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Research Article

A CFD investigation of the design variables affecting the performance of finned-tube heat exchangers

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ABSTRACT

A wide variety of heating and cooling applications use heat exchangers. The increase in energy prices, the requirement for size reduction, and restriction on greenhouse gas emissions has led to the need for finding ways to develop efficient heat exchangers. A cost-efficient way to enhance the model of a heat exchanger by visualizing the effects of the design parameters is using Computational Fluid Dynamics (CFD). The reason for this exploration was to lead an examination of the varieties/changes in the general intensity move process for a Finned-Tube Heat Exchanger (FTHE), also known as Air Coil Heat Exchanger (ACHE) with a variety of plan boundaries like the quantity of tubes, course of action of tubes, and the material utilized for the intensity exchanger. The widely used heat exchanger that uses refrigerant R314a and air as the working fluids was simulated with different design modifications. The simulated results exhibited as to how the number of tubes, arrangement of coils/tubes, material of tubes, and density / spacing of fins, effects the pressure drop, temperature and velocities profiles, and heat exchangers' transfer of a heat. The use of copper coils improved the heat transfer by approximately 61% as compared to aluminium coils.

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INTRODUCTION

An exchanger, utilized for different cooling and heating applications, is a gadget that is used to move heat between liquids [1]. Heat exchangers are classified in view of elements like the configuration of flow (single stream, parallel flow, counter flow, cross flow, and so on) and the kind of development (shell and tube, double pipe, plate and frame, spiral, compact, etc). The minimal intensity exchangers are utilized in applications that require small size and weight for heat to move between liquids. Reduced heat exchangers include at least one working liquid as gas.

Designing of a compact heat exchanger has over the years shown continuous development. The compact heat exchangers generally consist of tubes and fins and the design is based on crossflow configuration for heat transfer between the two working fluids [2]. The various types of configurations for compact heat exchangers are shown in Figure 1.

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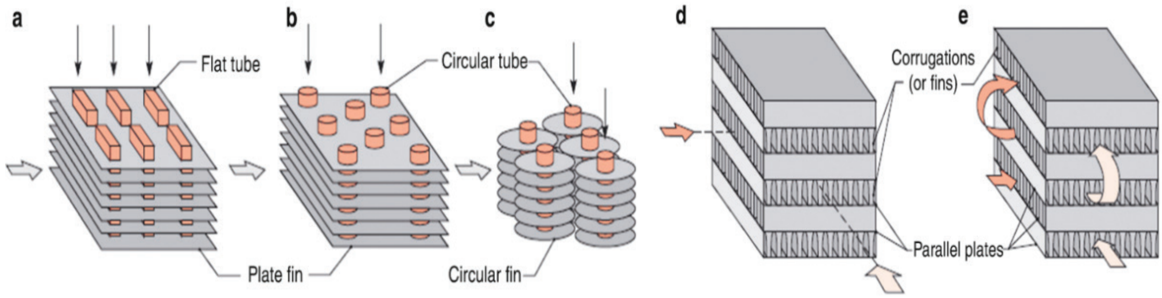

Figure 1. Compact heat exchanger cores [3]. (a) Fin-tube (flat tubes). (b) Fin-tube (circular tubes). (c) Fin-tube (circular tubes, circular fins). (d) Plate-fin (single pass). (e) Plate-fin (multi-pass).

Tubes

Tubes are the long circular or rectangular, usually staggered, which pass across the fins for heat transfer through which the refrigerant or the cold fluid of the heat exchanger flows. Circular tubes in the exchanger cause higher pressure drop outside the tubes compared to flat or elliptical tubes. Conversely, the flat tubes yield lower pressure deficit for stream typical to tubes because of the lower form drag and stay away from low-execution wake locale behind the tubes [4]. The tube layout in a Finned-Tube Heat Exchanger (FTHE) follows two basic arrangements (1) staggered or (2) inline (Figure 2).

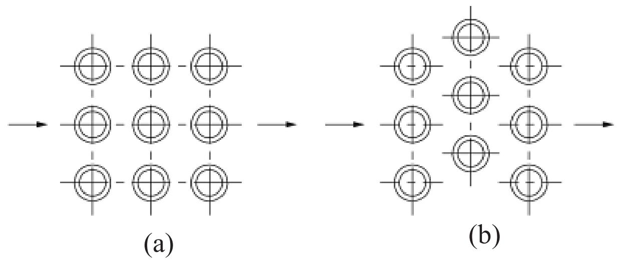

Figure 2. Tube layout (a) Inline (b) Staggered [4].

The basic distinction in these two patterns is that each alternate row is shifted half a transverse pitch in the staggered layout. Moreover, it has been observed that the number of rows effected overall thermal presentation of the exchanger. Thus, as number of tube rows increase it improves thermal performance as shown in Figure 3 [5].

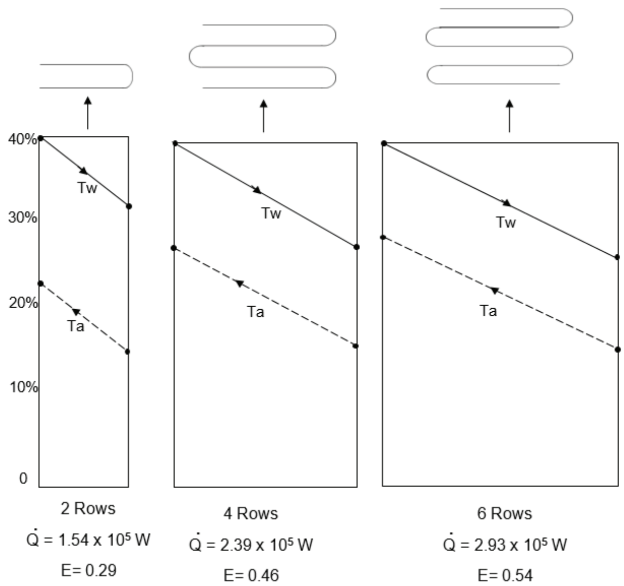

Figure 3. Performance of finned tube heat exchanger [5].

Fins

In a finned tube heat exchanger, the heat transfer surface area is increased by the fins. As the heat transfer coefficient is lower on the gas side as compared to the liquid side, fins are used there. There are various arrangements of fins that have been developed and designed for different types of application as illustrated in Figure 4. An increase in the number of fins per meter, reduces the overall size of the unit. However, the more the number of fins per meter, the exchanger becomes more sensitive to fouling, which causes accumulation of deposits on heat exchanger components. Thus, care must be given to ensure the process of fouling is minimized along with the overall size of the unit during design phase [6, 7]. The thermal performance of a heat exchanger varies by fin height in fin design. However, the flow conditions between the fins become laminar and the heat transfer is reduced if the height of the fins and number of fins are increased excessively. Turbulent flows are considered to be more effective in the process of heat transfer through a heat exchanger as it increases the overall heat transfer between the two working fluids. The thin layer of air which has already experienced considerable heat transfer, sweeps away from the surface and is replaced by new air because of turbulence. The “thermal entrance region is comparatively short for turbulent flow hence the temperature distribution is fully developed. Normally, heat transfer takes place in a fully developed region” [8]. Whereas, the

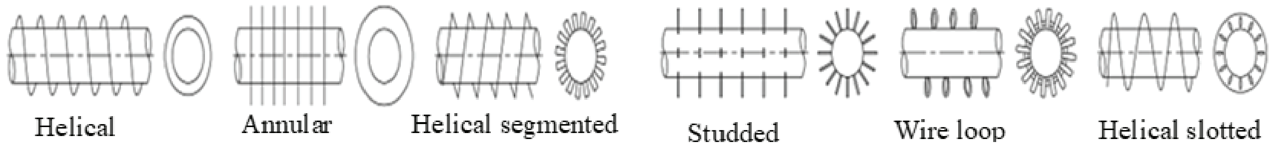

Figure 4. Forms of individually finned tubes [4].

heat transfer conductivity of the fluid relies entirely on the thermal conductivity of the fluid to transfer heat from the stream to the heat exchanger walls [9].

Materials

To construct heat exchangers, a variety of materials are used. The materials are chosen based on the type of application for which the heat exchanger is being manufactured. The thermal conductivity and material density defines at which rate heat passes through a specified material. The most used materials in the construction of heat exchanger are shown in Table 1. Copper has the highest thermal conductivity, and has the highest density. Thus, materials have to be carefully selected for a particular heat exchanger based on its applications. Furthermore, the cost of the materials also influences the decision of material selected for a particular type of heat exchanger.

Table 1. Material properties

Material	Thermal conductivity (W/m.K)	Density (kg/m^3)
Mild steel	54	7820
Aluminium	205	2700
Aluminium Alloy (AL99)	220	2710
Copper	400	8790
Cuprous nickel	30	8910

CFD

The design parameters of a heat exchanger have some effects which can be seen on its performance and can be analyzed experimentally and empirically to develop an optimum heat exchanger for a particular requirement. But with the advancement in computer technology and advanced numerical tools the whole processes can be carried out numerically to reduce the cost and effort required in the experimental and empirical studies. The CFD software packages solve the Navier-Stokes (NS) equation for analyzing and obtaining results for fluid flow. Moreover, they provide a suite of integrated components that combine to produce a powerful approach that address wide range of modeling needs.

A number of parameters affects the performance and functioning of the heat exchangers some of the parameters have been discussed in the preceding. The effect of these parameters can be studied experimentally or using numerical modelling. Experimental investigation is not only cumbersome but is also more expensive. CFD is an alternative has emerged as an effective tool to carry out such investigative studies. The paper discusses the results of a study which was carried out using CFD to see how the number of tubes, arrangement of coils/ tubes, material of tubes, and density/spacing of fins, effects the pressure drop, temperature and velocities profiles and heat transfer of a heat exchanger [10, 11]. The study is expected to give confidence to the readers to use CFD as a tool to experiment further with the designing of the heat exchangers in a bid to customize or improve the design.

RESEARCH MATRIX

The scenarios mentioned in Table 2 were simulated to see the effects of change in the following on the heat transfer of the compact heat exchanger:-

1) Number of tubes
2) Coil diameter
3) Tube arrangement
4) Tube material
5) Number of fins and fin spacing

Table 2. Details of scenarios

Scenarios	Number of tubes/ coils	Tube diameter [mm]	Tube arrangement	Tube material	Number of fins	Fin spacing [mm]
Model 1	3	15	Linear	Aluminium (Al99)	3	4
Model 2	6	11	Square	Aluminium (Al99)	3	4
Model 3	7	10	Triangular	Aluminium (Al99)	3	4
Model 4	7	10	Triangular	Copper	3	4
Model 5	7	10	Triangular	Copper	5	2

NUMERICAL MODELING

Commercially available CFD numerical code Star CCM+ was used for the complete numerical modelling process starting from the geometry creation of the system, meshing, solving of the complex mathematical equations (iteratively) to analysis of the results. A number of mathematical models are available within the software to solve the conservation of mass, momentum (Navier-Stokes) and transport equations for the turbulence model. For solving turbulent fluctuations, the k-ε turbulence model was used. The realizable k-ε model widely accepted for the analysis of turbulent flows similar to the understudy flow was however used for this study [12, 13]. It is a well-studied and documented model [14, 15].

Geometry Creation and Meshing

The geometry of the heat exchanger used in analysis for the overall performance of the exchanger was designed using the CAD model geometry generation option in STAR CCM+. The finalized geometry for one of the exchanger arrangements is shown in Figure 5. The following exchanger dimensional parameters for the fins and the domain used in the analysis of heat transfer were selected with the concept of minimizing the computational time along with insignificant effects on the results.

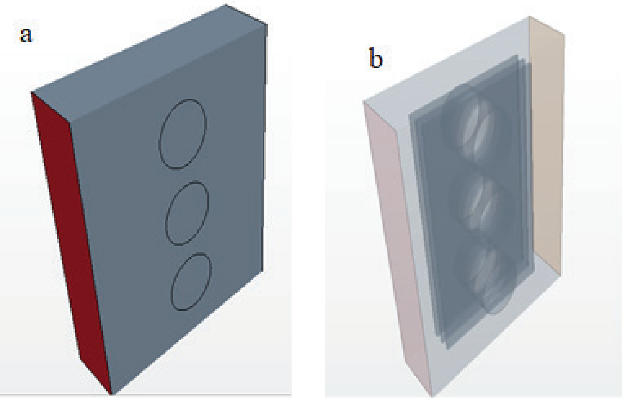

Figure 5. Heat exchanger CAD model (a) Solid (b) Transparent.

1) Dimension of domain are 160 mm x 200 mm x 40 mm.
2) Fins designed with dimensions of 120 mm x 160 mm x 2 mm with spacing between fins = 4 mm and 2 mm.
3) The coils of the exchanger were designed with different arrangements while maintaining the same mass flow rate and the positioning of the coils was based on the different patterns shown in Figure 2.

Meshing plays a vital role for achieving accurate and detailed flow in the tube [16]. The process of separating the geometry sphere into tiny number of cells, to resolve the flow equalities and obtain findings is called meshing. The rate of the flow equations solved by solver is influenced by the number of cells that may lead to in correct results. Thus, higher number of cells would yield for better and accurate results. Nevertheless, higher computational memory is required for solving the flow equations if higher number of cells are used. A common practice during the meshing is that rather than using the whole domain, high number of cells in area of interest are used, which allows to reduce the computational time and power required significantly. Hence, the meshing needs to be selected with a compromise in accuracy of the results and computational time. The meshed geometry used for analysis of the heat transfer via the heat exchanger is shown in Figure 6.

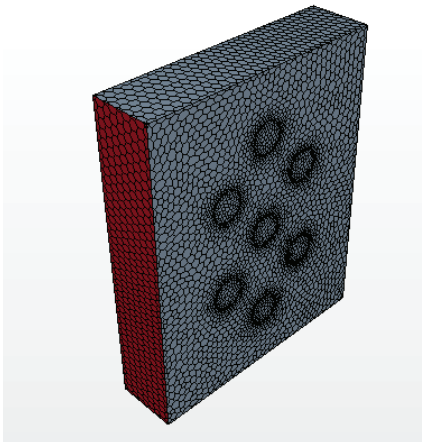

Figure 6. Meshed geometry.

Polyhedral mesh was used for the generation of the grid, as it provides better accuracy in results compared to other mesh options available in STAR CCM+. A foremost benefit of polyhedral mesh compared to others, the cells have many neighbors unlike tetrahedral [17]. Thus, allows the complex geometry to mesh properly.

ASSUMPTIONS AND CALCULATIONS

The inlet conditions for the air stream and coolant were assumed at 40°C and -27°C respectively. The properties of the working fluids at the fore mentioned temperatures are listed in Table 3.

The initial conditions of the air flow (i.e. temperature and speed), coolant (i.e. temperature) were determined on the basis of the geometry of the FTHE to ensure the flow through the exchanger falls in the turbulent flow regime, the environment temperature and the desired outlet temperature required for ambient environment of a room or building during summer time (i.e. between 20°C -25°C).

Eqs. (1-7) used for calculating other variables for performing the simulations are listed below, details in Table 3.

Table. 3. Properties of working fluid

Properties	Air	Coolant
Temperature [°C]	40	-27
Density [kg/m^3]	1.127	5.0739
Specific heat capacity [kJ/kg.K]	1.005	0.7911
Thermal conductivity (K) [W/m.K]	0.0271	9.4504x10^{-3}
Kinematic viscosity (ν) [m^2/s]	1.697x10^{-5}	1.966x10^{-5}
Cross Section (A) [m^2]	0.008	Variable according to design
Velocity (u) [m/s]	2.5	Variable to maintain mass flow rate
Prandtl number (Pr)	0.711	0.8252
Hydraulic diameter (DH) [m]	0.66667	Coil diameter
Reynolds number (Re)	9281.255	Variable with turbulence
Mass flow rate (ṁ) [kg/m^3]	0.02554	0.002492
Nusselt number (Nu)	31.3171	Depends on Nu
Turbulent intensity (I)	0.050711	Depends on Re

$$\dot{m} = \rho A u \tag{1}$$

$$Pr = (C p \mu)/K \tag{2}$$

$$Nu = 0.023 \times Re^{0.8} \times Pr^{0.4} \tag{3}$$

$$Re = \rho \times u \times d / \mu \tag{4}$$

$$DH \text{ (Rectangular or square)} = d \text{ (tube)} = 4xA/P \tag{5}$$

$$\mu = \nu \times \rho \tag{6}$$

$$I = 0.16 \times (Re)^{-1.8} \tag{7}$$

Initial data used for the working fluids to find the heat transfer between the working gasses is given in Table 3. R134a the most common refrigerant used for the purpose of heat transfer in a finned tube heat exchanger was used for this study. The conditions for air were considered based on the environmental conditions expected in hot countries. The values for the properties of the working fluids were calculated using the formulae listed above. The properties of the refrigerant at a constant pressure of 1.05 bar were used in this study.

RESULTS AND DISCUSSION

Results – Model 1

The first model of the heat exchanger (Figure 7) comprises of three coils with a radius of 15mm through the three fins of the exchanger design with the inlet air velocity of 2.5 m/s at 40°C. Aluminium alloy (AL99) was selected as the material for the coils of the exchanger. The results are shown in Figs. 8-10.

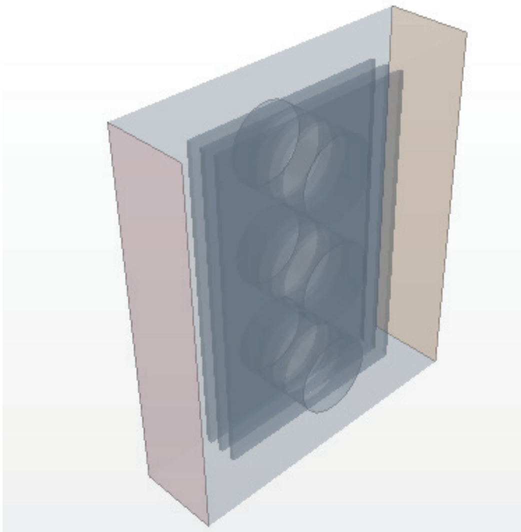

Figure7. Heat exchanger geometry-model 1.

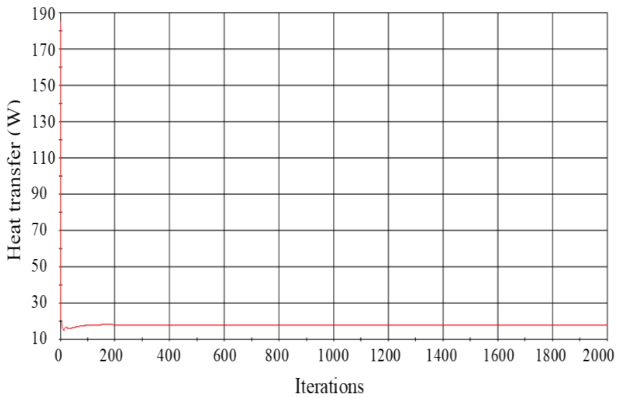

Figure 8. Heat transfer graph-model 1.

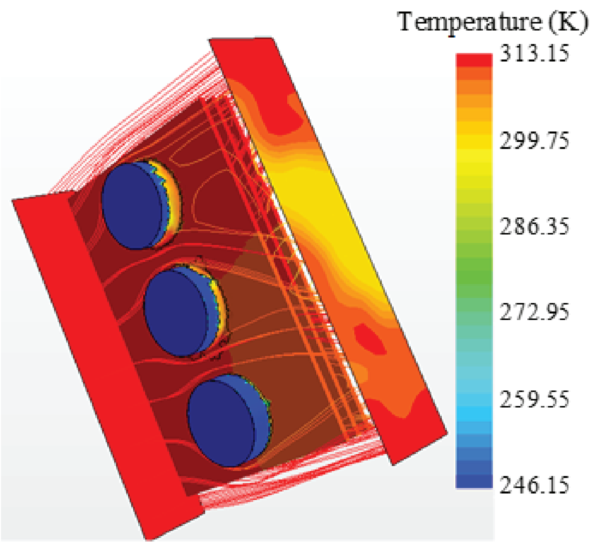

Figure 9. Temperature distributions at outlet-model 1.

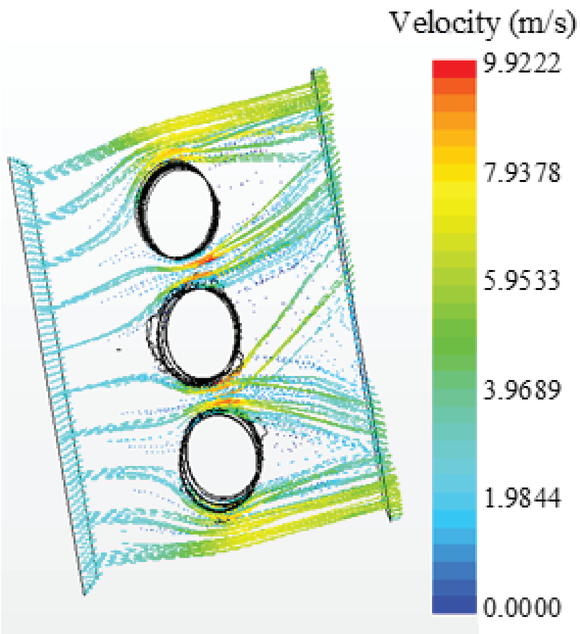

Figure. 10. Flow pattern and velocity profile-model 1.

Results – Model 2

Model 2 of the heat exchanger comprising of 6 coils with a radius off 11mm (same dimensions of the domain and fins as of Model 1) was used. The inlet conditions were kept the same as model 1 i.e. inlet of air at 2.5 m/s at 40°C and the cold fluid temperature at -27°C. The results for these conditions is shown in Figs. 11-13.

Results – Model 3

Model 3 of the exchanger was designed using seven coils of 10 mm radius. The geometry of the model 3 is illustrated

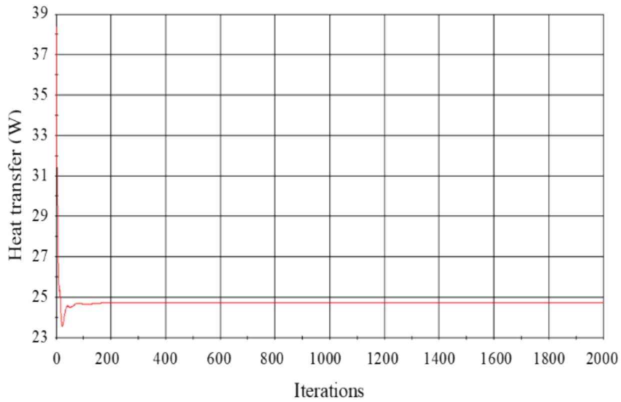

Figure 11. Heat transfer graph-model 2.

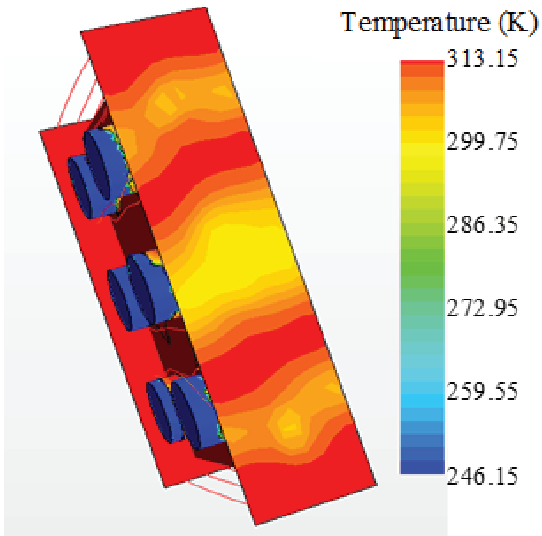

Figure 12. Temperature distribution-model 2.

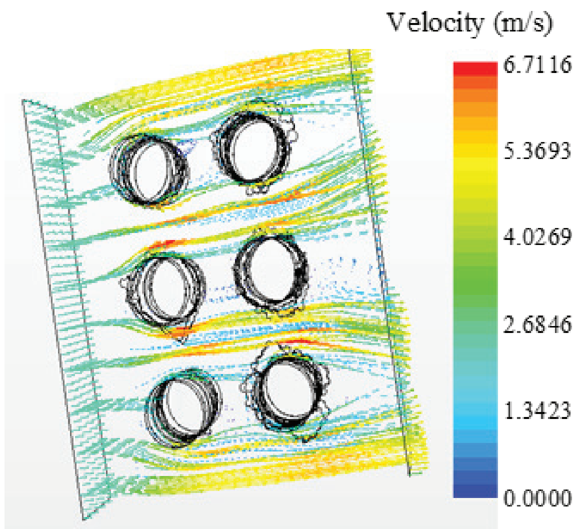

Figure. 13. Flow pattern and velocity profile-model 2.

in Figure 14, whereas the results obtained are shown in Figs. 15-17. This model yielded the best results, therefore the next two scenarios were modelled to simulate only the effect of the change in material of the heat exchange and number of fins on the heat transfer and the outlet temperature distribution.

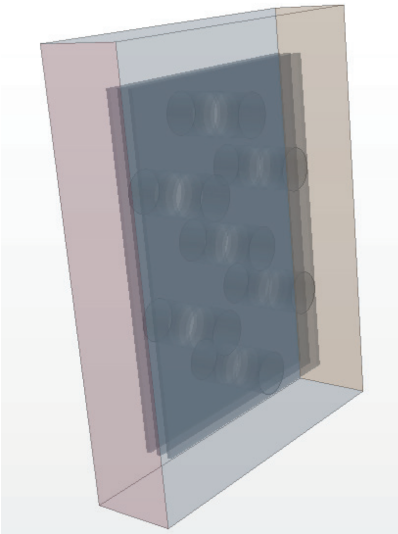

Figure 14. Heat exchanger geometry-model 3.

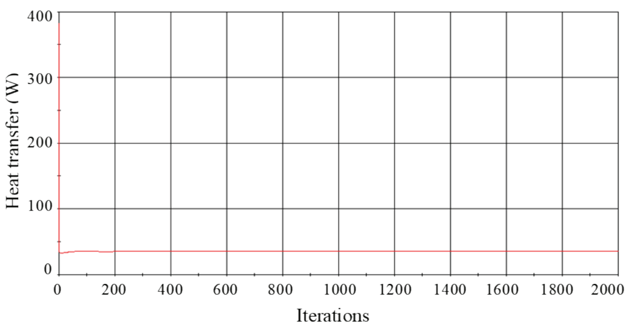

Figure 15. Heat transfer graph-model 3.

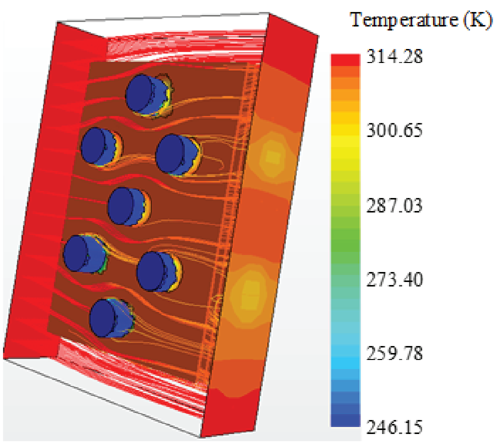

Figure 16. Temperature distributions-model 3.

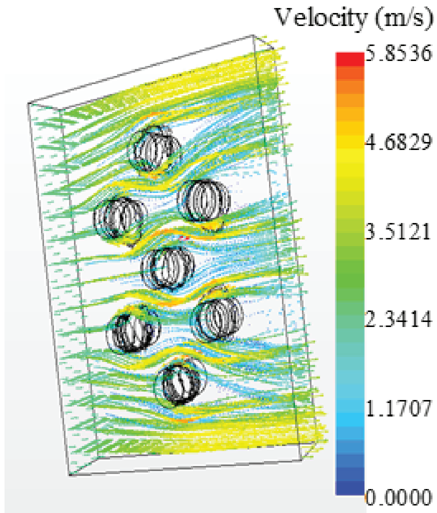

Figure. 17. Flow pattern and velocity profile-model 3.

Results – Model 4

After obtaining the results for the initial three designs, Model 3 arrangement was considered for further analysis to observe the change in the complete heat transfer with the change in heat exchanger material. Following aluminum the most commonly used material for finned tube heat exchangers, because of its high thermal conductivity value, is copper. However, the density of copper is a disadvantage for its use for the complete assembly of the heat exchanger. Hence, designers have to make a decision founded on the application of the heat exchanger to use aluminum or copper as the material for the exchanger. Figure 18 illustrates the heat transfer between the working fluids through the heat exchanger. Whereas Figure 19 illustrates the temperature distribution at the outlet that is improved as compared to the models with aluminum alloy used initially for the analysis of the change in heat transfer with varying number of tubes and their arrangements.

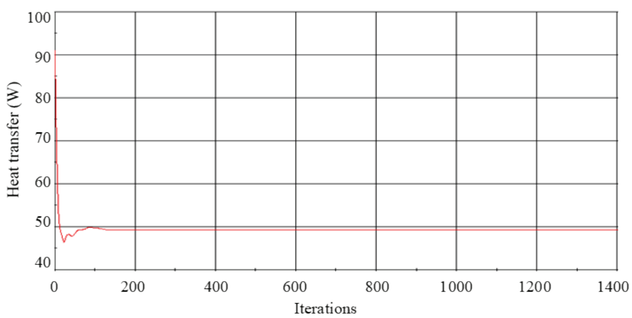

Figure 18. Heat transfer-model 4 (model-3 with copper fins/coils).

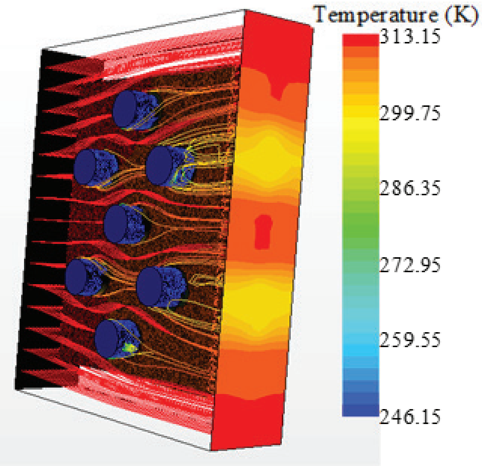

Figure 19. Temperature distribution-model 4 (model-3 with copper fins and coils).

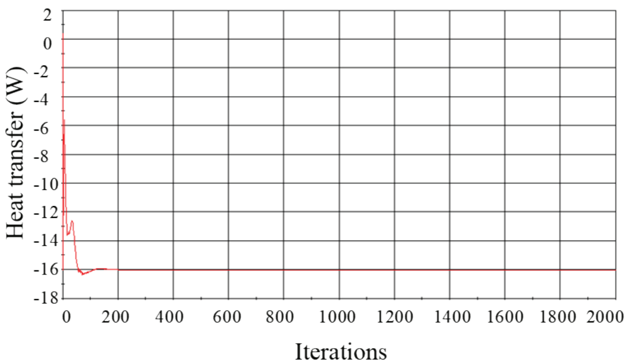

Figure 20. Heat transfer graph-model 5 (model 3 with 5 fins).

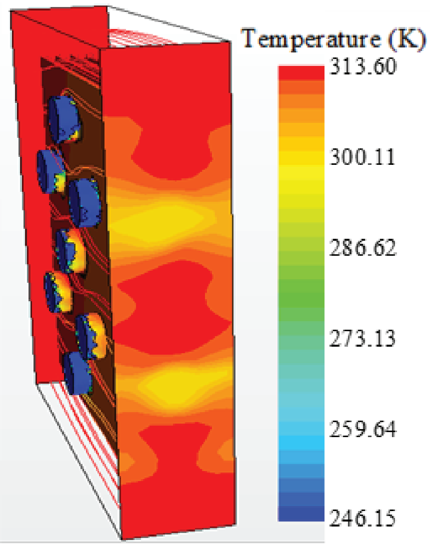

Figure 21. Temperature distribution - model 5 (model 3 with 5 fins).

Results – Model 5

The last simulation for the analysis of heat transfer variation was conducted with the increase in number of the fins. The fins were increased to five from three (that were used in the first four models). The temperature distribution at the outlet of the exchanger is shown in fig 20, fig 21 shows the value of heat transfer between the fluids with extra fins.

Pressure Drop – Model 1-3

Figs. 22-24 illustrate the pressure and velocity profiles for each of the initial models used for the analysis of heat transfer for the heat exchanger if we increase in number of tubes and change in the arrangement of the tubes the pressure drop for the exchanger decreases with it, respectively. The minimum pressure drop was obtained in Model 3 for the same inlet conditions of the air and the coolant. Moreover, the difference between the inlet and outlet velocities reduces with iterations in the heat exchanger geometry. Lastly, it can be deduced from the Figs. 22-24 the dead zones generated in the first model are comparatively high to those in model 3, hence as a consequence the effects are seen in overall heat transfer between the working fluids.

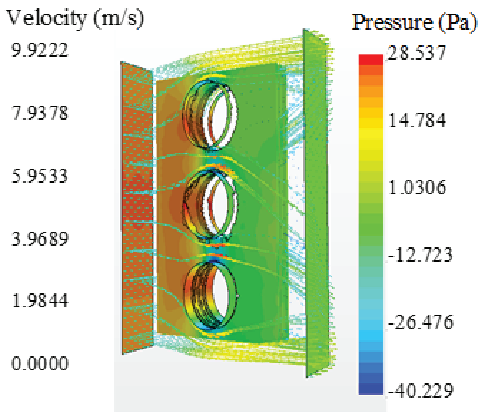

Figure 22. Pressure and velocity profile-model 1.

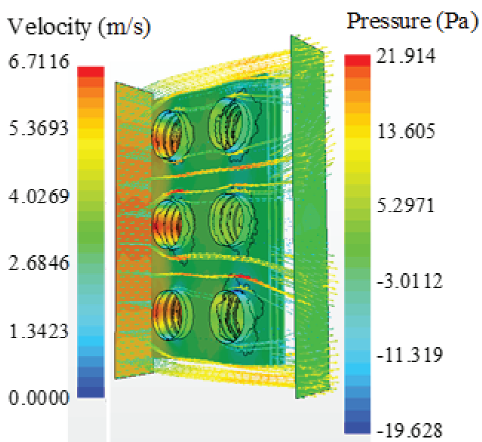

Figure 23. Pressure and velocity profile-model 2.

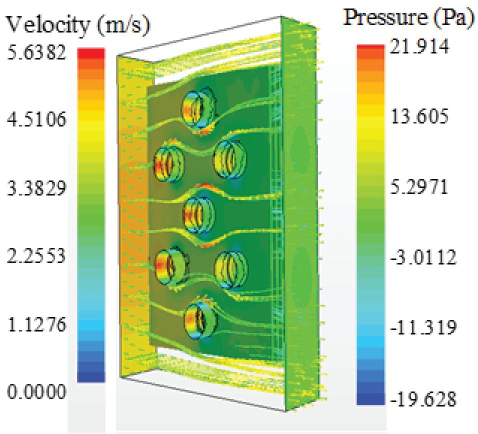

Figure 24. Pressure and velocity profile-model 3.

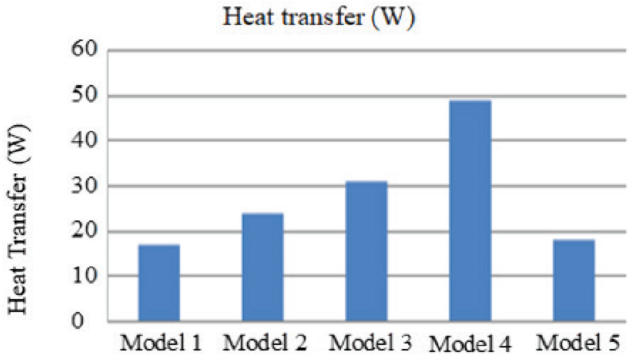

Figure 25. Heat transfer of heat exchanger models.

Comparison and Analysis

The simulations of the heat exchanger geometry were conducted with the variation in the number of coils and change in the arrangement of the coils initially. For heat exchanger in all three models selected, the mass flow rate for the air and the refrigerant were kept constant. The mass flow rate calculated for air was to be equal to 0.02554 kg/m^3 for the air inlet based on the dimensions of the geometry of the heat exchanger. The mass flow rate was obtained to be 0.002492 kg/m^3 for each refrigerant coil/tube for each model design of the heat exchanger. Increase in the number of coils increased the heat transfer between the working fluids. The overall performance of the heat exchangers can be evaluated from the calculated value of heat transfer between the two working fluids. The heat transfer for model 1 was obtained and was observed to be approximately equal to 17W. Alternatively the heat transfer between the two working fluids in the second design was obtained to be approximately equal to 24W. The heat transfer was further enhanced in the third design for which the value of heat transfer obtained was equal to 31W. Lastly, with the material changed from aluminum alloy (AL99) to Copper (Cu) for fins and coils it was observed the heat transfer was improved significantly and was obtained to be approximately equal to 50W. However, a reduction was observed in the heat transfer with the increase of fins for the same mass flow rates of the working fluids with aluminum as the material of the exchanger. The heat transfer value for model 5 (model 3 with increased fins) is negative (Figure 20), because the heat transfer was calculated from the fins/coils to air Figure 25 and Table 4.

Moreover, from the figures illustrated in results section it can be seen the temperature distribution at the outlet changed significantly. The results portray the area of minimum temperature obtained after the heat transfer via the exchanger increased from model 1 to model 3 with copper fins and coils. Conversely, because of the laminarization of the flow conditions between the fins, the increase in the number of fins for same flow rate and aluminum as the material it was reduced significantly.

The pressure drop for each model is represented in Figure 26. It can be observed from the graph that with the increase in number of tubes the pressure drop reduces. Since, pressure decline is directly proportional to the velocity of the working fluid, it can be deduced, in model 3 geometry of the heat exchanger the flow is fully developed and in return improves the overall heat transfer between the working fluids through conduction of tube and fin

Table 4. Details of scenarios with heat transfer

Scenarios	Number of tubes/ coils	Tube diameter [mm]	Tube arrangement	Tube material	Number of fins	Fin spacing [mm]	Heat Transfer (W)
Model 1	3	15	Linear	Aluminium (Al99)	3	4	17
Model 2	6	11	Square	Aluminium (Al99)	3	4	24
Model 3	7	10	Triangular	Aluminium (Al99)	3	4	31
Model 4	7	10	Triangular	Copper	3	4	50
Model 5	7	10	Triangular	Copper	5	2	19

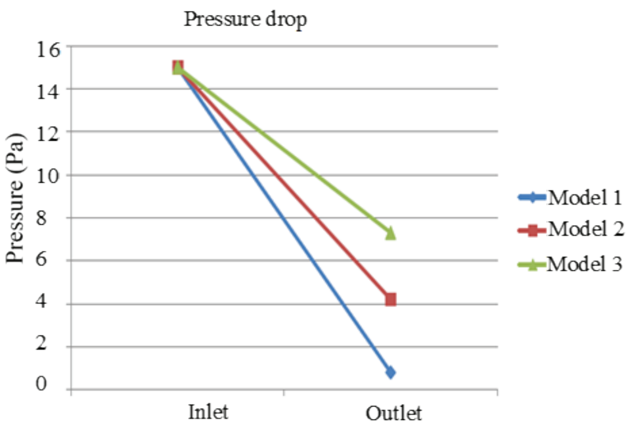

Figure 26. Pressure drop for different 3 heat exchanger models.

walls. Furthermore, the dead zones generated were reduced with iterations in the geometry of the heat exchanger, which also contributes towards the enhancement of heat transfer in the exchanger between working fluids (i.e. air and refrigerant R134a).

The laminar flow doesn't allow better heat transfer as compared to the turbulent flow conditions. Since the "thermal entry area is relatively short for turbulent flow and subsequently the temperature dissemination develops to be "completely developed". Ordinarily, heat transfer happens in "completely developed" area. The effects of variation in the tube dimensions and arrangements were observed in the overall heat transfer values obtained for each of the heat exchanger model [18][19]. Modifications in the geometry of the initial design were made in terms of the number of tubes and the arrangement of the tubes for cold fluid. As a result, improvement in the overall heat transfer was observed. Moreover, with the minimum temperature, the area at the outlet increased, which was found to be in agreement with the literature review conducted for the research.

Furthermore, the improvement in the overall heat transfer between the working fluids (i.e. air and R134 refrigerant) was observed with the change in the material of the fins and coils of the heat exchanger. The improvement was attained solely due to the difference in the thermal conductivity of the materials. However, the heat exchangers manufactured using copper as the material are heavier because of its high density compared to the other commonly used materials for manufacturing. [20] Hence, in applications where the weight of the heat exchanger is unconcerned, copper would be a better choice as the material of the exchanger.[21] However, in application where weight of the heat exchanger plays a significant role, materials such as Aluminum and its alloys provide the best performance for the heat transfer due to its high strength and low density compared to copper. [22] Cuprous nickel having much lower thermal conductivity compared to copper and aluminum is more suitable for applications requiring higher corrosion resistance. Thus, the selection of the material for the heat exchanger has to considered based on its desired application.[23][24]

Another critical factor in the designing phase of the heat exchanger requires the consideration of the pressure drop through the heat exchanger.[25] Higher pressure drops tend to provide better heat transfer coefficient, as pressure drop is directly proportional to the velocity of the fluid, which is proportional to the heat transfer coefficient. However, pressure drop above the allowable limit have an adverse effect on the heat exchanger's performance. It was observed the pressure drop was comparatively high in model1 and was reduced with modification made to the initial geometry and along with the reduction in the dead zones in the heat exchanger. Thus, within allowable pressure drop, heat transfer coefficient is the prime factors to be considered in the flow rates of the working fluids. Moreover, higher pressure drops are disadvantageous as they tend to increase the overall operational cost for the heat exchanger [26].

The results from the experiment conducted for the finned tube heat exchanger design optimization happens to be in agreement with the information gathered from the literature review of the heat exchangers and concentrates on the factors such as the effects of material, number of tubes, arrangement of coils/tubes and effects of pressure drop on the overall heat transfer. The results and the heat transfer were improved with each modification made from model 1 to model 3 used for the heat exchanger.

CONCLUSION

A comparative study was carried out to understand the effects of the design parameters such as the refrigerant tubes (coils) arrangement, number of tubes, and material on the overall heat transfer. The research was conducted with the aid of modern CFD packages such as STAR-CCM+ to carry out the numerical simulations.

The important results show that, for a constant mass flow rate of the working fluid and domain size, the heat transfer between the working fluids improved significantly with the increase in the number of coils and with variation in the arrangements of the refrigerant coils/tubes. The use of copper coils improved the heat transfer by approximately 61% as compared to aluminium coils due to better thermal conductivity. The results were found to be in agreement with the information gathered from the literature.

The research is expected to give confidence to the future researchers for undertaking further research in this field using numerical modelling. The study focused on a limited area with limited computational resources, further research can be conducted with variation in the fins design and employment of different refrigerants available for compact cross flow heat exchangers for enhancement the heat transfer between the working fluids, and comparing it with experimental data if possible.

NOMENCLATURE

I	Turbulence intensity
k	Turbulent kinetic energy
ε	Rate of dissipation of turbulent kinetic energy
$\dot{m}$	mass flow rate
ρ	density
u	velocity
Pr	Prandtl number
Nu	Nusselt number
Re	Reynolds number
μ	Dynamic viscosity
ν	Kinematic viscosity
d	Tube diameter
A	Cross sectional area
P	Perimeter
D_H	Hydraulic diameter
T	Temperature
K	Thermal conductivity

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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