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Design Optimization of Cross Flow Heat Exchanger

K. Ashok Kumar Raju[1], M. Vijay Kumar Reddy[2], A. Nagaraja[3]
[1,2,3]*Department of Mechanical Engineering, A.I.T.S, Rajampet*

Abstract— **Heat exchangers are catching more and more attention for their applications in Space heating, refrigeration, Air-conditioning, Power plants, Chemical Plants, Petro chemical plants and Natural gas plants. The Effectiveness of Heat exchanger plays major role while selecting a suitable Heat exchanger for respective application. Effectiveness can be found out by Theoretical approach, which includes lot of approximation, or Practical method, which includes prototyping and testing or Numerical method, it's a well proven method in modern days. Since the experiments cost long periods and great expenses than the numerical methods. Simulation based on computational fluid dynamics (CFD) [2] is a good approach to adapt.**

In this work, the authors have tried to optimize the Heat exchanger to get maximum effectiveness, by changing baffle arrangements. Totally five different baffle designs where considered to carry out the CFD analysis and to find the most effective design

Keywords— Optimization, Cross flow heat exchangers, Hypermesh, STAR-CCM, CFD Analysis.

I. INTRODUCTION

A heat exchanger is a device built for efficient heat transfer from one medium to another, whether the media are separated by a solid wall so that they never mix, or the media are in direct contact. They are widely used in space heating, refrigeration, air conditioning, power plants, chemical plants, petrochemical plants, petroleum refineries and natural gas processing. One common example of a heat exchanger is the radiator in a car, in which the heat source, being a hot engine-cooling fluid, water, transfers heat to air flowing through the radiator [i.e. the heat transfer medium].

Flow Arrangement

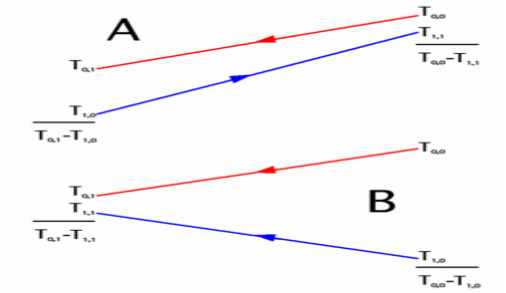

Figure.1: Flow Arrangement; A - Counter flow; B – Parallel Flow

Heat exchangers [3] may be classified according to their flow arrangement. In parallel-flow heat exchangers, the two fluids enter the exchanger at the same end, and travel in parallel to one another to the other side. In counter-flow heat exchangers the fluids enter the exchanger from opposite ends. The counter current design is most efficient, in that it can transfer the most heat from the heat transfer medium. In a cross-flow heat exchanger, the fluids travel roughly perpendicular to one another through the exchanger.

For efficiency, heat exchangers are designed to maximize [6] the surface area of the wall between the two fluids, while minimizing [6] resistance to fluid flow through the exchanger. The exchanger's performance can also be affected by the addition of fins or corrugations in one or both directions, which increase surface area and may channel fluid flow or induce turbulence. The driving temperature across the heat transfer surface varies with position, but an appropriate mean temperature can be defined. In most simple systems this is the log mean temperature difference (LMTD). Sometimes direct knowledge of the LMTD is not available and the NTU method is used Effectiveness (ε) is defined as the ratio of the actual heat transfer rate for a heat exchanger to the maximum possible heat transfer rate.

$$\varepsilon = \frac{q}{q_{max}} = \frac{C_h\,(T_{h,i} - T_{h,o})}{C_{min}\,(T_{h,i} - T_{c,i})} = \frac{C_c\,(T_{c,o} - T_{c,i})}{C_{min}\,(T_{h,i} - T_{c,i})}$$

Types of heat exchangers

- Shell and tube heat exchanger
- Plate heat exchanger
- Regenerative heat exchanger
- Adiabatic wheel heat exchanger
- Plate fin heat exchanger
- Waste heat recovery units
- Dynamic scraped surface heat exchanger
- Phase change heat exchanger

Shell and tube heat exchanger:-

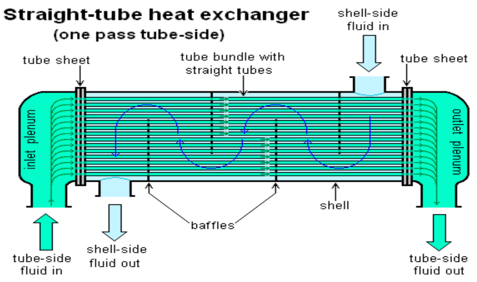

Figure.2. Shell and heat exchanger

Shell and tube heat exchangers consist of a series of tubes. One set of these tubes contains the fluid that must be either heated or cooled. The second fluid runs over the tubes that are being heated or cooled so that it can either provide the heat or absorb the heat required. A set of tubes is called the tube bundle and can be made up of several types of tubes: plain, longitudinally finned, etc. Shell and Tube heat exchangers are typically used for high pressure applications (with pressures greater than 30 bar and temperatures greater than 260°C.This is because the shell and tube heat exchangers are robust due to their shape. There are several thermal design features that are to be taken into account when designing the tubes in the shell and tube heat exchangers. These include:

Tube diameter: Using a small tube diameter makes the heat exchanger both economical and compact. However, it is more likely for the heat exchanger to foul up faster and the small size makes mechanical cleaning of the fouling difficult. To prevail over the fouling and cleaning problems, larger tube diameters can be used. Thus to determine the tube diameter, the available space, cost and the fouling nature of the fluids must be considered.

Tube thickness: The thickness of the wall of the tubes is usually determined to ensure:

- There is enough room for corrosion
- That flow-induced vibration has resistance
- Axial strength
- Ability to easily stock spare parts cost Sometimes the wall thickness is determined by the maximum pressure differential across the wall.

Tube length: heat exchangers are usually cheaper when they have a smaller shell diameter and a long tube length. Thus, typically there is an aim to make the heat exchanger as long as physically possible whilst not exceeding production capabilities. However, there are many limitations for this, including the space available at the site where it is going to be used and the need to ensure that there are tubes available in lengths that are twice the required length (so that the tubes can be withdrawn and replaced). Also, it has to be remembered that long, thin tubes are difficult to take out and replace.

Tube pitch: when designing the tubes, it is practical to ensure that the tube pitch (i.e., the centre-centre distance of adjoining tubes) is not less than 1.25 times the tubes' outside diameter. A larger tube pitch leads to a larger overall shell diameter which leads to a more expensive heat exchanger.

Tube corrugation: this type of tubes, mainly used for the inner tubes, increases the turbulence of the fluids and the effect is very important in the heat transfer giving a better performance.

Tube Layout: refers to how tubes are positioned within the shell. There are four main types of tube layout, which are, triangular (30°), rotated triangular (60°), square (90°) and rotated square (45°). The triangular patterns are employed to give greater heat transfer as they force the fluid to flow in a more turbulent fashion around the piping. Square patterns are employed where high fouling is experienced and cleaning is more regular.

Baffle Design: baffles are used in shell and tube heat exchangers to direct fluid across the tube bundle. They run perpendicularly to the shell and hold the bundle, preventing the tubes from sagging over a long length. They can also prevent the tubes from vibrating. The most common type of baffle is the segmental baffle. The semicircular segmental baffles are oriented at 180 degrees to the adjacent baffles forcing the fluid to flow upward and downwards between the tube bundles. Baffle spacing is of large thermodynamic concern when designing shell and tube heat exchangers. Baffles must be spaced with consideration for the conversion of pressure drop and heat transfer. For thermo economic optimization it is suggested that the baffles be spaced no closer than 20% of the shell's inner diameter. Having baffles spaced too closely causes a greater pressure drop because of flow redirection. Consequently having the baffles spaced too far apart means that there may be cooler spots in the corners between baffles. It is also important to ensure the baffles are spaced close enough that the tubes do not sag. The other main type of baffle is the disc and donut baffle which consists of two concentric baffles, the outer wider baffle looks like a donut, whilst the inner baffle is shaped as a disk. This type of baffle forces the fluid to pass around each side of the disk then through the donut baffle generating a different type of fluid flow.

Due to the many variables involved, selecting optimal heat exchangers is challenging. Hand calculations are possible, but much iteration is typically needed. As such, heat exchangers are most often selected via computer programs, either by system designers, who are typically engineers, or by equipment vendors.

In order to select an appropriate heat exchanger, the system designers [8] (or equipment vendors) would firstly consider the design limitations for each heat exchanger type. Although cost is often the first criterion evaluated, there are several other important selection criteria which include:

- High/ Low pressure limits
- Thermal Performance
- Temperature ranges
- Product Mix (liquid/liquid, particulates or high-solids liquid)
- Pressure Drops across the exchanger
- Fluid flow capacity
- Cleanability, maintenance and repair
- Materials required for construction
- Ability and ease of future expansion

Choosing the right heat exchanger (HX) requires some knowledge of the different heat exchanger types, as well as the environment in which the unit must operate. Typically in the manufacturing industry, several differing types of heat exchangers are used for just the one process or system to derive the final product. For example, a kettle HX for pre-heating, a double pipe HX for the 'carrier' fluid and a plate and frame HX for final cooling. With sufficient knowledge of heat exchanger types and operating requirements, an appropriate selection can be made to optimize [6] the process.

Problem description

In many researches held on Heat exchangers it is specified that effectiveness is the best way to measure its efficiency. So, in such cases, it is of extreme important to find the best design at which we get the Maximum effectiveness of Heat exchanger, which is the objective of this work.

To study the Effectiveness variation by varying the baffles in cross flow heat exchanger. Computational [5] validation of experimental data has rarely been conducted in the cross flow heat exchangers. The current work aims to not only add to the computational validations of cross flow heat exchangers [4] but also to thoroughly investigate the flow physics. Heat exchanger is well understood from a theoretical flow perspective but not as well from a computational aerodynamics perspective.

II. METHODOLOGY

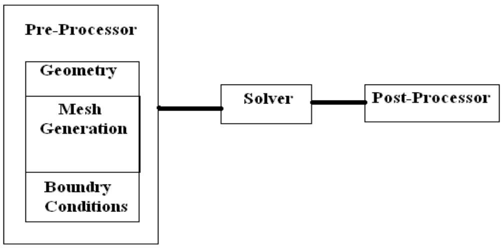

Figure.3. Methodology

Preprocessing:

Step 1: Construction of Geometry.

This problem has three geometries namely,

1. Hot fluid section
2. pipe section
3. cold fluid section

The geometries of given problem are created by using SOLIDWORKS software. The dimensions of the geometries are:

Shell cross section: 130 x 100 mm
Shell inlet and outlet : 80 x 80 mm
Height of the shell : 400mm
Tube internal diameter =46mm,
tube thickness =2mm
Length of tubes =420mm
No. of tubes=3

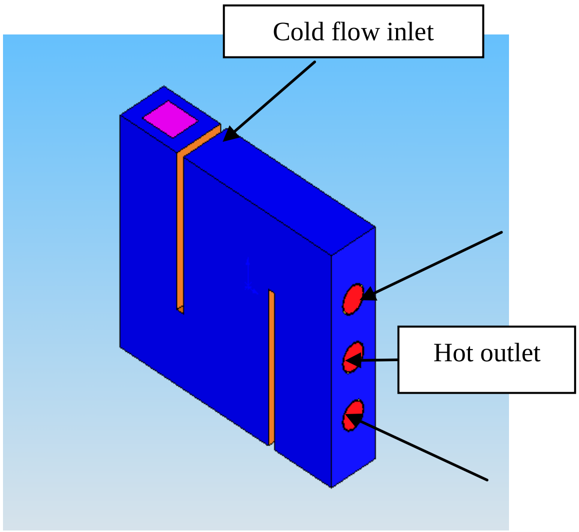

Figure.4. Crossflow heat exchanger with hotflow outlet and cold flow inlet

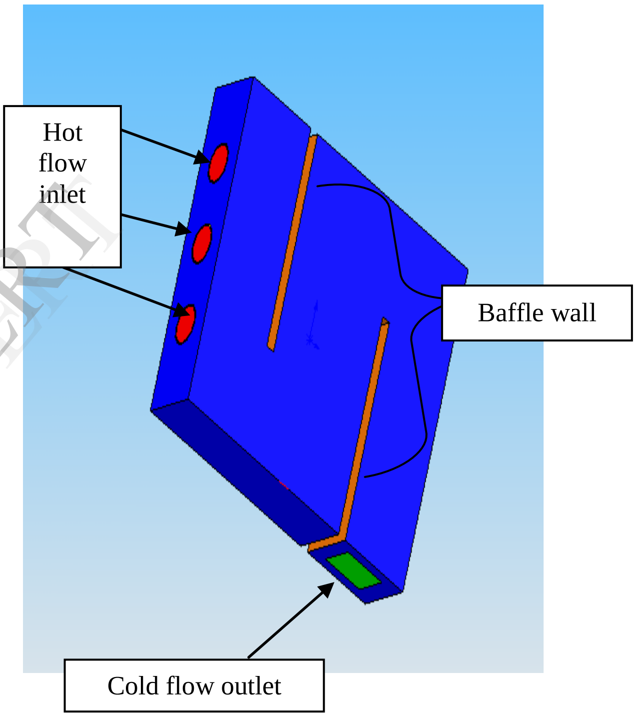

Figure.5.Crossflow heat exchanger with buffle walls, hot flow inlet and cold flow outlet

Step 2 : Meshing the Model

There are two types of meshing.

1. Surface mesh with triangular faces.
2. Volume mesh with Polyhedral and prism layer.

Since the geometries having some complexity[9], surface mesh was done by hypermesh [6] tool and volume mesh was generated in STAR-CCM+ with polyhedral faces.

Cell Type = Polyhedral

Total number of cells = 106352

No. Of interior faces = 423029

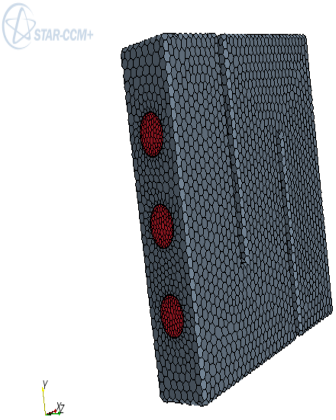

Figure.6.Meshed design space

Setting physics of the Problem

Since in this problem consists of three phases we need to select three physics, one for gas, second for liquid and another for SOLID.

Physics selected for gas and liquid :-

- Three Dimensional Flow.
- stationary
- Constant density
- Steady Flow.
- Segregated flow model
- TURBULENT FLOW with K-Epsilon model.

Physics selected for solid :-

- Three Dimensional Flow.
- STATIONARY
- CONSTANT DENSITY
- Steady Flow.
- Segregated solid energy.

The Boundary Conditions

In this problem there are two inlet one for coolant other for hot steam through the pipe, both are velocity inlet type. Similarly there are two outlets in which pressure outlet type for the hot steam (pipe fluid) and flow split outlet type for coolant outlet. The solid pipe cross section is given as symmetry type and remaining are keep as a wall which are smooth, no slip and adiabatic.

The velocity at both the inlet is 0.05 m/s. the pressure at the tube outlet is one atmosphere.

Coolant temperature =290k

Hot steam temperature = 420k.

Turbulent intensity is 5% for hot steam and 10% for coolant liquid used. The length scale are 5mm and 10mm for steam and coolant respectively.

Results and discussions:-

There are five cases have been analyzed by modifying length of the baffle.

Case-A:-

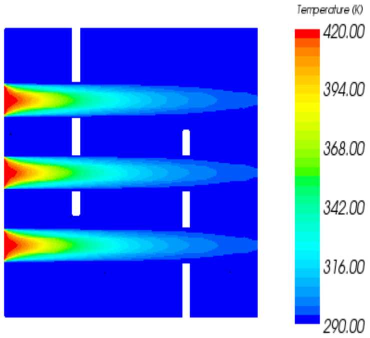

Figure.7. Temperature contour plot

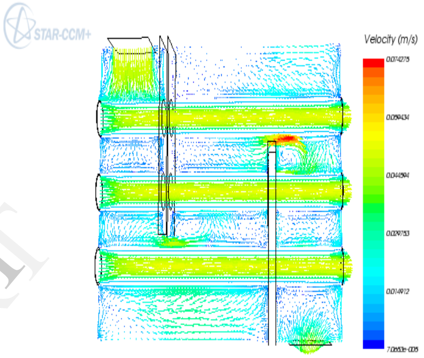

Figure.8. Velocity vector plot

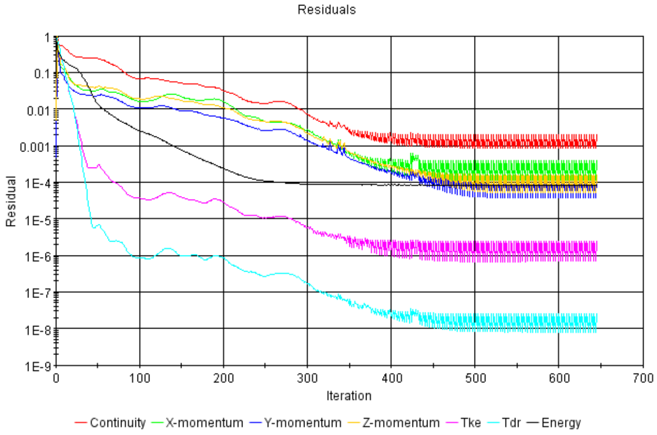

Figure.9. .Residual plot

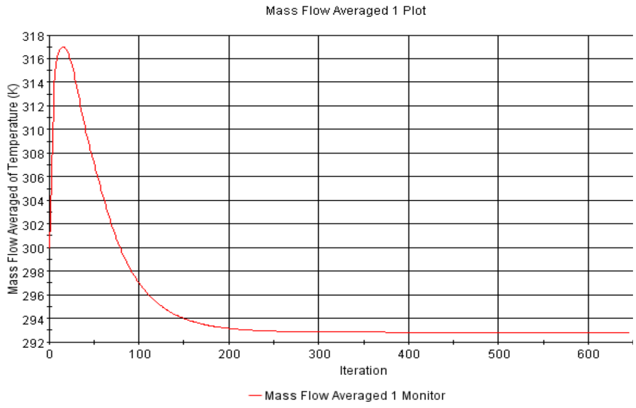

Figure.10.Hot outflow temperature plot

Case-B:-

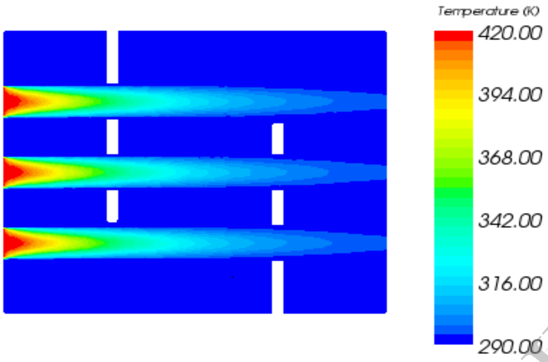

Figure.11. Temperature contour plot

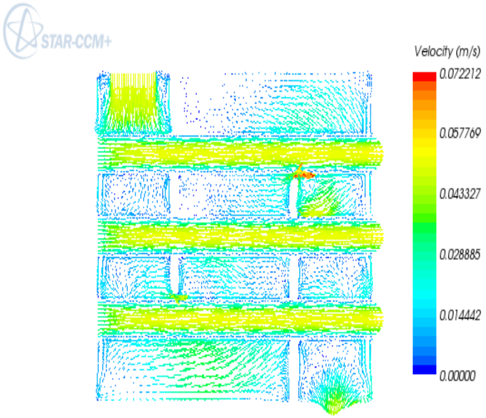

Figure.12. Velocity vector plot

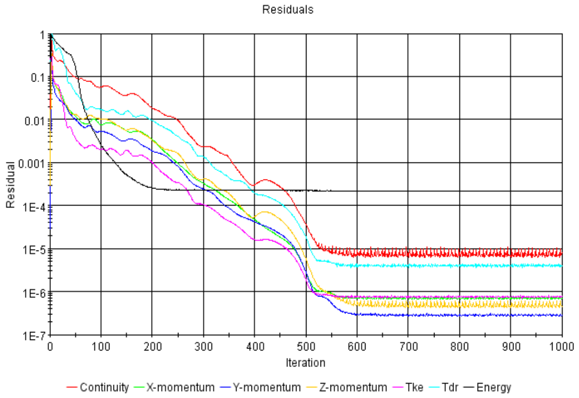

Figure.13. Residual plot

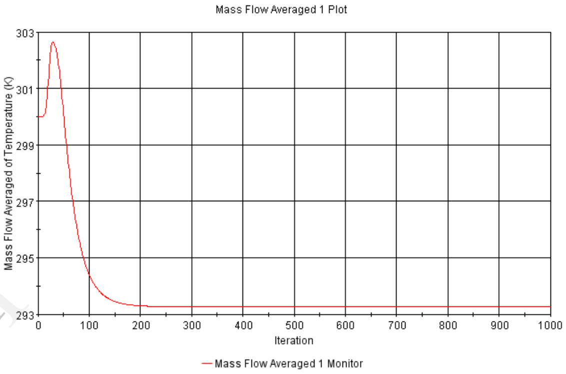

Figure. 14. Hot outflow temperature plot

Case-C:-

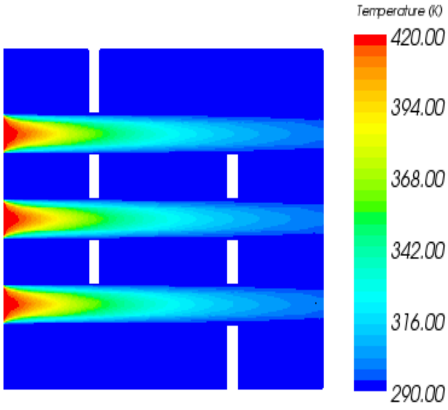

Figure.15. Temperature contour plot

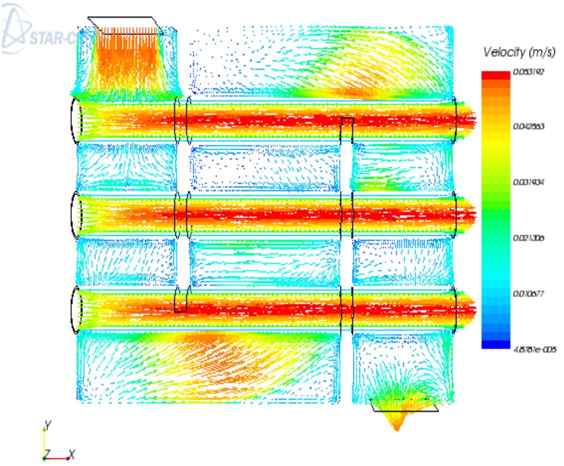

Figure.16.Velocity vector plot

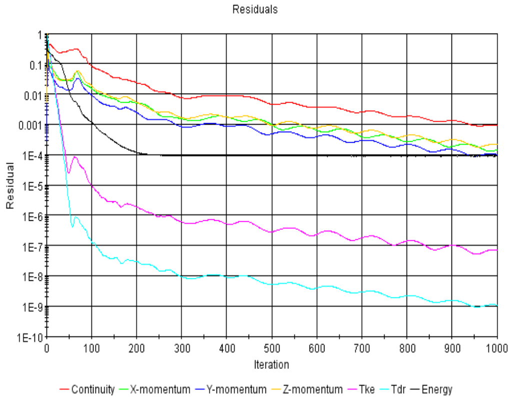

Figure.17.Residual plot

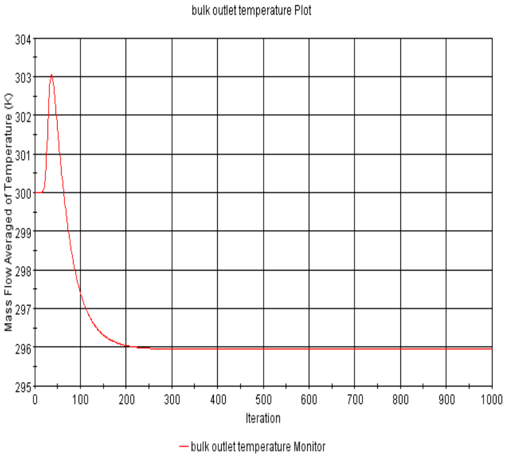

Figure.18. Hot outflow temperature plot

Case-D:-

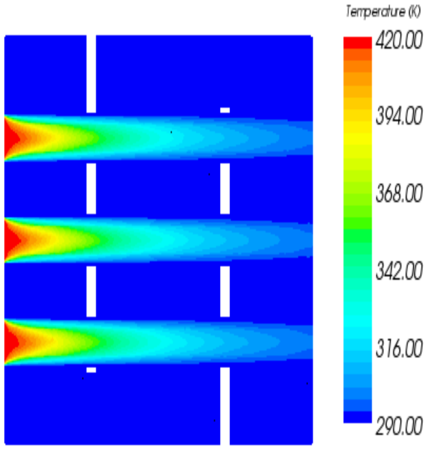

Figure.19.Temperature contour plot

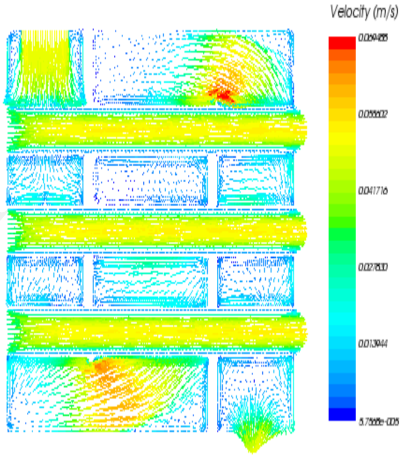

Figure.20. Velocity vector plot

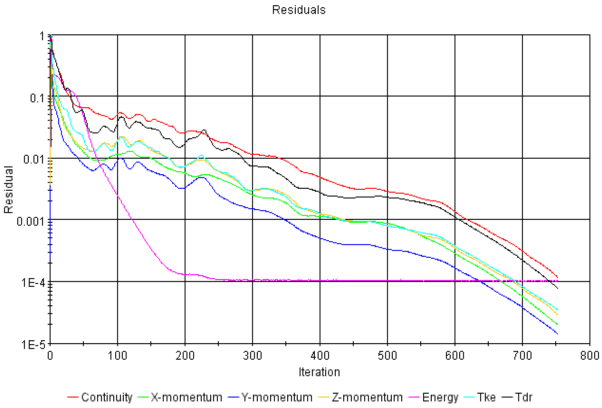

Figure.21.Residual plot

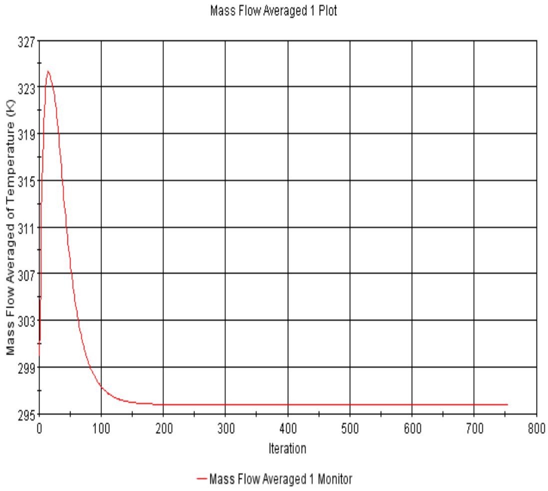

Figure.22. Hot outflow temperature plot

Case-E:-

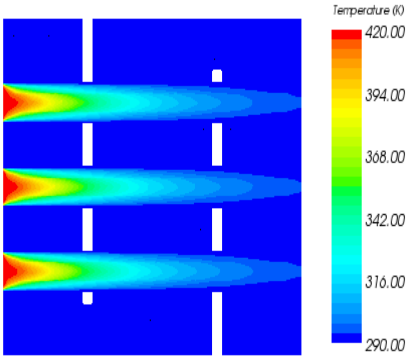

Figure.23.Temperature contour plot

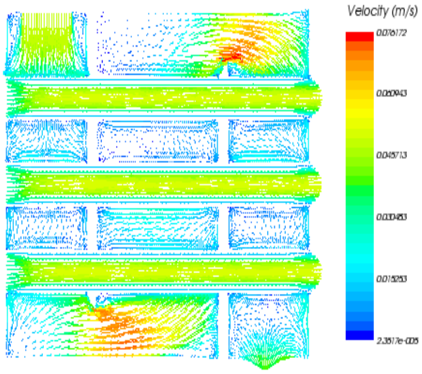

Figure.24.Velocity vector plot

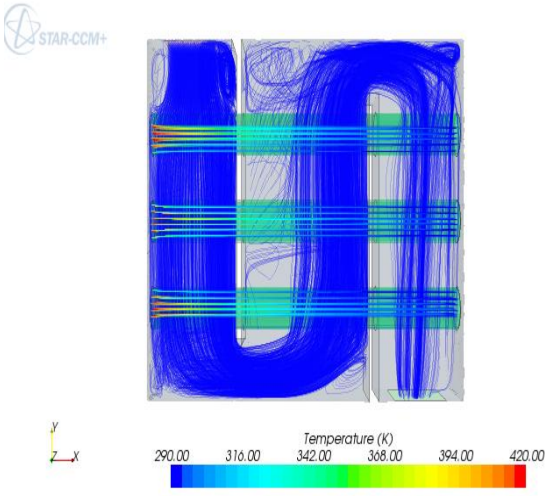

Figure.25. Streamlines plot

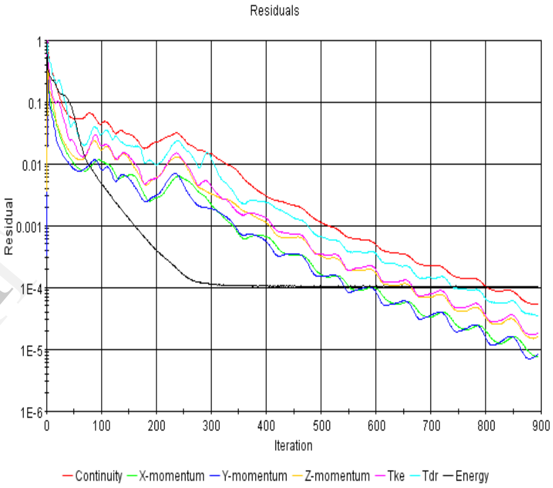

Figure.26. Residual plot

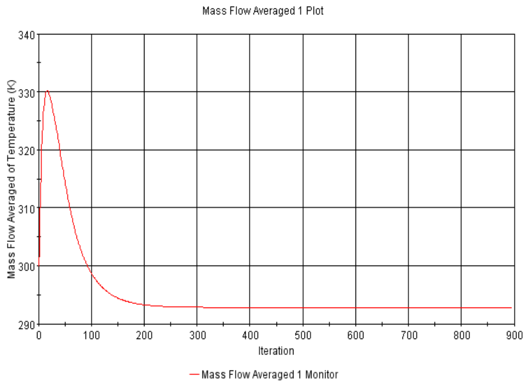

Figure.27. Hot outflow temperature plot

Table.1: Comparison of effectiveness values at various

case	Length of baffle (mm)	Outlet temperature(k)	Effectiveness (%)
A	260	292.813	0.978361538
B	270	293.262	0.974907692
C	300	295.95	0.954230769
D	330	295.75	0.955769231
E	340	292.80	0.978461538

baffle plate lengths

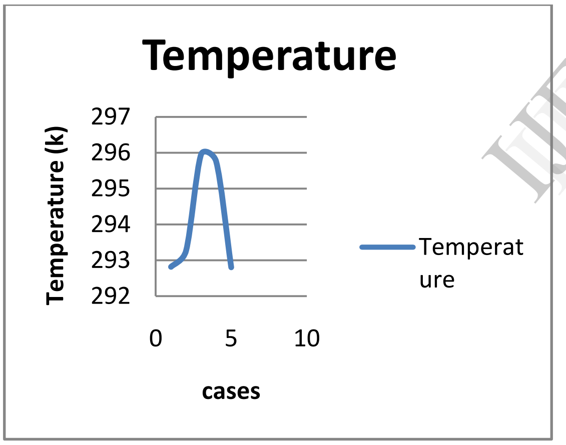

Figure.28. Temperature Variation after optimization

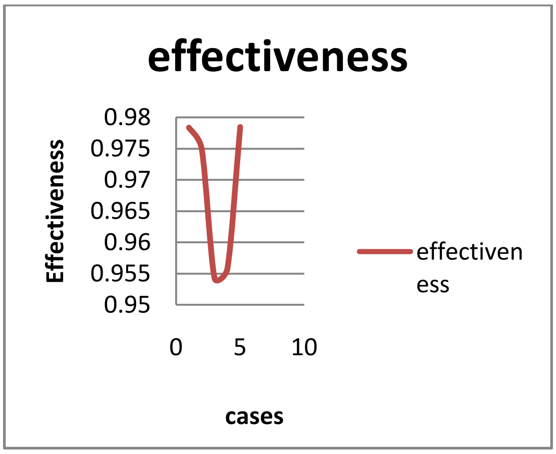

Figure.29. Effectiveness after optimization

III. CONCLUSIONS

The results states that simple modification in the baffle plate arrangement and design gives the significant changes in the effectiveness of the heat exchanger. In case A and E, the baffle length ends above and below the third tube, shows the good effectiveness and less dead regions are recirculation zones compared to the cases B and D. But in the case of C, the pressure buildup at the baffle end and so the recirculation zone is large. So if the tubes are fully submerged and the uniform flow over the tubes gives the better effectiveness.

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