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A numerical investigation of fluid flow maldistribution in inlet header configuration of plate fin heat exchanger

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Abstract

The common assumption made for the design of heat exchangers is that the fluid flow in the header and core part is uniform. It is found that the flow maldistribution is very significant in the direction normal to the flow direction in inlet header of the plate fin heat exchanger. In the present work numerical analysis of a plate fin heat exchanger accounting for the effect of fluid flow maldistribution in inlet header configuration of the heat exchanger is investigated. Various inlet configuration has been studied for various Reynolds Number. A modified header configuration with double baffle plate having two arrangements are proposed and simulated. The two dimensional parameters are used to evaluate the flow non-uniformity in header, gross flow maldistribution parameter (S_g), velocity ratio (θ). A validation of numerical work is done by comparing results of numerical analysis for conventional header with the experimental results from the literature. A series of velocity vectors and streamline graphs at different cross-section. The numerical results indicate that the flow maldistribution is serious in conventional header, while in the improved configuration less maldistribution occurs. The flow maldistribution parameter (S_g) and velocity ratio (θ) is less in improved configuration as compared with conventional header. The improved header can effectively enhance the efficiency of plate fin heat exchanger and uniformity of flow distribution.

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Keywords: flow maldistribution, plate fin heat exchanger, velocity ratio, inet header.

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1. Introduction

Plate-fin heat exchangers are employed in a wide variety of energy conversion applications such as power plants, petrochemical plants, radiators of transport vehicles to name a few and they exchange heat energy among two-fluids with different supply temperatures. A large extent of energy transfer takes place in these types of heat exchangers which are used in different applications. The heat exchangers used in these applications consume significant portion of energy, so improvement in the efficiency of plate and fin heat exchangers will save significant amount of energy. A major advantage of the plate fin heat exchanger over a conventional heat exchanger is that the fluids are exposed to a much larger surface area because the fluids spread out over the plates. In the design of the plate fin heat exchanger, it is generally assumed that the fluid flow distribution is uniformly distributed among all the parallel fin passages through the heat exchanger core. But in actual practices, it is impossible to distribute the fluid flow uniformly because of flow maldistribution. Flow maldistribution is a non-uniform distribution of mass flow rate in a heat exchanger core. Flow maldistribution depends on several factors such as heat exchanger's geometrical configuration (i.e. mechanical design, channel and header geometry and dimensions, manufacturing tolerances or imperfections), operating conditions (flow velocity changes along the headers, fluid viscosity, and multiphase flow). Flow maldistribution is a very important factor and it affects the performance of heat exchanger to large extent [1-2]. Jian Wen and Yanzhong Li [3] analysed the fluid flow maldistribution for the conventional header used in industry. According to him, a baffle with small holes of three different kinds of diameters was recommended to be installed in the header to control the flow maldistribution in the heat exchanger. The numerical result obtained effectively improved the performance of the heat exchanger. Zhang and Li Yanzhong [4] proposed a two modified headers with a two stage distributing structure to reduce the flow non-uniformity. They proved that the fluid flow distribution in plate-fin heat exchangers was more uniform if the ratios of outlet and inlet equivalent diameters for both headers are equal. Ranganayakulu and K. N. Seetharamu [5] studied a cross flow plate-fin compact heat exchanger, accounting for the combined effects of two-dimensional longitudinal heat conduction through the exchanger wall and non-uniform inlet fluid flow and temperature distribution was being carried out by using a finite element method. Jiao et al. [6] experimentally investigated the header configuration on flow maldistribution in plate fin heat exchanger. Their study suggests that the performance of flow distribution in plate fin heat exchanger has effectively improved by optimum design of the header configuration. Zhang and Yanzhong Li [7] studied analytically two stage flow distribution in header with inlet equivalent diameters in plate fin heat exchanger. It was verified that the fluid flow distribution in plate-fin heat exchangers was more uniform if the ratios of outlet and inlet equivalent diameters for both headers were equal. L. Sheik Ismail et al.[8] performed CFD analyses for three different types of heat exchanger with fin geometries in order to study the effect of flow maldistribution on the performance of heat exchanger. Modified header was proposed for improving the flow maldistribution for three heat exchangers. Three offset strip fins and 16 wavy fin used in for thermal simulation and j and f vs. Re design data are generated using CFD analysis only for turbulent flow region. M. A. Habib et al. [9] did CFD investigation on the flow maldistribution in air-cooled heat exchangers. The effects of the number of nozzles, nozzle location, nozzle geometry, nozzle diameter, and inlet flow velocity and the incorporation of a second header on the flow maldistribution inside the tubes of an air-cooled heat exchanger. The results indicate that incorporating a second header, a significant reduction in the flow maldistribution. In present work a modified header with different arrangement of baffle plate is proposed. The flow characteristics in the modified header are studied numerically.

Nomenclature

$\mathbf{S_g}$	gross flow maldistribution parameter
θ	velocity ratio
N	channel number
V_{max}	maximum Velocity
V_{min}	minimum Velocity
V_i	local Passage velocity
V_{avg}	average Passage velocity

2. Physical Model and Mathematical Model

2.1 The Physical Model

Four types of headers of plate fin heat exchanger are analysed using the CFD software FLUENT in order to study the flow maldistribution effect. The four types namely case 1, case 2, case 3 and case 4 are modelled in Design Modular. Case 1 shown in fig. 01 (a) is a conventional header which has the geometrical dimensions as follows, The Diameter of the inlet pipe is equal to 200 mm, the radius of the header is 154 mm and the length of the header is equal to 905mm. The case 2 is a double pass header with punched inline baffle plate inserted between the header. The holes in the baffle plate are of three different diameters as shown in figure 2 (a) in which the inline arrangement of holes is used. The diameters of hole used was10 mm, 20 mm and 30 mm respectively. In case 3 and case 4 shown in fig. 01 (b) the two types of baffle plates are used. The first baffle plate used is same as that of the case2 and second baffle plate is made of five holes with gradually increasing diameter and arranged along the centre axis of the header.

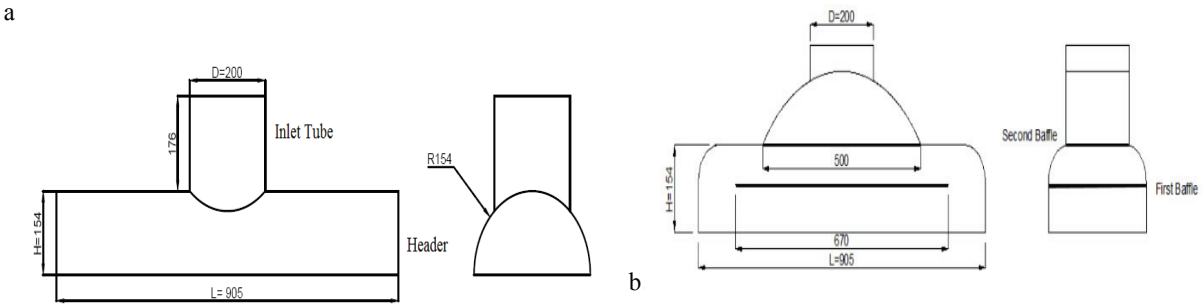

Fig. 1 Schematic drawing of header configurations (a) Conventional header (b) Modified header

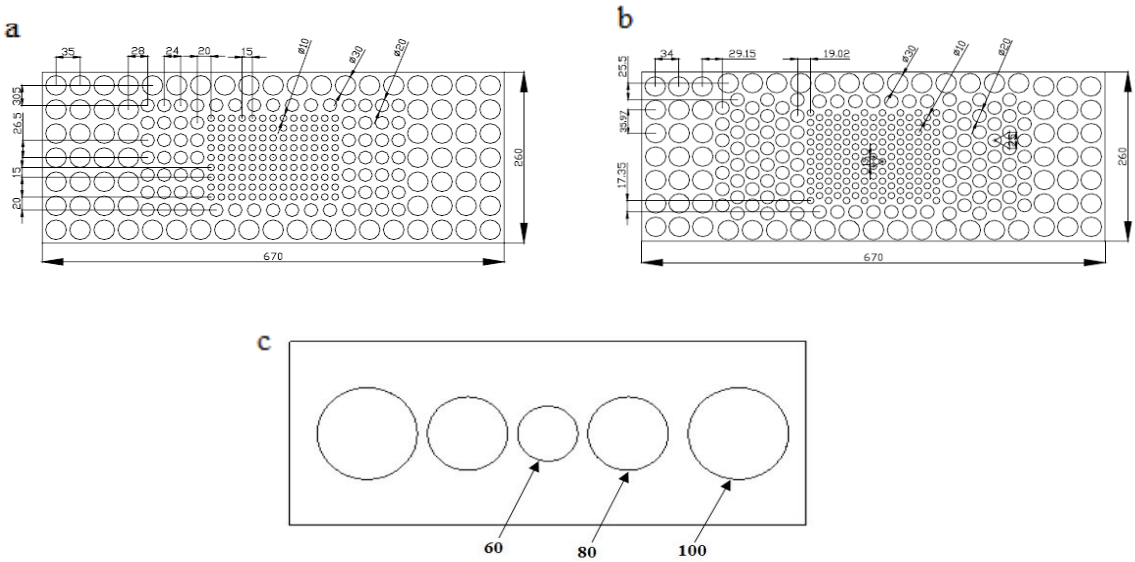

Fig. 2 Baffle plate arrangement used in inlet header configuration a) Inline arrangement [3] b) staggered arrangement [3] c) second baffle plate.

2.2 The mathematical model

Following are some the assumptions made in the CFD simulations; 1. The flow is stable in the extracted fluid domain. 2 The Fluid flow meets the boussinesq assumption and 3. The fluid in the domain is incompressible.

In this work CFD software FLUENT was employed to simulate the fluid flow distribution in the header of the plate fin heat exchanger. In FLUENT the conservation equation of mass, momentum and energy are solved using finite volume method. There are several turbulence models available in the code. The turbulence flow is calculated by the Semi-implicit SIMPLER method in the velocity and pressure conjugated problem and second order upwind differential scheme applied for the convective term. A realizable K-ε model was used to predict the turbulence flow in the header. The conservation equations are,

Mass Balance,

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Momentum Balance

x- momentum equation,

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\nu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

y- momentum equation,

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{\partial p}{\partial y}+\nu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right]$$

z- momentum equation,

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{\partial p}{\partial x}+\nu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right] \tag{2}$$

Boundary condition and convergent condition are as follows; At the Inlet fluid velocity is given and the pressure at the outlet vent is given. Adiabatic wall condition is applied and no slip occurs at the wall. Convergent criteria is specified to absolute residuals ≤ 1.0 x 10^-6.

2.3 Evaluation of flow maldistribution

In this work for the calculation of flow maldistribution two parameters are used, namely gross flow maldistribution parameter, and velocity ratio, which are denoted as S_g and θ respectively. They are defined as follow [4].

$$S_g=\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(V_i-V_{avg})^2} \tag{3}$$

$$\theta=\frac{V_{max}}{V_{min}} \tag{4}$$

Where N stands for the passage number, V_i stands for local passage velocity, V_{avg} stands for Average passage velocity. V_{max} and V_{min} is the maximum and minimum velocity of all passage.

2.4 Grid Intendancy Test

A grid independency study is performed to see that grid size do not affect the results of numerical simulation. Three grid sizes of tetra mesh were used for simulation of case 1 header viz. (i) course grid (ii) fine grid and (iii) Finer grid, the total number of fine grid element nearly 320000. The average velocity with course, fine and finer grid are 0.76332, 0.72773 and 0.73286 resp. One can observe that average velocity for three cases almost overlaps and nature of graph is also similar. This shows that the grid size do not affect the results of the simulation. Hence the fine grid size is chosen for further simulations.

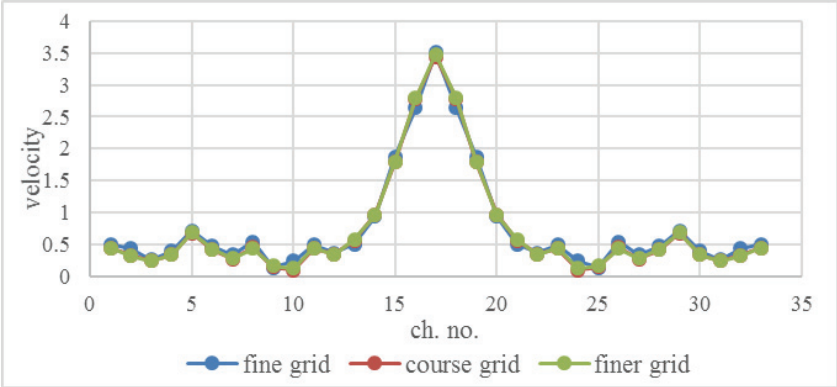

Fig. 3 Grid independency study.

3.0 Results and discussion

In this section results obtained by simulation are discussed. Firstly the numerical simulation for case1 (conventional header) is presented for three different Reynolds number. These results are then compared with the experimental work of Jian Wen et al. [3] for the validation of the model used in simulation. After this three cases of modified header with different arrangement of baffle plates are discussed. The two parameters are calculated for flow maldistribution analysis for all cases.

3.1 Results of Conventional Header

The results of conventional header are presented in this section and these results are used for the validation of the model. The result are split into two group; 1. Qualitative Result and 2. Quantitative Result. So as in qualitative analysis the velocity vectors and streamline graph are plotted along the four cross section as shown in fig.02.

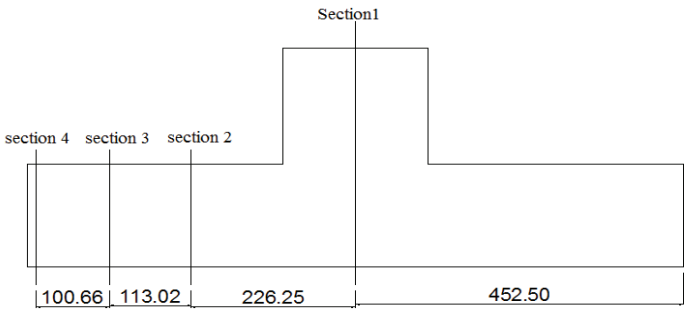

Fig. 4 Schematic diagram of plane location for testing.

The analysis is performed under the similar Reynolds number used in experiment done in literature (Re=60000, 50000, 40000). The velocity vectors and streamline graphs are plotted and compared with the experimental data. In the experimental work the velocity vectors and streamline graphs are plotted with the help of PIV (Particle Image Velocimetry) technique. These graphs show the inlet flow and vortex generation in the domain. The figure 5 and figure 6 shows the velocity vectors and streamline for different cross sections as shown in fig. 4. In the cross section 1 (fig. 4) the results shows that the flow maldistribution is very serious in normal direction to the flow velocity. The velocity is high at the central part of the header and reduces along the length of the header. Due to the sudden enlargement of the geometry the flow behaviour varies from inlet and the main flow separates from the surface resulting the generation of vortex. There is loss of Kinetic energy and pressure due to the generation of vortex. The

cross section 2 (Fig.4) is shifted along the length of the header. As the distance increases from inlet tube a small vortex enlarges gradually into a large scale vortex. So it can be concluded that the fluid is mainly distributed by the diffusion of vortex. The cross section 3 and cross section 4 is at the boundary of the header and observed that the distance between the section and inlet tube is increases the vortex may vanish at the end.

a b

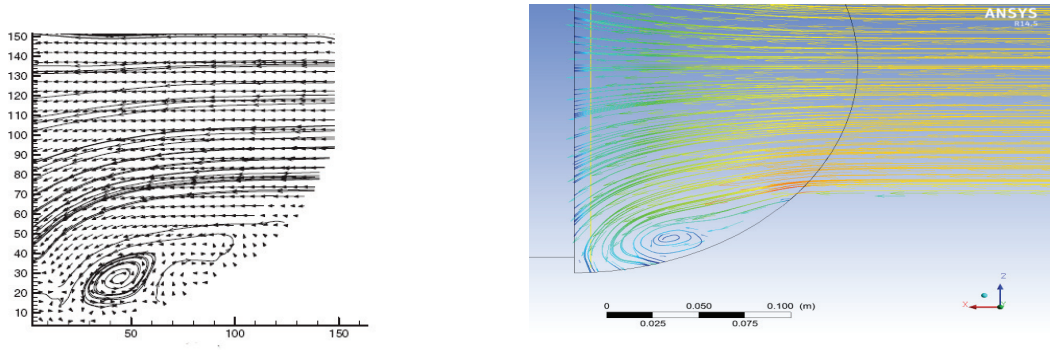

Fig. 5 Velocity vectors and streamline graph of case 1 header configuration for cross section 1 (a) experimental [3] (b) CFD

a b

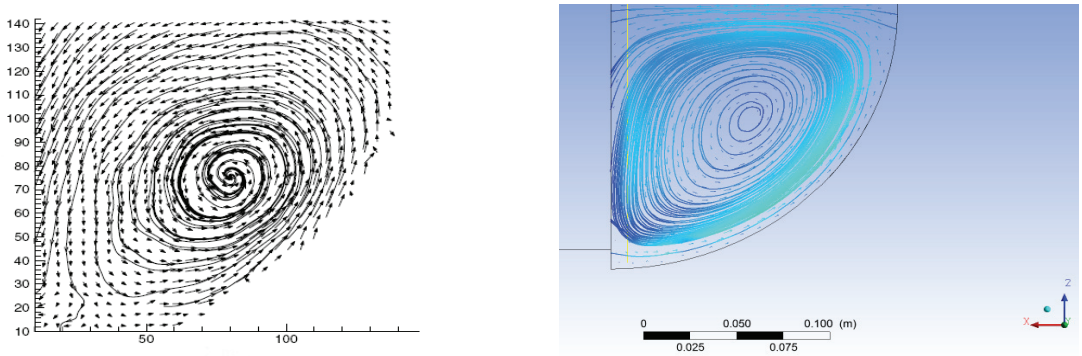

Fig. 6 Velocity vectors and streamline graph of case 1 header configuration for cross section 2 (a) experimental [3] (b) CFD

Table 01 represents the quantitative comparison between the CFD and experimental work. The flow maldistribution parameter along the header length of header configuration is calculated by using the equations 3-4. The results are used for the validation of the model used in simulation.

Table 1. Flow maldistribution Parameter comparison with literature.

Reynolds Number	**60000**		**50000**		**40000**	
	CFD	Jian Wen[3]	CFD	Jian Wen[3]	CFD	Jian Wen[3]
S_g	1.176	1.210	0.964	1.118	0.7411	0.778

3.2 Results of modified headers

The fluid flow distribution in header configuration with gross flow maldistribution parameter for all the cases of header for three Reynolds number (Re= 60000, 50000, 40000) is illustrated in table 2. The velocity of fluid is maximum in the centre part of the header and less in two ends of the conventional header and hence the flow maldistribution is high in conventional header. The results show that the maldistribution is serious in case1 header. In case 2 the distribution of flow along the length is improved by addition of punched baffle plate in the header and reduces the velocity at the centre part of the header. The velocity is nearly uniformly distributed in the improved

header configuration but in case 2 type headers due to baffle plate the average velocity is reduced significantly that means the loss of kinetic energy. The flow maldistribution parameter in case 2 is less as compared with case 1 type header. The double baffle plate having inline and staggered arrangement of punched hole of case 3 and case 4 type modified header the flow is well distributed with improved average velocity so the gross flow maldistribution parameter is less as compared with conventional header. The difference between the two values shows that the flow distribution is uniform in modified header of case 3 and case 4. As the values of S_g for case 4 is smaller as compared with the case3, case2. The case 4 configuration is better than the all other configurations of header and is because of insertion of two baffle plate with different punched holes into the header which improves the flow distribution. Also it is observed that in analysis effect of Reynolds number on the performance of flow maldistribution parameter, the flow maldistribution parameter reduces simultaneously with the reduction in Reynolds number.

Table 2. Flow maldistribution parameter for all case and different Reynolds Number.

Reynolds Number	60000	50000	40000
S_g Case 1	1.1760	0.9635	0.7411
S_g Case 2	0.3363	0.2812	0.2134
S_g Case 3	0.3974	0.3649	0.2998
S_g Case 4	0.2934	0.2536	0.2317

Different velocity contours for all header configurations is shown in fig. 7. The velocity contours shows that the velocity distribution at the centre part of a conventional header is high which results a non uniformity of flow in conventional header while improved header configuration with punched single baffle plate improves the non uniformity along the length but reduces the velocity at the end of header length. Fig. 7 (c) and (d) shows the velocity contours of the case 3 and case 4 arrangement. Two baffle plates are inserted into the header in each cases with inline arrangement for case 3 and staggered arrangement in the case 4 respectively. The baffle plates are inserted to see the effect on the flow distribution. Velocity contours of case 3 and case 4 shows that the velocity distribution is uniform along the header length. This is because of insertion of the plate and modification of the header.

a b c d

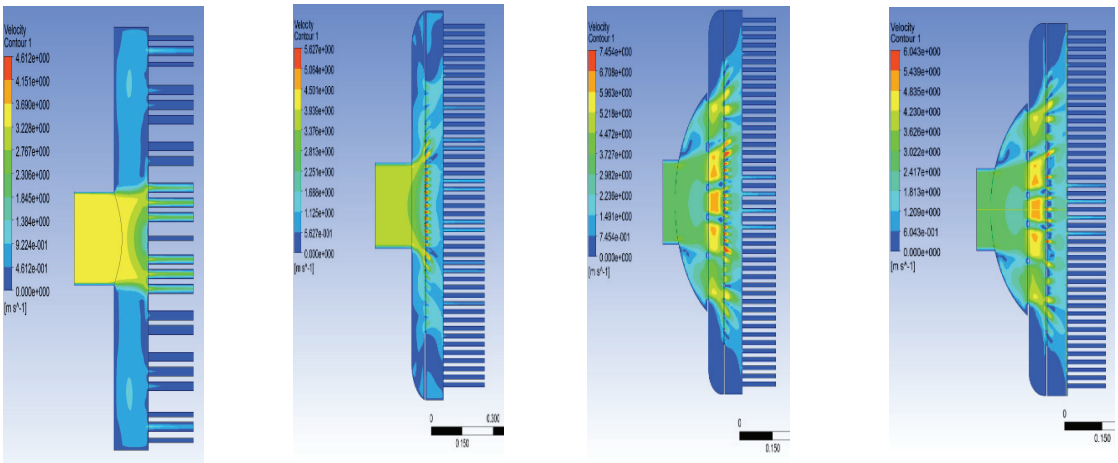

Fig. 7 velocity contours of all header configurations. (a) Conventional baffle plate (b) header with single baffle plate (c) modified header with double baffle plate (inline arrangement) (d) modified header with double baffle plate (staggered arrangement)

Table 3 shows the average velocity for three Reynolds number for all types of the header configurations. As can be seen from the results of case 2, which is a header with single baffle plate inserted into the header, the average velocity decreases from 1.64418 (Conventional header) to 1.029307. Reduction in average velocity is because of punched hole arrangement in single baffle plate, which results in the reduction in kinetic energy. As shown in table

3, the average velocity for all the Reynolds number for case 2 is less as compared with case 3 and case 4. Increase in average velocity in case 3 and case 4 is due to the double baffle arrangement. So, we can say that in case 3 and case 4, the loss in kinetic energy is recovered significantly, which in turn will increase the effectiveness of the heat exchanger for these cases.

Table 3 Average velocity for all cases and all Reynolds number

Case	Re=60000	Re=50000	Re=40000
Case 1	1.64418	1.308917	0.842614
Case 2	1.029307	0.914393	0.747628
Case 3	1.743004	1.327429	1.141219
Case 4	1.829282	1.414296	1.126841

The velocity ratio θ for all cases and Reynolds number is shown in table 4. The velocity ratio is high in conventional header as compared with modified header. Because of velocities at the extreme ends of case 1 header are lower for most of the fluid which is been flowing in centre part. So the velocity ratio is maximum in case1. In the modified header case 2 type velocity at the end of header length is reduced which leads to loss of kinetic energy. By the use of baffle plate the uniform velocity is distributed and the velocity ratio reduces.

Table 4 velocity ratio for all cases and all Reynolds number.

Case	60000	50000	40000
Case1	12.581	6.25114	29.2286
Case2	3.0111	4.8167	4.9375
Case3	2.07172	2.2847	2.5818
Case4	1.98187	1.9693	2.27026

4. Conclusion

In the present work the fluid flow maldistribution in conventional as well as modified inlet header configuration of plate-fin heat exchanger is studied numerically. Steady state computational fluid dynamics (CFD) models was simulated by using ANSYS Fluent. Simulations are done for the Reynolds number of 40000, 50000 and 60000. It can be concluded from the present study that Modified header configuration gives better velocity distribution in axial as well as radial direction. The results validate that CFD is well suitable to investigate complex flow pattern. The use of modified header configuration with double baffle plate having arrangement of inline and staggered, leads to the uniform flow distribution and improved flow maldistribution parameter. With the use of modified header with double baffle plates the kinetic energy is recovered which in turn will improve the effectiveness of heat exchanger. This type of modified header configuration can be used for the design of heat exchanger for effective performance. The conclusion of this paper is of great significance in the improvement of plate-fin heat exchanger.

References

[1] Shah R. K, Fundamentals of Heat Exchanger Design, John Wiley & Sons Publication, 2003.
[2] Kays W. M., A. L. London, Compact Heat Exchangers, reprint 3rd ed., Krieger Publish- ing, Malabar, FL 1998.
[3] Jian Wen, Yanzhong Li, Experimental investigation of header configuration improvement in plate–fin heat exchanger, Applied Thermal Engineering, 27 (2007) 1761–1770.
[4] Zhang Zhe, Li Yanzhong, Experimental Research on flow maldistribution in plate-fin heat exchanger, Chinese J. Chem. Eng., (2004)12 (1) 7-13.
[5] C h. Ranganayakulu, K. N. Seetharamu,The combined effects of wall longitudinal heat conduction and inlet fluid flow maldistribution in crossflow plate-fin heat exchangers, Heat and Mass Transfer 36 (2000) 247 ± 256.
[6] Anjun Jiao ,Rui Zhang , SangkwonJeong, Experimental investigation of header configuration on flow maldistribution in plate-fin heat exchanger, Applied Thermal Engineering 23 (2003) 1235–1246.
[7] Zhe Zhang, YanZhong Li, CFD simulation on inlet configuration of plate-fin heat exchangers, Cryogenics 43 (2003) 673–678.

[8] L. Sheik Ismail, C. Ranganayakulu,Ramesh K. Shah, Numerical study of flow patterns of compact plate-fin heat exchangers and generation of design data for offset and wavy fins, International Journal of Heat and Mass Transfer 52 (2009) 3972–3983.
[9] M. A. Habib, R. Ben-Mansour, S. A. M. Said, Correlations of flow maldistribution parameters in an air cooled heat exchanger, Int. J. Numer. Meth. Fluids 2008 56:143–165.
[10] Li-Zhi Zhang, Flow maldistribution and thermal performance deterioration in a cross-flow air to air heat exchanger with plate-fin cores, International Journal of Heat and Mass Transfer 52 (2009) 4500–4509.
[11] Anjun Jiao, SeungwookBaek, Effects of Distributor Configuration on Flow Maldistribution in Plate-Fin heat exchanger, Heat Transfer Engineering, 2005 26(4) 19–25.
[12] SeungwhanBaek, Cheonkyu Lee, SangkwonJeong, Effect of flow maldistribution and axial conduction on compact microchannel heat exchanger, Cryogenics 60 (2014) 49–61.
[13] R.Manikanda Kumaran, G. Kumaraguruparan, T. Sornakumar, Experimental and numerical studies of header design and inlet/outlet configurations on flow mal-distribution in parallel micro-channels, Applied Thermal Engineering 58 (2013) 205e216.
[14] M.A. Habib, R. Ben-Mansour, S.A.M. Said, M.S. Al-Qahtani, Evaluation of flow maldistribution in air-cooled heat exchangers, Computers & Fluids 38 (2009) 677–690.
[15] J.N. Mao, H.X. Chen, H. Jia, Y.Z. Wang,H.M. Hu, Effect of air-side flow maldistribution on thermal-hydraulic performance of the multi-louvered fin and tube heat exchanger, International Journal of Thermal Sciences 73 (2013) 46e57.
[16] A.A. Aganda, J.E.R. Coney, C.G.W. Sheppard, Air flow maldistribution and the performance of a packaged air conditioning unit evaporator, Applied Thermal Engineering 20 (2000) 515-528.