A Study of Performance Enhancement of Cross Flow Heat Exchanger through Variation in Holes on Fin Plate

OPEN ACCESS

AG-2023-1001

Volume: 3

Issue: 2

Month: April

Year: 2024

ISSN: 2583-7117

Published: 01.04.2024

Citation:

Rakesh Singh[1], Pankaj Shrivastava[2], Dr. B. Suresh[3]. "A Study of Performance Enhancement of Cross Flow Heat Exchanger through Variation in Holes on Fin Plate." International Journal of Innovations In Science Engineering And Management, vol. 4, no. 1, 2023, pp. 01–10.

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Abstract
At the moment, there is a lot of focus on how to make cross flow heat exchangers operate better. In this study, we use the computational fluid dynamics (CFD) programme to conduct a numerical study of a cross-flow heat exchanger in ANSYS Fluent. A heat exchanger with a dimple on its fine surface will work better. To model and statistically examine the impact of spherical dimples on the heat exchanger's performance, we used a cross flow heat exchanger. Attaching the smooth fin plate and fin holes was the subject of numerical research for varying fin areas and fin hole densities. We used an intake air temperature of 299.45 K and a constant tube surface temperature as our boundary conditions. In order to get the best possible outcome, it was necessary to evaluate the temperature effectiveness, fin plate temperature, outlet temperature, and heat transfer enhancement balance. Case 6 having maximum outlet temperature and temperature effectiveness which is 303.421 K, and 13.835% respectively. Due to heat transfer between air and fin plate temperature of fin plate is minimum in case 6 and maximum in case 1 which is 319.048 K, and 319.628 K respectively.

Keyword: Heat exchanger, Cross flow, computational fluid dynamics, spherical dimples, fin plates, etc.

I. INTRODUCTION

Heat exchangers are employed for the purpose of facilitating the transfer of thermal energy from one medium to another. The media in question can exist in a gaseous, liquid, or hybrid state. The media can be physically divided by a solid barrier to avoid intermingling, or it can be in direct access to each other.[1] Heat exchangers are essential components that are necessary in order to fulfil the thermal demands of a given process, either by providing heating or cooling.[2] A furnace or steam boiler is the typical source of direct heat input to the system. So, if the heat transfer process at the exchangers is inefficient, the boiler or steam will have to work harder.[3][4]

Heat exchangers have the potential to enhance the energy efficiency of a system by facilitating the transfer of heat from systems where it is surplus to requirements to other systems where it may be effectively utilised.[5][6] One typical use for heat exchangers is to allow the transfer of heat from one process stream to another or from one process stream to a utility stream. The temperature of these utility streams is not always constant.[7][8].

Using gaskets, welds, or brazes to connect corrugated plates, "plate and frame heat exchangers" guarantee that fluids do not mix. In order to make it easier for fluid streams to flow, the plates include input and exit apertures on each corner.[9][10]

Within the interplate gaps, a network of hot-cold-hot-cold streams organises the fluid flow pathways in a sequential fashion. Hot fluids flow downwards along the plates of a countercurrent flow arrangement, while cool fluids flow upwards along the same plates.[11] "The plate and frame heat exchanger" stands out due to its large heat transfer area, great turbulence induction capabilities, and impressive fouling resistance. When compared to other types of heat exchangers, tubular ones have lower efficiency and heat transfer coefficients overall.[12] However, due to higher wall shear stress, the fluids undergo a substantial pressure drop, which in turn increases pumping costs.[13][14]

Novel surface changes and geometrical designs to optimise heat transfer efficiency in cross-flow heat exchangers are understudied. There is still a need for new heat transfer mechanisms that don't increase pressure drop, even if ribbed surfaces and vortex generators exist.[15] Few comprehend the impact of several improvement approaches and their interplay in cross-flow heat exchangers. Flow velocity, fluid characteristics, and temperature gradients affect heat transfer enhancement methods, hence they need additional study.[16] Few studies have addressed the practical issues of scaling up improved cross-flow heat exchanger designs for industrial applications, including manufacturability and cost. Bridging these research gaps may lead to more efficient and sustainable heat transfer solutions for HVAC systems, thermal power production, and other sectors.[17][18][19]

II. OBJECTIVE

- To study the effect of adding fin plate in the tube surface.
- To study the effect in ambient air due to propose different design of the fin plate.
- To study the effect in temperature of tube by adding the fin plate in its surface.
- To study the temperature behavior in fin plate.
- To study the velocity behavior of the ambient air due to adding the fin plate.

III. RESEARCH AND METHODOLOGY

A. Computational domain

In case of all design of cross-flow heat exchanger model was modelled using CATIA software and the geometric parameters for tube, air domain, and fins used by (Paul et al., 2023) [20]. The heat exchanger model consists of four circular tubes and 2, 3, and 4 square and rectangular fins. The material used for all the fins and tubes was steel with a thermal conductivity of 14.9 W/m.K. Each tube is 110 mm in length with a 23 mm inner and 27 mm outer diameter. In all cases the fins are modify for reduce the temperature of tube. In all cases 2 fins with dimple on its surface are present. The changes made in the adding of one and two fins between the old fins, which are having dimples. Particular fins parameter are describe below in cases section. Air domain having a width, length, and height of 302.4 mm, 110 mm, and 220 mm respectively. The locations of tube centers were (2 L/7, L/4), (2 L/7,19 L/28), (5 L/7, 9 L/28) and (5 L/7, 3 L/4), where L denotes the length of the fin as shown in Figure 3.3 with all the necessary dimensions. For the comparison study, different cases were studied. Table 1 shows the different cases investigated in the present work.

1. Case 1 – Fins with dimple

This computational domain has two square fins with length, thickness, and fin spacing of 126, 1, and 20 mm. The back and front surfaces of this fin have 5.5 mm dimples. Figure shows dimple location.

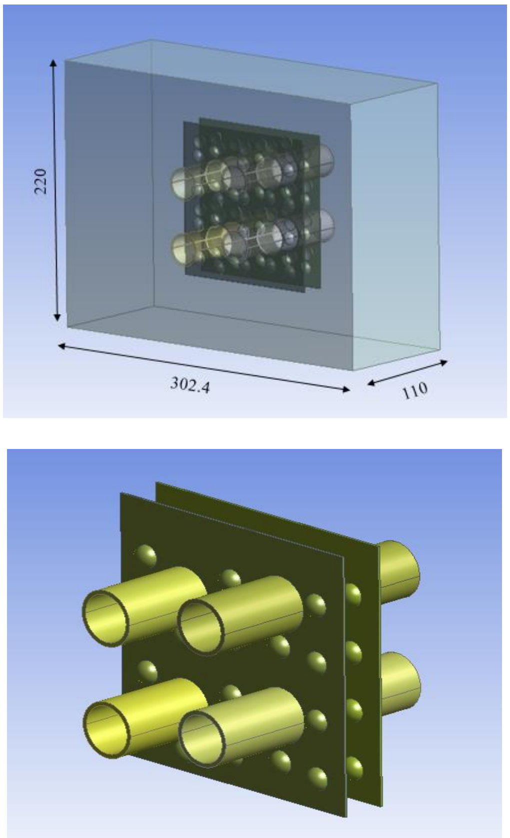


Figure 1 Computational domain of case 1

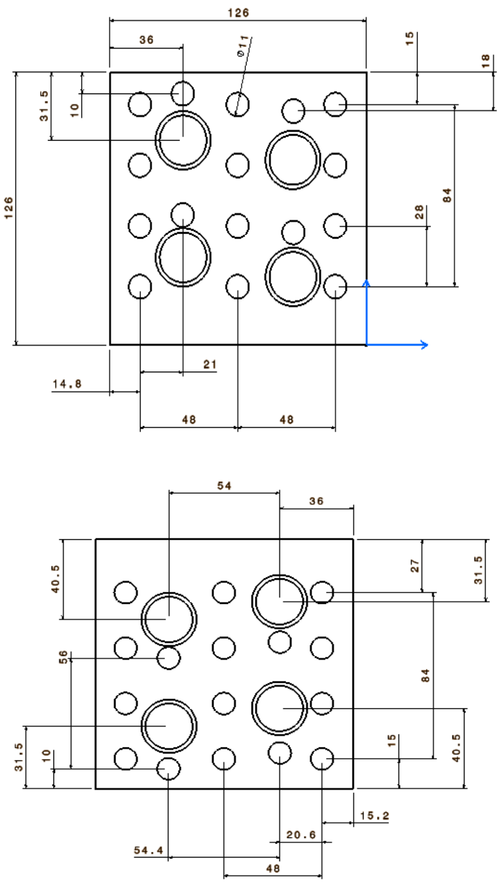
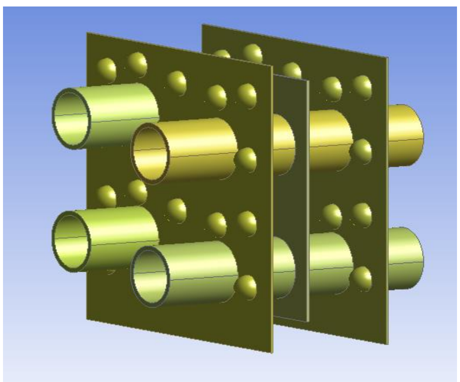


Figure 2 Dimension representation of dimple, fin plate and tube of case 1

2. Case 2 – Fin 96 × 126

This computational domain has 3 fins. Case 1 uses two fins with length, thickness, and fin spacing of 126, 1, and 50 mm. Third fin joins dimpled fins. The back and front surfaces of this fin have 5.5 mm dimples. Dimple placement did not change. The new or third fin is 96 mm long, 106 mm tall, and 1 mm thick. Figure provides further details.



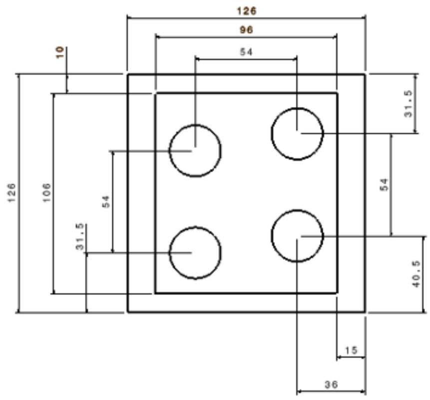


Figure 2 Computational domain and dimension representation of fin plate and tube of case 2

3. Case 3 – 126 × 126

This example uses the identical parameters as instance 2, except for the third fin. The new fin is 126 mm long and tall. Third fin between two dimpled fins.

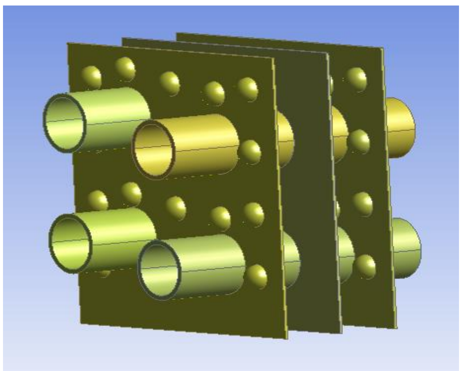
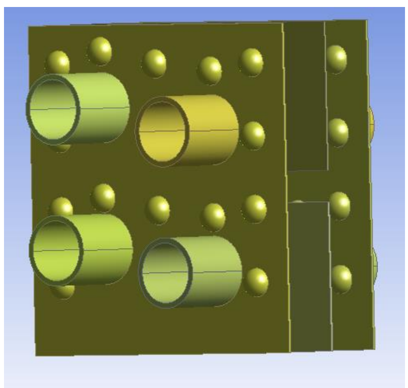


Figure 4 Computational domain of case 3

4. Case 4 – 4 fins (126 × 57)

This computational domain has 4 fins and is in the midst of the dimples. Smooth surfaces on both new fins. Case 3's fin has two identical parts: 126 mm long and 57 mm tall. Show in figure.



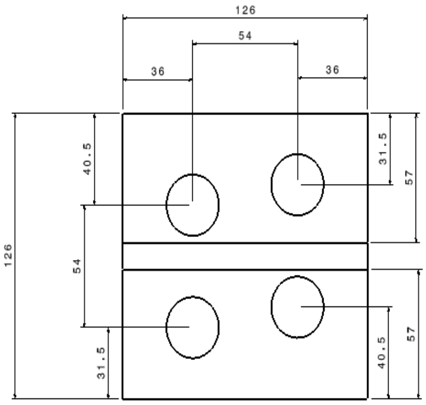


Figure 5 Computational domain dimension representation of fin plate and tube of case 4

5. *Case 5 – 15 holes*

This example has three fins of 126 mm length and height. Only the first and last fin plates have dimples, while the middle one has 15 holes of 6 mm diameter. Figure below shows location.

6. *Case 6 – 21 holes*

Case 5 fins have 15 holes. So it rises to 21. The remaining domain design parameters are the same as in example 5. The figure shows hole locations.

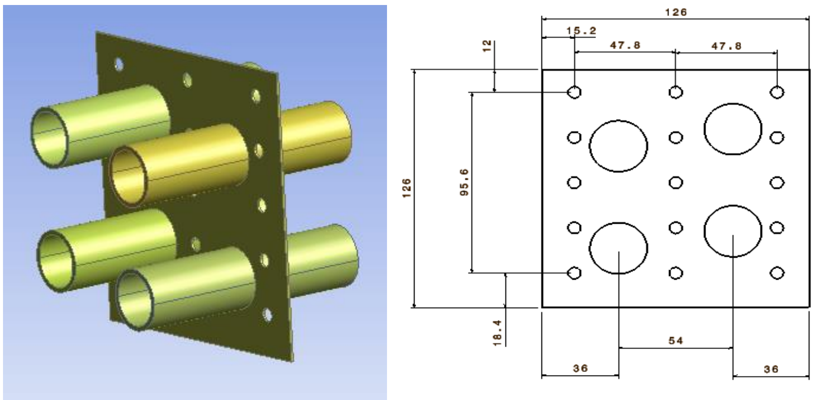


Figure 6 Computational domain and dimension representation of fin plate and tube of case 5

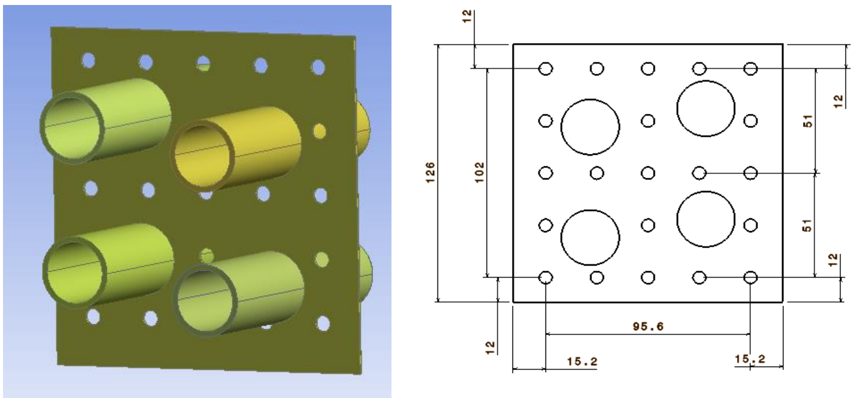


Figure 3 Computational domain and dimension representation of fin plate and tube of case 6

B. *Mesh generation*

The air enclosure, fin plate, and tube must be considered while meshing a cross-flow heat exchanger. The mesh elements employed are mostly tetrahedral and hexahedral. Mesh components vary in size by domain. The tube and fins, with their more complex shape and higher resolution, use 0.002 meters elements. This greater resolution properly captures heat transport and fluid dynamics in tubes and fin surfaces.

A 0.01-meter element size is suitable for the air enclosure, which has simpler geometry. This bigger element size decreases computing costs while replicating enclosure flow and heat transfer phenomena with sufficient fidelity.

The mesh's elements and nodes rely on the domain size and resolution. Finer meshes with more elements and nodes provide more accurate results but demand more processing power. Thus, the mesh density must balance processing resources and analytical accuracy. Based on these factors, the table shows the amount of elements and nodes created for each domain.

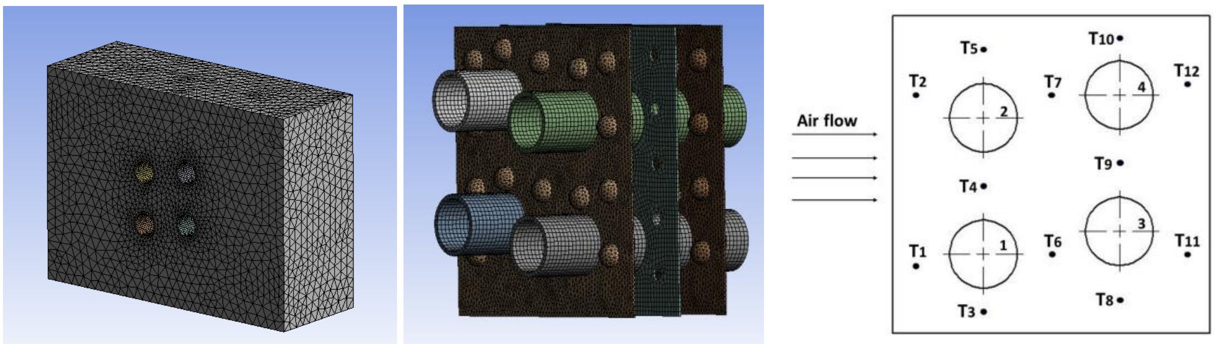


Figure 4 Mesh generation of computational domain and notation of tube

C. Boundary condition

This study uses ANSYS FLUENT for numerical analysis. The flow field was turbulent and simulated in steady state. We used the Standard k-ε turbulence model. Pressure-velocity coupling with no slide at solid surfaces was solved using the pressure-based solver and coupled scheme solution technique. Second-order upwind discretization solves momentum, energy, and pressure equations. The computational domain's working fluid is ambient air, which is assumed to be incompressible and constant Velocity and pressure inlets and outlets as similar use in (Paul et al., 2023)[20]. The inlet air temperature is 299.45 K and uniform velocity is 0.5 m/s. To extensively use cross-flow heat exchangers as HVAC condensers and evaporators, evaporation and condensation must be constant temperature. This assumed constant but varying surface temperatures for four tubes. Surface temperatures for tubes-1 to-4 were 323.06 K, 325.90 K, 329.30 K, and 334.87 K. This research only considers four tubes with symmetric boundary conditions on the computing domain's right, left, bottom, and top surfaces. This assumption allows analysis of the heat exchanger's shape and other tubes.

Table 1 Thermo-physical properties of air and steel

Properties	Unit	Air
Density	Kg/m3	1.225
Specific heat	kJ/kgK	1.006
Thermal conductivity	W/m.K	0.0242
Viscosity	Kg/m-s	1.7810^{-05}

D. Validation

Model validation employed 32 dimples on fin surface configuration numerical results. Section 3.5 describes computational domain design parameters. Calculating temperature effectiveness, which measures dimensionless heat exchanger performance, is a standard way to evaluate thermal performance. Figure 9 compares temperature efficacy from this investigation with Paul et al. (2023)[20]. Validating the outcome differs somewhat. Thus, the reference publication and this simulation study are compatible.

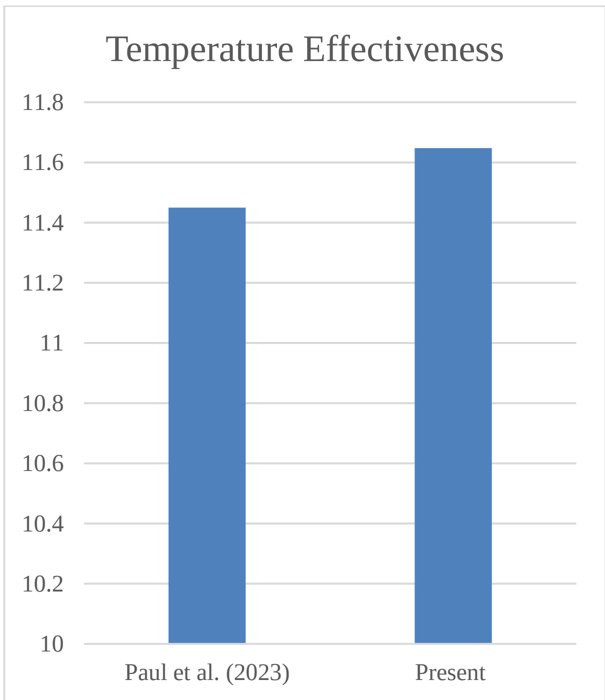


Figure 9 Validation Result

IV. RESULT AND DISCUSSION

A. *Temperature contour*

Tube temperature is varied in all circumstances, as stated in boundary conditions. Tube and fin plate have linked walls, allowing conduction. Conduction raises fin temperature. Fins and tubes are in air domain with perpendicular airflow. All cases had 0.5 m/s airflow at 299.45 K. Lower the fin plate-placed tube fluid temperature. Place dimples on fin plate to lower tube temperature.

In Case 1, 32 dimples on both sides of a fin plate increase heat exchange between tubes, fins, and air. Convective heat transfer raises exit air temperature. In Case 2, adding a fin plate between the dimpled fin plates increases contact area and convective heat transmission. The air temperature rises and the fin temperature drops. Case 3 improves convective heat transmission by attaching three fins to the tube and positioning them similarly to Case 2. Thus, air temperature rises and fin temperature falls. Splitting the third fin in two changes surface area in Case 4. Despite the adjustment, convective heat transfer remains strong, resulting in a similar temperature trend to Case 3. Case 5, like Case 3, has the same fins save for 15 holes on the third fin plate. These perforations increase air-fin plate contact area, lowering fin temperature and raising air temperature owing to convective heat transfer. Finally, Case 6, like Case 5, but with 21 holes on the third fin plate, increases convective heat transmission due to greater contact area. Thus, air temperature exceeds Case 5 and fin temperature drops. Figure 10, and 11 shows air, fin plate, and tube temperature contours.

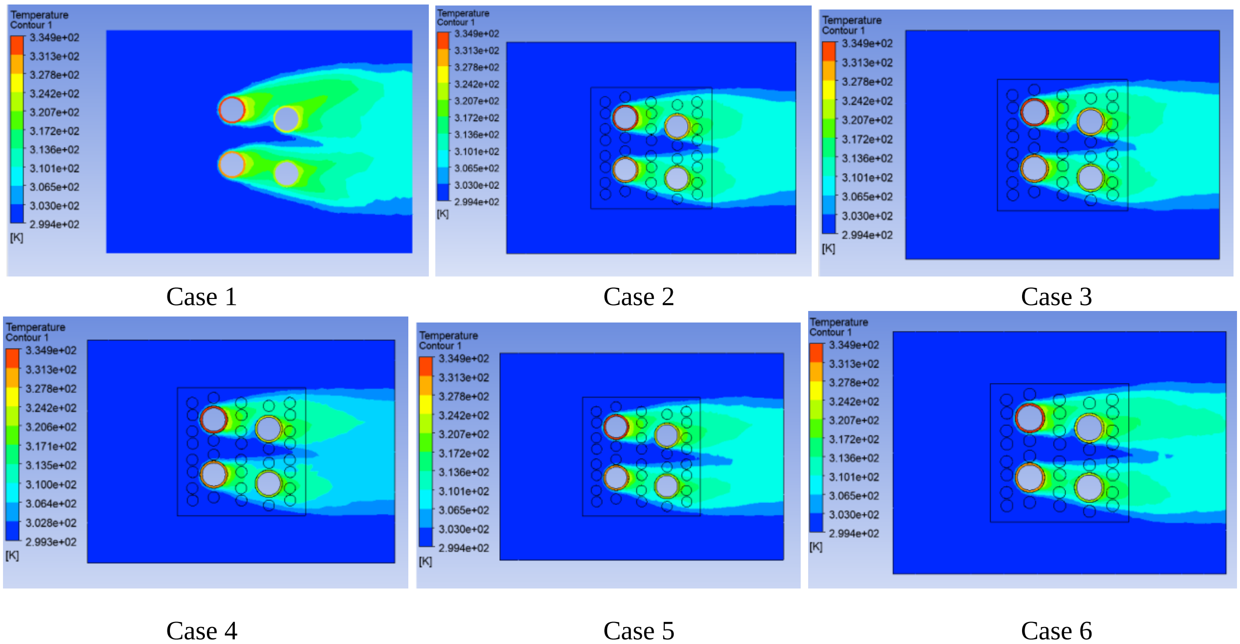
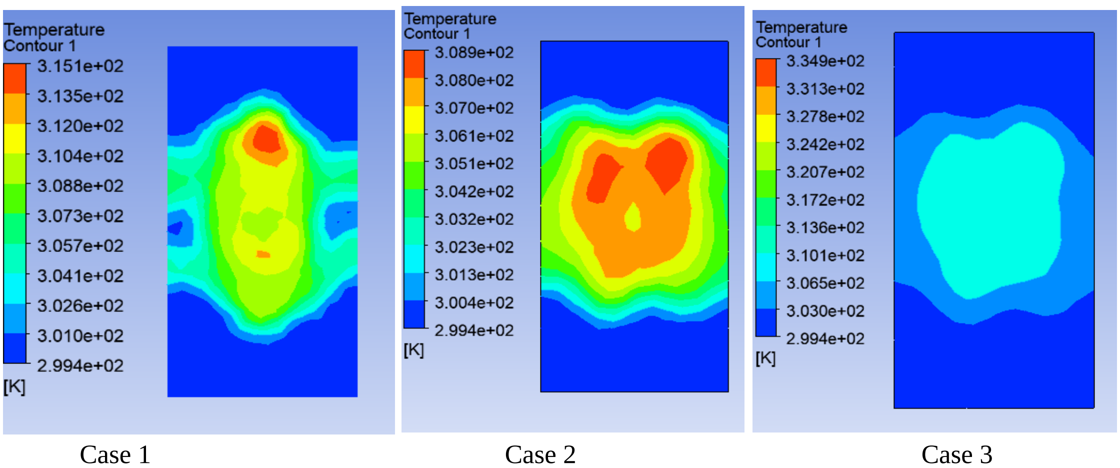
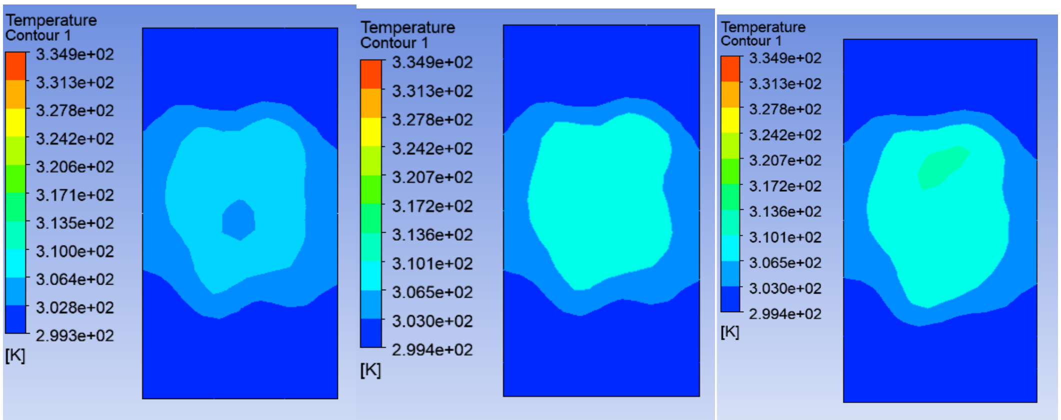


Figure 5 Temperature contour in air domain at middle along the width





Case 4 Case 5 Case 6

Figure 6 Temperature contour of air domain at outlet

It's clear that greater fin plate areas increase exit temperature. Cases 1, 2, and 3 have the biggest fin areas. Thus, Case 3's outlet temperature is 303.224 K, higher than Cases 1 and 2. Case 4, where the fin plate area is less than Case 3, lowers the exit temperature to 303.108 K. Case 6 has a fin plate with 21 holes for better heat conduction, therefore the output temperature peaks at 303.421 K. The increased contact area between the air and the fin plate in Case 6 facilitates convective heat transfer, resulting in the maximum exit temperature. Figure 12 shows that fin plate size and design characteristics significantly affect thermal performance, with greater fin areas often resulting in higher output temperatures.

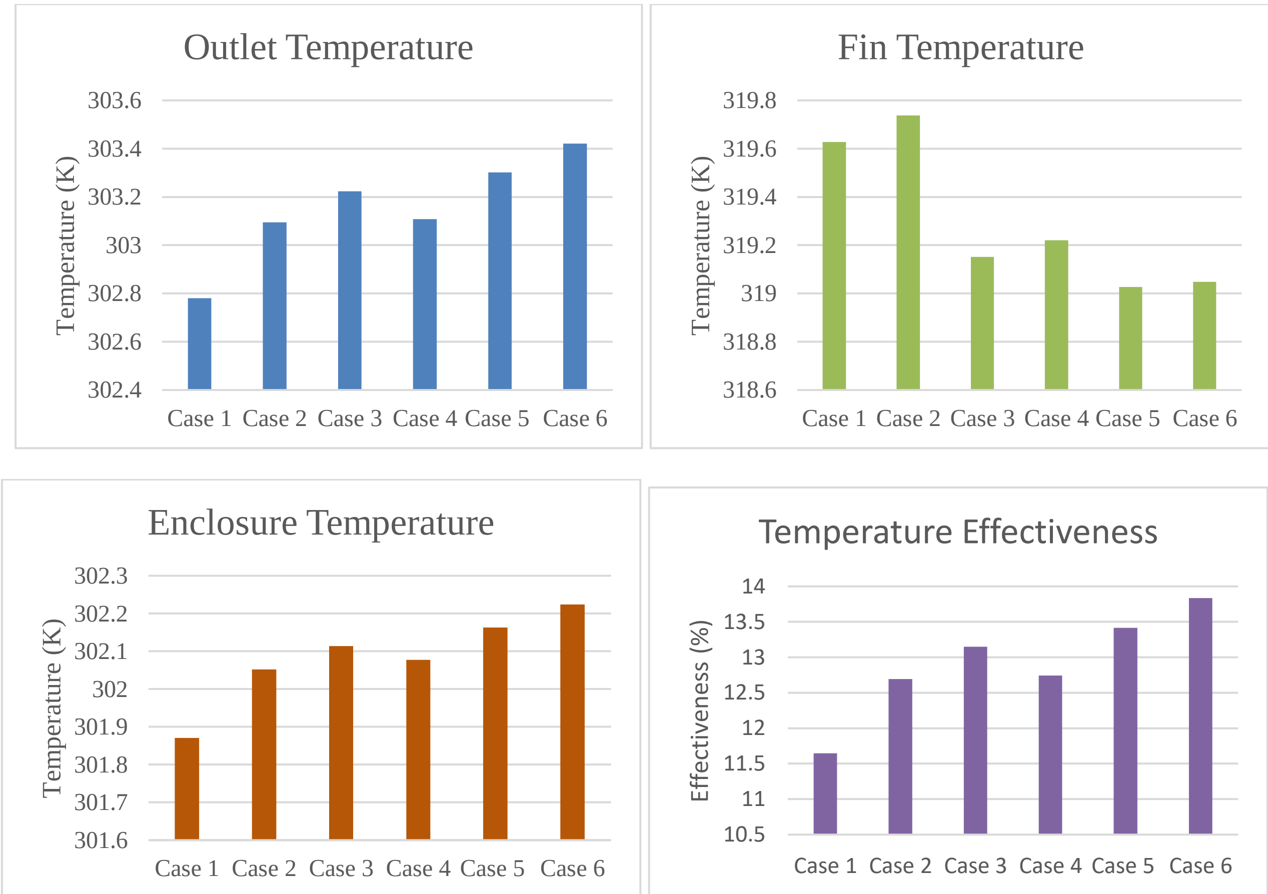


Figure 7 Outlet, Fin Enclosure temperature and Temperature effectiveness comparison

B. *Temperature effectiveness comparison*

Calculating temperature effectiveness, which measures dimensionless heat exchange performance, is a typical way to evaluate heat exchanger thermal performance. Visualising temperature effectiveness helps choose a heat exchanger for improvement based on heat transfer potential. Temperature effectiveness (E) may help choose a compact heat exchanger design where thermal performance is the main priority without pressure drop penalty. The formula for E introduced in is:

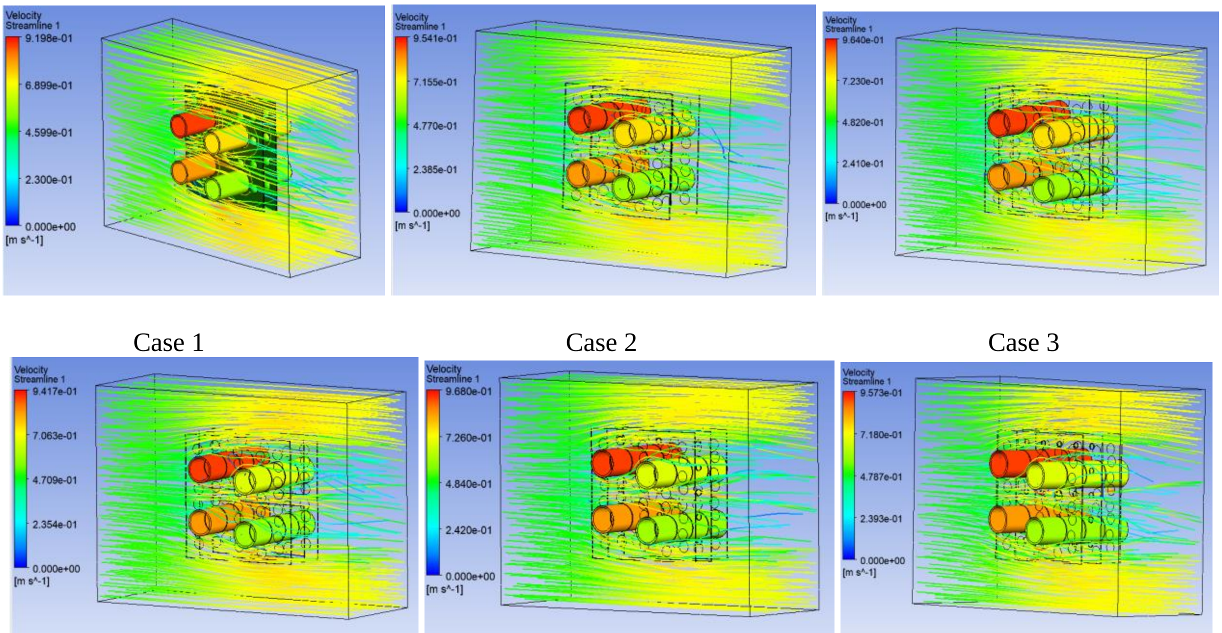
$$E = \frac{T_o - T_i}{T_{h,in} - T_i}$$

Here, T_(h,in) is equal to the arithmetic mean of the outer surface temperatures of four circular tubes. To and Ti is the outlet and inlet temperature of the air respectively.

The example with the highest efficacy, 13.147 %, is case 3 in figure 12 because its fin plate area is the largest. Thus, air outlet temperature determines temperature effectiveness. Case 4 has less fin plate area than case 3, hence its efficacy is lower. In scenario 6, output temperature is highest in all circumstances, hence effectiveness is 13.835%.

C. *Velocity contour*

The computational domain of the cross-flow heat exchanger has 0.5 m/s airflow. Air particles acquire velocity as they impact with the fin plate and tube surfaces, as seen in figure 4.30. Increasing fin area increases maximum velocities. Due to turbulence, velocities peak between successive tubes. When air particles hit the third fin plate, their velocity rises. In situations 5 and 6, air travelling through middle fin plate holes has greatest velocity. The perforations change airflow dynamics, making air particles travel more efficiently and increasing velocities in selected places.



Case 4 Case 5 Case 6

Figure 8 Velocity streamline of all cases

V. CONCLUSION

This research quantitatively analysed the impact of connecting the fin plate to the tube surface and increasing its area to improve heat transfer to output temperature and temperature effectiveness. Analysis included creating holes on the third or new fin plate to improve heat transmission. This research discovered the following:

- In the study of cross flow heat exchanger result shows that heat transfer is directly proportional to fin plate area.
- In case 1, 2, and 3, the exit air temperature is 303.224 K because case 3 has the most fin area.
- Outlet temperature directly affects temperature effectiveness. If output temperature is highest, temperature effectiveness is likewise greatest.

- Comparing case 1, 2, and 3, case 3 has the highest outlet temperature and 13.147 % temperature effectiveness.
- Case 4 has 303.108 less fin area and outlet temperature than case 3. Thus, its temperature efficacy is lower than 12.743% in instance 3. More than case1.
- Case 6 has the most air interaction. Maximum outlet temperature and temperature effectiveness are 303.421 K and 13.835% in all situations.
- Heat transfer from fin plate to air lowers fin plate temperature when output temperature is highest. Case 6 has the highest outlet temperature, hence its fin temperature is 319.048 K, whereas case 1 has 319.628K.

Future cross-flow heat exchanger performance studies might lead to significant advances. Expanding numerical research to include more geometric configurations and surface alterations is one option. Researchers might study how dimple size, shape, and distribution affect heat transmission efficiency. To understand how fluid flow rates, temperatures, and operational conditions affect heat exchanger performance, examine them. To confirm the effectiveness of design adjustments, future research might experimentally validate numerical results. Experimental studies may reveal real-world performance characteristics and improve numerical models and simulation methods. The future of cross-flow heat exchanger performance enhancement is large and varied, giving many opportunities for study and invention to optimise heat transfer system efficiency and effectiveness.

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