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FLOW DISTRIBUTION ANALYSIS IN A HEAT EXCHANGER WITH DIFFERENT HEADER CONFIGURATIONS

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ABSTRACT

This study presents the numerical results of liquid flow distribution in parallel flow heat exchanger. The basic header has a hydraulic diameter of 12mm with 120mm header length, and is distributed to nine parallel tubes with a 3mm diameter of 400mm length. Here, the flow distribution for different header cross section (like circle, square, rectangle and triangle) and inlet flow rate are numerically analyzed. It was found that for circular cross sectional header, at lower inlet velocity, the flow ratio at the front part of the header was higher when compared with the rear part. With increasing the inlet flow rate, the flow ratio is found to be lower at the front part of header tube, and is higher for the rear part of header. For square and rectangular header it is found that the flow ratio is low at the front part of the header when compared with the rear part of header at all the inlet flow conditions. For triangular cross sectional header upto Re 10000, the flow rate at the fourth tube is higher when compared with all other tubes, but at higher flow rate the flow distribution is uniform. When compared with all the four types of headers at various inlet flow rates, the triangular header produces more uniform distribution.

Keywords: heat exchanger, flow mal-distribution, CFD, fluent.

Nomenclature

A	- Cross-sectional area (m^2)
P	- Cross-sectional perimeter (mm)
D_h	- Hydraulic diameter (mm)
Q_i	- Volume flow rate for i^{th} tube (m^3/s)
Q	- Total volume flow rate (m^3/s)

Greek symbols

β_i	- flow ratio for i^{th} tube
β	- Average flow ratio for the total tubes
Ø	- Maldistribution

Subscript

I	- i^{th}

1. INTRODUCTION

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. Maldistribution of flow in heat exchangers is known to significantly affect their performance. Maldistribution 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 flatplate 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.

2. LITERATURE REVIEW

Toshisuke Kubo *et al* [1] formulated the flow rate ratio of each branch pipe taking the diffuser effect on the divided flow and the nozzle effect on the confluent flow which is caused by branching streams in a header into consideration. R.A. Bajura [2] analytically investigated the performance of flow distribution systems for both intake and exhaust manifolds. And he formulated dimensionless parameters characterizing the performance of manifolds from the analytical model. A.K. Majumdar *et al* [3] made numerical predictions of the flow distribution in parallel and reverse flow manifold syatems and obtained a novel finite-difference procedure, he performed a parametric computation to demonstrate the effect of the governing non-dimensional parameters on the flow distribution. Steve H. Choi *et al* [4] numerically studied the effect of an area ratio for a Reynolds number of 50, ansd a typical flow condition was observed in the electronic packaging. And found that among the area ratios (4, 8 and 16), the case of AR=4 produced the best coolant distribution. Sooyoun Kim *et al* [5] investigated the effects of header shapes and the Reynolds number on the flow distribution in a parallel flow manifold to be used in a liquid cooling module for electronic packaging. Heehak Ahn *et al* [6] gave the fundamental flow distribution question of how to design manifolds of low Reynolds number flow with both numerical analysis and experimental. Miao Zhengqing *et al* [7] have derived continuous and discrete mathematical model to study the distribution and combining flow characteristics in platens along header axes and in connecting tube within each individual platen, respectively. Akhilesh V. Bapat *et al* [8] carried out a careful assessment of friction factor and heat transfer by properly accounting for flow area variations and the accompanying non-uniform flow distribution in individual channels. LU Fang *et al* [9] made a discrete model matching the real physical phenomena have been proposed, to predict the pressure distribution in headers. An experimental evaluation of relevant flow characteristic parameters has been carried out to support the discrete model calculations. V.V. Dharaiya *et al* [10] studied the flow distribution through a plate-fin heat exchanger (straight Z-type flow) with parallel microchannels and minichannels is studied by using Computational Fluid Dynamics (CFD) code FLUENT. And it was found that the flow maldistribution is quite severe with constant cross-sectional area headers. Chi-Chuan Wang *et al* [11] studied experimentally and numerically investigates the single-phase flow into parallel flow heat exchangers with inlet and outlet rectangular headers having square cross section and 9 circular tubes. And found that the mal-distribution can be eased via reducing the branching tube size or increasing the entrance settling distance at the intake conduit. Chi-Chuan Wang *et al* [12] presented the experimental results of liquid flow distribution in compact parallel flow heat exchanger through a rectangular and 5 modified inlet headers (i.e., 1 trapezoidal, one multi-step, 2 baffle plates and 1 baffle tubes header). And found that the baffle tube yields the best flow distribution for it removed the vortex flow, and it is applicable for all the flow rates.

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

3. OBJECTIVE

The objective of this work is to analyze the heat exchanger numerically and to investigate the flow distribution in the heat exchanger with different header configurations.

4. METHODOLOGY

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.

4.1. CFD Analysis

Various steps involved in CFD are (i) geometric modeling, (ii) grid generation, (iii) defining governing conservation equation for mass and momentum with turbulence and boundary conditions. Convergence criteria are applied while execution of code and maximum limit chosen for this purpose is10^{-6} for mass, momentum, kinetic energy and dissipation rate of turbulence.

4.2. Numerical models and boundary conditions

$$\nabla.\left(\rho\vec{v}\right) = 0 - - - (1)$$

$$\nabla.\left(\rho\vec{v}\vec{v}\right) = -\nabla p - \nabla\left(\frac{2}{3}\rho k\right) + \nabla.\vec{\sigma} - - - (2)$$

Continuity equation (1) and momentum equation (2) are solved with appropriate boundary conditions. Second order momentum upwind differencing scheme is used. k **-** **ε** turbulence model with standard wall functions is used. Velocity corresponding to the Reynolds number is specified at inlet of the dividing header. Atmospheric pressure is specified at the outlet of the combining header. No slip condition is applied on all walls. Water at atmospheric pressure is used as the fluid. It is assumed that flow is fully developed in the header and there is no flow separation in boundaries.

5. VALIDATION

For any numerical analysis the procedure that is followed must be validated. In this analysis the work published by Mr. Ing Youn Chen *et al* in the paper titled Characteristic of flow distribution in compact parallel flow heat exchanger, part I: Typical inlet header, published in the journal named Applied Thermal Engineering in the year 12th June 2011 is validated. 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 geometry of the test section consist of parallel tubes with

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the length of 400mm and 3 mm inner diameter with a pitch of 10 mm and header sizes with square cross section of 7mm X 7mm. 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, 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 valid.

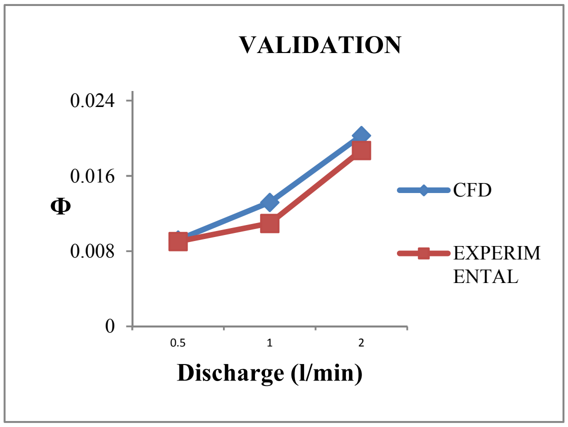

Figure-1. Discharge and non uniformity.

GEOMETRY OF HEAT EXCHANGER

In this work the flow maldistribution of heat exchanger at different cross-sectional headers like circular, rectangular, square and triangular header with various flow rate 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 is analyzed.

The Figure-2 shows the geometrical dimensions of the heat exchanger. The header shapes are modified as square, circular, rectangular and triangular cross sections. The hydraulic diameter of all the four different shape of headers is same. The hydraulic diameter for various headers are calculated using the formula:

$D_h = 4A/P$

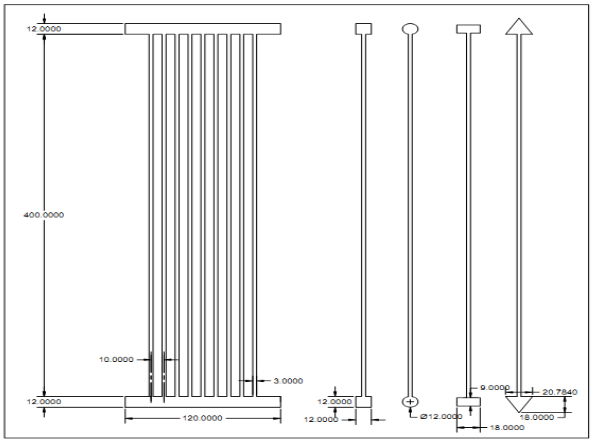

Figure-2. Geometrical cross section of Heat Exchanger and its various headers'.

7. GRID INDEPENDENCE TEST

In this analysis the geometry is discretized using tetrahedral mesh shown in Figure-3. To conduct the grid independent test the model is discritized by 9000000, 1050000 and 1150000 cells. The Figure-4 shows that there is only a slight variation in flow distribution when using 10, 50,000 cells and 11, 50, 000 cells. So for the further analysis are carried out with the use of 10, 50, 000 cells.

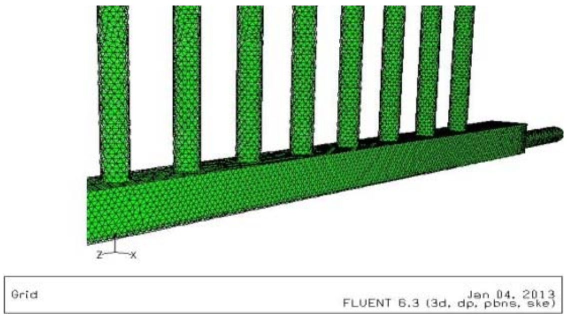

Figure-3. Mesh model of heat exchanger.

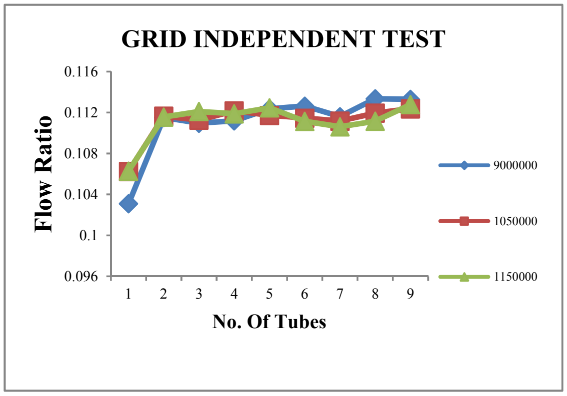

Figure-4. Flow ratio and no. of tubes for different mesh size.

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8. RESULT

8.1 Parameters for calculating the flow distribution

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

$\beta_i = Q_i/Q$

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, Ø is

$Ø = \sqrt{\sum i^N{}_{=1}(\beta_i-\beta)^2/N}$

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 Ø indicates the higher mal-distribution.

8.2. Effect of circular header on flow distribution

The Figure-5 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 tubes in the rear end of the header.

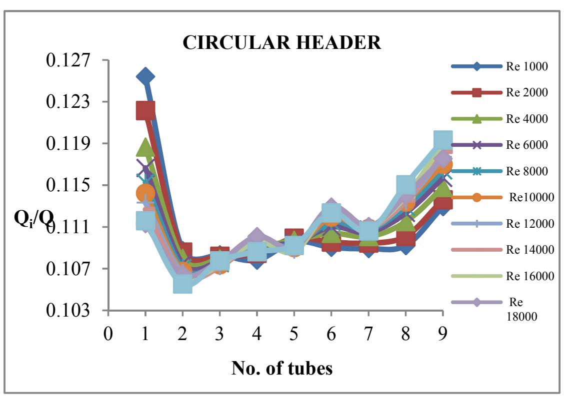

Figure-5. Flow ratio and no. of tubes for circular header.

8.3. Effect of rectangular header on flow distribution

The Figure-6 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 maximum at the rear part of the header. And there is a slight decrease in the flow ratio at the initial tubes when the Reynolds Number is increased.

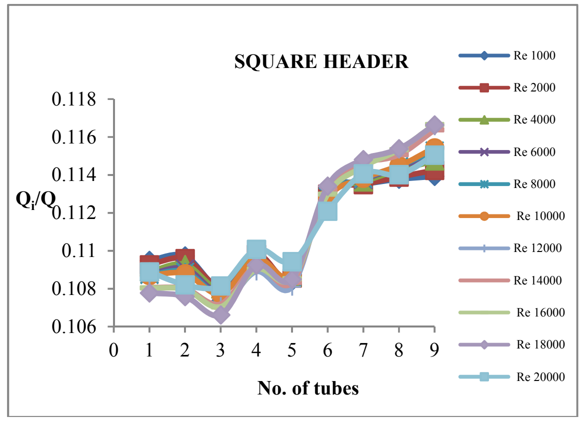

Figure-6. Flow ratio and no. of tubes for rectangular header.

8.4. Effect of square header on flow distribution

The Figure-7 gives the relation between the flow ratio 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 in 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.

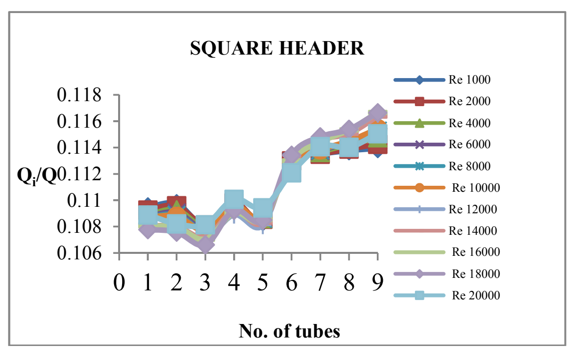

Figure-7. Flow ratio and no. of tubes for square header.

8.5. Effect of triangular header on flow distribution

The Figure-8 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 4^{th} tube and there is a uniform flow of the fluid in all the other tubes.

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For Reynolds Number ranging from 1000-6000 there is a high flow ratio at the 4^{th} tube and the flow ratio at remaining Reynolds Number ranging from 8000-20000 give a uniform flow.

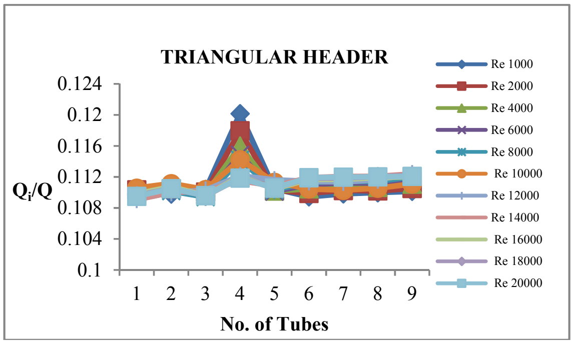

Figure-8. Flow ratio and no. of tubes for triangular header.

8.6. Non uniformity

The Figure-9 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.

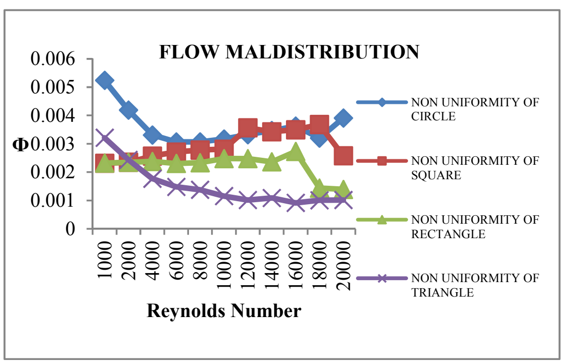

Figure-9. Non uniformity and Reynold no. for different cross sectional header.

8. DISCUSSIONS

The Figure-10 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 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.

9. CONCLUSIONS

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.

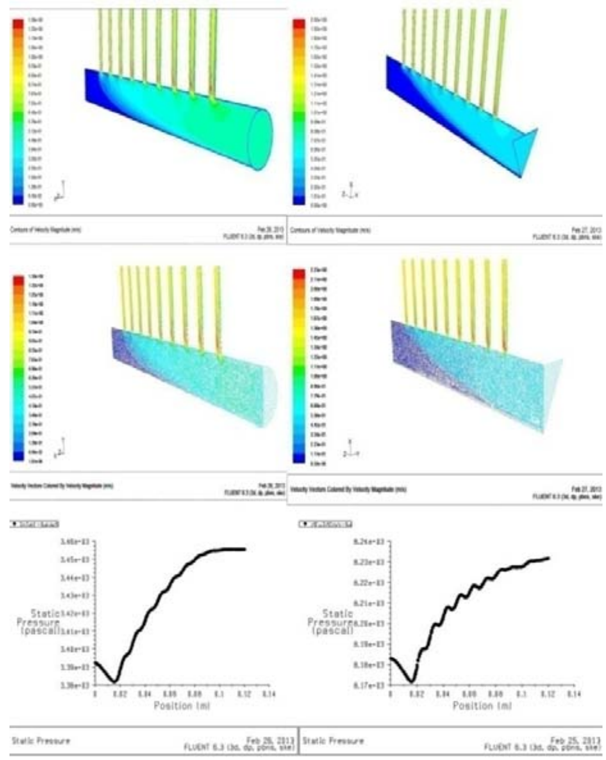

Figure-10. Velocity contour, velocity vector plot and static pressure graph for circular header and triangular header.

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