in the rectangular cross sectional header, in square cross sectional header the flow ratio is minimum at the initial tubes and it increases at the tubes in the rear part of the header. When the flow rate is increased there is a slight decrease in flow ratio in initial tube and there is a slight increase in the flow ratio at the tubes in the rear part of the header.

3.1.4 Effect of Triangular Header on Flow Distribution

The Figure 6 depicts the relation between the flow ratio at different lateral tubes ranging from 1-9 for triangular cross sectional header. The analysis of flow distribution at the triangular cross sectional header give us a clear idea the flow ratio is high only at the 4th tube and there is a uniform flow of the fluid in all the other tubes. For Reynolds Number ranging from 1000-6000 there is a high flow ratio at the 4th tube and the flow ratio at remaining Reynolds Number ranging from 8000-20000 give a uniform flow.

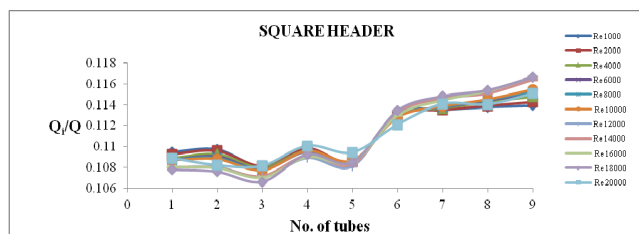


Figure 5. Flow Ratio and No. of Tubes for square header for area ratio 0.4417.

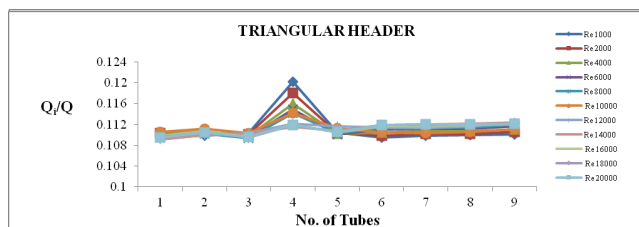


Figure 6. Flow Ratio and No. of Tubes for triangular header for area ratio 0.4417.

3.1.5 Non Uniformity for Area Ratio 0.4417

The Figure 7 gives the relationship between Non-Uniformity of fluid flow at different cross sectional headers for various inlet flow condition. From the analysis the mal-distribution for triangular cross sectional header is very low when compared to the other three headers.

3.2 Flow Ratio Variation in each of the Lateral Tubes for Area Ratio 0.7853

The results of flow distribution as a function of the Reynolds number are represented. As the Reynolds number increases, the percent flow rate in the last channel also increases, while the percent flow rates in other channels decrease. The higher the Reynolds number, the more non-uniform the flow distribution becomes. It shows that the Reynolds number effect on flow mal-distribution is more significant in the rectangular, circular and square header than in the triangular header. The first three pipes are considered as the front end of the header, the next three as the mid-end of the header, and the last three pipes are taken as the rear end of the header.

3.2.1 Effect of Circular Header on Flow Distribution

The Figure 8 depicts the flow rate at different lateral pipe numbering from one to nine. In the circular cross-sectional header for different flow rate it has been found that for very lower Reynolds number the flow ratio at all the tubes are almost uniform, with increase in Reynolds number the flow ratio at the first tube decreases and it increases at the tubes at the rear end of the header.

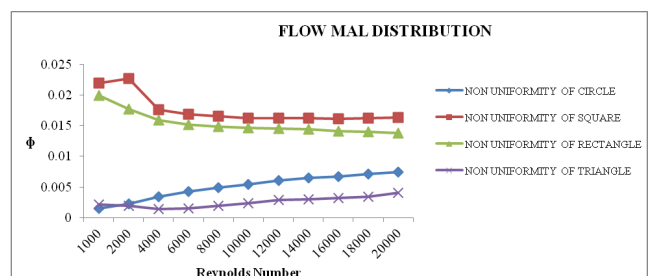


Figure 7. Non Uniformity and Reynold No. for different cross sectional header at area ratio 0.4417.

3.2.2 Effect of Rectangular Header on Flow Distribution

The Figure 9 depicts the relation between the flow ratios at different lateral tube ranging from 1-9 for the rectangular cross sectional header. From the various Reynolds number ranging from 1000 to 20000 the flow ratio is minimum at the front part of the header and it maximum at the rear part of the header. And there is a slight increase in the flow ratio at the initial tubes and a slight decrease in the flow ratio when the Reynolds Number is increased.

3.2.3 Effect of Square Header on Flow Distribution

The Figure 10 gives the relation between the flow ratios at different lateral tubes ranging from 1-9 for square

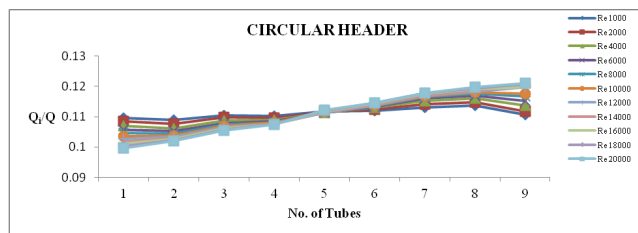


Figure 8. Flow Ratio and No. of Tubes for circular header at area ratio 0.7853.

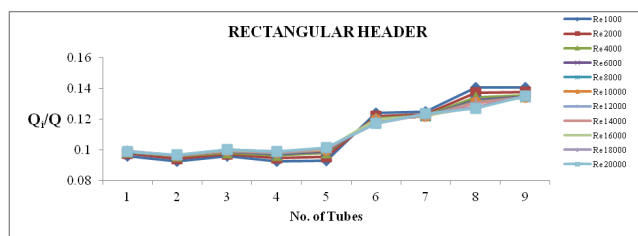


Figure 9. Flow Ratio and No. of Tubes for rectangular header at area ratio 0.7853.

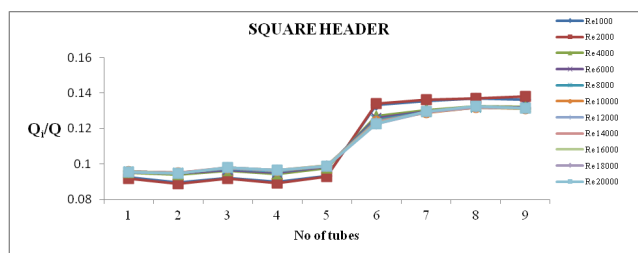


Figure 10. Flow Ratio and No. of Tubes for square header at area ratio 0.7853.

cross sectional header. The analysis of flow distribution in square cross sectional header is almost similar to that of flow distribution in the rectangular cross sectional header, in square cross sectional header the flow ratio is minimum at the initial tubes and it increases at the tubes in the rear part of the header. When the Reynolds number is increased there is a slight increase in flow ratio at the initial tube and there is a slight decrease in the flow ratio at the tubes at the rear part of the header.

3.2.4 Effect of Triangular Header on Flow Distribution

The Figure 11 depicts the relation between the flow ratios at different lateral tubes ranging from 1-9 for triangular cross sectional header. In the triangular cross-sectional header for different flow rate it has been found that for Reynolds number varying from 1000-1200 there is a lower flow ratio at the 1st pipe than the flow ratio increases till the 5th tube than the flow ratio decreases rapidly till 6th tube and it slightly increase at the rear end. The flow ratio at tubes for Reynolds number 1200-20000 increases from the tubes at front end of the header to the tubes at rear end of the header.

3.2.5 Non Uniformity for Area Ratio 0.7853

The Figure 12 gives the relationship between Non-Uniformity of fluid flow at different cross sectional headers for various inlet flow condition. From the analysis the mal-distribution for triangular cross sectional header is very low when compared to the other three headers.

3.3 Flow Ratio Variation in each of the Lateral Tubes for Area Ratio 1.2271

The results of flow distribution as a function of the Reynolds number are represented. As the Reynolds

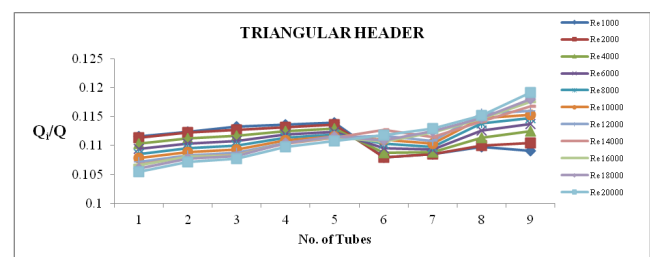


Figure 11. Flow Ratio and No. of Tubes for triangular header at area ratio 0.7853.

number increases, the percent flow rate in the last channel also increases, while the percent flow rates in other channels decrease. The higher the Reynolds number, the more non-uniform the flow distribution becomes. It shows that the Reynolds number effect on flow mal-distribution is more significant in the rectangular, circular and square header than in the triangular header. The first three pipes are considered as the front end of the header, the next three as the mid-end of the header, and the last three pipes are taken as the rear end of the header.

3.3.1 Effect of Circular Header on Flow Distribution

The Figure 13 depicts the flow rate at different lateral pipe numbering from one to nine for a circular cross-sectional header. In the circular cross-sectional header from different flow ratio it has been found that for lower Reynolds number the flow ratio at the front part of header is high and it decreases at the tubes in the rear end of the heat exchanger. And when the Reynolds Number is increased the flow ratio at the front part of the header decreases and it increases at the tubes in the rear end of the heat exchanger.

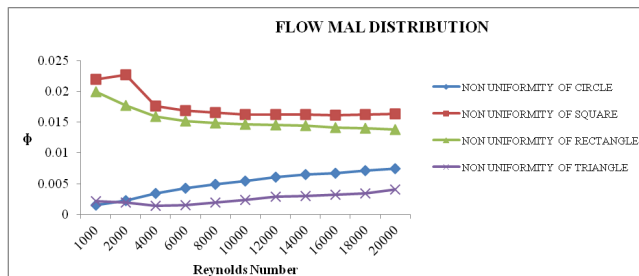


Figure 12. Non Uniformity and Reynold No. for different cross sectional header at area ratio 0.7853.

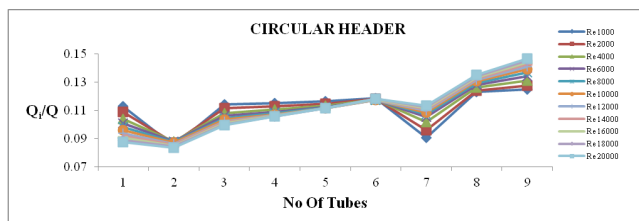


Figure 13. Flow Ratio and No. of Tubes for circular Header at area ratio 1.2271.

3.3.2 Effect of Rectangular Header on Flow Distribution

The Figure 14 depicts the relation between the flow ratios at different lateral tube ranging from 1-9 for the rectangular cross sectional header. From the analysis it has been found that for various Reynolds Number ranging from 1000-20000 the flow ratio is maximum variation at the front end of the header and in the rear end of the header to we have variation but is less when compared to the front end, the tubes at the mid-end of the header are more uniform. And there is a slight decrease in the flow ratio at the initial tubes when the Reynolds Number is increased.

3.3.3 Effect of Square Header on Flow Distribution

The Figure 15 gives the relation between the flow ratios at different lateral tubes ranging from 1-9 for square cross sectional header. The analysis of flow distribution in square cross sectional header is almost similar to that of flow distribution in the rectangular cross sectional header, in square cross sectional header the flow ratio is minimum at the front part of the header tubes and it increases at the tubes in the rear end of the heat exchanger. When the flow rate is increased there is a slight decrease in flow ratio in initial tube and there is a slight increase in the flow ratio at the tube at the rear end of the heat exchanger.

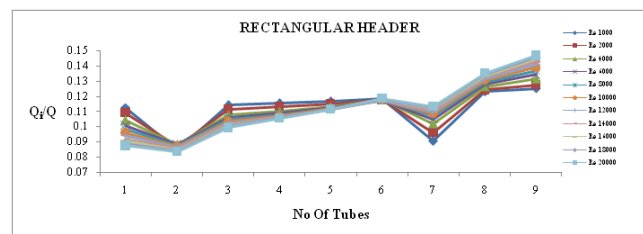


Figure 14. Flow Ratio and No. of Tubes for rectangular Header at area ratio 1.2271.

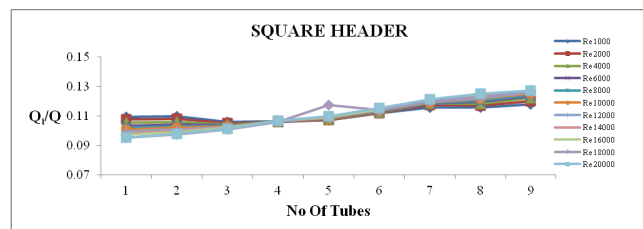


Figure 15. Flow Ratio and No. of Tubes for square Header at area ratio 1.2271.

3.3.4 Effect of Triangular Header on Flow Distribution

The Figure 16 gives the relation between the flow ratios at different lateral tubes ranging from 1-9 for triangular cross sectional header. The analysis of flow distribution at the triangular cross sectional header give us a clear idea the flow ratio is high almost uniform at all the front, mid and rear end of the header. The triangular header has a better flow distribution when compared with the other, three types of header.

3.3.5 Non Uniformity for Area Ratio 1.2271

The Figure 17 gives the relationship between Non-Uniformity of fluid flow at different cross sectional headers for various inlet flow condition. From the analysis the mal-distribution for triangular cross sectional header is very low when compared to the other three headers.

The Figure 18 shows the velocity contour, velocity vector plot and static pressure graph of dividing header for the better and the worst mal-distribution values achieved at triangular header, and circular header for the Re 16000. From the figure it is found that the total pressure drop in circular cross section is higher when compared to

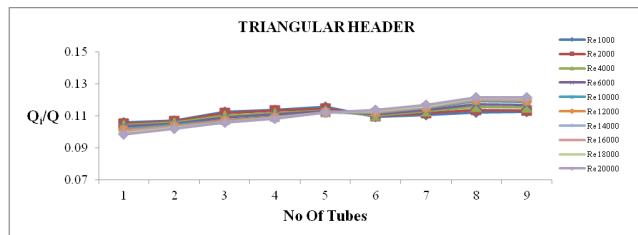


Figure 16. Flow Ratio and No. of Tubes for triangular Header at area ratio 1.2271.

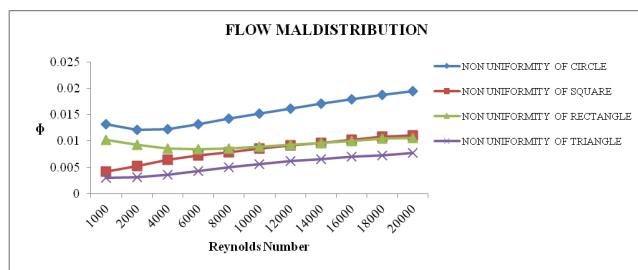


Figure 17. Non Uniformity and Reynold No. for different cross sectional header at area ratio 1.2271.

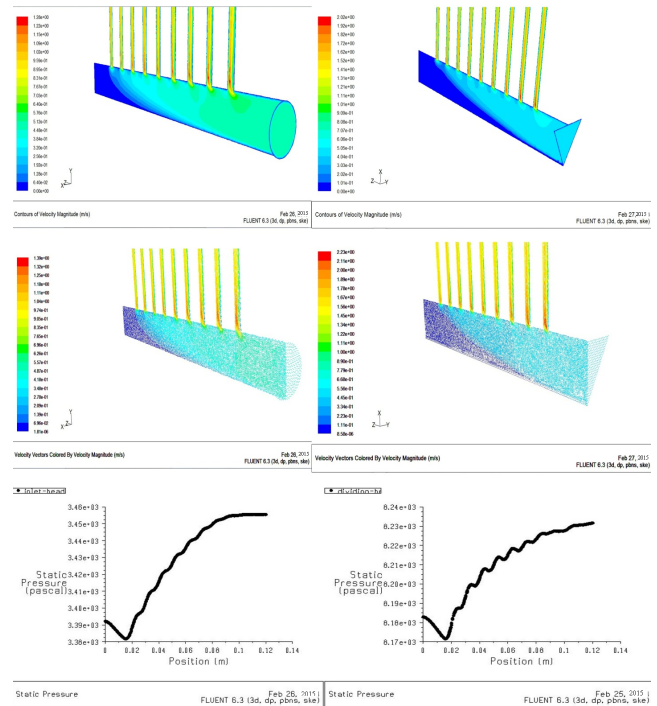


Figure 18. Velocity Contour, Velocity vector plot and Static pressure graph for Circular header & Triangular header of area ratio 0.4417.

the total pressure drop in triangular cross section. With low pressure drop in triangular cross section, the velocity distribution is uniform. Because of uniform velocity distribution in the header the flow maldistribution is minimum in heat exchanger with triangular cross sectional header.

4. Conclusion

The present single-phase flow distribution analysis in compact parallel flow heat exchanger is investigated by numerical simulation subjected to different flow rates and different cross sectional headers. From the analysis it has been found that the flow maldistribution is very high for circular cross sectional headers when and is low for triangular cross sectional header when compared with other configurations. In all the configurations of the headers if the inlet flow rate is increased the flow maldistribution is also increased. It is also observed that the pressure distribution and velocity distribution in the header are the major parameters which will affect the flow distribution through the lateral pipes.

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