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Implementation of Peltier Cooling in Hermetically Sealed Electronic Packaging Unit for Sub-sea Vessel

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ABSTRACT

This paper presents the methodology adopted for implementation of Peltier cooling in hermetically sealed electronic packaging units used in sub-sea vessels. In sub-sea vessels, sonar front-end electronics is packaged in hermetically sealed electronic packaging units. The thermal design of the unit is a highly challenging task considering the heat dissipation of 300W from the electronics, non-availability of chilled air for cooling and IP68 sealing requirements. Cooling fans cannot be integrated, since these units are to be placed in acoustically sensitive pressure capsule area of the subsea vessel. The electronic cooling in this unit is achieved using conduction cooling with external fins. To enhance the cooling, suitable Peltier cooling (Thermo-electric cooling or TEC) module is selected and implemented with the system. Computational fluid dynamic analysis of the unit is carried-out to study the air-flow and thermal performances with Peltier cooler. The unit is realised and the estimated temperatures validated by experimental temperature measurements on the realised unit. The measured temperatures are within the safe operating limits of the electronic components and hence the cooling design of the unit is satisfactory. It is also observed that maximum temperature reduction has occurred at 1.5A current and card edge temperature of Printed circuit board lowered by 9.28 °C by implementing Peltier cooling.

Keywords: Hermetically sealed electronic packaging unit; Conduction cooling; Peltier cooling; Sub-sea vessel, FloTherm

NOMENCLATURE

I	Current
L	Length of thermoelectric module
P	Power
p	Pressure
Q	Heat
Q_h	Heat released to the hot side of thermoelectric module
Q_c	Heat absorbed from the cold side of thermoelectric module
Q_{max}	Maximum heat input at cold side of the thermoelectric module
S	Source term
ΔT	Temperature difference across TEC
T_{amb}	Ambient temperature
T_{load}	Temperature of load being cooled
T_{cold}	Temperature of cold surface
T_h	Temperature of hot side
t	Thickness
U	Free stream velocity
V	Supply voltage
W	Width of thermoelectric module
υ, ν, ω	Components of velocity in x, y and z directions respectively
θ	Thermal resistance
ϕ	Dissipation term
ρ	Density

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1. INTRODUCTION

In sub-sea vessels, sonar front-end electronics are packaged in various hermetically sealed electronic packaging units (HSU). These are located in the pressure capsule of the vessel. External dimensions of the unit are 330 mm (height) x 380 mm (width) x 430 mm (depth). The HSU is designed for packaging of nine conduction cooled printed circuit boards, VME Power supply and VME back plane. It is a sealed enclosure for 1 bar external pressure. 3D model of HSU is as shown in Fig. 1.

The thermal design of the unit is a highly challenging task[1] considering the heat dissipation of 300 W from the

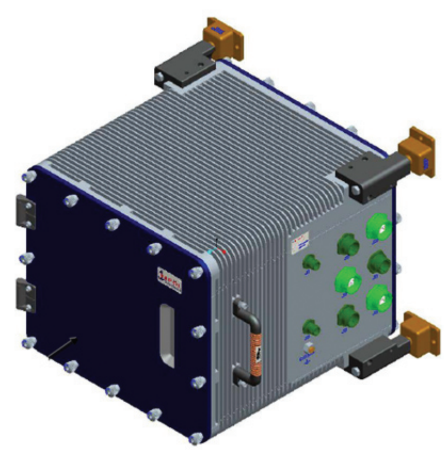

Figure 1. HSU 3D model.

electronic components, non-availability of the chilled air for cooling and the IP68 sealing requirements. Fans also cannot be used for cooling, since these units are to be placed in acoustically sensitive capsule area of the subsea vessel where fans may increase acoustic noise. Hence cooling is achieved by natural convection through fins[2] provided at outer surface. Conductively cooled PCBs are used in the HSU. The heat generated at the components inside the PCB is transferred to the cold plate placed over the electronic components through conduction. From the cold plate, the heat flows out to the outer surface of the HSU by conduction. Fins are provided at the outer surface of the HSU. From the fins, heat flows out to the ambient air through natural convective heat transfer.

The objective of the present work is to enhance the heat transfer from HSU by implementing thermoelectric[3,4] cooling. A thermoelectric refrigeration system employing heat pipes and a phase change material was developed by Raffat[5]. Yu-Wei Chang conducted the experimental investigation of thermoelectric air-cooling module for electronic devices[6]. Zhang conducted the analysis of thermoelectric cooler performance for high power electronic packages[7]. Chien-Yi Du Experimentally investigation and numerical analysed the one-stage thermoelectric cooler[8]. Dubi studied the thermoelectricity in atomic and molecular junctions[9]. A transient thermal behaviour of thermoelectric cooler was predicted by Cheng[10]. Dizaji[11] conducted the experimental study of a novel air-water based thermoelectric cooling unit. Minichannel water cooled-thermoelectric refrigerator was investigated by Murat[12].The present work includes the selection of optimum thermocouple, numerical simulation and experimental validation of the HSU cooled using TEC modules.

2. SELECTION OF TEC MODULES

TEC working is based on the Peltier Effect. In this effect, when an electrical current flows through a junction of dissimilar materials, a temperature difference is produced.

The procedure for selection is as follows[13].

Step 1: Quantify the amount of heat to be dissipated (Q_c).

Step 2: Estimate the lowest heat load temperature (Minimum T_{load}).

Step 3: Determine the ambient temperature (T_{amb}).

Step 4: Estimate the hot surface and cold surface temperatures of thermoelectriccooler with difference in temperature between the same

Step 5: State the number of stages minimum required for meeting the required ΔT. In general, ΔT_{max} achievable for 1, 2 and 3 stages are approximately 65 °C, 90 °C, and 110 °C, respectively.

Step 6: The appropriate thermoelectric cooler to be selected from normalised universal performance curve provided by TEC manufacturer (shown in Fig. 2).

Step 7: Estimate $\Delta T/\Delta T_{max}$. where, ΔT is determined from step 4 and ΔT_{max} is determined from step 5.

Step 8: In Fig. 2 draw a horizontal line on the graph corresponding to $\Delta T/\Delta T_{max}$.

Step 9: Obtain the optimum value of Q/Q_{max} at the intersection of the horizontal line just drawn and the diagonal optimum Q/Q_{max} line. Obtain also the maximum value of Q/Q_{max} at the intersection of the horizontal line (drawn in step b) and the right vertical axis.

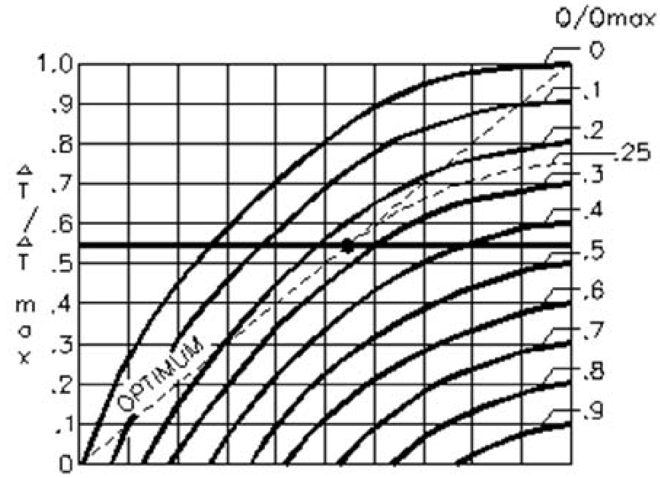

Figure 2. Normalised universal curve of TEC.

Step10. Divide the total heat load (from step 1) by the Q/Q_{max} ratio to calculate the optimum and maximum Q_{max}.

Optimum Q_{max}= Total heat load (Q_C) / (Optimum (Q/Q_{max})

Maximum Q_{max} = Total heat load (Q_c) / Maximum (Q / Q_{max})

Step 11: Thermoelectric cooler is identified with rated Q_{max}, which is the maximum heat that can be pumped at $\Delta T = 0$(i.e., $T_{cold} = T_{hot}$). Fromstep 10,thermoelectriccooler can be selected such that maximum $Q_{max} <$ rated $Q_{max} <$ optimum Q_{max}. For conservative designs, select a rated Q_{max} that ranges from 1.5 to 2 times the maximum Q_{max}.

The foregoing procedures are used to select thermoelectric cooler for enhancing cooling performance of HSU. The selection parameters are given as follows.

$$T_h = T_{amb} + (\theta) \times (Q_h) \quad (1)$$

where T_h is temperature of hot side (70 °C), T_{amb} is temperature of ambient (50°C), and θ is Thermal resistance (0.3°C/W).

$$Q_h = Q_c + P_{in} \quad (2)$$

where Q_h is heat released by TEC (W), Q_c is heat absorbed by TEC (W), and P_{in} is power input to TEC (W).

Q_h = 20/0.3 = 66.66 W

$Q_h = Q_c + P_{in} = Q_c + 2\,Q_c = 3\,Q_c$

Therefore,

Q_c = 22.22W (Assume COP = 0.5, $P_{in} = 2Q_c$)

For a single stage cooler ΔT_{max} = 65 °C [Step 5]

Therefore,

$$\Delta T / \Delta T_{max} = 20/65 = 0.3076 \quad (3)$$

By [step 6] the following values were determined.

$\Delta T / \Delta T_{max}$ = 0.3076

Max Q / Q_{max} = 0.70

Opt Q / Q_{max} = 0.2

$$\text{Opt } Q_{max} = Q_c / Opt(Q / Q_{max}) = 22.22/0.2 = 111.1\text{W} \quad (4)$$

$$\text{Max } Q_{max} = Q_c / \max(Q / Q_{max}) = 31.742\text{W} \quad (5)$$

31.742W < Rated Q_{max} < 111.1W

Rated Q_{max} = 2 times 31.746 or 70W (approximately) [Step e]

All thermoelectric coolers are rated for $V_{\max}$, $I_{\max}$, $Q_{\max}$ and $\Delta T_{\max}$, at a specific T_h. By the above calculations rated $Q_{\max}$ for ΔT = 20 °C is obtained. Based on the rated $Q_{\max}$ value obtained, TEC has selected from RS component. The selected TEC was ET-127-14-11[14]. The specification is given in Table 1.

Table 1. Specifications of TEC ET-127-14-11

T_{hot} = 25 °C					Dimensions (mm)		
I_{MAX} (A)	V_{MAX} (V)	Q_{MAX} (W)	ΔT (°C)	R_{tc} (Ω)	*L*	*W*	*t*
8.5	15.7	77.1	72	1.59	40	40	3.8
T_{hot} = 50 °C							
8.5	17.26	84.81	82	1.59	40	40	3.8

3. PERFORMANCE CHARACTERISTICS TESTING OF TEC MODULES

The experiment setup for the testing of thermoelectric cooler is as shown in Fig. 3. It consists of thermoelectric cooler, voltmeter, ammeter, DC source regulator for power supply, LM 36 sensors, Arduino Mega 2560 and Parallax DAQ (Software). The thermal sensors are positioned on the cold and hot side of the TEC. Specially designed heat sink was mounted on the heat side of TEC for proper dissipation of heat. Ambient temperature recorded at the commencement of the experiment was 31.74 °C.

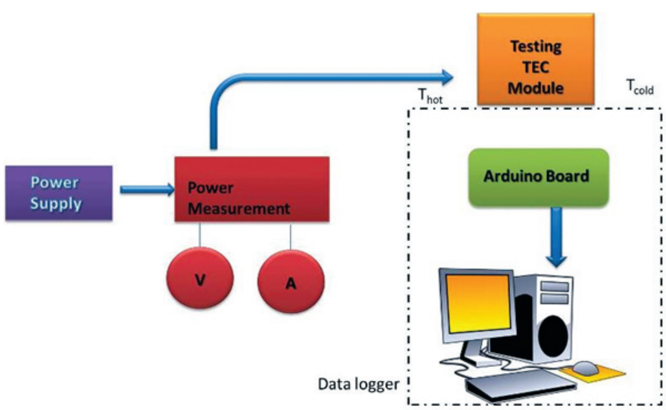

Figure 3. Block diagram of TEC testing.

The test has conducted by varying input current supply to TEC. The testing continued till the temperature of hot and cold side attains the steady state. The temperatures were directly recorded in the computer with the aid of data logger, consisting of Arduino Mega 2560 and Parallax DAQ (Software). At every 1 minute time interval temperatures were recorded. The various performance curves of TEC ET 127-14-11 were plotted. The obtained performance characteristics curves are as shown in Fig. 4.

The results indicated that the maximum temperature difference between cold and hot side is 20 °C at 42W supply power. The minimum cold side temperature was 21.97 °C at 2A current. It has been observed that ΔT increases until 4A current or 40W power, then gradually decreases with increases of power supply or current. So at no load condition the optimum current is determined by 2A.

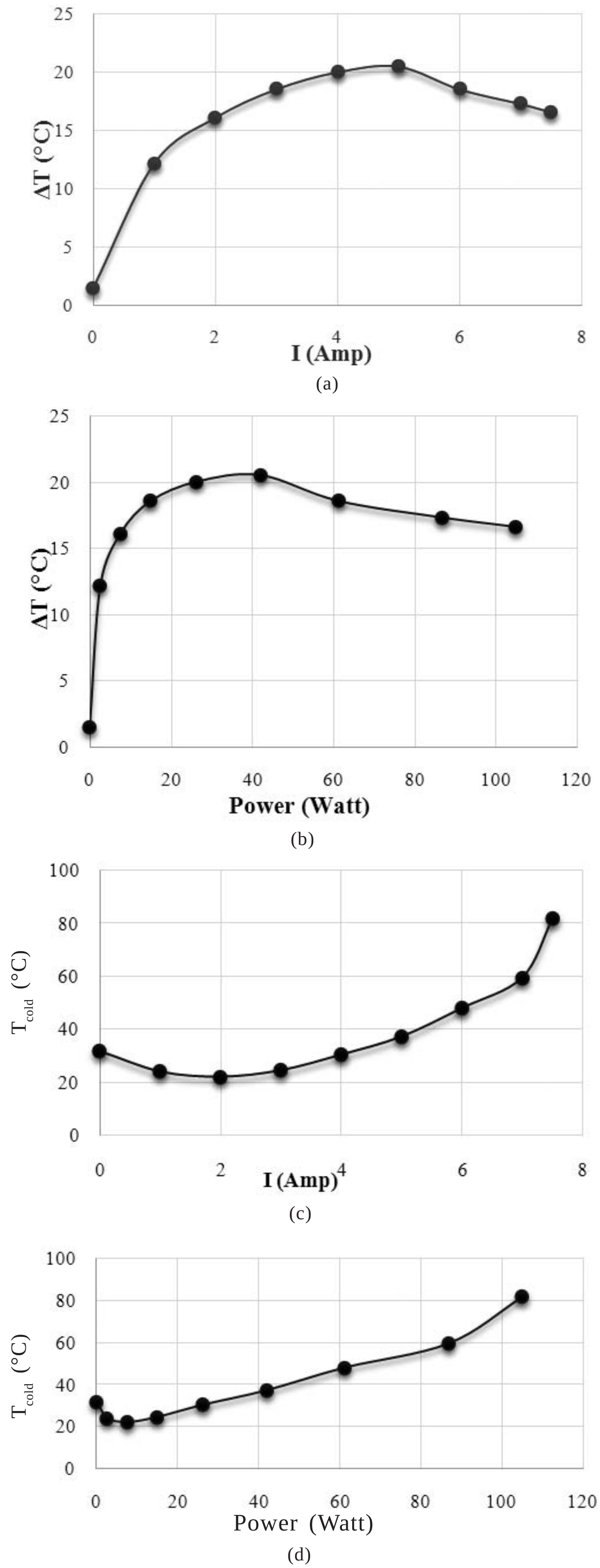

Figure 4. Performance curves of selected TEC: (a) ΔT vs Current, (b) ΔT vs Power, (c) T_{cold} vs Current, and (d)T_{cold} vs Power.

4. SOFTWARE SIMULATION ANALYSIS OF HSU WITH AND WITHOUT TECS

A computational fluid dynamics (CFD) analysis of the HSU is carried-out to evaluate its airflow and thermal performances. The analysis was conducted using the commercial thermal analysis software package FloTherm 9.2. FloTherm uses advanced CFD techniques to predict air flow, temperature and heat transfer in components, boards and complete systems.

In the system, a three dimensional, steady, incompressible, turbulent fluid flows with heat transfer is assumed. In FloTherm, the conservation equations are converted to finite volume form. The solution domain is split into a number of grid cells. Finite volume equations are derived by volume integration over each grid cell[15].

The finite volume equations in differential form are

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho U) = 0 \tag{6}$$

Momentum equations

X- Momentum equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \upsilon U) = \frac{\partial \rho}{\partial x} + \nabla.(\mu \nabla \upsilon) + S \tag{7}$$

Y- Momentum equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \upsilon U) = \frac{\partial \rho}{\partial y} + \nabla.(\mu \nabla v) + S \tag{8}$$

Z- Momentum equation

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \upsilon U) = \frac{\partial \rho}{\partial z} + \nabla.(\mu \nabla \omega) + S \tag{9}$$

Energy equation

$$\frac{\partial \rho T}{\partial t} + \nabla.(\rho \upsilon T) = -p(\nabla.U) + \nabla.(k \nabla T) + \phi + S \tag{10}$$

where U is free stream velocity, S denotes the source term, denotes the dissipation term, p is the pressure, is the density, υ, v and ω are the components of velocity in x, y and z directions respectively.

Based on the complexity in the geometry and the type of mode of heat transfer applied to the model, the FLOTHERM solves the governing equations. The output obtained by solving the equations can be viewed in the form of temperature contours in the visual editor.

The thermal performance is conducted at two different conditions, HSU without mounting thermoelectric coolers and with mounting 10 numbers of thermoelectric coolers on the top and bottom side of HSU (5 modules on each side). The steady state results were obtained as temperature contours. The results obtained in the simulation for an ambient 30 °C are as shown in the Fig. 5 and Fig. 6.

The maximum temperature at the wedge surface of HSU, obtained from the simulation for the existing HSU which uses conventional cooling method (without TECs) and HSU with TECs at various operating currents are as shown in Fig. 7.

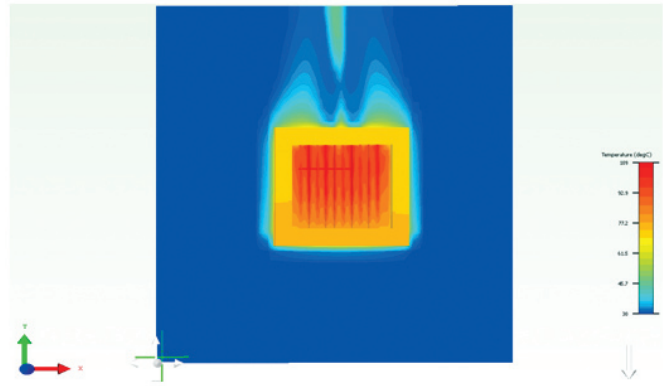

Figure 5. Temperature contour of HSU without TECs at 0A, [T_{max} = 109 °C].

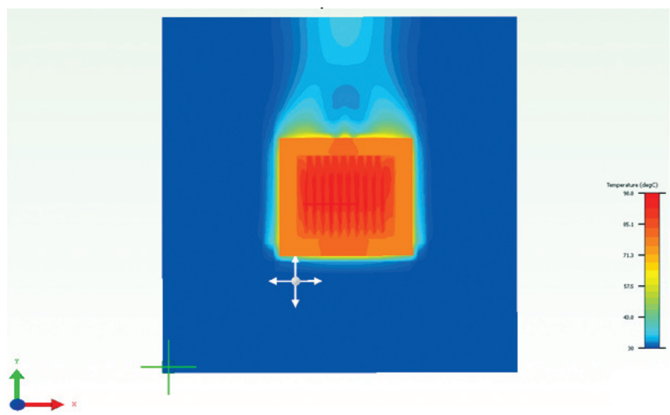

Figure 6. Temperature contour of HSU with TECs at 1.5A, [T_{max} = 98.8 °C].

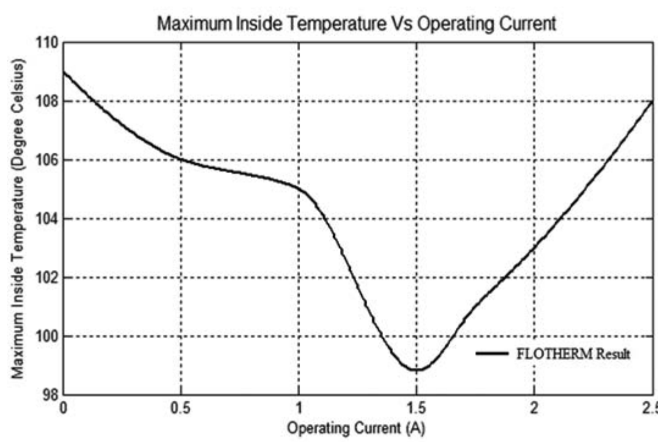

Figure 7. FloTherm temperature results vs operating current graph.

The results show that at an ambient of 30 °C the maximum PCB's junction temperature decreases by implementing thermoelectric cooling modules on the top and bottom sides of HSU. The reduction in temperature depends upon the operating current supplied to TEC's. Maximum reduction has occurred at 1.5A current. The maximum temperature reduction was 10.2 °C. So the reduction in temperature reduces the energy consumption of PCBs and increases the reliability.

5. EXPERIMENTAL VALIDATION OF HSU WITH AND WITHOUT TECS

The experimental set up for the measurement of maximum temperature inside the HSU is as shown in Fig. 8. It consist of HSU with thermoelectric coolers mounted on top and bottom sides, regulated DC power supply for thermoelectric modules, voltmeter, ammeter, LM35 temperature sensor for measuring maximum temperature, and Arduino Mega 2560 for access reading directly from computer. 250W Resistive load has been used for heat dissipation into HSU. One PCB is designed to dissipate 25W Power.

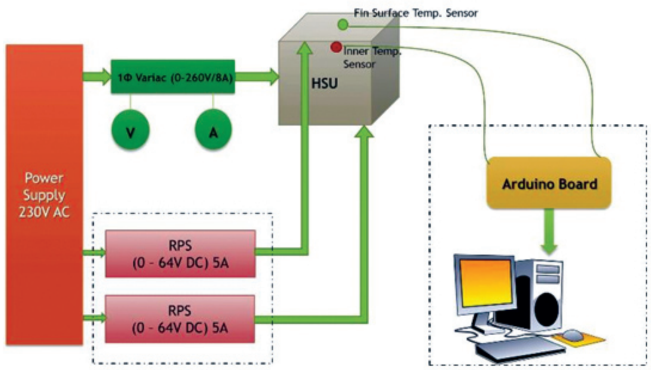

Figure 8. Block diagram for experimental setup.

Initially, the maximum temperature inside HSU without mounting TECs has determined. Then the test was conducted by mounting TECs on HSU. Test was repeated by supplying variable DC operating current such as 0.5A, 1A, 1.5A, 1.75A, 2A, and 2.5A to TECs. The testing continued till the maximum temperature attains the steady state. Resistive heat load for dissipating heat inside HSU has obtained by supplying current and voltage to specially designed PCBs.

The Maximum inside Temperature of HSU with TECs and without TECs results are plotted in a Temperature vs Time graph as shown in Fig. 9. The steady state maximum inside temperature of HSU vs various operating currents graph is as shown in Fig. 10.

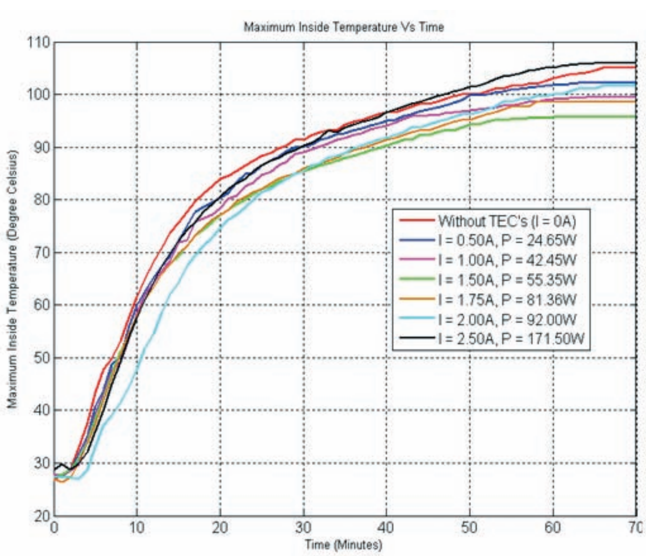

Figure 9. Graphs between maximum inside temperature of HSU vs time.

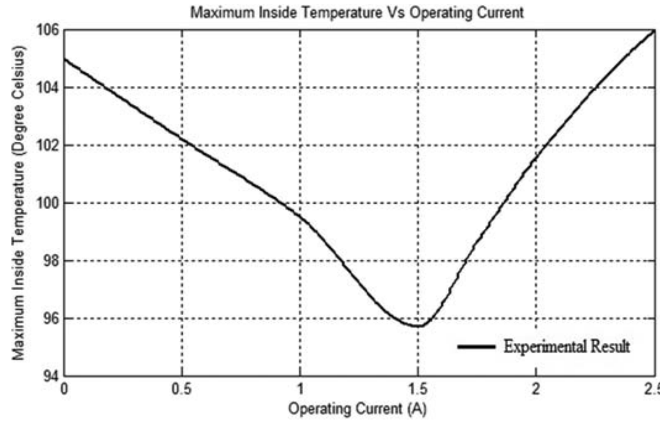

Figure 10. Graphs between maximum inside temperature of HSU vs operating current.

Comparing the temperature inside HSU without mounting TECs with mounting TECs at 1.5A current supply, 9.28 °C temperature reduction is obtained. The comparison graph is as shown in Fig. 11.

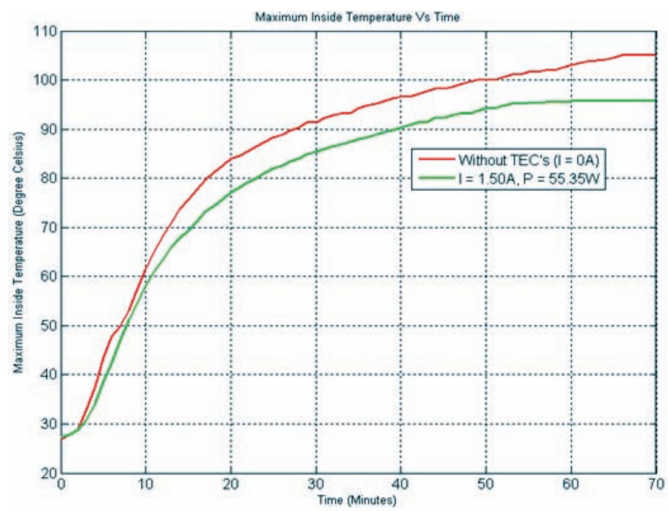

Figure 11. Comparison graphs between maximum inside temperature of HSU vs Time at without and with TECs of optimum current 1.5A.

6. COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

The comparison of PCB junction temperature obtained from the numerical simulation and the experiment at steady state is as shown in the Table 2. The maximum temperature vs operating current of experimental and numerical results are plotted in Fig. 12.

7. CONCLUSIONS

A modified model of HSU is generated for a hybrid thermal management system with TECs based active path in parallel with natural convection cooled rectangular fin based passive path. ET-127-14-11- thermoelectric cooler was selected from the normalised universal curve for TEC selection. I_{max}, V_{max}, Q_{max} and ΔT_{max} are determined at the specific value of

Table 2. Comparison of simulation and experimental results

Operating current 'I' (Amp)	Maximum inside temperature of HSU (°C)	
	Simulation Result	Experimental result
0.00	109.0	104.98
0.50	106.0	102.20
1.00	105.0	99.50
1.50	98.8	95.70
1.75	101.0	98.63
2.00	103.0	101.56
2.50	108.0	105.95

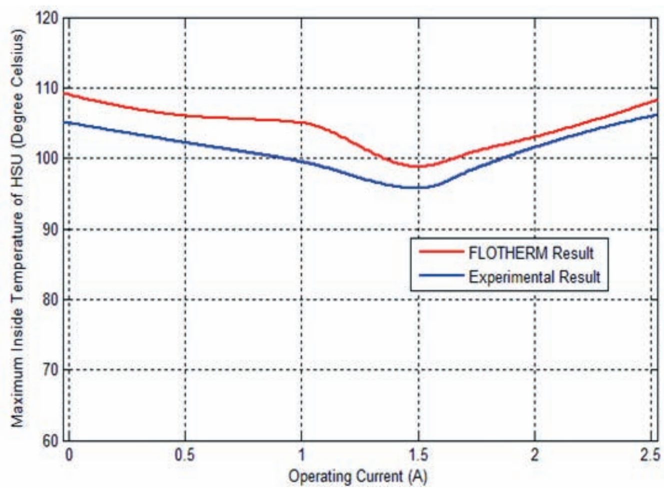

Figure 12. Comparison graphs between numerical and experimental temperature results vs operating current.

hot side temperature. The performance characteristic curves of selected TEC were plotted by conducting experiment.

The enhancement of thermal performance of HSU, with an approximate heat dissipation of 250W by implementing TECs was analysed both numerically and experimentally. The optimum operating current for the operation of TECs are determined both numerically and experimentally. In both the cases 1.5A was found to be the optimum current.

The maximum inside temperature without mounting TECs on HSU obtained from simulation by FloTherm was 109 °C. The experimental result was 104.98 °C. The simulation values reasonably agree with the experimental values by 3.69 per cent.

The maximum inside temperature of HSU by implementing TECs with an optimum operating current supply of 1.5 A was obtained from numerical simulation as 98.8 °C. The experimental result was 95.70 °C. The deviation from the simulation value was 3.14 per cent.

The experimentally measured temperatures were within the safe operating limits of the PCB components and hence the cooling design of the HSU is satisfactory. It was observed that the card edge temperature of HSU lowered by 9.28 °C by implementing thermo electric cooler.

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In the present work, he conducted thermal measurements of HSU with cooler.

Mr Sajith Kumar P.C. obtained his BTech (Mechanical Engineering) from College of Engineering, Trivandrum and MTech (Mechanical Engineering) from IIT, Madras. Presently working as Scientist and heading the Structural and Thermal Engineering Division at DRDO-Naval Physical and Oceanographic Laboratory, Kochi, India. His areas of interest include hydrodynamics of underwater structures and electronic packaging for sonar application.
In this work, he contributed towards selection of Peltier cooler modules and evaluation of simulation and experimental results.