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Design, and CFD Analysis of Compact Plate-Fin Micro Channel Heat Exchanger Using DMLS Technology

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***Abstract*: This paper aims for designing cross-flow compact plate-fin micro channel heat exchangers which has its huge applications in military and Aerospace industries. Direct metal laser sintering (DMLS) technique is used for fabrication of this HE, considering the process parameters like laser power, layer thickness, building direction and hatching angle. ANSYS Computational fluid dynamics (CFD) analysis is carried out for one layer of fins of HE considering the mass flow rates for water and air as mh = 0.009 kg/s and mc = 0.012 kg/s. Here water is used as hot fluid and air is used as coolant. Rhinoceros 3D is used for designing the heat exchanger.**

***Keywords*: Microchannel heat exchanger, Fins, DMLS, CFD, Heat transfer, Support generation.**

1. Introduction

A heat exchanger(HE) is a device which is used to transfer heat energy between two or more fluids or between solid to fluid and solid to solid. Typically, HE is used for cooling and heating of a fluid streams and condensation or evaporation of multi and single component fluid stream [1].

In cross flow type of heat exchanger, the direction of fluid flow is normal to each other. This is one of the most common type of heat exchanger used in industrial applications and best suited for extended surface (fins) HE because it simplifies the header design [1]. Thermodynamically, effectiveness of cross flow HE lies in between Parallel flow and counter flow arrangements of HE. Fins are the extended surface provided in heat exchangers to enhance the cooling process. As shown in below figure 1 fluid 1 and fluid 2 are flowing normal to each other and is an unmixed flow arrangement. Fluid 1 is the hot fluid which is to be cooled and fluid 2 is the coolant or cold fluid. The heat transfer surface is a surface which is in direct contact with the fluid where heat transfer by conduction takes place. The fins will take away the maximum heat from the fluid and transfer it to the neighbouring fluid or surrounding environment.

DMLS is an additive manufacturing technology which uses powder bed fusion process to manufacture a solid part layer by layer. The fabrication is carried out by putting a computer aided design (CAD) file in to the 3D printer. It is also known as selective laser melting (SLM) and Laser powder bed fusion (LPBF). This technology makes use of high intensity laser to melt and fuse metallic powder together. The processing parameters like hatching angle, building direction, laser power, powder layer thickness are to be considered while printing [3].

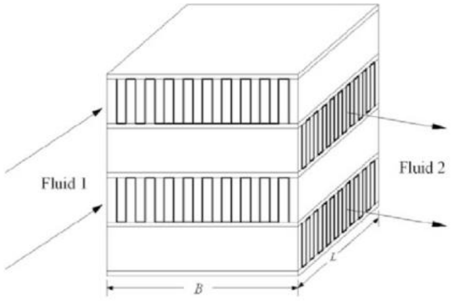

Fig. 1. Cross flow extended surface heat exchangers

2. Design Calculations

1 Fin thickness for both air and water side t = 0.6mm
2 Fin height for air side bc = b2 =10mm
3 Fin height for water side bh=b1= 4mm
4 Distance between each fin $a_{h/c}$ = 0.35
5 Number of fins per unit length N=27 fins/inch
6 Total number of water passages Nw= 7
7 Total number of air passages Na= 8
8 Wall thickness b/w air and water passage t= 1mm
9 Length of HE in flow direction of water L1= 80mm
10 Length of HE in flow direction of air L2= 60mm
11 Height of HE L3 = 126mm
12 Number of water fins =81
13 Number of air fins= 60
14 Total Dim. of HE = L*B*H = 100*80*124 mm

The aspect ratio(α) for water and air channel is calculated by the following formula where c is for cold channel, h is for hot channel

$$\alpha_{c/h}=a_{h/c}/b_{h/c} \quad (1)$$

which is 0.0875 and 0.035 respectively.

Hydraulic Diameter is calculated for water and air side of the heat exchanger.

$D_{h,1}=4\times A_{0,1}\times L_1/A_1$ (2)

Where A_1 is total area of either waterside/air side, $A_{0,1/2}$ is the frontal area of airside/waterside blocked by the fins at the entrance and thus the hydraulic diameter is 0.7855mm for water side and 0.7233 mm for air side.

Compactness of the micro channel heat exchanger can be proved by having the surface density value $\beta > 700$, where β is given as follows.

$$\beta = \frac{Total\ area}{Total\ volume} = 1.029213\ m^2/10.08\times10^{-4}\ m^3 \quad (3)$$

$\beta = 1021.04\ m^2/m^3$. Thus $1021.04 > 700$ the designed heat exchanger is compact heat exchanger.

Dimensionless Number like Renolds no. and Nusselt number are calculated by the following formula

$$Re_{e,h}=\frac{G_h D_h}{\mu} \quad (4)$$

$$Re_h = \frac{40.20\times0.7855\times10\text{^}-3}{0.0004903} = 64.40$$

$$Re_c = \frac{5.51\times0.7233\times10\text{^}-3}{0.000018} = 221.$$

Nusselt Number for water side (aspect ratio = 0.0875, μ_b = 0.0004903 kg/ms at 55°C, μ_w = 0.000678 at 38°C)

$$N_u = 8.235\times(1-1.883\times\alpha_c + 3.767\times\alpha_c^2 - 5.814\times\alpha_c^3 + 5.361\times\alpha_c^4 - 2\times\alpha_c^5\times)^{-0.14} \quad (5)$$

$$= 8.235\times(1 - 1.883\times0.0875 + 3.767\times0.0875^2 - 5.814\times0.0875^3+5.361\times0.0875^5\times(0.00049/0.0006)^{-0.14} = 7.08$$

Nusselt Number for air side (acpect ratio = 0.035)

$$N_u = 8.235\times(1-1.883\times\alpha_c + 3.768\times\alpha_c^2 - 5.814\times\alpha_c^3 + 5.361\times\alpha_c^4 - 2\times\alpha_c^5) \quad (6)$$

$$N_u = 8.235\times(1 - 1.883.(0.035) + 3.767.(0.035)^2 - 5.814(0.035)^3 + 5.361(0.035)^4 - 2(0.035)^5 = 7.728$$

Prandtl number of water at 55°C = 3.071
Prandtl number of air at 25°C = 0.7147

Stanton number for water side S_{th} (specific heat C_p= 4066J/kg at 55°C)

$$S_{t,h} = \frac{h}{G\times Cp} = (5851.47)/(40.20\times4066) = 0.0357 \quad (7)$$

Stanton number for air side (specific heat C_p = 10063 J/kg at 25°C)

$S_{t,c}$ = (277.36)/ (5.51×10063) = 0.0502

Convection heat transfer coefficient, for water (at 55°C, k = 0.6492 W/mk)

$$h_h = \frac{Nu\times K}{Dh} \quad (8)$$

$= (7.08\times0.6492)/0.7855\times = 5851.47$ W/k

Convection heat transfer coefficient, for air (at 25°C k = 0.02596 W/mk)

$h_c = (7.728\times0.02596)/0.7233\times = 277.36$ W/k

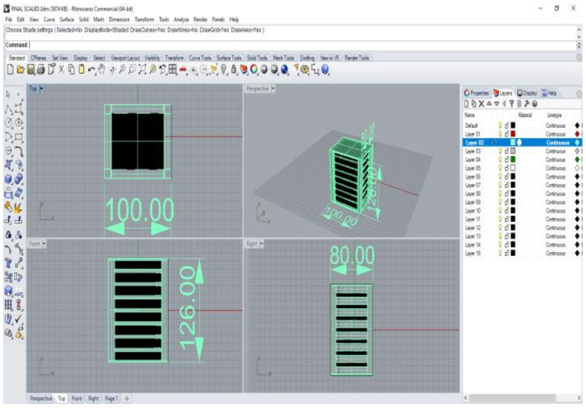

Fig. 2. Top, side, isometric view in Rhino 3D

The design developed is plate fin Heat exchanger because of its higher efficiency and effectiveness. Overall surface efficiency is more than 90% for such compact micro channel heat exchanger. The plate between the water domain and air domain is 1mm thick. Water header and Air header is been designed for equal distribution of water and air in its respective domains [3].

Fig. 3. Fin design of water and air domain

Fig. 2 and Fig. 3, shows the complete design of heat exchanger and fins. The minimum thickness that can be printed by DMLS process is 0.5 mm, by EOS and SLM 3D printers, hence the thickness of fin is kept as 0.6 mm so that fabrication becomes easier [5]. The curve provided at the top and end of the fin is to provide good strength and eliminate the support in the fins. The distance between each fins on both water side and air side is kept as 0.35 mm. There are no separate parts for this Heat exchanger, as it is designed as a whole, it can be manufactured as a single component by additive manufacturing DMLS process, no need for the assembly process. As it a single component it has very high mechanical strength compared to other manufacturing process.

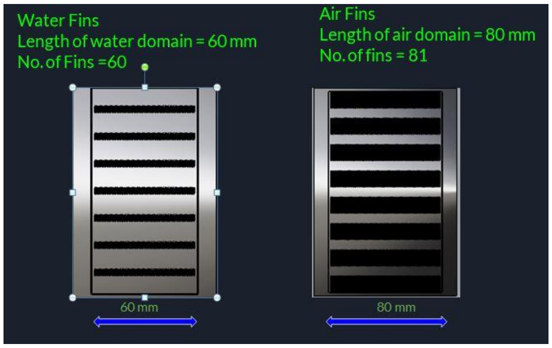

Fig. 4. Water and air domain

Fig. 4 shows the length and number of fins in the water and air domain. This HE is accumulated by 8 air domain and 7 water domain, Height of Air fins are 2.5 times greater than water fin so as to pass the larger quantity of air than the water which will in turn help for the maximum temperature drop of water. When DMLS comes in to picture radius, fillets provide higher strength than the L joint or 90˚ joint [4].

3. CFD Analysis

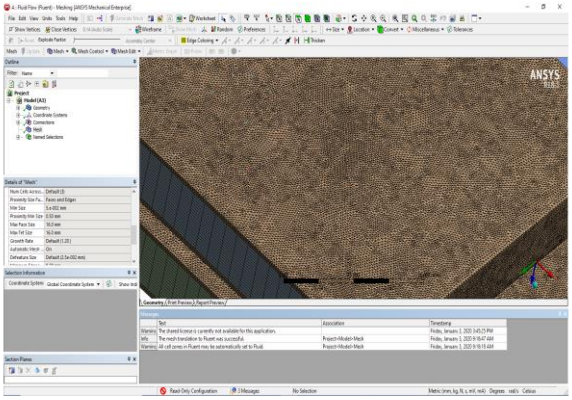

Fig. 5. Tetra mesh

Tetra Mesh is used for the meshing purpose with the element size as 0.3 mm, span angle centre as Medium, maximum element size as 0.6 mm and no inflations were used because of the dimension complexity of 0.6 mm thickness fins are involved.

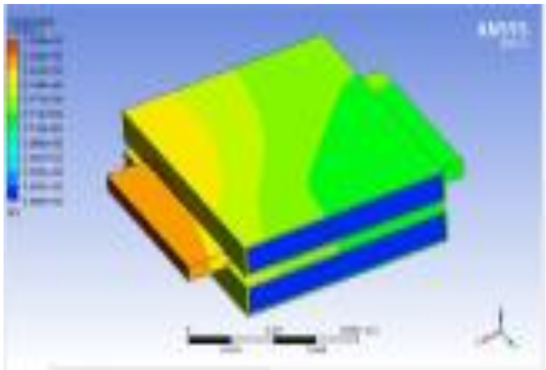

Fig. 6. Temperature distribution of the HE

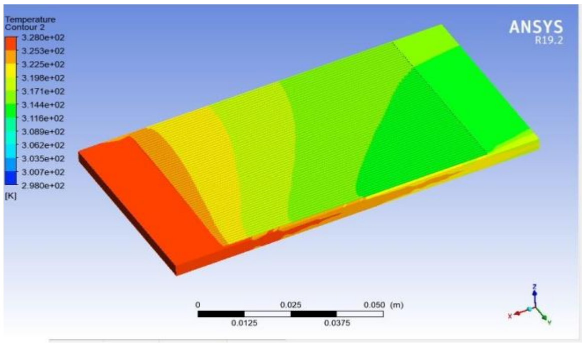

Fig. 7. Temperature distribution of water domain

Fig. 6 and 7 shows the satisfactory temperature distribution along the fins and walls of the heat exchanger. Temperature absorption is higher at the air inlet side and slowly it reduces at the air outlet side as observed by the above temperature distribution. From the CFD simulation it was observed that water temperature is dropped from 328K to 316 K which is 12℃ drop which is quite satisfactory. By increasing the mass flow rate of water further temperature drop of water can be obtained.

4. Support Generation

Support generation is one of the most important and crucial aspect in Direct Metal Laser Sintering. Magic's software is used for this purpose. This software consists of large number of inbuilt supports, we can˚ also build our own support with respect to model design. The supports should be generated in such a way that it should not distort the original model and also support the model till the printing get completed, and it should be easily removable.

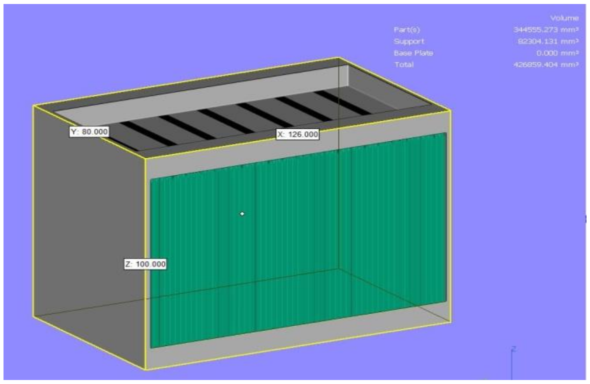

Fig. 8. Horizontal orientation

The basic model should be designed in such a way that minimum supports are required, as a result machining time, powder consumption, and overall cost can be reduced to higher extent. Orientation and selecting the base for printing is the major aspect in support generation. It has been proven that 45˚ is the best possible orientation to reduce powder consumption, number of building layer, machining time and overall cost.

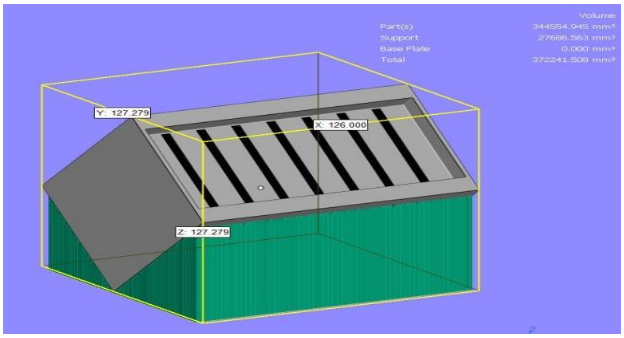

Fig. 9. 45˚ orientation

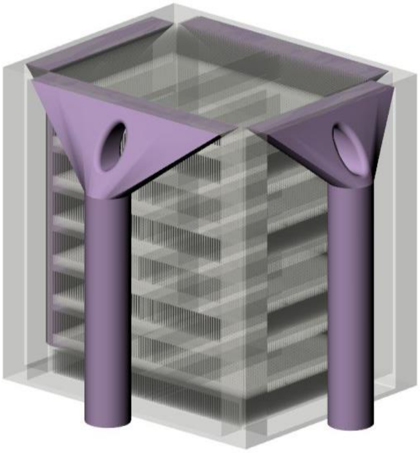

Fig. 10. Hollow pipe and bracket support

The vertically build samples are 6.8% stronger than the horizontally build sample. 60 degrees can be used for maximum elongation. Lowest strength and bad elongation can be observed at 0 degree. 45 degrees is best suited for strength and ductility aspects. 0° has the worst elongation and the lowest strength. Mechanical properties of DMLS parts built along the vertical direction were higher than those built in the horizontal direction. Tensile properties of samples built along the vertical axis were better than those made along the horizontal axis.

5. Conclusion

The current study is made to formulate the mathematical model, design and analysis of cross-flow compact plate fin micro channel heat exchanger which is suitable for Additive manufacturing. DMLS technique is been used to fabricate this heat exchanger. Computational fluid dynamics analysis is done and 12℃ temperature of water has been dropped which is quite satisfactory. By adjusting or increasing the mass flow rate of air further temperature drop can be easily obtained. As the thickness of the fins is 0.6 mm it is very difficult to fabricate this using traditional manufacturing, which is accurately achieved by 3D printing technology. 45˚ is the best possible orientation to reduce powder consumption, number of building layer, machining time and overall cost. Fin thickness is inversely proportional to the efficiency of Heat exchanger. By adding more number of air water domains effectiveness of heat exchanger can be further improved.

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