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Heat Transfer Analysis of a Biomimetic Plate Heat Exchanger with Bird Feather Pattern

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Abstract - *The following study is the heat transfer analysis of conventional compact brazed plate heat exchanger consisting of 10 plates wherein a bird feather pattern is designed using biomimetic approach at certain heights on the surface of the plate to improve heat transfer and pressure drop of the PHE. The inspiration behind this is that birds can maintain suitable body temperatures even in most adverse environments. Heat transfer in birds takes place through conduction, convection and radiation. The structure of bird feathers plays a major role in thermoregulatory mechanism of birds and has been known to offer excellent heat transfer rates. With the help of additive manufacturing techniques, PHEs with any complex pattern can be designed and manufactured. In this study, different heat exchangers have been modelled with an attempt to mimic the pattern of bird feathers in order to increase heat transfer area and turbulence. CFD simulations were then performed using SolidWorks Flow Simulation tool for the same operating conditions with hot-water and cold-water inlet temperatures equal to 90^0 C and 25^0 C respectively, and a mass flow rate of 0.05 kg/s to compare the heat transfer rate, pressure drop and effectiveness of the conventional PHE and the ones designed by biomimetic approach. The simulation results were validated by numerical and experimental results of an existing PHE with Chevron pattern. However, it has been observed that the Chevron-type PHE offers better heat transfer rates compared to the biomimetic ones due to effective use of patterned area.*

Key Words: plate heat exchanger, feather pattern, heat transfer rate, turbulence, CFD

1. INTRODUCTION

Heat exchangers find their applications in almost all kinds of industries due to their compactness and high heat transfer area as the fluid is spread out over the plates. The have an alternating flow of hot and cold fluid between the metal plates and are usually available in 2 configurations, viz. gasketed and brazed. The gasketed versions are used for large-sized PHEs whereas smaller units tend to be brazed wherein the plates are aligned side by side using vacuum soldering process. This creates a joint at each point of contact between the plate and the brazing material providing a better sealing and allowing the heat exchanger to withstand high pressures. The inlet and outlet ports provide separate flow paths or the hot and cold fluid.

The performance of PHEs largely depends upon the type of pattern used on the plates. The Chevron pattern is the most commonly used pattern in conventional heat exchangers. Geometric factors such as Chevron angle, corrugation pitch, depth of printing, dimensions of the plates as well as the flow type (viz. laminar, transition, turbulent) highly affect the thermohydraulic performance of PHEs. The patterns on the plates offer better heat transfer rates by increasing the heat transfer area. However, they might also lead to considerable pressure drop due to friction resulting in high pumping power requirements. Thus, heat transfer rate and pressure drop should be the main criteria for deciding the type of plate pattern during optimization process.

Biomimetic approach helps in solving real life problems by analyzing and mimicking the patterns and behaviors in nature. Several researchers have proved that the use of fractal structure in heat transfer devices lead to an improvement in heat transfer rate and decrease in pressure drop. A fractal is a pattern in nature that repeats itself at smaller and smaller scales. Examples for the same are tree branches, leaf veins, bird feathers, etc. The following study is inspired by the effective thermoregulation in birds which is brought about by the pattern of their feathers. Heat transfer in birds takes place via 3 modes viz. conduction and convection through air, conduction through solid elements of the feather as well as radiation. However, 95% of the heat transfer occurs through conduction and convection alone and this can be beneficial from the point of view of heat exchanger design. Thus, effective thermohydraulic solutions can be deduced from the strategies in nature. In this study, different plate heat exchangers were modelled with bird feather-like pattern and CFD simulations were performed using SolidWorks Flow Simulation tool. In the simulations, operating conditions at a flow rate of 0.05 kg/s and hot/cold inlet temperatures of 90^0 C and 25^0 C are used for single phase parallel flow. The model was validated using numerical and experimental results for a state-of-the-art Chevron-type plate heat exchanger.

2. LITERATURE

Baris Gurel et. al. [1] have investigated the flow and thermo hydraulic performance of a compact brazed plate heat exchanger with lung pattern using biomimetic approach. The study is based on the fact that human lungs are one of the best heat exchangers known till date and have a very high compactness which is the ratio of effective heat transfer area and total volume of the PHE. Simulations were performed using ANSYS Fluent on the lung patterned heat exchanger and the results thus obtained were compared with the conventional Chevron-type PHE. The use of lung pattern resulted in 71.3% increase in heat transfer rate and 67.8% decrease in pressure drop along with 6.66% reduction in total volume. Huang et. al. [2] investigated the thermal and hydraulic performance of fractal heat exchangers with major focus on fractal channels. A fractal structure is a pattern that nature repeats on smaller scales. According to the research, the use of fractal geometries as found in blood vessels, leaf veins, human lungs, tree branches, etc. in heat transfer devices offers higher heat transfer rates while minimizing flow resistance and the resulting pressure drop. One of the major findings of the research was the direct relationship between number of branching and heat transfer capabilities of the device. Gang Wang, Yu Gu et. al. [3] conducted an experimental and numerical investigation of a fractal tree-like heat exchanger manufactured by 3D printing. The performance of the HE was evaluated from both thermal and hydraulic perspectives. Their findings reveal that a fractal-tree-like heat exchanger can improve hydrodynamic performance, reduce pressure drops and has great heat transfer ability and coefficient of performance. The results were obtained for a fractal H-type and Y-type heat exchanger and a 23% improvement in heat transfer rate was achieved in comparison with conventional spiral tube heat exchanger. Pingnan Huang, Guanping Dong et. al. [4] performed numerical investigation of the fluid flow and heat transfer characteristics of a tree-shaped microchannel heat sink with variable cross-section. The analysis was performed on three different heat sink geometries with ribs, cavities and a smooth structure respectively using ANSYS Fluent software. The tree-shaped heat sink with cavities was found to have highest comprehensive performance as the cavities increase branching effects. Blair O. Wolf and Glenn E. Walsberg [5] studied the role of the plumage in thermoregulatory mechanism of birds. Their findings suggest that dry heat transfer through bird plumage occurs via 3 avenues, viz. conduction and convection through air, conduction through solid elements of the feather and radiation. However, around 95% of the heat transfer occurs through conduction and convection alone. The structure of bird feathers consists of a quill, a number of barbs and their further branches known as barbules. The intersecting barbules increase the surface area of the feather, thus increasing heat transfer through convection. This principle was the driving motivation behind the biomimetic approach in designing and analyzing plate heat exchangers with bird feathers patterned on them.

3. VALIDATION

In order to validate the results of the CFD simulations, the numerical results were compared with the experimental results obtained from [1] for a conventional compact brazed Chevron-type plate heat exchanger. The same Chevron angle (30^0), mass flow rate (0.167 kg/s) and inlet temperatures of hot and cold fluid as 32.8^0C and 25^0C respectively have been used for geometry creation and boundary conditions. The model consists of 10 plates with the same material (AISI 316 Stainless Steel). The length, width and thickness of the plate was kept as 431 mm, 125.5 mm and 2 mm respectively. The value of specific heat capacity of water was taken to be constant and equal to 4182 J/KgK and thus, the ambient temperature was considered to be 20^0C by referring the property table for water.

The outlet temperature of the hot fluid at the end of the numerical analysis was obtained as 29.80^0 C with a deviation of 0.33% from the experimental outlet temperature which was equal to 29.9^0 C. According to the experimental results, the actual heat transfer rate of the referenced PHE was 2167W whereas the value of the same obtained from CFD analysis was 2094.41W. Thus, the experimental data and numerical results are in good agreement with a deviation of 3.35%. Hence, the same method can be used for heat transfer analysis of plate heat exchanger designed by biomimetic approach.

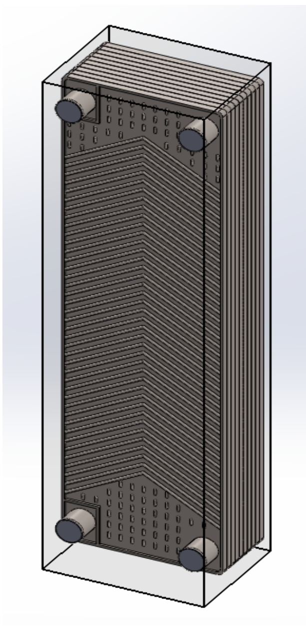

Fig -1: CAD geometry referenced PHE

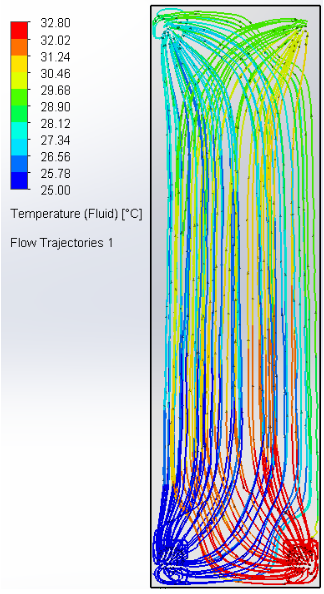

Fig -2: Flow trajectories for referenced PHE

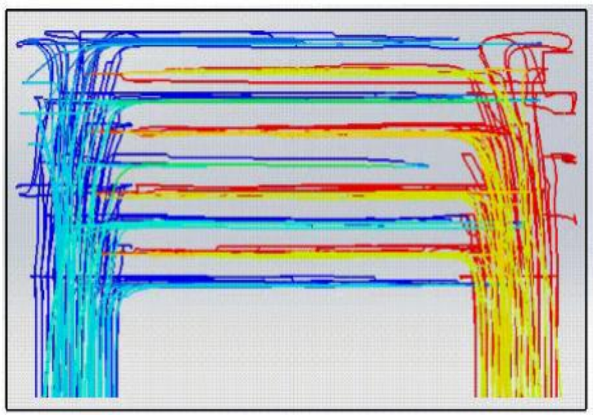

Fig -3: Flow trajectories showing alternating hot/cold fluid for referenced PHE

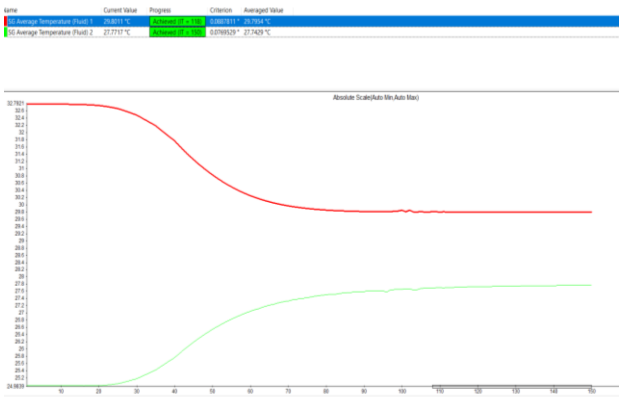

Fig -4: Temperature distribution curves for referenced PHE

4. RESULTS AND DISCUSSION

In this study, CFD simulations for heat transfer analysis were performed on 5 different compact brazed plate heat exchangers with different geometries of bird feathers patterned on them. The design method for the same has been validated through numerical and experimental results of a pre-existing study. In the simulations, mass flow rate of 0.05 kg/s and hot/cold inlet temperatures of 90^0C and 25^0C have been used for single phase parallel flow and the results obtained were used to compare the conventional Chevron-type PHE with biomimetic models. The basic dimensions for all the PHEs have been kept the same as that for the referenced model. The value of specific heat capacity of water is taken as 4178 J/KgK for the normal operating conditions.

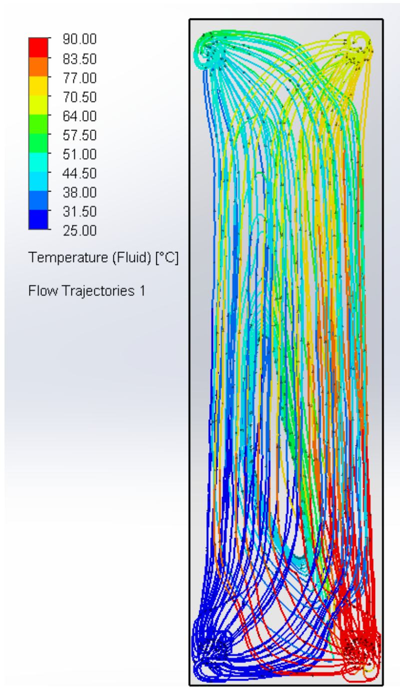

Fig -5: Flow trajectories for Chevron PHE

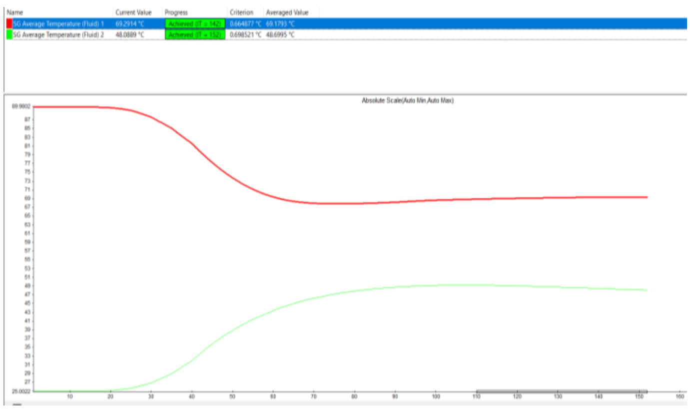

Fig -6: Temperature distribution curves for Chevron PHE

The flow trajectories for the Chevron PHE have been shown in fig. 5. It can be seen from the same that the hot and cold fluids flow over a major portion of the plate area and thus, there is an effective utilization of heat transfer area and the corrugated patterns. With the onset of turbulence due to the corrugations, the temperature of the hot fluid goes on decreasing rapidly indicating an increase in heat transfer rate. Fig. 6 shows the temperature distribution curves for hot and cold fluid throughout the flow. The hot water outlet temperature is obtained as 69.29^0C whereas the temperature of cold water at the outlet is 48.08^0C. The heat transfer rate thus calculated is equal to 4326.32 W.

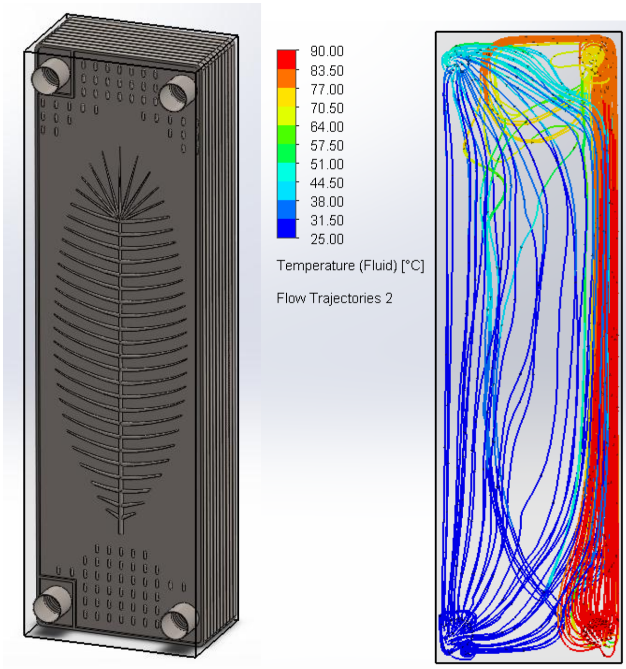

Fig -7: Geometry and flow trajectories for biomimetic model with sparse barbs

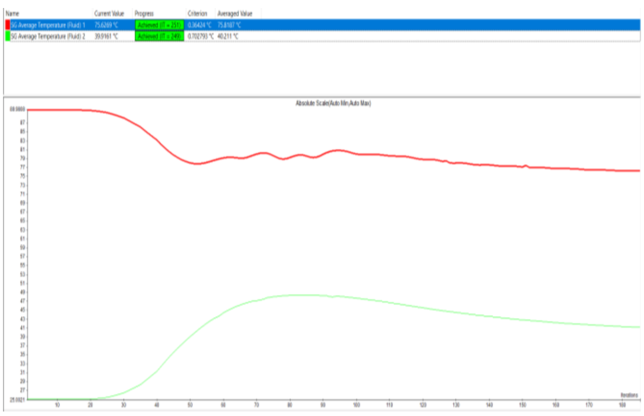

Fig -8: Temperature distribution curves for biomimetic model with sparse barbs

Fig. 7 shows the geometry and flow trajectories for biomimetic PHE model with sparse barbs without any barbules present. It can be seen from the figure that most of the hot and cold fluid travels along the edges of the plate. This leads to a poor utilization of the heat transfer area and hence, the effect of the plate pattern on heat transfer rate is negligible. The required turbulence is not initiated in this model since the fluid passes over the flat portions of the plate. The temperature distribution curves for the model are shown in fig. 8 and the hot/cold outlet temperatures are obtained as 75.62^0C and 39.92^0C respectively. The heat transfer rate so achieved is 3003.98 W which is considerably lower than that for the Chevron PHE.

An almost similar condition occurs in the case of the biomimetic PHE model with dense barbs as can be seen from fig. 9. The temperature distribution curves for the model are shown in fig. 10 and the temperature of hot and cold fluid is obtained as 74.87^0C and 39.87^0C respectively from the CFD analysis. The heat transfer rate again is lower than that for Chevron PHE and is found to be 3160.66 W.

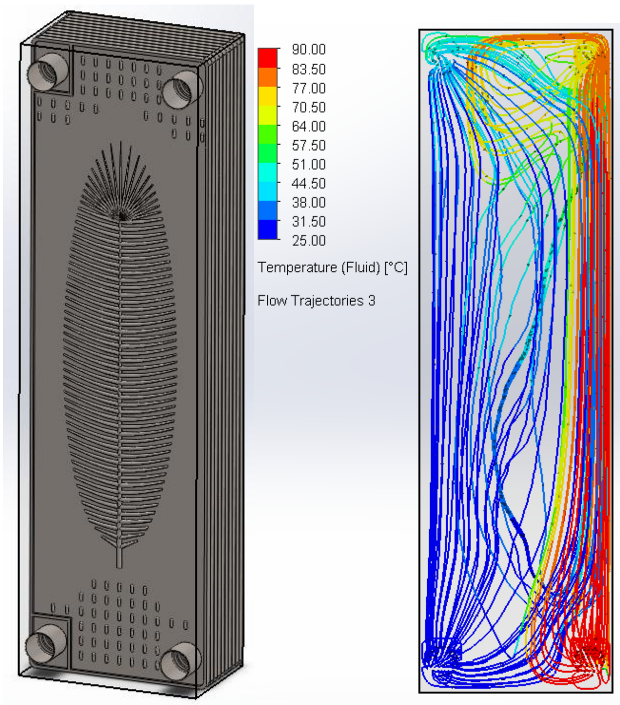

Fig -9: Geometry and flow trajectories for biomimetic model with dense barbs

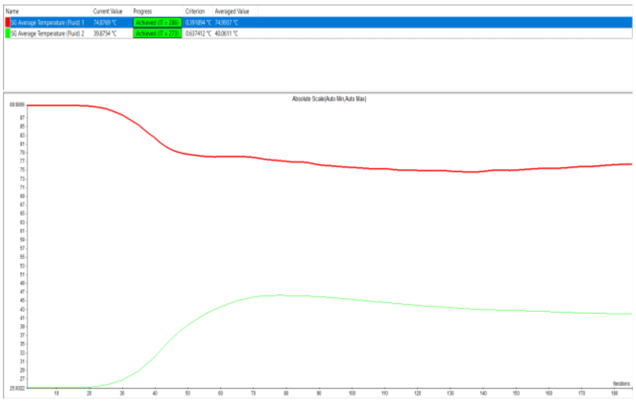

Fig -10: Temperature distribution curves for biomimetic model with dense barbs

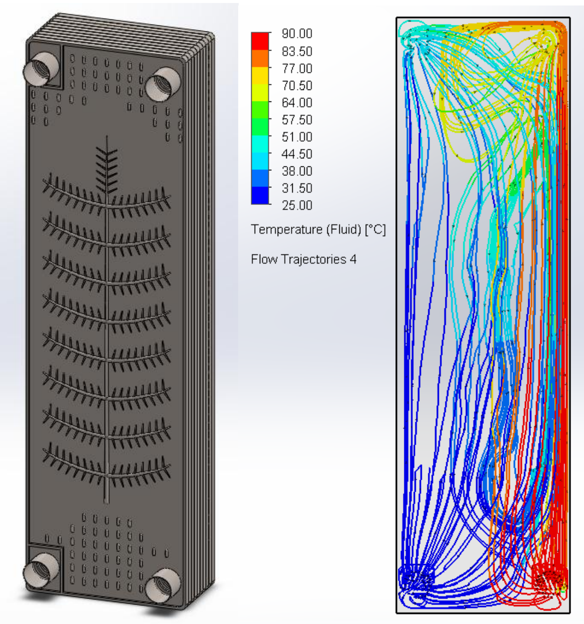

Fig -11: Geometry and flow trajectories for biomimetic model with short barbs and non-intersecting barbules

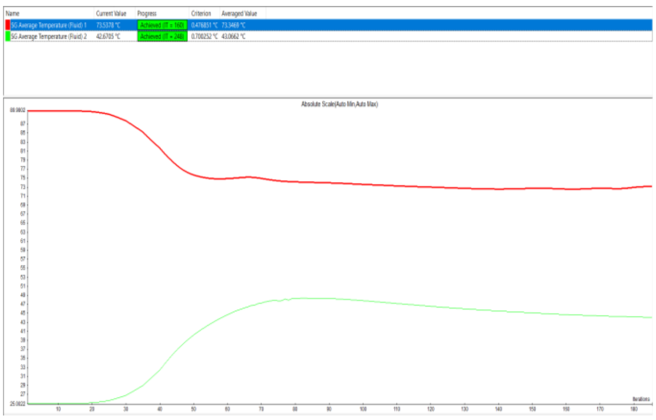

Fig -12: Temperature distribution curves for biomimetic model with short barbs and non-intersecting barbules

The geometry and flow trajectories for biomimetic PHE model with short barbs and non-intersecting barbules has been shown in fig. 11. The hot water flow lines indicate that most of the fluid is passing close to the edge of the plate and the corrugations or patterns are not being utilized to their full potential. The added benefit of turbulence that comes with plate patterns is not achieved in this case as well. The temperature distribution curves for the same as shown in fig. 12 show the hot and cold-water outlet temperature as 73.54^0C and 42.67^0C resulting in a heat transfer rate of 3440.58W for the given values of mass flow rate and specific heat capacity of the fluid.

In the biomimetic model with long barbs and non-intersecting barbules, as shown in fig. 13, a better utilization of the plate area for heat transfer takes place. The flow lines seem to be more spread out over the plates and a greater drop in temperature of the hot fluid can be seen. The temperature distribution curves of the hot and cold fluid are shown in fig. 14 and the outlet temperature of the hot and cold side is 71.46^0C and 44.66^0C respectively. The turbulence caused by effective utilization of the patterned area on the plate results in a better heat transfer rate which is equal to 3875.09 W.

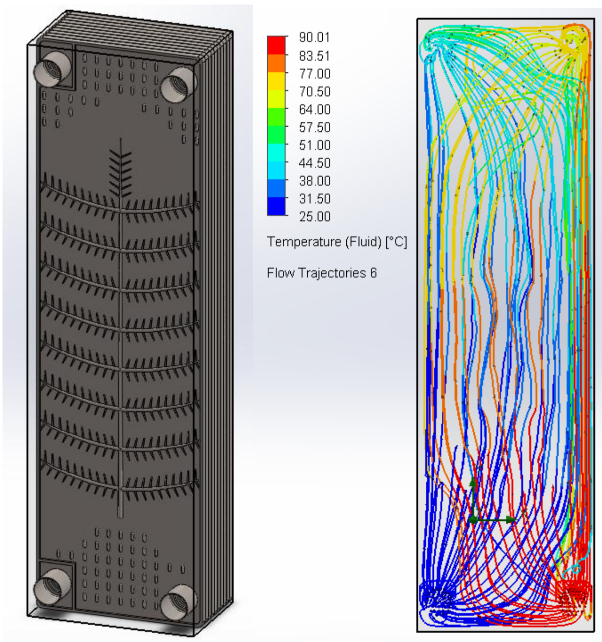

Fig -13: Geometry and flow trajectories for biomimetic model with long barbs and non-intersecting barbules

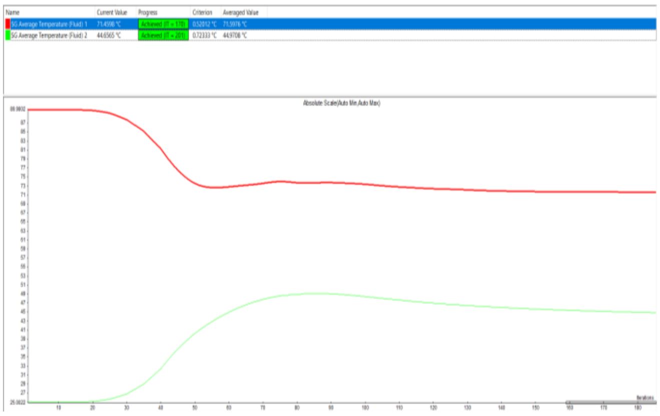

Fig -14: Temperature distribution curves for biomimetic model with long barbs and non-intersecting barbules

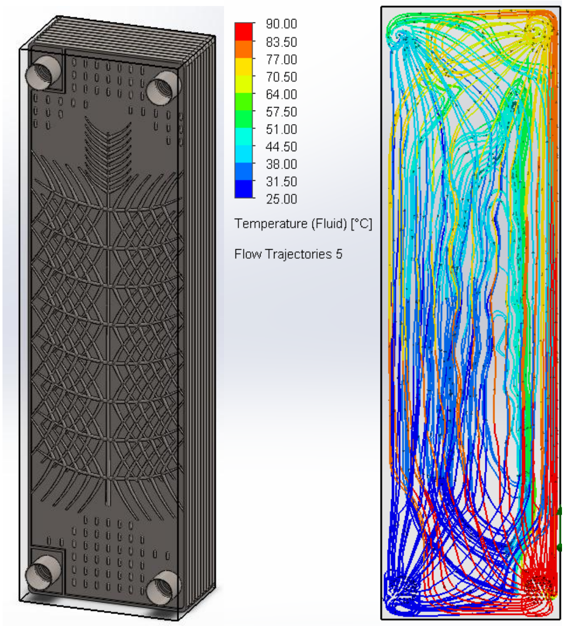

Fig -15: Geometry and flow trajectories for biomimetic model with long and intersecting barbules

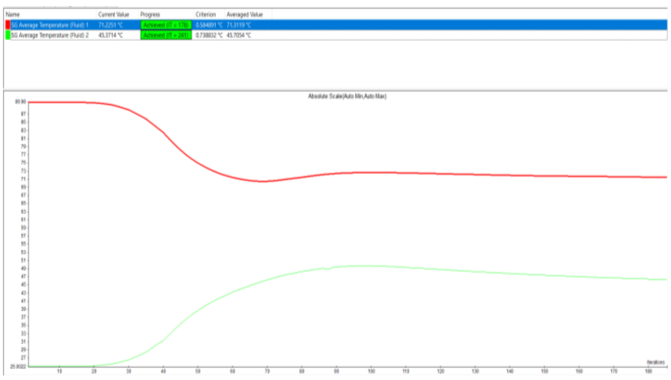

Fig -16: Temperature distribution curves for biomimetic model with long and intersecting barbules

Fig.15 shows the geometry and flow trajectories for biomimetic PHE model with long barbules that intersect with each other and increase the effective surface area. A quite similar structure can be seen in case of birds at the microscale where a number of barbules come together to form a mesh-like fractal geometry. However, due to manufacturing considerations, the relative size of the barbules is kept pretty large in case of the proposed PHE model. It can be seen from fig. 15 that a much better utilization of plate area takes place in this model as compared to other biomimetic models mentioned above. The outlet temperature for hot and cold fluid is 71.23^{0}C and 45.37^{0}C respectively as can be seen from the temperature distribution curves given in fig. 16. The heat transfer rate thus obtained is equal to 3923.14W which is much better than other biomimetic models but not as good as that for conventional Chevron-type PHE. The effective utilization of plate area and formation of turbulent boundary layer is quite better in case of Chevron-type heat exchanger leading to higher heat transfer rate.

4. CONCLUSION

The Chevron-type heat exchanger was found to have a better heat transfer rate as compared to the ones designed by biomimetic approach. This is due to the effective utilization of heat transfer area offered by the corrugated plates as well as formation of turbulent boundary layer. However, the project does not take into consideration the effect of plate pattern on the pressure drop which is a major criterion while designing any heat exchanger. Also, the results for different PHE models have been obtained for single phase parallel flow. However, significant variation in the results might be obtained for counter flow wherein the both the hot and cold fluids flow in opposite directions. The flow simulations can be carried out for different orientations of the plate patterns which might lead to considerable variations in results e.g. by increasing the number of feathers per plate, the number of barbs per feather, the number of barbules per barb as well as the length and width of the feathered pattern. The brazing material used in actual practice is different from the plate material and thus, has a different value of thermal conductivity. This needs to be considered for obtaining more accurate results. Even though the effect of radiation in thermoregulatory mechanism of birds is negligible, it can highly affect the results obtained for PHEs in terms of temperature difference and heat transfer rates. The project does not consider the effects of radiation which might lead to a large deviation in the results obtained through experimentation and numerical analysis.

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REFERENCES

[1] Investigation of Flow and Heat Transfer of Compact Brazed Plate Heat Exchanger with Lung Pattern, Baris Gurel, Volkan Ramazan Akkaya et. al.

[2] Review of Fractal Heat Exchangers, Zhiwei Huang, Yunho Hwang, Vikrant Aute, Reinhard Radermacher

[3] Experimental and numerical investigation of fractal-tree-like heat exchanger manufactured by 3D printing Gang Wang, Yu Gu, Luhaibo Zhao, Jin Xuan, Gaofeng Zeng, Zhiyong Tang, Yuhan Sun

[4] Numerical investigation of the fluid flow and heat transfer characteristics of treeshaped microchannel heat sink with variable cross-section, Pingnan Huang, Guanping Dong, Xineng Zhong, Minqiang Pan

[5] The Role of the Plumage in Heat Transfer Processes of Birds, Blair O. Wolf and Glenn E. Walsberg

[6] Nature-Inspired Structures Applied in Heat Transfer Enhancement and Drag Reduction, Zhangyu Zhu, Juan Li, Hao Peng and Dongren Liu

[7] An experimental investigation on the heat transfer and friction coefficients of a small plate heat exchanger with chevron angle, Saeed Mohebbi & Farzad Veysi

[8] Energy, Radiation and Temperature Regulation in Plants, Hamlyn G Jones and Eyal Rotenberg

[9] Investigation of Brazed Plate Heat Exchangers with Variable Chevron Angles, S. Muthuraman

[10] Modeling and Design of Plate Heat Exchanger, Fábio A.S. Mota, E.P. Carvalho and Mauro A.S.S. Ravagnani

[11] Fundamentals of heat and mass transfer, Theodore L. Bergman, Adrienne S. Lavine

[12] Heat transfer – A practical approach, Yunus Cengel