Study of Different process parameters of heat exchanger used in Aerospace

[1]Manish Kumar Singh, [2]Prof. A.P.S Bhadoriya

[1]Research Scholar, [2]Associate Professor
Oriental college of Technology,
Bhopal (M.P)

***Abstract*: Heat exchangers are used in aerospace engines have large heat transfer coefficient, large surface area per unit volume and low weight. This study presents the airside performance of fin and tube compact heat exchangers with plain fin configuration. Hot air coming from compressor and flows across the tube bank and cold fluid flows inside the tubes. The effect of fin thickness, fin and tube material on the thermal-hydraulic characteristics is examined. Three-dimensional are carried out to investigate heat transfer and fluid flow characteristics using the Commercial Computational Fluid Dynamics Code ANSYS fluent 16.0. Results are compared for three different material GH3044, S66280 and GH2132 also find out optimum heat transfer rate. After selecting best material GH3044, it investigate the temperature variation for three different fin thickness 0.08 mm, 0.1mm and 0.2 mm**

***Keywords*: Heat transfer rate, fin thickness, fin spacing, Nusselt number, compact heat exchanger**

1. Introduction

The aircraft speed has increased from subsonic to supersonic over the last decades because of the advent and improvement of the aircraft jet engine. In recent times, the technologic study on the aerospace plane made a greater demand of speed (up to 5 Mach) and as the outcome, the engine for hypersonic aircraft come to be a challenge of 21st century. As new gas turbine utilized in aero engines, to attain greater thermal efficiency, the inlet temperature of turbine increases and increasing pressure ratio inside the compressor are most frequently used methods. With the improvement of engine technology, inlet temperature of current turbine is extreme outside the allowable metal temperature ranges, which is impending near about 2000 K. As the material properties development lagged behind the demand of practical application, turbine inlet temperature increased further by using highly sophisticated cooling techniques. Fin-tube compact heat exchangers show potential applications in aero engines for their great efficiency. As associated with the conventional heat exchangers utilized on the ground, those utilized in aero engines are more compact and undergo higher temperatures and larger difference in temperature. The change in temperature over the exchanger depth and the slope of temperature in the adjacent wall area are more exposed, they may reach a number of hundred degrees.

Heat exchangers are device that transfer heat between two fluids that are at different temperature while possessing them from mixing with each other. heat exchanger are normally utilized in practice in a wide variety of application, from heating as well as air conditioning systems in a domestic, to chemical processing as well as power production in large plant. A heat exchanger in which two fluids exchange heat by coming into straight interaction called direct contact heat exchanger. Example of such kind is open feed water heaters, desuperheaters and jet condensers. . Here in this work we have considered the four different velocity that is 5, 10, 15, 20 m/s and in each case air exit temperature get calculated and then based on the temperature at the exit here we have calculated the heat transfer rate (q), the value of heat transfer rate calculated with the help of numerical method is then compared with the value of heat transfer rate given in the base paper Lingdong et.al [1]. Here in this analysis it considered the material GH2132 for tube and fins. The thickness of fins for this analysis is 0.1 mm, whereas the gap in between the two fins is near about 1.1 mm.

2. Developing Solid Model

In order to attain the above aim here initially it has to advance the solid model of heat exchanger established on the structure utilised shown in Lingdong et.al [1] the symmetrical requirement of heat exchanger utilized in the inspection is essential where the tube bank formations contain the tube outside diameter (D), transverse tube pitch (P_t), longitudinal tube pitch (P_l), and number of tube rows (N). They are picked as D = P_l = 3.0 mm, P_t = 6.0 mm and N = 12 in this research. The plain finned tube formation comprises additional constraints with the fin pitch (F_p) and fin thikness (d_f), which are specified to be F_p = 1.1 mm and d_f = 0.1 mm. because of the periodicity and regularity of the heat exchanger structure for mathematical exploration it deliberated the two dimensional that is 2D airflow channel as shown in the fig. here the solid model of the heat exchanger is equipped in the project segmental of Ansys.

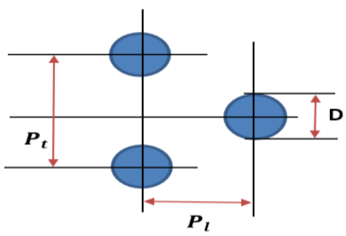

Fig.3.1 showing the geometric condition of tube

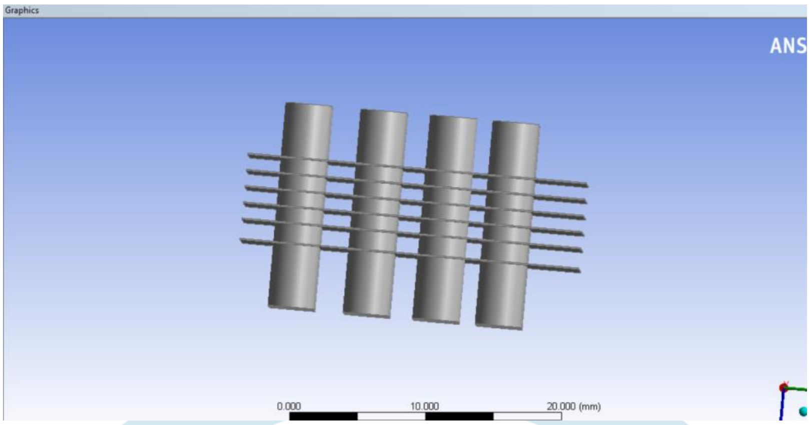

Fig.3.2 shows the solid model of compact heat exchanger used in the analysis

The computational domain which is considered during the analysis. The fin domain is inside this computational domain which is used for to increase the heat transfer rate. The model showing the fin inside the computational domain is shown in the fig.

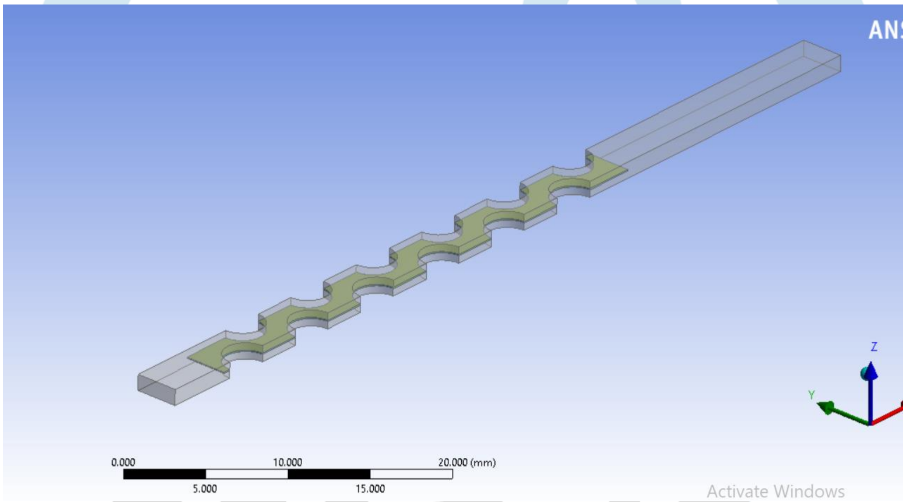

Fig 3.5 Solid model for computational analysis

The geometry of the above model is purely based on the geometric configuration taken during the analysis performed by Lingdong et.al [1].

3. Air Condition and Air Physical Properties

Air coming from the compressor and entering the heat exchanger in the aero engine operation assume to operate at altitude of 11 km and flies at mach 0.8 as given in Lingdong et.al [1]. During the analysis it considered the local atmospheric temperature and pressure that is calculated as 216.65 K and 22.63 kPa [17]. The inlet total pressure recovery coefficient is assume to be 0.97, the compressor compression ratio considered during the analysis is 25, the compressor efficiency is 0.90, and the air adiabatic index is 1.4, the air temperature and pressure at the inlet of heat exchanger is considered to be same as those at the compressor outlet, and it is considered as 653.99 K and 0.84 MPa [18].

To perform the CFD analysis on the heat exchanger here it takes the FLUENT module of ANSYS. ANSYS (FLUENT) basically used for the analysis related to fluid flow and heat transfer. For performing the analysis first it open the ANSYS workbench and then FLUENT module as shown in the fig.

4. Meshing

After developing the solid model of given geometry, it is then discretizing in to number of elements and node because the numerical analysis is completely depends on the number of elements and number of nodes. So to discretize the complete solid model in number of small element here it used the different tool to enhance the mesh.

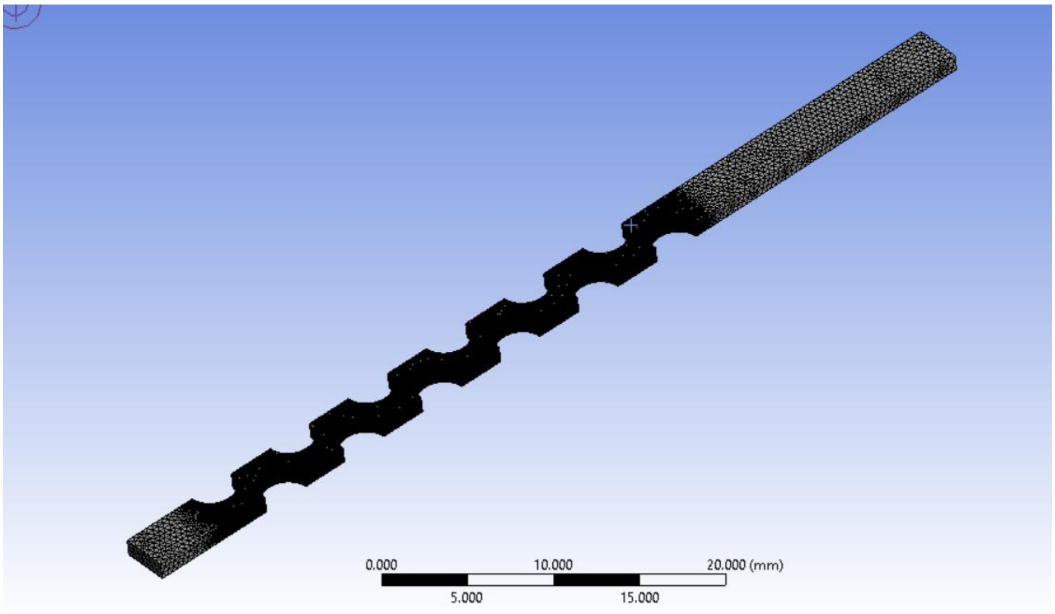

Fig.3.8 Mesh of the given geometry

5. Selection of Material

5.1 Material Used

For the primary investigation it's been occupied the material identical as that of taken by Lingdong et.al [1]. So here is allowing for the GH2132 alloy (Fe-25Ni-15Cr) is elected as the fin material, whose thermal conductivity is set as 14.2 W/ (m^2-K), the material features of GH2132 is shown in the below table

Table 3.1 Properties of material GH2132

Properties	values
Density	7.99 g/cm^3
Specific heat	447 J/kg-k
Thermal conductivity	14.2 W/m-C

Subsequently evaluating the above material to raise the enactment of heat exchanger here it reflects the two unlike materials to proliferate the rate of heat transfer. So here it measured the two materials one is GH3044 as well as the other one is S66280. The material assets of these material is shown in the below table.

Table 3.2 Properties of material GH3044

Properties	**values**
Density	8.89 g/cm^3
Specific heat	440 J/kg-k
Thermal conductivity	11.7 W/m-C

Table 3.3 Properties of material S66280

Properties	values
Density	7.98 g/cm^3
Specific heat	460 J/kg-K
Thermal conductivity	12.2 W/m-C

6. Governing Equations and Boundary Condition

- Here in this work the problem is defined by the law of mass, momentum and energy. The present study stretches from the transitional range (2000<Re<4000) flow to turbulence range flow (Re > 4000). Equations that govern the problem of flow are in the transitional range turbulence model.
- Turbulence consists of small scale fluctuation in the flow characteristics over time. It is a complex process, mainly because, it is a three dimensional and unsteady. And it can have a significant effect on the characteristic of the flow. Turbulence occurs when the inertia forces in the fluid become significant compared to viscous forces and is characterized by a high Reynolds number.
- **The continuity equation:**

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

- **The momentum equation:**

In x-direction

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{\partial P}{\rho\partial x}+\frac{\mu}{\rho}\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right]$$

- **The energy equation:**

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial w}=\frac{\lambda}{\rho C_p}\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right]$$

- **Boundary condition:**

The upstream boundary (inlet)

$$u = constant$$

$$T = constant$$

$$v = w = 0$$

Fin and tube wall surface (no slip condition)

$$u = v = w = 0$$

$$T = const$$

The downstream boundary (outlet)

$$\frac{\partial u}{\partial x}=\frac{\partial v}{\partial x}=\frac{\partial w}{\partial x}=0$$

Top symmetry boundary on the x-y plane

$$\frac{\partial u}{\partial z}=\frac{\partial v}{\partial z}=\frac{\partial T}{\partial z}=0$$

$$w = 0$$

Here in this analysis the frontal air entering the heat exchanger is at different speed because it considered four different velocity of air that is 5, 10, 15 and 20 m/s.

7. Validation of CFD Model and Computation

In order to validate the CFD model of heat exchanger used in aero engines, here it first find out the temperature of air at the exit of heat exchanger for different velocity. Here in this work we have considered the four different velocity that is 5, 10, 15, 20 m/s and in each case air exit temperature get calculated and then based on the temperature at the exit here we have calculated the heat transfer rate (q), the value of heat transfer rate calculated with the help of numerical method is then compared with the value of heat transfer rate given in the base paper Lingdong et.al [1]. Here in this analysis it considered the material GH2132 for tube and fins. The thickness of fins for this analysis is 0.1 mm, whereas the gap in between the two fins is near about 1.1 mm.

7.1 For calculating the maximum velocity

Maximum velocities of airflow inside the compact heat exchanger are calculated based on relation given for the staggered tube arrangement in Cengel. The relation used for calculating maximum velocity inside the computational domain is given below.

$$V_{max} = \frac{P_t \times V}{2(P_d - D)} \quad (1)$$

Where; D = diameter of tube

V = velocity of air at inlet

P_t = transverse distance in between the two tubes of same row

P_d = diagonal distance between the center of two tubes of adjacent row

7.2 For Calculating the Reynolds number

To calculate the Reynolds number of air flowing inside the computational domain, maximum velocity of air flowing inside the domain were considered in a particular case of staggered fin tube type compact heat exchanger [29]. For calculation following relation were used

$$Re = \rho_{air} \times V_{\max air} \times L_c / \mu_{air} \quad (2)$$

Where; ρ_{air}= Density of air

$V_{\max air}$= Velocity of air

μ_{air} = Dynamic viscosity of air

7.3 Heat transfer

In order to calculate the heat transfer from hot air to fin and tube following relation were use. During the heat transfer from hot air to cold fluid flowing inside the tube, many researcher have found that the thermal resistance during the heat transfer from tube to cold fluid is less as compared to the thermal resistance, during heat transfer from air to tube and fins [6, 22, 29]. So during the calculation of heat transfer and heat transfer coefficient it mainly concern toward the heat transfer from air to fin and tube and neglect the thermal resistance toward the cold fluid domain which is very less as compared to the thermal resistant toward the air side. Due to this here it calculate the local heat transfer coefficient in between air and tube, and not calculating the value of overall heat transfer coefficient

7.4 Heat transfer Rate

To calculate the heat transfer rate at different velocity following formula used.

$$Q = \dot{m} C_P \Delta T \quad (3)$$

Where, m = mass flow rate of air.

C = specific heat of the air

ΔT= change in temperature between inlet to outlet.

7.5 Mass flow rate of air and logarithmic mean temperature difference

$$\dot{m} = \rho_{air} \times V_{air} \times A_c \tag{4}$$

For calculating the mean temperature difference for particular staggered type arrangement of fin and tube type compact heat exchanger following relation were used as given in the base paper. To calculate ΔT_m following formula mention in the base paper and Cengel and Gajar used.

$$\Delta T_m = \frac{(T_{in}-T_w)-(T_{out}-T_w)}{ln[(T_{in}-T_w)/(T_{out}-T_w)]} \tag{5}$$

Where,

T_{in}= Temperature at inlet

T_{out}= Temperature at outlet

T_w =Temperature of the tube wall or fin.

7.6 To calculate heat transfer coefficient

$$Q = hA\Delta T_m \tag{6}$$

Where, h = average heat transfer coefficient (W/m^2-k)

A = surface area of domain

ΔT_m = logarithmic mean temperature difference.

To calculate the surface area of domain following calculation is use.

$$A = L \times W - \left(\frac{\pi}{8} \times D^2\right) \times N \tag{7}$$

Where L = length of fin.

W =width of fin

D = diameter of tube

N = no of tube in computational domain.

7.7 Fin Efficiency

During the analysis, it found that the thickness of fin is a measure concern for the heat transfer. To find the effectiveness of different fin thickness here we have calculated the value of fin efficiency at different velocity of air.

For calculating the fin efficiency following formula where used which is given in the base paper. The formula for calculating the fin is

$$\eta_f = \frac{tan(mr\emptyset)}{mr\emptyset} \tag{8}$$

Where $$m = \sqrt{\frac{2h}{K_f \times \delta_f}} \tag{9}$$

h is the heat transfer coefficient, K_f thermal conductivity of fin material, δ_f fin thickness. Where $\emptyset$ can be find through the below formula

$$\emptyset = \left(\frac{R_{eq}}{r} - 1\right)\left[1 + 0.35ln\left(\frac{R_{eq}}{r}\right)\right] \quad (10)$$

Where, r is the tube radius and

$$R_{eq} = r\left[1.27\frac{X_m}{r}\left(\frac{X_l}{X_m} - 0.3\right)^{1/2}\right] \quad (11)$$

Where

$$X_m = \frac{P_t}{2},\ X_l = \left[\left(\left(\frac{P_t}{2}\right)^2 + P_l^{\,2}\right)/2\right]^{1/2} \quad (12)$$

$P_t =$ Transverse pitch and

$P_l =$ Longitudinal pitch

➢ **Case 1 velocity 5 m/s**

Here in this case velocity of frontal air is 5 m/s and the temperature of air at the inlet is 653.98 K. After applying the boundary condition it find out the air exit temperature. The contour plot of air temperature distribution for this case shown in fig.

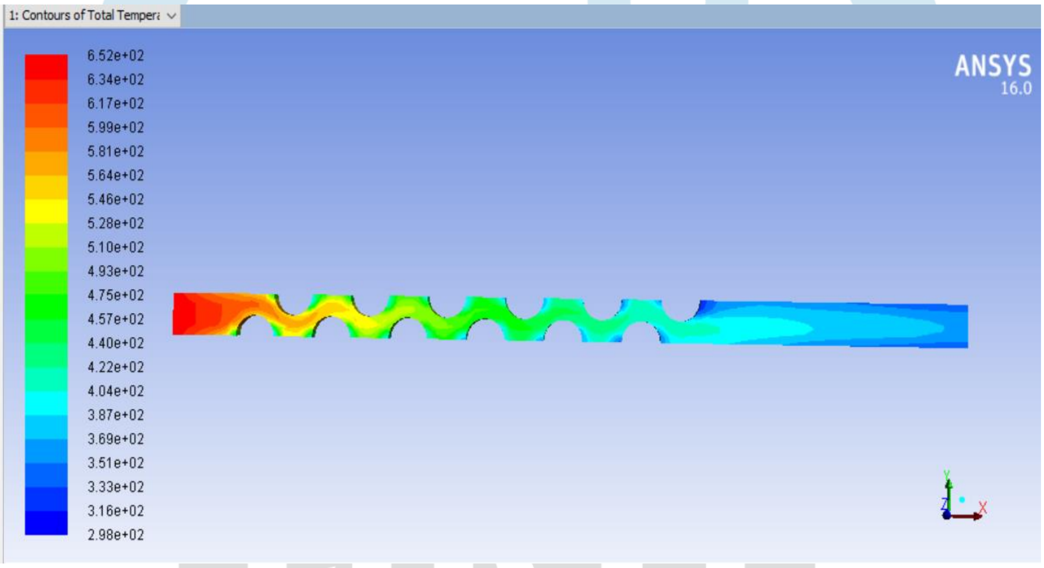

Fig.5.1 Temperature contour of heat exchanger at 5 m/s velocity- case 1

From the above analysis, it observe that the temperature of air at the exit of heat exchanger is 421 K from the numerical analysis it also find out the change in velocities and velocity vectors.

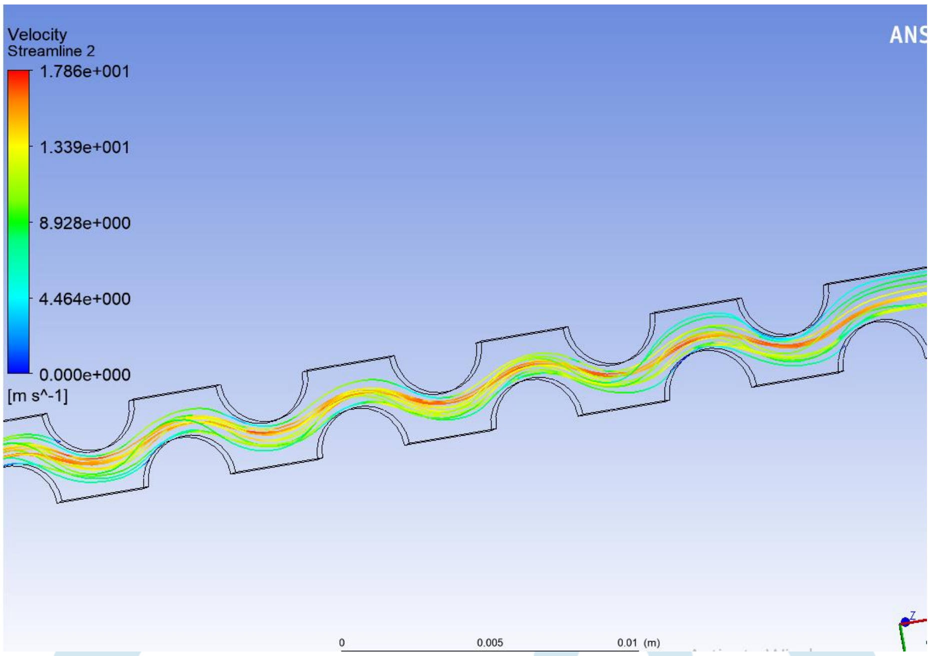

Fig.5.2 Velocity contours for case 1

Comparison of value of temperature of air at the exit and heat transfer coefficient calculated through numerical analysis with the value of temperature and heat transfer coefficient given in the base paper.

Table.5.3 Comparison of numerical values and base paper value

Velocity (m/s)	Heat transfer coefficient (h) (W/m^2K) calculated through numerical analysis	Heat transfer coefficient (h) (W/m^2K) from base paper	Error (%)	Heat transfer rate (W) calculated form numerical analysis	Heat transfer rate (W) values from base paper	Error (%)
5	588.88	550	7.06	18.15	18	14.62
10	1018.6	985	3.4	33.24	31	7.2
15	1335.53	1300	2.7	47.9	44	8.86
20	1684.16	1600	5.2	54.059	52	3.95

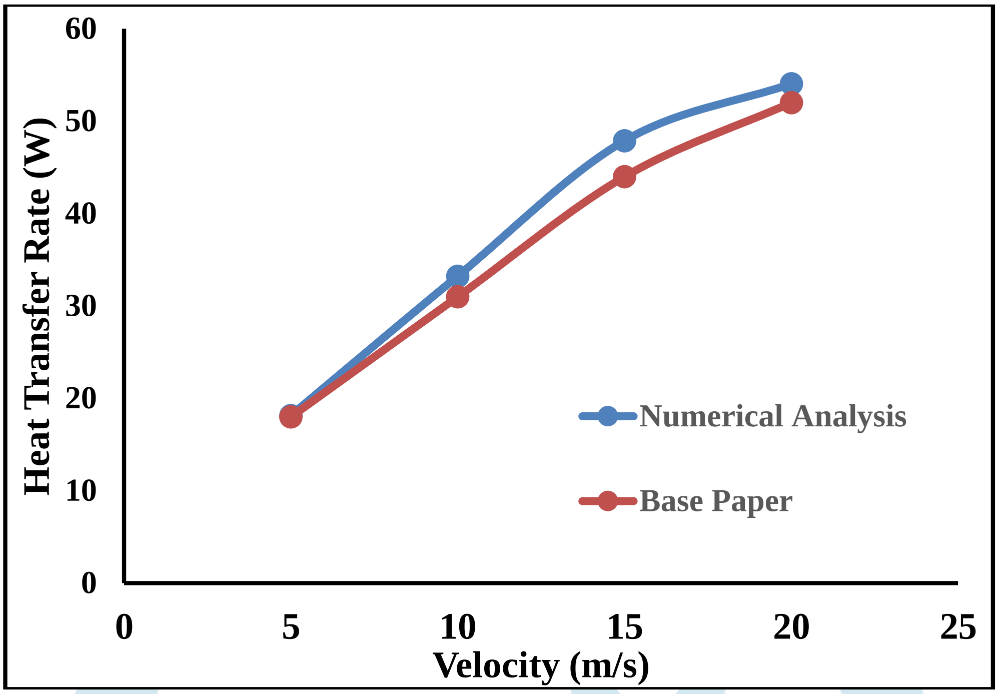

Fig.5.5 Comparison of heat transfer rate at different velocity of air

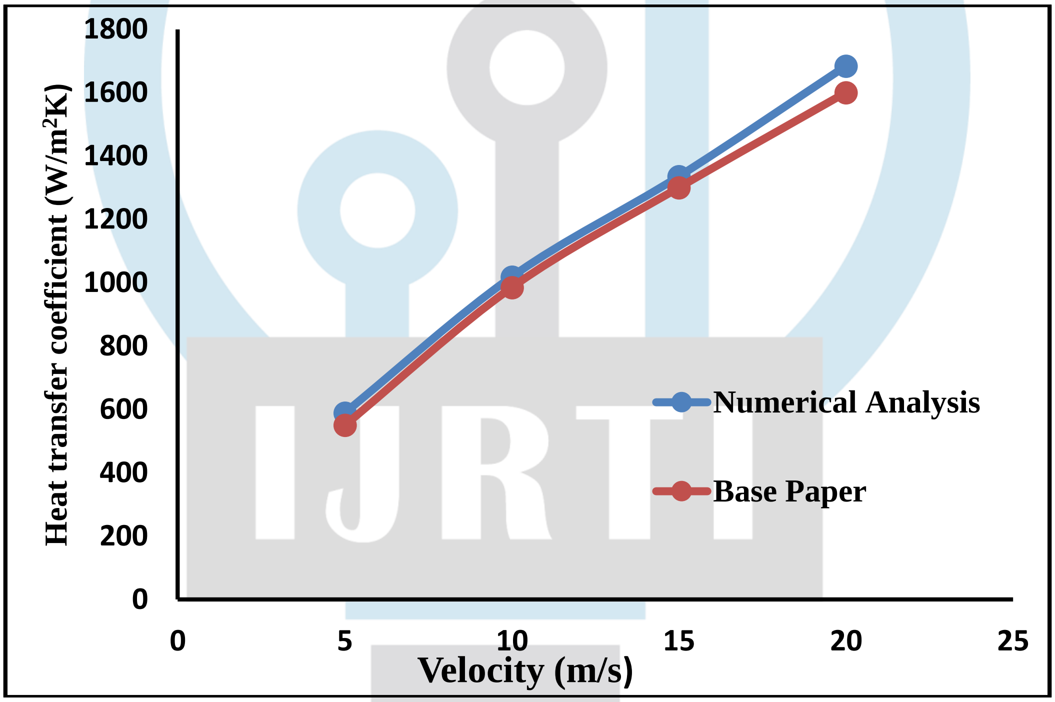

Fig.5.6 showing the comparison of heat transfer coefficient for different velocity

From the above comparison it is shown that the value of temperature at the exit of heat exchanger obtained from the CFD analysis is closer to the value of temperature obtained from the base paper. It also analyzed that the value of heat transfer rate at different velocity of air obtained from the numerical analysis is close to value obtained from the base paper and follow the same trend as follow in the base paper. So after analyzing the graph it shows that the CFD model of heat exchanger that is developing in this work is correct.

8. Optimization of Material Used For Tube and Fins Manufacturing

For finding out the effect of different material used for tube and fins manufacturing it has already analyzed the material GH2132 in chapter four and find out the temperature of air at the exit at different velocities. Further

8.1 GH3044 Material Used for the Tube and Fins

Here in this case it has taken as GH3044 material as a material used for the manufacturing of tubes and fins. The material property of this material is mention in chapter 4. Here in case it is analyzed at different velocity of air and find out the temperature of air at the exit of heat exchanger. Here it also considered the four cases at different velocity.

➢ **Case 1 At velocity 5 m/s**

The temperature contours for this material at velocity 5 m/s shown in the fig. and calculate the pressure distribution throughout the computational zone. The other boundary condition will remain same as used in Material GH2130.

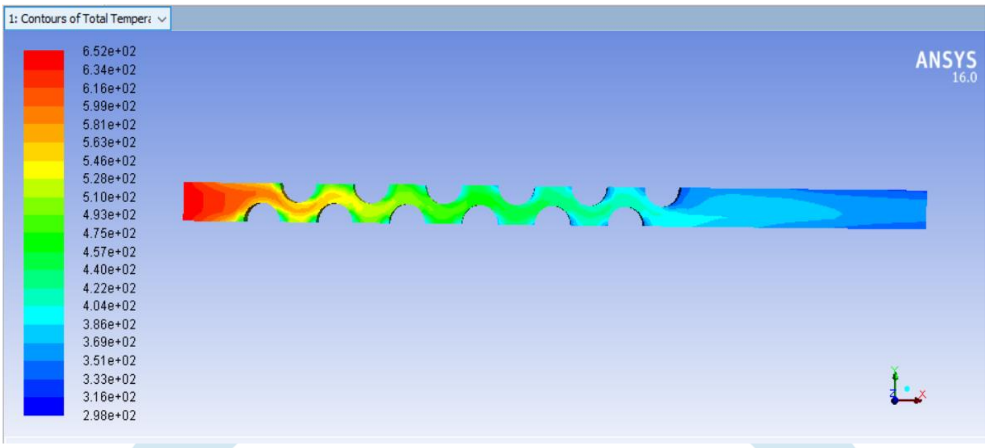

Fig.5.7 contours of temperature at velocity 5 m/s material GH3044

The value of temperature at the exit for velocity 5 m/s is near about 357 K. the temperature contour through the heat exchanger is shown in the above fig. The temperature distribution at the exit of heat exchanger shown in the below fig. for the further calculation average temperature is taken at the exit.

➢ **Case 2 At velocity 10 m/s**

The contour of temperature and pressure at the computational domain for velocity 10 m/s shown in fig.5.8

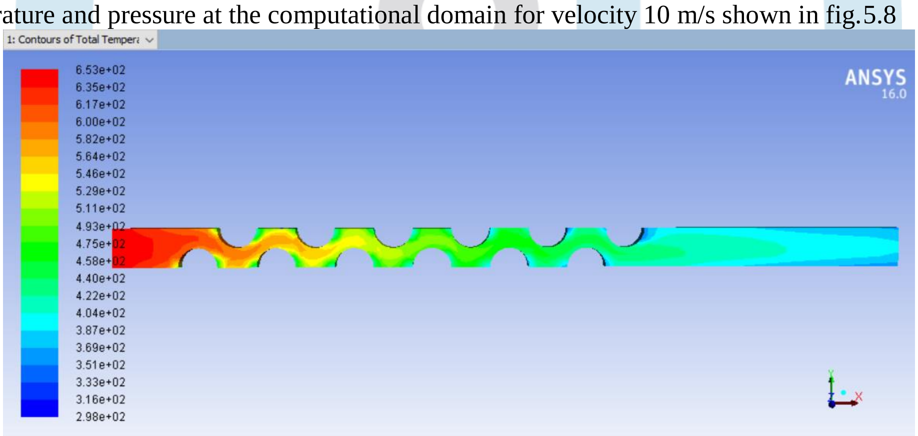

Fig.5.8 Contours of temperature at velocity 10 m/s material GH2130

8.2 S66280 Material Used for the Tube and Fins

Here in this section it considered the S66280 material for the tube and fins and analyzed the effect of this on the temperature and pressure distribution throughout the computational domain. The material property of S66280 is mention in the chapter 4. The other boundary conditions will remain same as that of section of material GH2130. For this material also it has considered the four different velocity and find out the temperature of air at the exit.

- **For velocity 5 m/s**

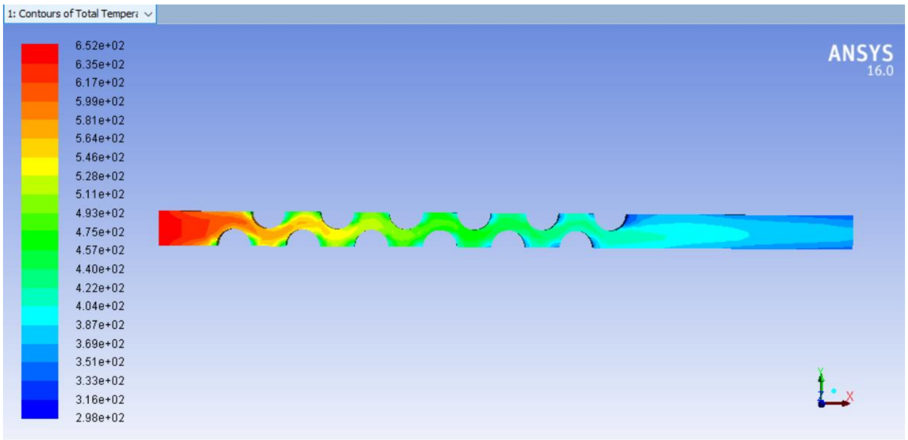

Fig.5.9 Contours of temperature at velocity 5 m/s material S66280

From the above analysis, it is found that the temperature at the exit is near about 365 K. the temperature distribution at the exit of heat exchanger is shown in the fig. below.

- **For velocity 10 m/s**

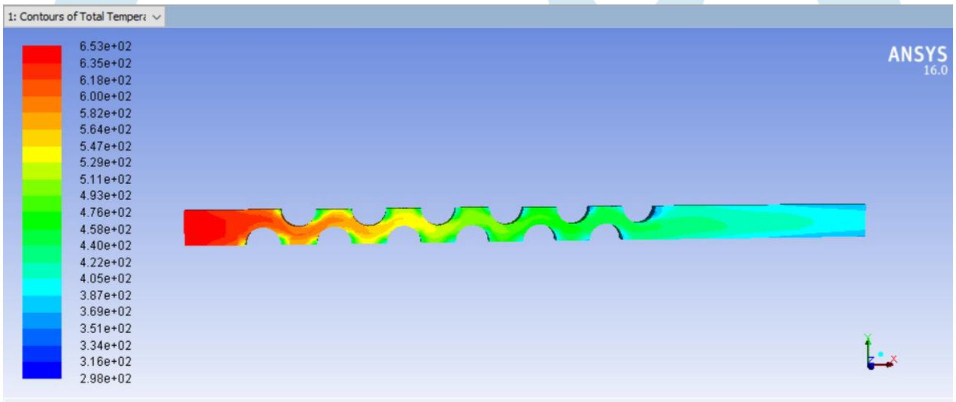

Fig.5.10 temperature contour for velocity 10 m/s

Average temperature at the exit for velocity 15 m/s is near about 390 K.

8.3 Comparison of Different Material

After analyzing the three different materials, comparison of all this material on the basis of temperature of air at the exit which is shown in the table 5.3 below.

Table.5.6 Comparison of Temperature for Different Material

Case	Velocity of air (m/s)	Temperature (K) For material GH2132	Temperature (K) for material GH3044	Temperature (K) for material S66280
1	5	366	357	365
2	10	393	386	390
3	15	403	397	401
4	20	410	405	415

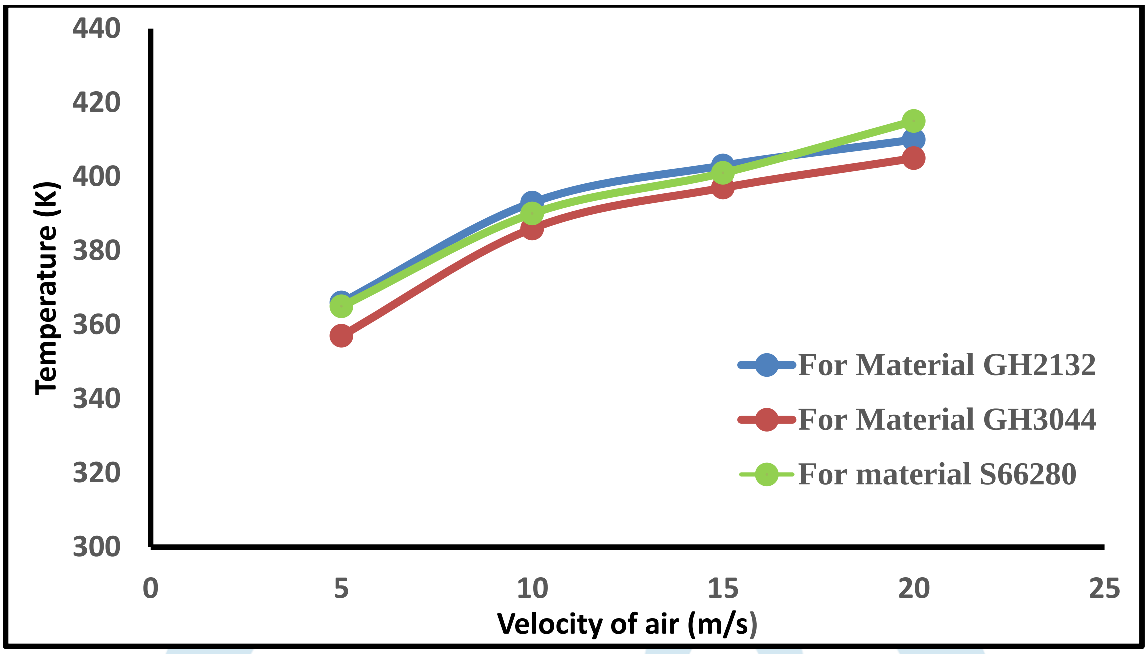

Fig.5.11 Comparison of Air Exit Temperature for Different Material

From the above comparison graph, it found that the temperature at the exit of heat exchanger is minimum for material GH3044 at every velocity of air. Through this analysis, it is found that as the material density, specific heat and thermal conductivity changer the heat transfer capacity of the material also changes. From the analysis it is also observed that though the thermal conductivity of material GH3044 is low as compared to the material S66280. Heat transfer is more in material GH3044 because the density and specific heat is also playing some role in heat transfer.

9. Effect of Fin Thickness

After finding out the effect of material on the heat transfer rate, here it has also analyzed the effect of tube fin thickness on the heat transfer rate and the temperature of heat exchanger. In order to find out the effect of fin thickness, Here it considered 0.08, 0.1 and 0.2 mm thickness fin during the numerical simulation. Model having fin thickness 0.1 is already analyzed in chapter four. In order to analyze the effect fin thickness, here we have considered the constant velocity of air that is 10 m/s.

9.1 Fin having 0.08 mm thickness

In this section of analysis here it considers the solid mode of computational domain having the fin thickness 0.08 mm. To find out the effect of thickness analysis performed on this model and then temperature of air at the exit is calculated. The temperature contour for this model analysis is shown in the fig. during the analysis of this model velocity of frontal air is taken as 10 m/s and the other boundary conditions is same as that of case 1 in chapter 4 and the material is GH3044.

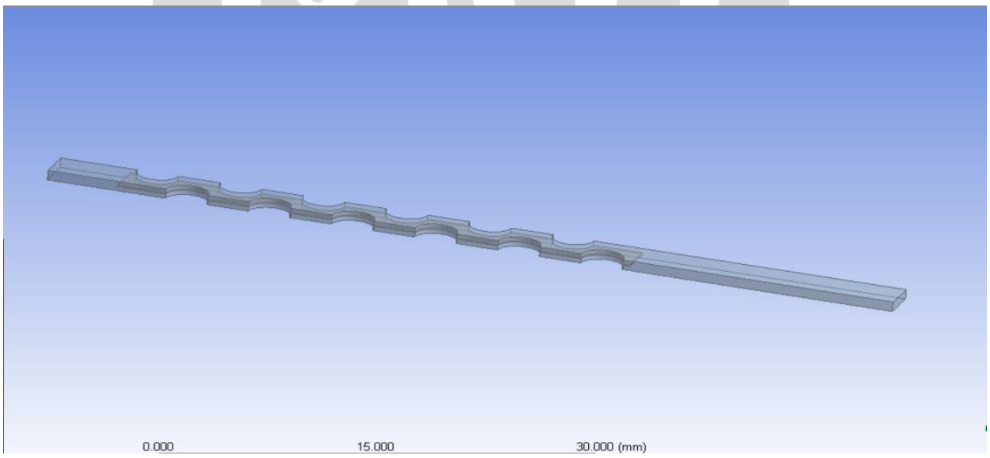

Fig.5.12 Solid model of computational domain having fin thickness 0.08 mm

During the analysis of this model only thickness of fin get change whereas the thickness of Computational fluid domain cannot change and it remains constant as 1.1 mm

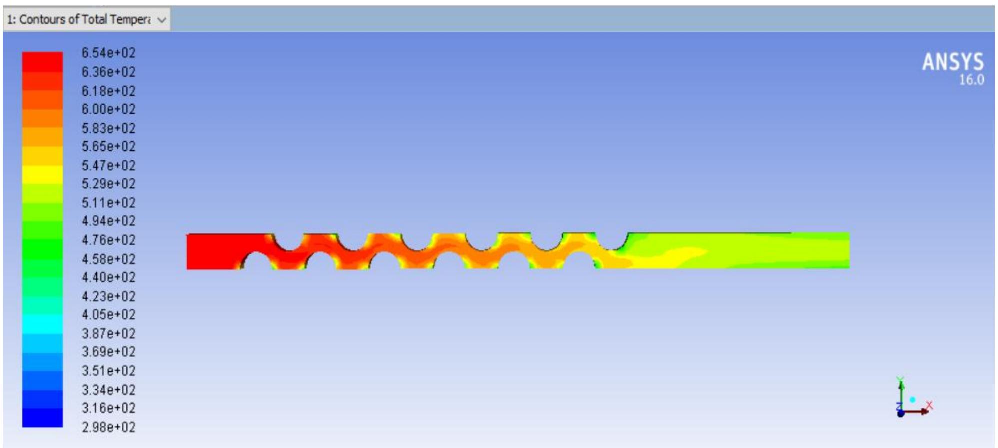

Fig.5.13 Contours of temperature at model having fin thickness 0.08 mm

9.2 Fin having 0.2 mm thickness

Here in this model the computational domain have fin of thickness 0.2 mm. whereas the material and boundary conditions were same as considered for model having fin thickness 0.08 mm. it calculate the temperature of air at exit. The contour plot of temperature for this domain is show in the fig. 5.8

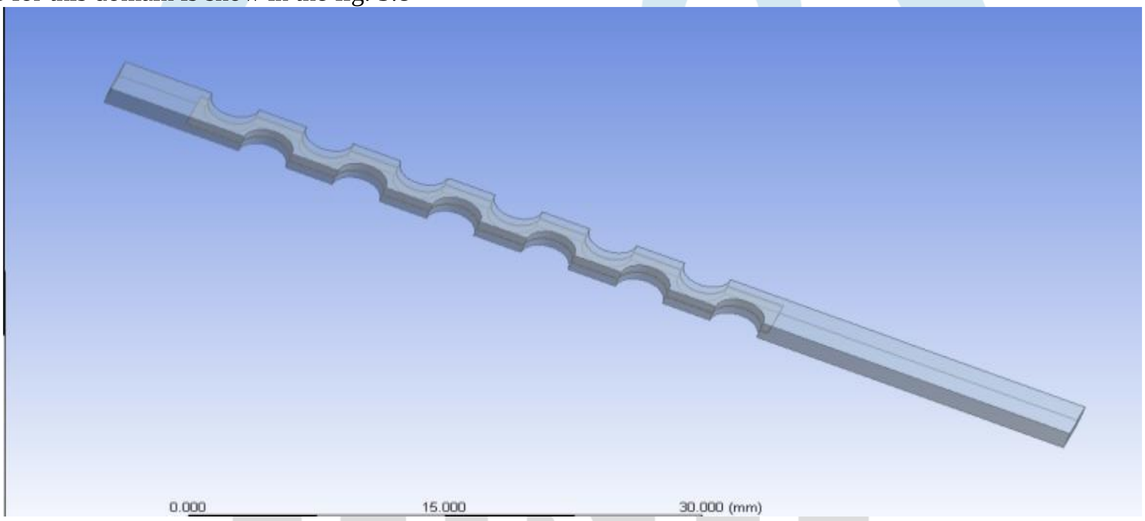

Fig.5.14 Solid model of computational domain having fin thickness 0.2 mm

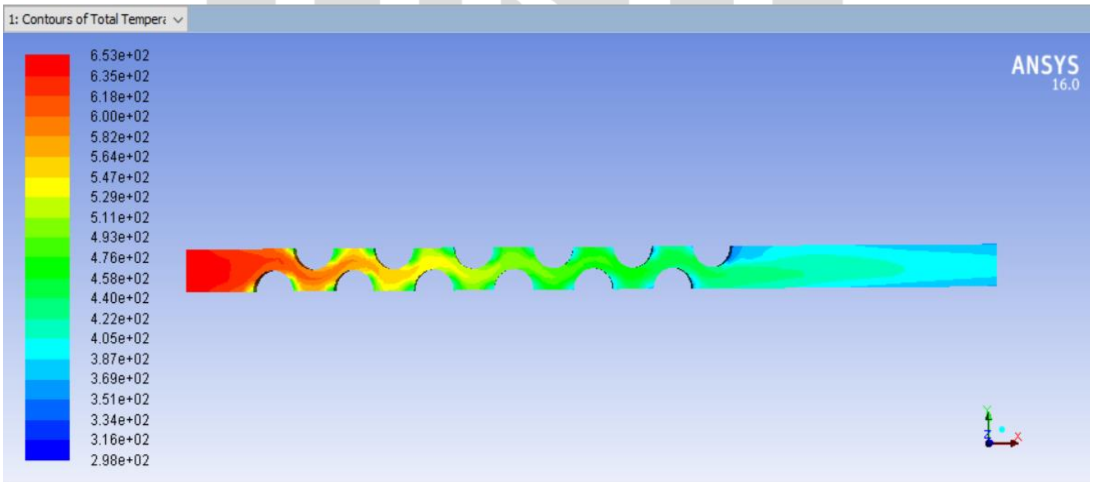

Fig.5.15 Contour of temperature having fin thickness 0.2 mm

9.3 Comparison of solid Model having Different Fin Thickness

In order to optimize the fin thickness here it compares the entire model having different fin thickness as find the best one.

Table.5.7 Comparison of temperature for model having different fin thickness

S.N	Thickness of Fin (mm)	Temperature of air at the exit
1	0.08	505
2	0.1	386
3	0.2	384

From the above table it is concluded that the temperature of air is minimum in the case having fin thickness 0.2 mm, where as it is maximum in the case having fin thickness 0.08. Here it is analyzed that as the thickness of fin decreases the temperature of air get increase and as the thickness get increased the value of temperature get decrease. With the help of this analysis it can predict the material which is best suitable for the heat transfer without doing any experimental work. It also helps in the design of heat exchanger.

10. Conclusion

- Here it finds out the effect of material on the temperature of air at the exit, for analyzing the effect, it considers the different steel alloy which is GH2132, GH3044 and S66820.
- From the graph it is found that as the velocity of air increases the value of heat transfer increases for all the three material.
- GH3044 shows the maximum value of heat transfer as compared to the other material. From the graph it is conclude that the value of heat transfer for GH3044 is on an average 12 % more than the GH2132 material.
- it is found that as the thickness of fin increases from 0.08 mm to 0.2 mm the heat transfer rate increases, whereas beyond 0.2 mm thickness value of heat transfer again start decreasing.
- It is concluded from comparison graph of fin thickness that the use of fin thickness 0.2 mm is better as compared to the other fin thickness and shows 10 % increment in heat transfer as compared to 0.1 mm fin thickness.

References

[1] Lingdong Gu, Jingchun Min, Xiaomin Wu, Lijun Yang, ‘Airside heat transfer and pressure loss characteristics of bare and finned tube heat exchangers used for aero engine cooling considering variable air properties’ International Journal of Heat and Mass Transfer 108 (2017) 1839–1849.
[2] Erika Y. Rios-Iribe , Maritza E. Cervantes-Gaxiola, Eusiel Rubio-Castro,Oscar M. Hernández-Calderón, ‘Heat transfer analysis of a non-Newtonian fluid flowing through a Plate Heat Exchanger using CFD’ Applied Thermal Engineering 101 (2016) 262–272
[3] S. Baghdar Hosseini, R. Haghighi Khoshkhoo, M. Javadi, ‘Experimental and Numerical Investigation on Particle Deposition in a Compact Heat Exchanger’ Applied Thermal Engineering (2016), doi: http://dx.doi.org/10.1016/j.applthermaleng.2016.12.110
[4] Selma BenSaad, CarolineGentricc, Jean-Franc¸oisFourmiguéa, PatriceClémenta, Jean-PierreLeclerc ‘CFD and experimental investigation of the gas–liquid flow in the distributor of a compact heat exchanger’ chemical engineeringresearchanddesign92 (2 0 1 4) 2361–2370
[5] Pavel Peukert, Jan Kolar, and Karel Adamek, ‘An investigation of a compact heat exchanger unit using CFD with experimental support’ EPJ Web of Conferences ,59 02066 (2015)
[6] Zhang L. W., Balachandar S., Tafti D. K. and Najjar F. M. 1997.Heat Transfer enhancement Mechanisms in Inline and Staggered Parallel Plate Fin Heat Exchanger. International Journal of Heat and Mass Transfer 40(10):2307-2325
[7] Xiangdong X, Xingjuan Z, Peng K, Chao W, Han Y, Chunxin Y. Study on the heat transfer characteristic of compact heat exchanger based on experimental data. Procedia 255 Engineering 2015; 121: 293-299.
[8] Camilleri R, Howey D.A, McCulloch M.D. Predicting the flow distribution in compact parallel flow heat exchangers. Applied Thermal Engineering 2015; 90: 551-558.
[9] Bari S, Hossain S.N. Design and optimization of compact heat exchangers to be retrofitted into a vehicle for heat recovery from a diesel engine. Procedia Engineering 2015; 105: 472-266 479.
[10] Hassan H, Zahra H. Investigating the effect of properties variation in optimum design of compact heat exchanger using segmented method. Chemical Engineering Research and Design 2016; 112: 46-55.
[11] Adina T.G, Alexandru D, Luminit G.P, Mihai C, Bogdan M.D. Entropy generation assessment criterion for compact heat transfer surfaces. Applied Thermal Engineering 2015; 280 87: 137-149.
[12] Baghdar H, Haghighi K, Javadi M. Experimental and numerical investigation on particle deposition in a compact heat exchanger. Applied Thermal Engineering 2017; 115: 406-417.

[13] S. Shin, K.S. Lee, S.D. Park, J.S. Kwak, Measurement of the heat transfer coefficient in the dimpled channel: effects of dimple arrangement and channel height, J. Mech. Sci. Technol. 23 (2009) 624–630.

[14] S.Y. Won, P.M. Ligrani, Flow characteristics along and above dimpled surfaces with three different dimple depths within a channel, J. Mech. Sci. Technol. 21 (2007) 1901–1909.

[15] J.J. Brandner, E. Anurjew, L. Buhn, E. Hansjosten, T. Henning, U. Schygulla, A. Wenka, K. Schubert, Concept and realization of microstructure heat exchangers for enhanced heat transfer, Experimental Thermal and Fluid Science 30 (2006) 801–809.

[16] Mushtaq I. Hasan, A.A. Rageb, M. Yaghoubi, Homayon Homayoni, Influence of channel geometry on the performance of a counter flow microchannel heat exchanger, International Journal of Thermal Sciences 48 (2009) 1607–1618

[17] Mirkovic, Z., Heat Transfer and Flow Resistance Correlation for Helically Finned and Staggered Tube Banks in Cross Flow, Heat Exchangers: Design and Theory Source Book, (edited by N. H. Afgan and E. U. Schlünder), Hemisphere, Washington, D. C, pp. 559-584, 1974.

[18] X.F. Peng, G.P. Petrson, Convective heat transfer and flow friction for water flow in microchannel structures, Int. J. Heat Mass Transfer 39 (1996) 2599–2608.

[19] M.H. Yazdi, S. Abdullah, I. Hashim, K. Sopian, A. Zaharim, Entropy generation analysis of liquid fluid past embedded open parallel microchannels within the surface, Eur. J. Sci. Res. 28 (3) (2009) 462–470.

[20] H. Abbassi, Entropy generation analysis in a uniformly heated microchannel heat sink, Energy 32 (10) (2007) 1932–1947.

[21] Kyoungmin Kim, Min-Hwan Kim, Dong Rip Kim, Kwan-Soo Lee, Thermal performance of microchannel heat exchangers according to the design parameters under the frosting conditions, International Journal of Heat and Mass Transfer 71 (2014) 626–632