

Effect of Plate orientation in a Cross-Flow Heat Exchanger with Metallic Finned Plates using CFD analysis

Sammam Rahman*, Anurag Nandi

Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh

ABSTRACT

Heat exchangers have become an integral part of our modern life from boilers in power generation industries to refrigeration systems in our households. Its main utilizations include evaporation, condensation, cooling and heating of fluids to achieve numerous thermal outputs, which are the desired outcomes of various thermodynamic cycles. Heat exchangers can be classified into parallel flow, counter flow, cross-flow and hybrid flow types, of which cross-flow is a type worth investigating for its higher efficiencies depending on the surface area it covers. This paper aims to dive into the possibilities of modifying a cross-flow type HX through analysis and comparison of the angular positions of metallic finned plates placed around the tubes. The objective of this analysis is to find a more efficient design among the conventional HX, which comprises of metallic plates with integrated fins placed in various angular positions along the fluid flow direction instead of conventional straight ones, that has the potential to facilitate more convection heat transfer and increase the system efficiency if implemented. The investigation will be conducted through CFD analysis in ANSYS Fluent, using hot and cold fluids to observe the rate of heat transfer between them as they circulate throughout the HX. The inlet and outlet temperature data of the fluids will be recorded, along with graphs showing the outlet temperature variation with each orientation change of the plates used in the HX design, thus, facilitating the final verdict on the heat transfer efficiency of these models. The generated data and graphs will be analyzed to compare the output temperatures of both hot and cold fluids, which will provide a logical illustration of the heat transfer capacity of the HX models with varying plate orientation, enabling to adopt a better design in heat transfer applications for higher efficiency and better feasibility.

Keywords: HX, Plates, Orientation, CFD, ANSYS



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1. Introduction

Thermal apparatus engineered to facilitate heat transfer between two fluids is termed as heat exchanger[1].The fluids circulating through the HX can be single or dual phase and can be either separated or in direct contact based on the type of HX used[2].The condition of separation is achieved through a separating wall having a high thermal conductivity which has the capacity to enable the exchange of heat between the source and working fluid while also restricting them from mixing[3].Classification of heat exchangers on the basis of fluid flow direction can be done in four ways including the cross-flow heat exchanger. In a cross-flow HX, the working and source fluids flow perpendicular to each other i.e., they have a 90° variation between their flow directions[4].The whole system is primarily composed of a cooling interior through which the fluid to be cooled flows and a fan, which circulates the surrounding air through the interior to enable heat transfer between the hotter and colder fluid through forced convection[5].Integration of fins in this type of HX will accelerate the heat transfer between the fluids due to increased surface area according to the following equation :

$$\dot{Q} = hA_s\Delta T \quad (1)$$

where, A_s is the surface area exposed to the incoming cooling fluid flow and ΔT is the temperature difference between the inlet and outlet fluids. Fins can be either blended on the flow tubes of the HX or the metallic plates around the tubes, as both cases provide a higher surface area for heat transfer. In case of finned plates, the typical design utilized in the cross-flow HX models include a straightforward position of the metallic

plates, which can be further optimized if their orientation with respect to incoming fluid flow can be varied, allowing more surface area of the plates and tubes to come into contact with the fluid, thus, enabling higher convection heat transfer within the system. The study of this proposed design optimization can be conducted through CFD analysis in ANSYS Fluent, which will mitigate the need for apparatus and live experiments to gather data, thus, nullifying the need for experimental and setup costs and facilitating quick output data for investigation with negligible time consumption. Cross-flow heat exchangers have a wide variety of applications, such as-wind turbine cooling, indoor agriculture, residential and industrial ventilation, dehumidification, data center cooling, car radiators etc.[6] Optimization of the conventional design for more efficient heat transfer will open the possibilities for further breakthroughs in this field, which has the potential to generate far advanced, optimized and efficient models of cross-flow heat exchangers for implementing in energy and power generation industries in the near future.

2. Objectives

The goal of this analysis is to propose a modified model of the existing ones for a cross-flow HX and verify its feasibility through comparison of the output data using CFD analysis. Towards that end, the objectives of this analysis can be stated as:

- To design the model using 3D CAD software;
- To create the analysis setup in ANSYS Fluent;
- To simulate the setup in CFD and record output data;

d) To compare the recorded results and reach a logical conclusion.

3. Methodology

The study conducted in this paper comprises of the illustrated systematic flow of analysis segments in figure-1.



Fig.1 Flowchart of the analysis process utilized in this study

3.1 Design and Rendering of the HX models

The cross-flow HX model to be utilized in this analysis is a single tube, 8-passes one, with a total tube length of 1869.87 mm (1.86987m). A total of six 50x10 mm and 400 mm long metallic plates made of Aluminum are placed around the tubes, with four 15x2.5 mm gaps between six fins integrated on each plates. The model is modified through changing the orientation of plates to 30° and 45° for the proposed analysis of this paper. The 3D modelling is done using SOLIDWORKS and the rendering using Keyshot. Figure-2 illustrates the 3D rendered models of the proposed cross-flow HX designs to facilitate a realistic view.

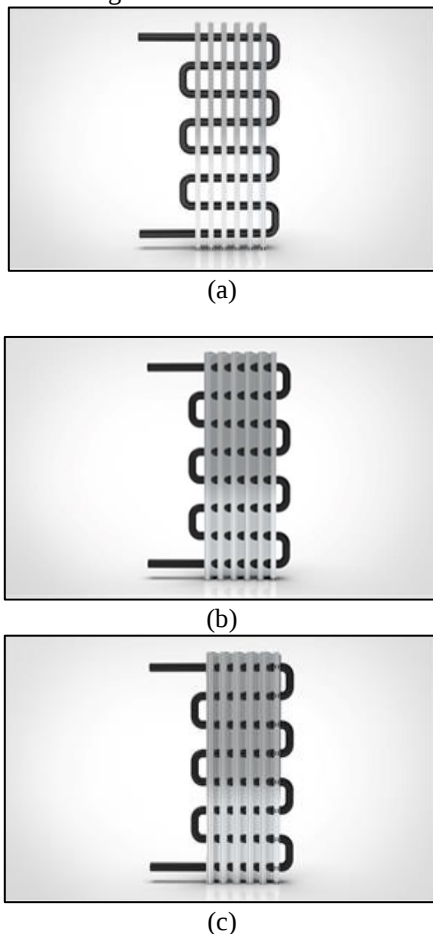


Fig.2 3D rendered model of the cross-flow HX with plates oriented (a) 0°, (b) 30° and (c) 45°

3.2 Meshing of the Models in ANSYS

The designed HX models require meshing in ANSYS Fluent before proceeding to the actual simulation and generating simulated results of the analysis, on which meshing quality i.e, mesh size, type and number of nodes and elements can have a significant impact. Table-1 depicts the meshing parameters employed in this analysis to achieve the expected outcome with accuracy as high as possible through CFD interface.

Table 1 Meshing Parameters of the HX models in ANSYS

Meshing Parameter	0° model	30° model	45° model
Element type	Tetrahedrons	Tetrahedrons	Tetrahedrons
Element size	45 mm	45 mm	45 mm
Nodes	214,899	209,828	216,129
Elements	10,48,497	10,16,361	10,40,584

ANSYS Student 2024 R2 version was used during the analysis, which has limitations of 524,288 nodes and 10,48,576 elements. To accommodate for the allowable parameters, the tabular data represents the maximum quality of mesh that could be achieved in this study. Figure-3 provides a clearer picture of the degree of meshing achieved for each cross-flow HX models in the ANSYS fluent interface.

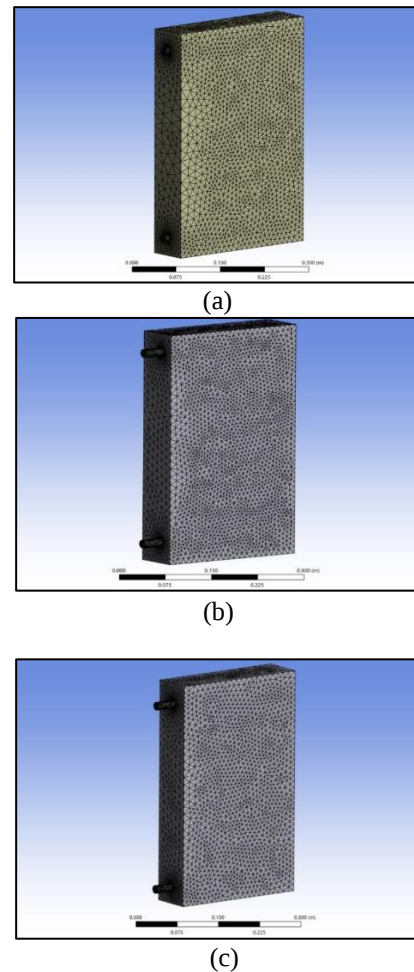


Fig.3 View of Meshed HX models in ANSYS Fluent with plates inclined (a) 0°, (b) 30° and (c) 45°

3.3 Simulation in CFD Interface

The simulation of convection heat transfer through the cross-flow HX models were conducted through the utilization of energy equation model, that enabled study of heat transfer in CFD interface, allowing the model to experience the effects of temperature difference. Gravity effects were also considered in this analysis in the negative y-direction to visualize a practical setup. Up to 300 iterations were performed on the simulation setup of HX for convergence of the results, in an attempt to generate results with higher accuracy and precision. Figure-4 illustrates the setup of the CFD analysis attempted for the proposed study of cross-flow HX models, visualizing the fluid flow directions involved in the convection heat transfer.

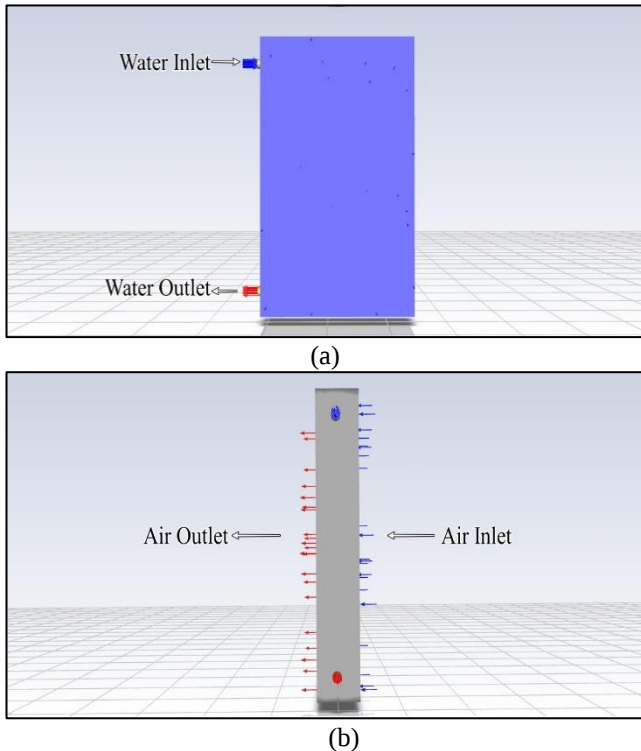


Fig.4 (a) Front , and (b) Side view of HX model setup in CFD interface

3.4 Recording Simulation Results

The conducted CFD analysis of the proposed cross-flow HX utilized water as the working fluid which enters the system through the 15 mm diameter tubes in a hot (high temperature) state, whereas, air served as the cooling fluid, entering the system at a 90° to the water inlet. Convection occurs between the heated plates (due to hot water) and air, reducing the temperature of water as a result of coming into contact with the metallic plates cooled by air due to convection. Water and air exit the system perpendicular to each other, with a reduction and increase in their outlet temperatures respectively. The CFD simulation was conducted with water and air having temperatures of 100°C(373K) and 25°C(298K) respectively at the inlets. After a successful simulation run, the gradually occurring change in the water temperature and the metallic plates due to convection heat transfer in the cross-flow HX can be visually observed through the ANSYS fluent interfaces depicted in figures-5,6 and 7 which illustrate the temperature gradients occurred due to air velocity of 15 m/s.

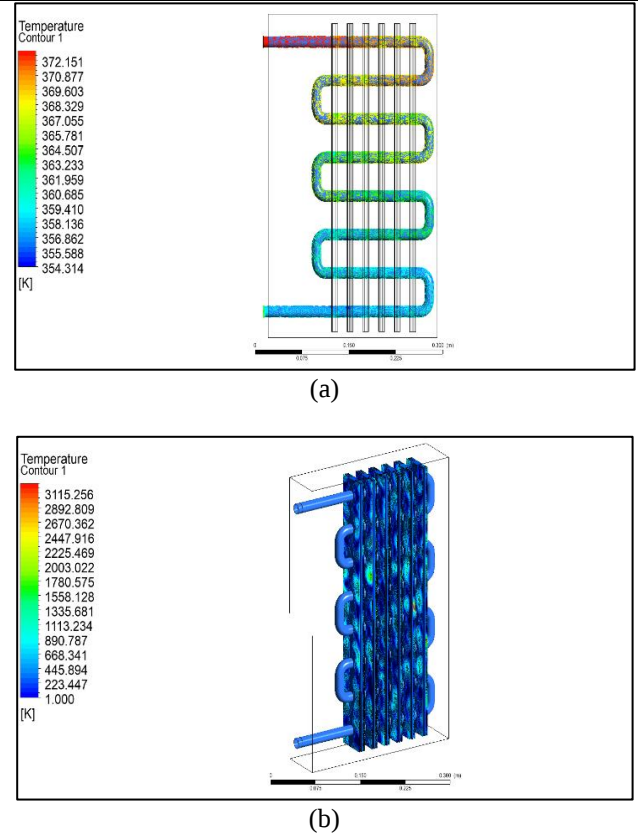


Fig.5 Temperature gradient due to convection in (a)The water tubes and (b)Metallic plates at an air velocity of 15 m/s for a cross-flow HX with plate orientation of 0°.

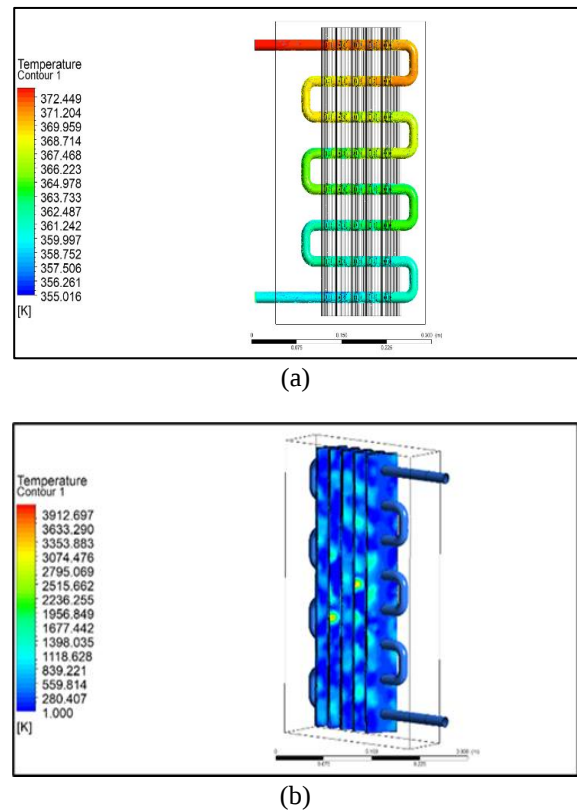
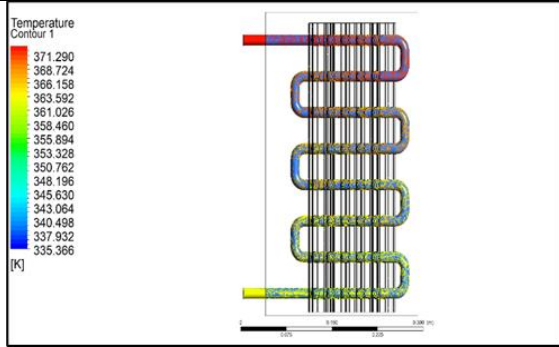
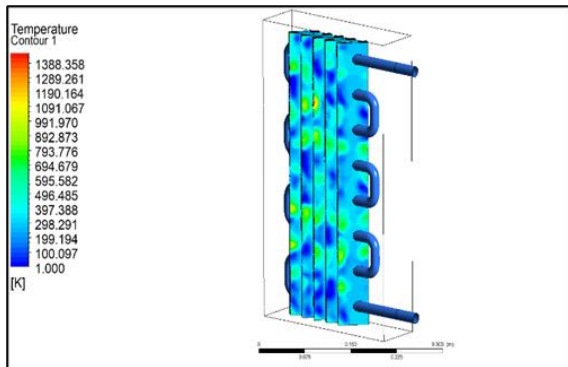


Fig.6 Temperature gradient due to convection in (a)The water tubes and (b)Metallic plates at an air velocity of 15 m/s for a cross-flow HX with plate orientation of 30°.



(a)



(b)

Fig.7 Temperature gradient due to convection in (a)The water tubes and (b)Metallic plates at an air velocity of 15 m/s for a cross-flow HX with plate orientation of 45°.

3.5 Result analysis and comparison

The varying data generated from the simulation in CFD is tabulated with graphs to illustrate the variation in each cross-flow HX models corresponding to the outlet temperatures of both hot(water) and cold(air) fluids in the following section. The analysis is iterated for different air velocities to validate the accuracy of the outcome. The HX model indicating the lowest outlet temperature for the hot fluid can be termed as the more efficient one, as it possesses the capacity to transfer more heat through convection.

4. Results

In the study conducted for this paper, water velocity was kept constant throughout the simulation at 0.5 m/s, however, air velocity was varied for generating more data in an attempt to validate the results. The convection heat transfer coefficient between the Aluminium plates and air was taken to be 1000 W/m².°C. Tables-2,3 and 4 highlight the resultant data from the CFD analysis of convection in the introduced cross-flow HX models at varying air velocities.

Table 2 Water and Air Outlet temperatures at 5 m/s Air Velocity

HX Model	Water Outlet Temp.(°C)	Air Outlet Temp.(°C)
Straight Plates(0°)	93.312	25.677
Inclined Plates(30°)	94.021	25.656
Inclined Plates(45°)	91.325	25.679

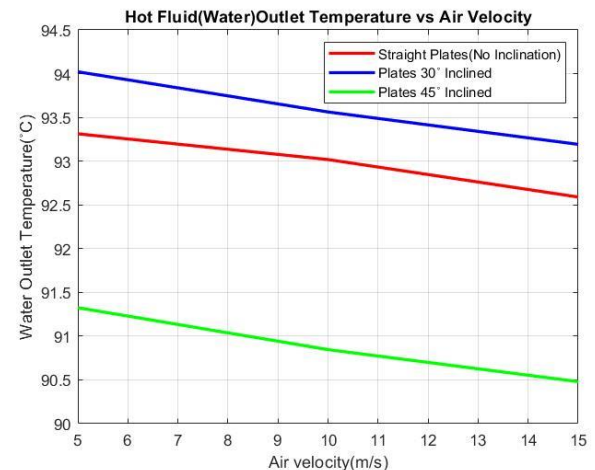
Table 3 Water and Air Outlet temperatures at 10 m/s Air Velocity

HX Model	Water Outlet Temp.(°C)	Air Outlet Temp.(°C)
Straight Plates (0°)	93.018	25.604
Inclined Plates (30°)	93.562	25.52
Inclined Plates (45°)	90.846	25.556

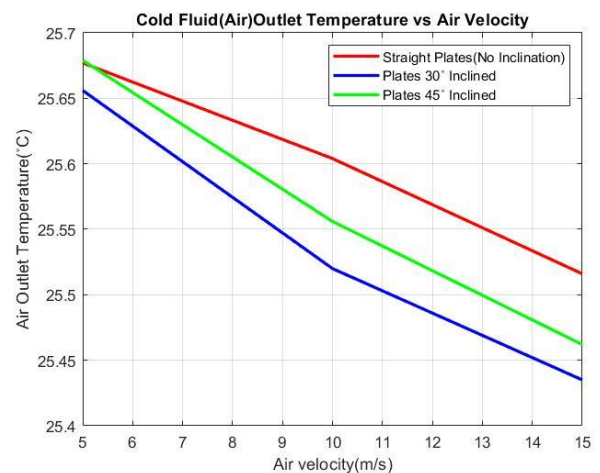
Table 4 Water and Air Outlet temperatures at 15 m/s Air Velocity

HX Model	Water Outlet Temp.(°C)	Air Outlet Temp.(°C)
Straight Plates (0°)	92.59	25.516
Inclined Plates (30°)	93.192	25.435
Inclined Plates (45°)	90.48	25.462

Figure-8 illustrates the graphical variation in water and air outlet temperatures for each of the cross-flow HX models at different air velocities, which provides a clearer overview of the degree of convection in each of the models.



(a)



(b)

Fig.8 Outlet Temperature vs air velocity graph for (a) Water and (b) Air

5. Discussion

Observation and interpretation of the generated tabular data and graphs provide a logical conclusion that, inclination of metallic finned plates in a cross-flow HX have a discernible impact on the convection heat transfer within the system suggesting that inclination of plates has the potential of both increasing and decreasing the rate of heat transfer depending on the degree of orientation. The outcome of the study conducted in this paper depicts that, keeping the plates 30° inclined with respect to the incoming air flow results in higher water outlet temperatures than the temperatures observed while avoiding any inclination (0°), which is a loss of efficiency even though design modification has been implemented. It implies that 30° inclination causes an exposure of lesser surface area, which lowers the rate of convection heat transfer. On the contrary, inclination of plates at a 45° angle with respect to the cooling fluid flow resulted in lower water outlet temperatures than the above mentioned two cases, which leads to the final verdict that, in a cross-flow HX, positioning the metallic plates to be in a 45° orientation with respect to the incoming cold fluid flow can significantly increase the convection heat transfer rate and facilitate more efficient cooling of hot fluids due to exposure of a larger surface area to the incoming cold fluid. Thus, this model (45° inclined) of cross-flow HX is an optimal, modified and more efficient design over the conventional ones and is worth further investigation for better optimizations in the near future.

6. Conclusion

Use of fins and metallic plates in cross-flow HX models have been implemented in past studies to achieve a more efficient degree of heat transfer due to larger exposure of heat transfer surface area, however, changing the orientation of plates to observe and study the effects have not been introduced to the thermo-fluid field before. Our study attempted to delve deeper into this case analysis by harnessing the advantages of CFD interface, thus, achieving a concrete outcome by avoiding the difficulties of fabricating the actual setup while simultaneously introducing a newer and modified concept into the application of finned surfaces around a HX. The analysis initiated achieved a successful verdict on the proposed modification of existing cross-flow HX designs, paving the path for further studies on realizing

the practical implementation of this model. However, CFD analysis conducted in this paper had some limitations due to the use of ANSYS student version, which provided limited amount of nodes and elements during meshing. Higher quality meshing and more accurate results could have been achieved if the official version was implemented in this type of analysis. In addition, analysis of more angular orientations of plates, such as 15°, 60° etc. were not possible due to the software and design limitations, which leaves a room for further research and investigation of this study. Live investigation and experiment through utilization of this setup is also worth attempting for studying the feasibility of the proposed HX model in practical applications, which should be the ultimate goal of any proposed modifications.

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NOMENCLATURE

- $\dot{Q}$: heat transfer rate in Watts
 h : convection heat transfer co-efficient in W/m².°C
 ΔT : temperature difference in °C