Corrugated Technology based Copper Heat Exchanger for Efficient Thermal Management of Inverter System

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Abstract — Work performed and explained in this paper demonstrates: analysis of existing aluminum heat exchangers used in inverters, designing and manufacturing technology used for new heat exchanger which utilizes copper metal, installation and its thermal testing on inverter system.

Keywords— *Thermal conductivity (k), Junction Thermal Resistance (R_{THJ}), Heat flux (q).*

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1. INTRODUCTION

Thermal management of inverter system is achieved by the use of only passive cooling mechanism where mainly aluminum (Al) metal is highly preferred over copper to form hardware cooling structures.

A. LITERATURE SURVEY

Work performed by Scot K. Waye, Jason Lustbader, Matthew Musselman, and Charles King , [1] , demonstrates an air-cooled inverter configuration using an optimized heat exchanger in an inverter consisting of an aluminum heat sink with equally spaced rectangular channels. Through a parametric computational fluid dynamics study, the heat sink was optimized for weight and volume by varying geometric parameters, including channel height, length, width, and device location. The test bench for this project used compressed air. The air passed through a plate heat exchanger for temperature control and entered the heat exchanger test section, shown in Figure 2. Ceramic resistance heaters (8 mm × 8 mm) provided the heat load; power was adjusted to yield the desired junction temperature for each flow rate.

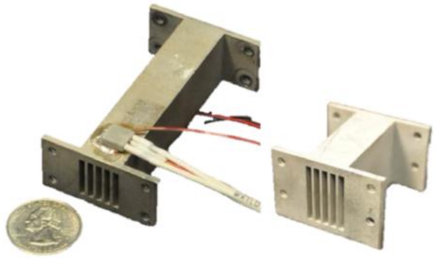

Fig. 1. Baseline (left) and optimized (right) sub-module heat exchangers fabricated from 6063 aluminum. Heaters are mounted on the top and bottom of the test section, one near the inlet edge and the other farther back. The flanges are for experimental convenience in attaching the test section to the inlet and outlet manifolds.

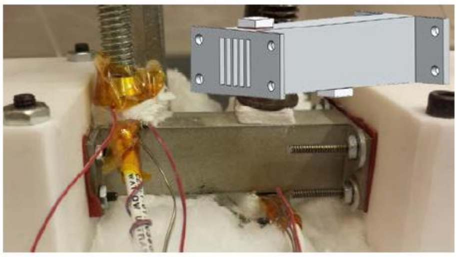

Fig. 2. Baseline aluminum sub-module test section. Ceramic resistance heaters providing the heat load are located on the top left and bottom right of the test section. Air flows from left to right.

Paper [2] proposed by Mark Gerber, Jan Abraham Ferreira, illustrates direct and indirect heat removal structures made using aluminum metal basically for high density inductors. Same can also be applied for transformer used in inverters by slightly modifying the design.

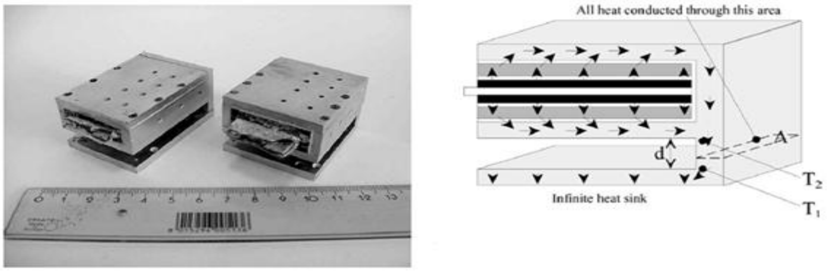

Fig 3 : **Extreme left** :Photograph of the two structures. Left: indirect heat removal; right: direct heat removal. **Extreme right : I**ndicates heat flow path.

Research study [3] conducted by Jeong Hyun Kim, Gyo Woo Lee on “Performance Evaluation of Extruded-Type Heat Sinks Used in Inverter for Solar Power Generation”, evaluates heat release performances of the three extruded-type heat sinks that can be used in inverter for solar power generation. Numbers of fins in the heat sinks (namely E-38, E-47 and E-76) were 38, 47 and 76, respectively. Heat transfer areas of them were 1.8, 1.9 and 2.8m^2. The heat release performances of E-38, E-47 and E-76 heat sinks were measured as 79.6, 81.6 and 83.2%, respectively. The results of heat release performance show that the larger amount of heat transfer area the higher heat release rate. While on the other, in this experiment, variations of mass flow rates caused by different cross sectional areas of the three heat sinks may not be the major parameter of the heat release.

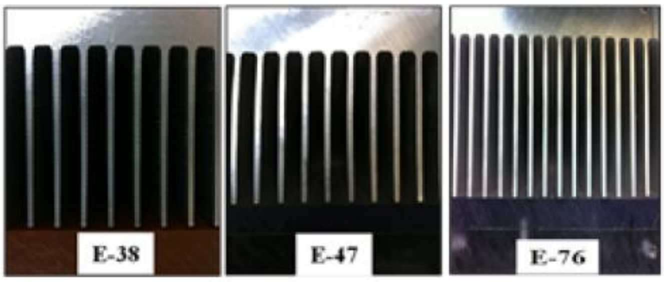

Fig 4: Extruded-type heat sinks (namely E-38, E-47 and E-76) with 38, 47 and 76, respectively.

B. INVERTERS THERMAL MANAGEMENT VARIOUS TOPOLOGIES (EXISTING)

There exist many heat sink designs which are currently used in the market. Two such heat sink topology on inverter is placed in fig number 5.

Fig 5: **Left** : Thermal Management Topology 1 , **Right** : Thermal Management Topology 2

2. SENSOR USED IN THIS THERMAL TEST :

A. ‘PTC-Cu’ HEAT SENSOR :

A new PTC-Cu based temperature/heat sensor is shown in figure 6 below. It is possible to measure temperature/heat of above 1000^{0}C using this PTC-Cu sensor. PTC & Cu both of them are joined with cyanoacrylate ester. in a suitable solvent like acetone, nitromethane.

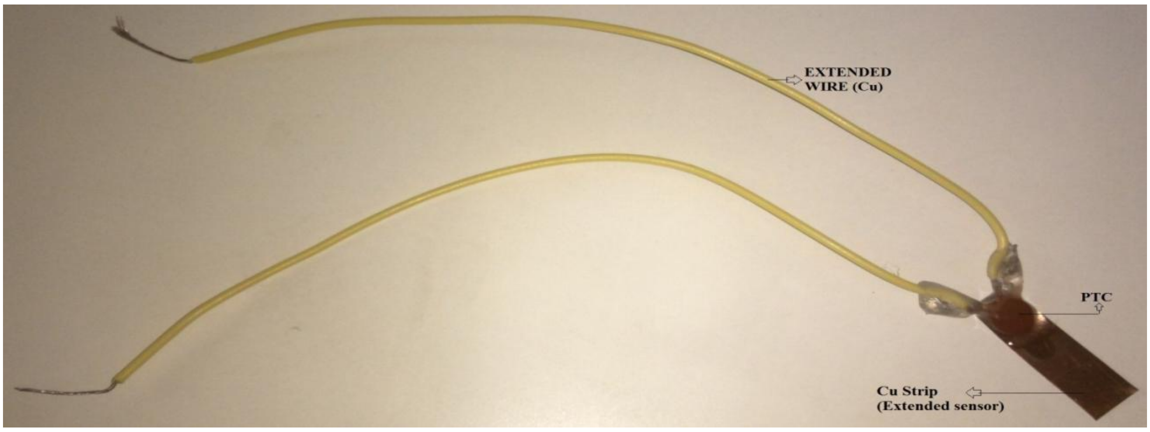

Fig 6: PTC-Cu Based Heat/Thermal Sensor

B. TESTING OF “PTC-CU” HEAT SENSOR :

Since PTC has been used, the sensor’s resistance will increase with increase in the temperature/heat being sensed. But practically, slight fluctuation in the resistance value will happen. Simple experiment was conducted where temperature of water was raised linearly using a heat source as shown in figure number 7.

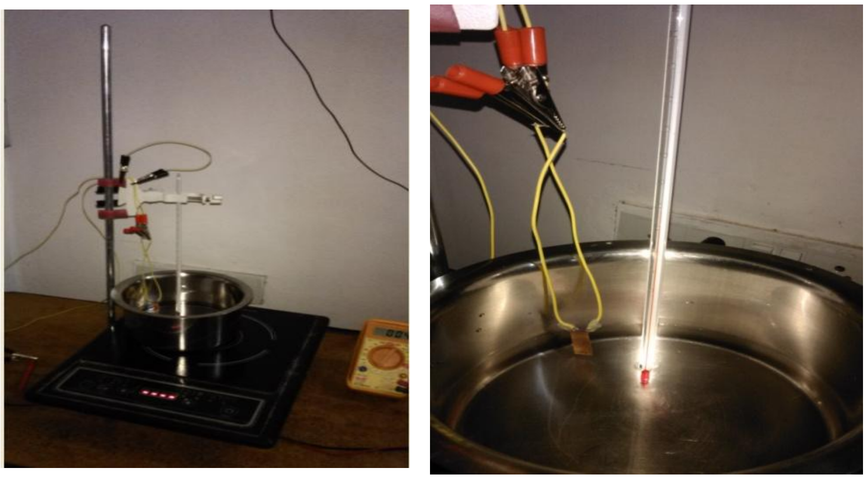

Fig 7: Experimental Setup For Testing PTC-Cu Heat Sensor

C. PTC-Cu DATA SHEET :

TABLE 1 : PTC-Cu DATA SHEET

TEMPERATURE ‘T’ (^{0}C)	**RESISTANCE ‘R’ (KΩ)**
40	4.70
41	4.90
42	4.92
43	4.95
44	5.1
45	5.3
46	5.6
47	5.7
48	5.9
49	6.3
50	6.4
51	6.9
52	7.3
53	7.4
54	7.5

Average of Temp (T) = $\frac{705}{15} = 47^0\text{C}$

Average of Resistance ‘R’ = $\frac{88.87}{15} = 5.92\text{K}\Omega$

$$\mathbf{1\ K\Omega} = \frac{47}{5.92} = 7.93 = \mathbf{8^0C} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad \mathbf{(1)}$$

3. THERMAL TEST ON INVERTER :

A. INITIAL TEST : THERMAL TEST ON ALUMINUM HEAT SINK

PTC-Cu sensor was used to test inverter’s temperature which has been presented in this paper. General purpose digital heat sensors/indicators or mercury thermometers are not suitable to measure temperature above 600^{0}C. Basically in thermal management in both mechanical field and electronics field, run time temperature data/ information need to be obtained accurately as well as efficiently. Fluctuations noted in PTC-Cu based sensor is very negligible. Exact resistance value reading at a specific temperature value is indicated via multi-meter connected to the extended wires of this sensor. Ω value fluctuation seen on the multimeter is very less. For inverter’s temperature sensing , 4 PTC-Cu sensors were used to measure temperature of aluminum heat sinks located at 4 heat source locations within the inverter marked as L1 , L2 , L3 & L4 in below figure 8 and Resistance table was obtained shown in below TABLE 2. TABLE 3 is derived based on the equation1. Experiment was conducted at room temperature 27^{0}C.

Note :
C1 & C2 : component1 and component 2 attached to Aluminum heat sink located at L1 .
C3 : component 3 attached to Aluminum heat sink located at L4.

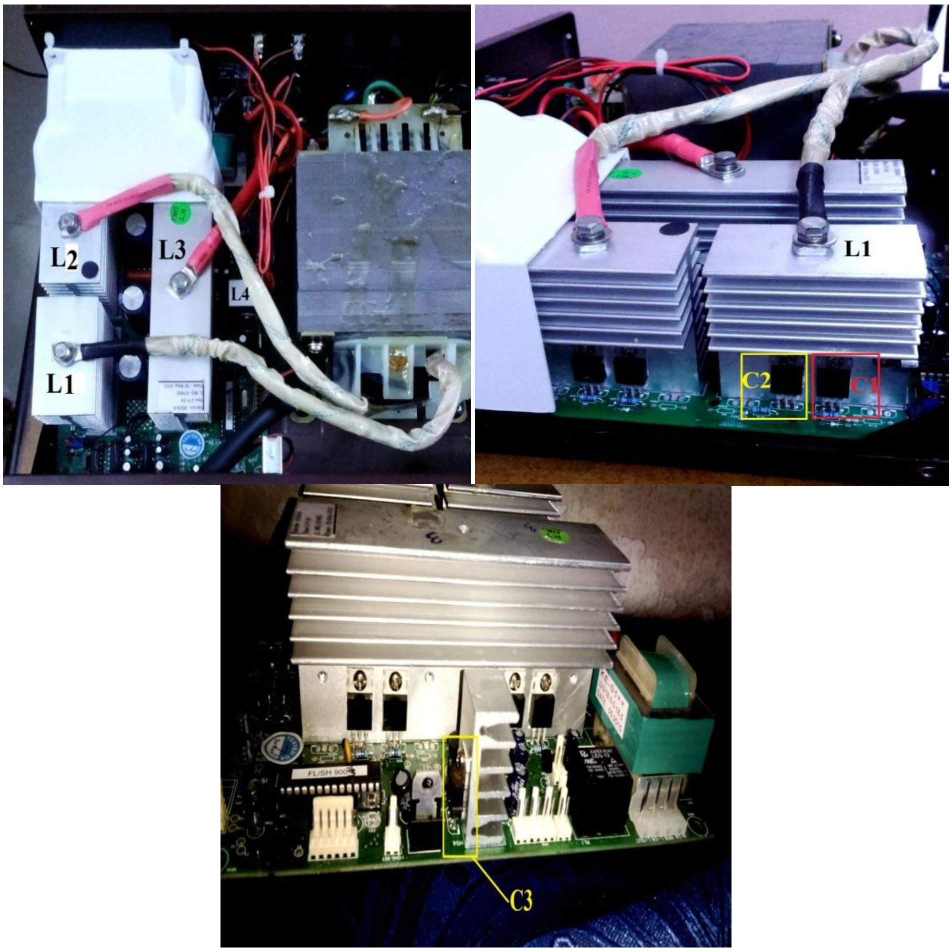

Fig8 : **Left**: “Al” heat locations within the inverter. **Middle** : C1,C2 location . **Right** : C3 location

B. DATA OBTAINED :

TABLE 2 : RESISTANCE OFFERED BY ALUMINUM HEAT SINKS AT LOCATIONS L1-L4

Time (min)	Sensor 1 S1 in KΩ at L1	Sensor2 S2 in KΩ at L2	Sensor3 S3 in KΩ at L3	Sensor4 S4 in KΩ at L4
0	3.67	3.89	3.52	3.94
10	4.07	4.47	4.02	4.55
20	4.62	5.23	4.62	5.08
30	4.71	5.46	4.96	5.30
40	4.79	5.16	4.84	5.13
50	4.31	4.80	4.60	5.11
60	4.16	4.90	4.38	5.10

TABLE 3 : TEMPERATURE OF ALUMINUM HEAT SINK AT LOCATIONS L1-L4 & COMPONENT TEMPERATURE

Time (min)	Temp T1 in ^{0}C	Temp T2 in ^{0}C	Temp T3 in ^{0}C	Temp T4 in ^{0}C	Temp of C1 & C2 in ^{0}C at L1	Temp of C3 in ^{0}C at L4
Initial 0.00	29.20	31.12	28.72	31.52	25.00	27.00
10	32.56	35.76	32.16	36.40	26.50	28.50
20	36.96	41.84	36.996	40.64	27.50	31.00
30	37.68	43.68	39.68	42.40	28.00	31.50
40	38.32	41.28	38.72	41.04	27.50	32.00
50	34.48	38.40	36.80	40.88	27.50	32.50
60	33.28	39.20	35.04	40.80	27.50	34.00

C. CALCULATION : R_{THJ}

When heat flows from heat source towards heat sink, junction resistance is developed denoted by R_{THJ}. R_{THJ} is offered b/w C1 & Aluminum heat sink at L1 , C2 & Aluminum heat sink at L1, C3 & Aluminum heat sink at L4. Assuming C1 and C2 temperature to be equal, only C1 is considered in this manuscript.

Formula = $\frac{\text{Higher Temp} - \text{Lower Temperature}}{\text{Power}}$

Power consumed by the inverter = 90W where Load = 2 Fans (45W each with rpm 400)

TABLE 4 : R_{THJ} B/W COMPONENTS & ITS ALUMINUM HEAT SINK

Time (min)	**Temp of C1 in ^{0}C at L1**	**Temp of "Al" heat sink in ^{0}C at L1**	**R_{THJ} b/w C1 and "Al" heat sink at L1location**	**Temp of C3 in ^{0}C at L4**	**Temp of "Al" heat sink in ^{0}C at L4**	**R_{THJ} b/w C3 and "Al" heat sink at L4 1 location**
Initial 0.00	25.00	29.20	0.046	27.00	31.52	0.050
10	26.50	32.56	0.067	28.50	36.40	0.087
20	27.50	36.96	0.105	31.00	40.64	0.107
30	28.00	37.68	0.107	31.50	42.40	0.121
40	27.50	38.32	0.120	32.00	41.04	0.100
50	27.50	34.48	0.077	32.50	40.88	0.093
60	27.50	33.28	0.764	34.00	40.80	0.075

D. CALCULATION : HEAT FLUX

Heat flux produced by single component (i.e C1) has been calculated.

Area under C1 = 0.4cm^2

Heat flux (q) = $\frac{Q}{A}$ Power utilized/Area = $\frac{90W}{0.4}$ = $\mathbf{225W/cm^2}$

4. COPPER HEAT SINK :

A. BASIC OF DESIGNING :

[4] Only aluminum heat sink at location L1 and at location L4 was replaced by newly designed copper heat sink.

New cooling unit (shown in fig 9,C) which has been designed using copper, consist of 2 parts. First part is the "corrugated triangular fins" structure (fig 9,A) and the second part is the "base"(fig 9,B). Number of fins (N), height of fins (H), spacing between fins (Pf), fin thickness (Ft or (Ta= Tb1=Tb2)) and base plate thickness (b) , base plate length (w) & width (L) will vary from one application to other. The structure shown in (fig 9,C) is a long running structure. This complete structure can be folded into any geometrical shape such as one shown in cylindrical form (fig 6,D). Base plate acts as an extra supporting part which will provide mechanical support as well as it will improve thermal conduction. If number of fins are less then height is to be increases when heat flux value is high. Even for high heat flux if number of fins are more then height of fins should be kept low but spacing between fins must be taken care.

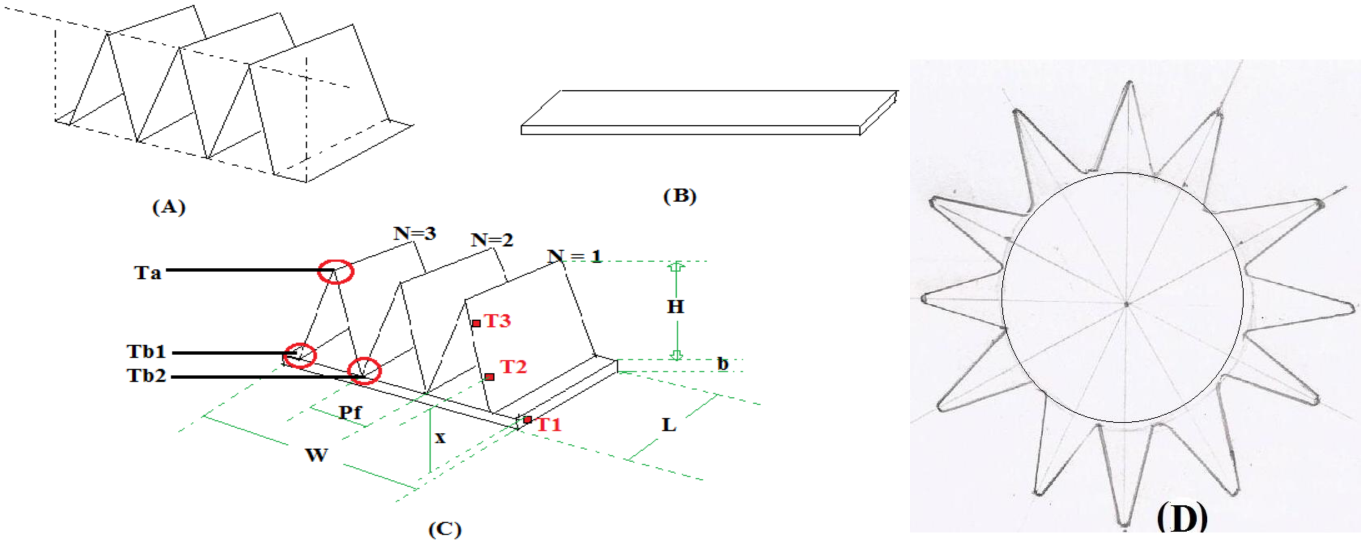

Fig 9 : (A) shows the corrugated triangular fins structure . (B) Base plate. (C) Complete unit. (D) Square/Rect Structure. (E) Circular/ Cylindrical Structure

From above fig (9,C), Two conditions/cases are illustrated for heat transfer to take place to take place through corrugated structure. The T1,T2 &T3 represents highest temperature, mid temperature and low temperature respectively The flow of heat (Q) will always happen from higher temperature zone to lowest temperature zone in contact .

Thus Q = f1(T1, T2, strip geometry, material) (2)

The relation between T1 and T2 is in the form of temperature difference (T1-T2) and ‘x’ is the separation distance between T1 & T2.

Q = f2 (T1-T2, strip geometry, material) (3)

Case 1:

If (T1-T2) = 0 (i.e.: when T1 = T2)

Then Q = 0 (means no heat/ thermal transfer rate is being taking place between points at T1 & T2

Case 2 :

If T1>T2

Then Q>0 (means heat transfer rate increases)

$Q \alpha \frac{A.(T1-T2)}{L}$

$Q = \frac{K.A.(T1-T2)}{L}$

$Q = - \frac{K.A.(T2-T1)}{L}$ (unit: watts)

$Q_x = - K.A\frac{dT}{dx}$ (4)

This is the heat transfer at x direction.

For y and z direction (in 3D representation), Q is given as:

$Q_y = - K.A\frac{dT}{dy}$ (5)

$Q_z = - K.A\frac{dT}{dz}$ (6)

Note: for a very thin copper strip, heat conduction in 3D form can be neglected. Heat flow in any 1 direction can be considered for simplicity.

Heat Flux (q) is defined as the ‘rate of flow of heat’ and Critical heat flux is the ‘thermal limit of a phenomenon where a phase change occurs during heating’.

$$\mathbf{q} = \frac{\boldsymbol{Q}}{\boldsymbol{A}}$$

B. ROLE OF INDIVIDUAL PARAMETERS ON THERMAL CONDUCTIVITY

[5] Thermal Conductivity (K) = $\frac{Q.L}{A.\Delta T}$

(7)

1. Temperature difference (ΔT) :

Greater the temperature difference between the two ends of the bar or the strip, greater will be the rate of heat flow.

$Q \alpha \Delta T$ (8)

2. Cross-sectional area (A):

A bar twice as wide conducts twice the amount of heat.

$Q \alpha A$ (9)

3. Separation length/ distance (L) :

Rate of heat transfer is always inversely proportional to the length of the bar.

$Q \alpha \frac{1}{L}$ (10)

4. Time (t):

Heat flow (Q) directly depends on the amount of time that passes. Twice the time, twice the heat

C. TECHNOLOGY USED TO DEVELOP CORRUGATED COOLING UNIT USING COPPER

Technology which has been decided to be used is “corrugated fin technology”. Where ever it is required to have high fin density on a restricted surface area at low weight and low manufacturing cost, corrugated fin technology is given much more importance compared to other technologies such as :

- Extruded
- Bonded
- Die-casting
- Skiving
- Machining
- Forging

- Stamping
- Folding

Corrugated fins are manufactured by folding continuous strip of copper or aluminum in either a square wave , rect wave , u-wave or in a triangular wave patterns. After folded fins are manufactured, one can attach a base strip which helps increasing the heat transfer surface area. Below fig 8 represents the machine used to form triangular corrugated fin structure.

Fig 10: **Left**: Complete View Of The Manually Controlled Corrugated Machine. **Right** : Triangular Press Region Of The Machine.

D. COPPER HEAT SINKs AT L1 & L4 LOCATIONS

Based on the basic rules used to develop heat sinks, 2 new copper heat sink has been developed to replace aluminum heat sink at L1 and at L2 locations shown in fig 11.

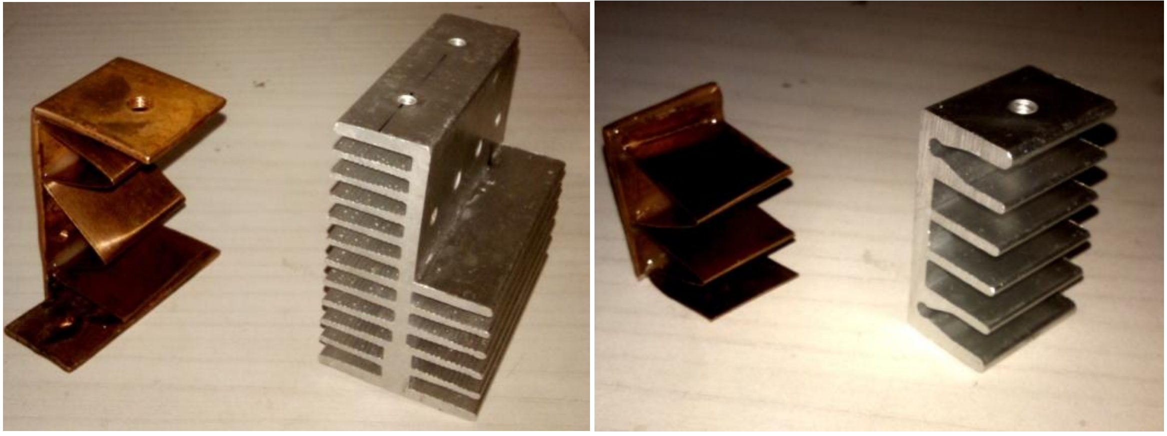

Fig 11: **Left** : "Cu" Based Heat Sink at L1 (DEVELOPED) & "Al" Heat Sink at L1 (EXISTING) .**Right** : "Cu" Based Heat Sink at L4 (DEVELOPED). **Right** : "Al" Heat Sink at L4 (EXISTING)

Below figure 12- represents the complete inverter PCB Board view with "Cu" heat sinks.

Fig 12: Front View

Fig 13: Angular View

Fig 14: Top View

Fig 15 : View of L4 location with “Cu” Heat Sink

E. GEOMETRICAL SPECIFICATIONS :

Below fig 16 shows geometrical specification of old and newly developed heat sink.

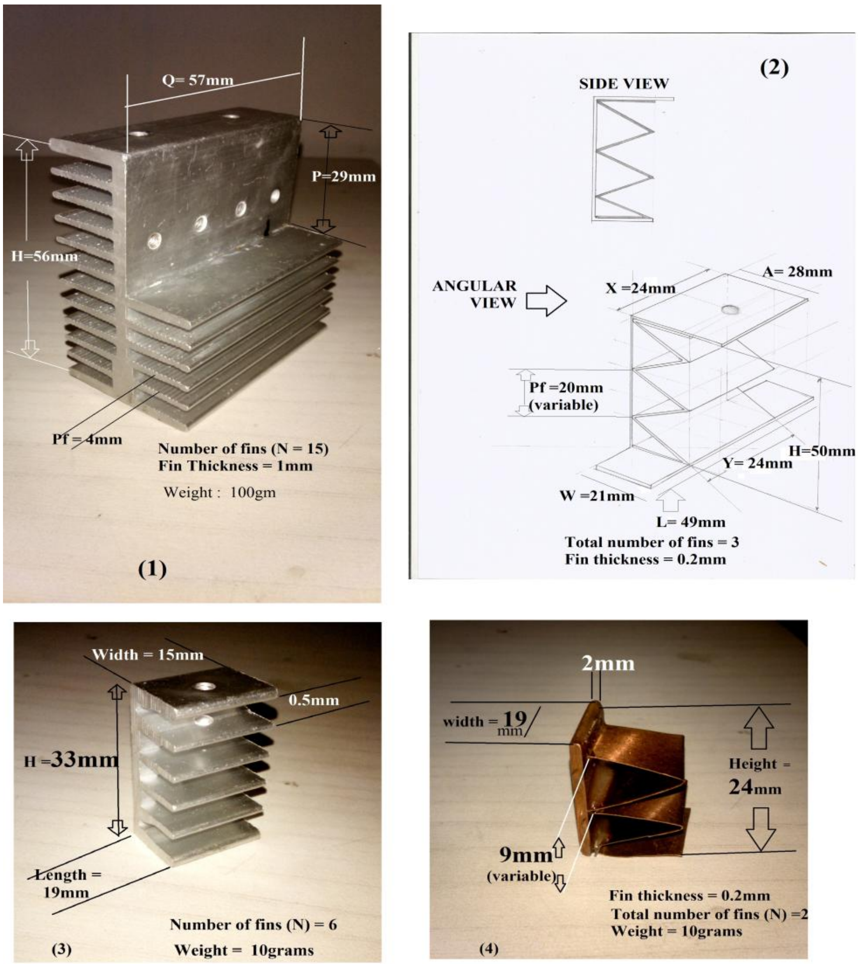

Fig 16 : (1) “Al” Heat Sink At L1 . (2) “Cu” Heat Sink At L1. (3) “Al” Heat Sink At L4. (4) “Cu” Heat Sink At L4.

5. TEST WITH COPPER HEAT SINK :

A. DATA OBTAINED :

Corrugated Copper heat sinks at L1 & L2 locations were tested in the similar way followed for "Al" heat sink.

TABLE 4 : RESISTANCE OFFERED BY CORRUGATED COPPER HEAT SINKS AT LOCATIONS L1& L4

Time (min)	**Sensor 1** **S1 in (KΩ) placed on copper heat sink at L1**	**Sensor4** **S4 (KΩ) placed on copper heat sink at L4**
0	4.26	4.19
10	4.88	4.36
20	4.85	4.80
30	4.48	4.94
40	4.39	5.08
50	4.39	5.20
60	4.40	5.23

TABLE 5 : TEMPERATURE OF Cu HEAT SINK AT LOCATIONS L1 & L4 & COMPONENTs C1 & C4 TEMPERATURE

Time (min)	**Temp (^{0}C) of Cu Heat Sink at L1**	**Temp (^{0}C) of C1 at L1**	**Temp (^{0}C) of Cu Heat Sink at L4**	**Temp (^{0}C) of C3 at L4**
0	34.08	27	33.52	27.5
10	39.04	27.5	33.88	27
20	38.80	27	38.40	29
30	35.84	28.5	39.52	28
40	35.12	27	40.64	29
50	35.12	27	41.6	20
60	35.20	27	41.84	29

B. COMPARISION

Every detail obtained during the test with aluminum heat sink was compared with data obtained using corrugated copper heat sink. It was observed that copper heat sink's temperature was higher than aluminum heat sink and C1, C2, C3 components temperature was observed to be lower than what was observed during aluminum heat sink's case. This proved that since copper heat sink was consuming heat from the component rapidly, its temperature raised keeping the main component's temperature at low level. This has been plotted as a graphical representation.

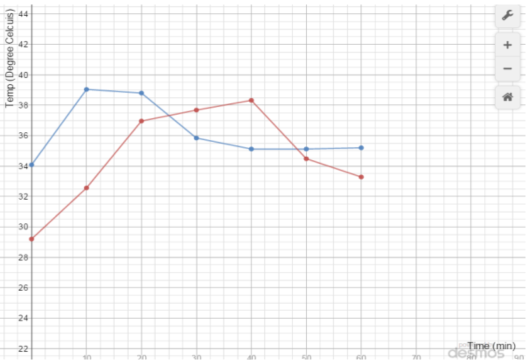

Fig 17: L1 Temperature plot of Copper heat sink (blue) & aluminum heat sink (red) on y-axis w.r.t time on x-axis

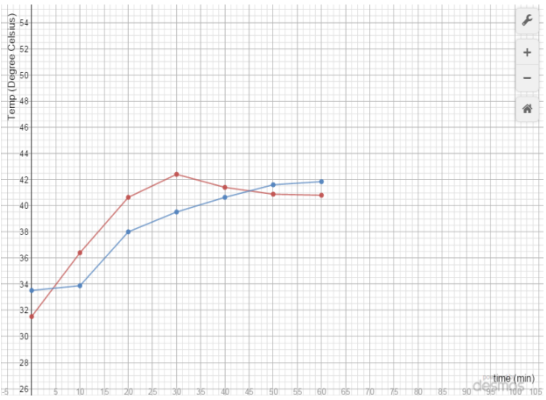

Fig 18: L4 Temperature plot of Copper heat sink (blue) & aluminum heat sink (red) on y-axis w.r.t time on x-axis

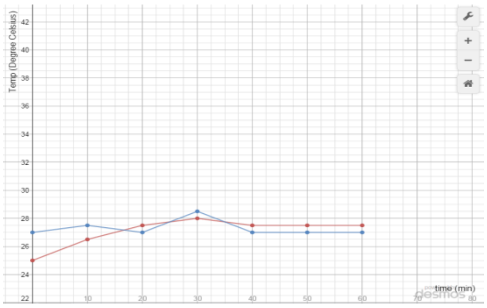

Fig 19: C1 temperature during "Al" heat sink (red) & "Cu" Heat sink (blue)

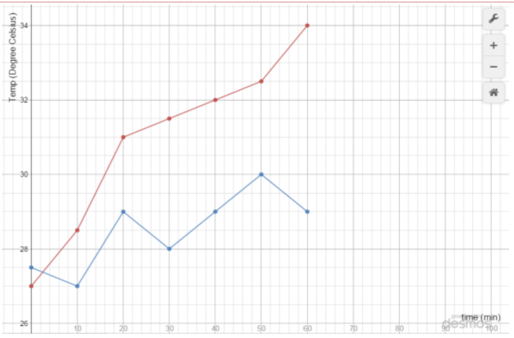

Fig 20: C3 temperature during "Al" heat sink (red) & "Cu" Heat sink (blue)

6. CONCLUSION :

Work performed and explained in this paper demonstrates: analysis of existing aluminum heat exchangers used in inverters, designing and manufacturing technology used for new heat exchanger which utilizes copper metal, installation and its thermal testing on inverter system. Thermal test (depicted in above given tables 1-5 and figures 1-20) on aluminum & copper heat sinks, showed improved thermal management performance of newly designed corrugated copper over aluminum heat sink also implying that the thermal resistance path provided by Cu heat sink is low.

7. REFERENCES :

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