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Multi-objective Optimal Thermal Heat Sink Design Using Evolutionary Method

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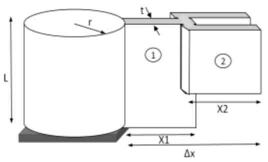
Graphical abstract



Abstract

Single and multi-objective thermal performance of heat sink are considered using evolutionary optimization method. The main objective is to obtain an optimal heat sink design for solving thermal problem on CPU electronic package. In this case, single and multi-objective particle swarm optimization are explored for searching the optimal dimensions of plate fin heat sink design. The optimal design could maximize the heat dissipation and minimize the size of heat sink. Based on the previous research finding and preliminary simulation results, thickness and length of plate fin are selected for optimization. Analysis has been conducted to obtain the best convergence rate of iteration process and optimum values of the fitness functions. This study has demonstrated the usefulness of optimization engine in order to obtain the optimal design of heat sink with area reduction is about 27.15% and heat dissipation has increased by 79.33%.

Keywords: Heat sink model; heat transfer model; multi objective optimization; particle swarm optimization; plate-fin heat sink

■1.0 INTRODUCTION

Particle Swarm Optimization (PSO) is relatively new heuristic evolutionary method includes some tuning parameters that had an influence on the algorithm performance, which is exploration and exploitation tradeoff. Exploration is the ability to test numerous regions in problem space in order to find a good optimum value while exploitation is the ability to conduct the search around a promising candidate solution in order to find the accurate optimum value [1].

In recent years, researchers have used artificial intelligent approach based on PSO algorithm to investigate the thermal design. Rao and Patel [2, 3] used PSO for thermodynamic optimization of cross flow plate-fin and shell-and-tube heat exchanger (STHEs). Soheil and Ganji [4] investigate the temperature on heat source using PSO algorithm. With rising advancement of micro-semiconductor technology, it increased the heat dissipation of microelectronic devices especially CPU[5]. This has led a reduced size of electronic device, which increased the power density of the component to produce a high speed processing data [6]. However, these capabilities have increased the heat dissipations and temperature of component, which finally shorten the life span of the devices [7]. It shows that the temperatures of the component are inversely related to the performance reliability and life expectancy of electronics equipment [8].

Heat dissipation in integrated circuit chips and other electronic components have reached the current limit of air-cooling technology, which required advanced cooling solution [9]. It is estimated that the failure rate of electronics components grew exponentially with risen temperature, which in the next 5 to 10 years will become a major bottleneck to the development of the microelectronic industry [10]. In this situation, more electronic packages are required to have some form of thermal enhancement to adequately remove the heat and maintain the temperature of the component [11]. To improve the thermal performance, one of the comment methods used is heat sink.

During the last decades, some researches have been conducted for enhancing the thermal performance or characteristics of heat sinks. Andrea and Stefano [12] used optimal configuration for natural convection in finned plated. They expressed the simplified relation of the fins heat exchange to determine the optimum value of fins spacing, which can increase the heat flux densities by 20, but the method only applied by using convection and radiation heat transfer based on the plate heat sink. Shih and Liu [13] proposed a formal systematic optimization process to plate-fins heat sink design for dissipating the maximum heat generation from electronic component by applying the entropy generation rate to obtain highest heat transfer efficiency. However their methods were developed without multi selection of parameters constraint on the design.

Zhang and Liu [14] performed in line shape and structure to achieved maximal performance of heat transfer for basic plate heat sink but it was done through theoretical analysis and numerical solution. Later on, in 2010, Azarkish and Sarvari [15] had developed a genetic algorithm to find out the optimum geometry and number of fins. They successfully maximized the heat transfer rate but only focus on heat sink design based on longitudinal fin array. Noda and Ikeda [16] investigated the development of new configuration for crimped fin heat sink based on the current radial heat sink design using experiment analysis. However the method was done without using evolutionary algorithm approach.

Jang and Yu [17] reported the optimal geometry configuration with various types of fin arrays on pin-fin radial heat sink design. They have investigated the effect of geometric parameters on thermal resistance and heat transfer coefficient of the heat sink. Meanwhile, Patil and Kabudake [18] presented the experiment and numerical investigation of natural convection in heat sink consists of a horizontal circular base and rectangular fins. Both of the previous studies only apply to the light–emitting diode (LED) application.

This paper will focus on the use of swarm optimization based on heat sink design for CPU component that has very high capability in processing more data at higher speed. To reduce the temperature of this electronic package, the process of heat transfer need to be increased with respect to a certain parameter range. Thus to optimized the system, a proper selection of parameter in the heat sink is crucial to obtain the thermal design [19]. In this case the mathematical model was developed and PSO algorithm has been applied to achieve high performance heat sink design [20].

■2.0 HEAT SINK MODEL

To study the performance of heat sink, thermal resistance need to be calculated using thermal circuit models, which consist of resistance thermal network and heat transfer equations. Model on actual heat sink placed in Intel was based H61 express chipset. Two metrics, namely total heat dissipation rate of heat sink and size of heat sink were optimized. Metric used to analysis the performance of PSO performance in terms of single and multi-objective analysis.

The total heat dissipation rate of heat sink for Figure 1 is defined as [21]:

$$Q = \frac{\Delta T}{R_{\text{sink}}} \tag{1}$$

The size of heat sink for Figure 1 is evaluated simply as [21]:

$$A = \left(200 \cdot \left(x_1 + x_2\right) + 3\right)^2 \tag{2}$$

Cooling system configuration consists of a heat sink is attached directly to heat source (CPU) with thermal interface material (TIM) placed in between heat source and heat sink as shown in Figure 1. Based on resistance thermal network model as given in Figure 2 for the baseline system the processes were presented.

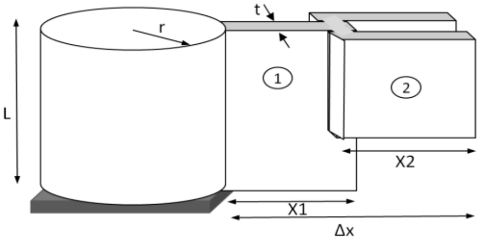


Figure 1 Heat sink model

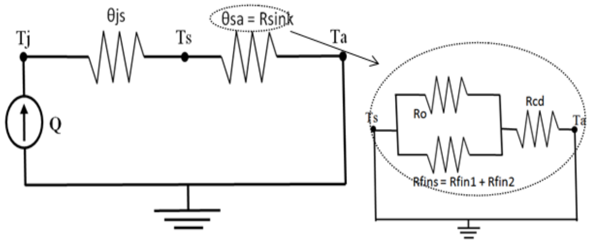


Figure 2 Baseline system thermal resistance network

θ_{js} and θ_{sa} represent the heat spreading resistance with respect to the heat source (CPU) and heat sink respectively. The model is subjected to the following assumptions: uniform heat transfer coefficient, constant thermal properties and no bypassing flow effect.

Parameter R_{sink} is the overall thermal resistance of the finned surface and ΔT is the temperature difference between heat sink and ambient temperature [21]. R_{sink} is estimated by

$$R_{\sin k} = \frac{\Delta \text{T}}{\dfrac{n}{R_{fins}} + h(2\pi rL - ntL + \pi r^2)} + \frac{\ln r}{2\pi kL} \tag{3}$$

where n is the number fins and R_{fins} is the thermal resistance of each fin, which is represented by

$$R_{fins} = R_{fins1} + R_{fins2} \tag{4}$$

R_{fins1} and R_{fins2} represent the fins in region 1 and region 2, which can be calculated using Equation (4) respectively

$$R_{fins} = \frac{1}{\sqrt{hP_1 kA_{c1}}\tanh(\text{m}_1 h)} + \frac{2}{\sqrt{hP_2 kA_{c2}}\tanh(\text{m}_2 h)} \tag{5}$$

where the parameter m_1, m_2, A_{c1}, A_{c2}, P_1 and P_2 is given

$$m_1 = \sqrt{\frac{hP_1}{kA_{c1}}}, m_2 = \sqrt{\frac{hP_2}{kA_{c2}}} \tag{6}$$

$$A_{c1} = (t \cdot L_1), A_{c2} = (t \cdot L_2) \tag{7}$$

$$P_1 = (2 \cdot L_1 \cdot x_1), P_2 = (2 \cdot L_2 \cdot x_2) \tag{8}$$

The perimeter P is the surface area per unit length of fins, and Ac represents the cross sectional area for heat conduction of each fin.Using Equation (1) as a heat sink model for analysis, several variables are considered to determine the pattern of heat dissipation rate. Figure 3 shows the relationship between the parameters, heat dissipation and thermal resistance for the current design of heat sink. The results show that the length of area 1 is (x_1) and length of area 2 (x_2) are proportional to the heat dissipation and inversely proportional to the thermal resistances which support the pattern of heat sink analysis. Figure 4 shows the value of heat dissipation is inversely proportional to the thickness of fin (t) but proportional with the number of fins (n).

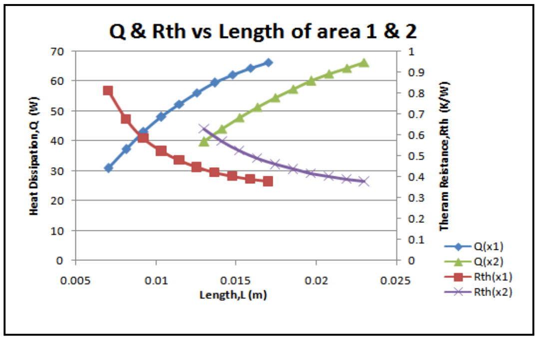


Figure 3 Heat dissipation vs area of length 1 and 2

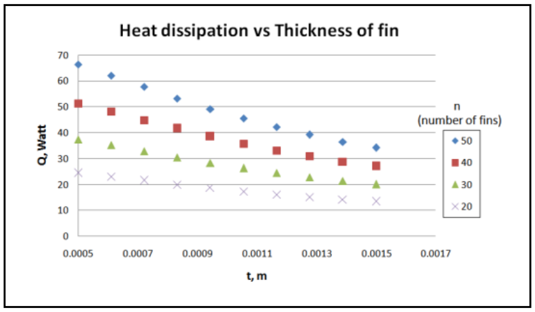


Figure 4 Heat dissipation vs thickness of fins

■3.0 PARTICLE SWARM OPTIMIZATION

The analysis of single and multi-objective using heat dissipation and area heat sink as a fitness or objective function in the study were presented. The decision variables are length and thickness of fins. The proposed search technique applies standard algorithm, which consist position and velocity that given by [22].

$$V_{i+1} = wV_i + c_1 r_1(\text{pbest}_i - X_i) + c_2 r_2(\text{gbest}_i - X_i) \tag{9}$$

$$X_{i+1} = X_i + V_{i+1} \tag{10}$$

The decision parameters x_1 , x_2 and t are randomly generated though the problem space by following current optimum solution. The iteration process changes the velocity of each solution towards its ‘pbest’ and ‘gbest’ locations. Equation (9) calculates a new velocity (V_{i+1})for each solution based on its previous velocity, the best location it as achieved (‘pbest’) so far, and the global best location (‘gbest’), the population has achieved. Equation (10) updates individual solution’s position (X_i) in solution space. The correction factor (acceleration) ‘c_1’ and ‘c_2’ in Equation (9) represent the weighting of the stochastic acceleration terms that pull each other particle toward ‘pbest’ and ‘gbest’ position. The two random number,‘ r_1 ’ and ‘ r_2 ’ in Equation (9) are independently generated in range [0, 1]. There are two sections are presented in this study. The first section discusses the analysis on single objective while second section discusses on the analysis for multi objective optimization problem.

3.1 Single Objective Optimization

Single objective consists one objective/fitness. This approach was executed using following steps. First, values of a set of design variable consist of x_1, x_2 and t was assume based on design specification. Second, the fitness function were evaluated and formulated. Next was utilizing PSO algorithm by selecting a new set of values for design variables. Lastly, iterate the previous step until a maximum value of fitness function is found. Figure 5 shows the flowchart for single objective procedure.

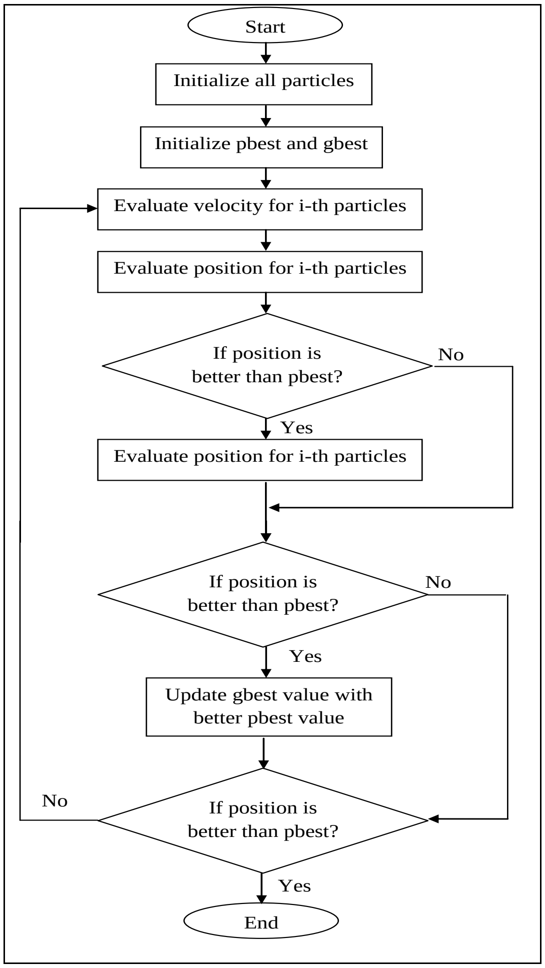


Figure 5 Flowchart for single objective optimization

Figure 6 shows the optimized parameters proposed by PSO. The results show that the maximum value of heat dissipation (watt) can be identified. The value of the fitness functions influence by variable x_2 followed by x_1 and t . It has also been concluded that the both of length of area 1 (x_1) and length of area 2 (x_2) must be compromised in order to suit with the CPU dimension.

Figure 7 shows the effect of the weight on the convergence and fitness function during optimization process. The plots show that by increasing the value of weight, the fitness function value was not optimized and the suitable weight to be used is in range of 0.4-0.6, with 0.5 picked as most preferable.

Figure 8 shows the effect of correction factor parameters (c_1, c_2) of the fitness function. It concludes that the convergence and the fitness function value improved from 2 to 0.5. Fitness value remains almost the same with correction factor at the range of 0.6 to 0.2, which 0.4 was selected as the suitable parameter due to its slightly improved the convergence compare to other as shown in Figure 9.

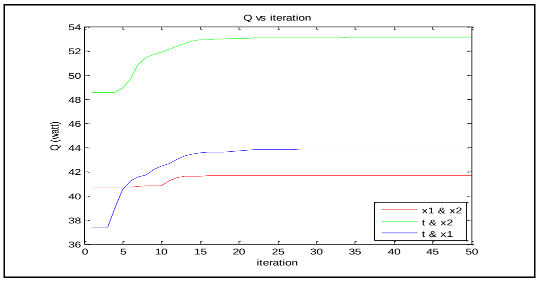


Figure 6 Convergence of PSO studies using different variable

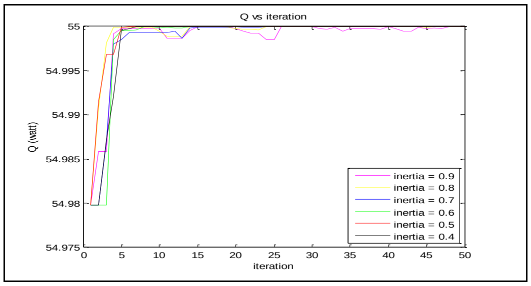


Figure 7 Effect on the convergence of PSO with variation of inertia

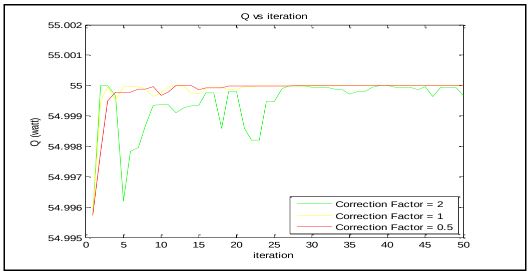


Figure 8 Effect on variation of correction factor on fitness function value and convergance of the algorithm. (c1,c2 = 2,1,0.5)

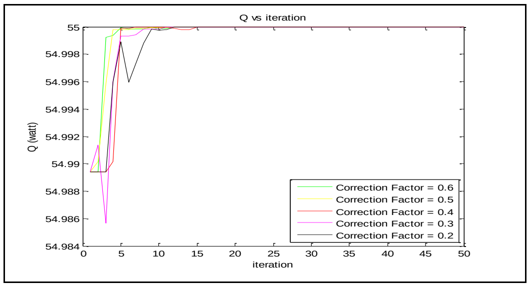


Figure 9 Effect on variation of correction factor on fitness function value and convergance of the algorithm. (c1,c2 = 0.6-0.2)

Table 1 presents the optimized value of the design variables using single objective for current heat sink design. Results show that PSO can be used as an optimization tool in proposing high performance heat sinks. It proposed suitable design parameters within certain range in order to produce a required heat dissipation rate. The results show that the new design of heat sink with new dimension had increased heat dissipation by 20 watt using 0.4 as the value of correction factor and 0.5 as inertia which optimized the length and thickness of fins.

Table 1 Comparison of heat sink design (single objective)

Parameter	**Heat Sink**	
	Current Design	***New Design***
Length of area 1, x1(cm)	1.3	1.32
Length of area 2, x2(cm)	1.8	1.78
Fin thickness, t (cm)	0.1	0.05
Number of fins, n	50	50
Heat Dissipation, (watt)	30	50

3.2 Multi Objective Optimization

Multi objective optimization is a process for simultaneously optimizing several interdependent objective or fitness functions. Heat dissipation and size of heat sink was investigated in this study. Figure 10 shows the flowchart for multi objective procedure.

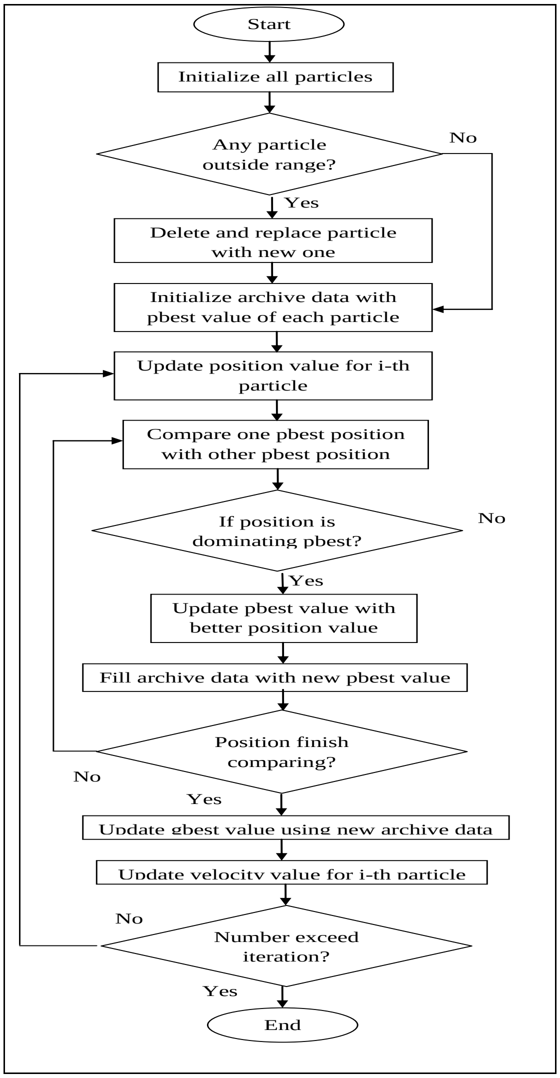


Figure 10 Flowchart for multi objective optimization

The procuder start by determined the value of design variable of x_1, x_2 and t based on design specifications. Then both fitness functions were formulated respectably. Next, the PSO algorithm was executed to find a new selection design variables using tournament selection and Pareto domination methods. Lastly, the previous step was iterated until optimal Pareto front is found. In order to achieve a high heat dissipation rate, thermal resistance of heat sink must be as minimum as possible since it is inversely proportional to heat dissipation as given in Equation (1). The objective is to maximize heat dissipation rate with minimum size of heat sink. The obtained Pareto-optimal solution would resemble a concave front and for every fixed value for each fitness/objective function, there is one optimal value for other fitness function [23].

Each value of Pareto optimal front represent a pair of values that compromise each other, where the lowest values of one fitness function would give highest value on another fitness function. Figures 11 and 12 show a Pareto optimal solution with respect to heat dissipation and thermal resistance respectively. The Pareto fronts for 500 iteration will produce elite non-dominated solution while others are considered to be dominated solution [24]. As the size of area of heat sink is decreasing, the heat dissipation will also decline which will increase a thermal resistance produced by heat sink.

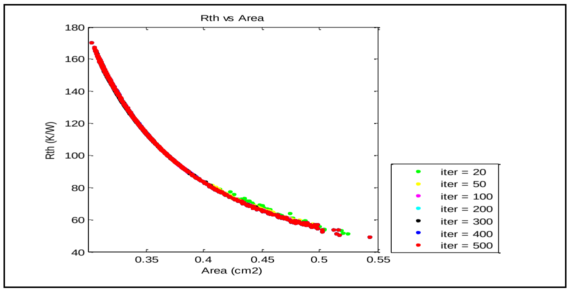


Figure 11 Pareto optimal solution of Q (watt) and 1/Area (Graph Q vs 1/Area)

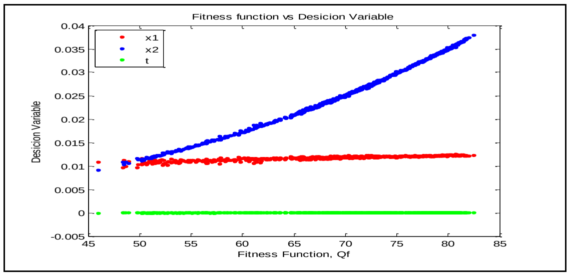


Figure 12 Pareto optimal solution of Rth and Area (Graph Rh vs Area)

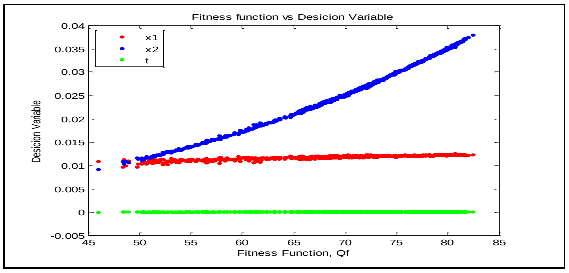


Figure 13 Distribution of heat sink design variables along its Pareto front for heat dissipation, (Qf)

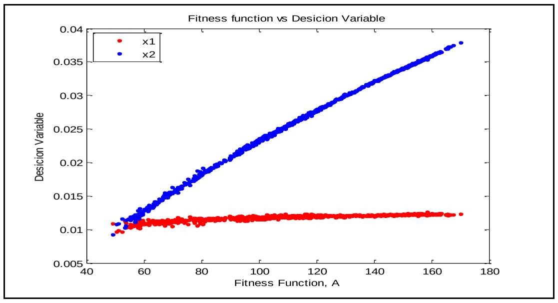


Figure 14 Distribution of heat sink design variables along its Pareto front for Area, (A)

Figures 13 and 14 show the heat sink variables with respect to the fitness function. Figure 11 presents that the thickness of fin does not vary significantly along the Pareto optimal front. On the other hand, the aspect of length of area 2, (x_2) and area 1, (x_1) increase continuously along withincreasing of heat dissipation rate. Similar conclusion can be made on Figure 12 that length of area 2, (x_2) and area 1, (x_1) increase continuously along with increasing of area of heat sink. Thus it is clear that heat dissipation rate is proportional to the size of heat sink area [25]. Next the qualities of a Pareto-optimal set have been measured using performance indices (PIs) with respect to distribution and distance of the solutions [26]. The proposed equation was used to determine the convergence of Pareto solution. Below is the calculation of distribution based on *Spacing* knows asSP proposed by Schott [27]:

$$SP(S) = \sqrt{\frac{1}{|S-1|}\sum_{i=1}^{|S|}(\mathrm{d}_i - \bar{d})^2}, \qquad (11)$$

$$d_i = \min_{s_k \in S \wedge s_k \neq s_i} \sum_{m=1}^{|M|} | f_m(s_i) - f_m(s_k)|, \qquad (12)$$

Another PI, Equation (13) is used to calculate average distance from Pareto solution set, (P) to solution set, (S). A *Seven Point Average Distance* (SPAD) proposed by Schott [27] was used:

$$SPAD(\mathrm{P}, S) = \frac{1}{|R|}\sum_{i=1}^{|\mathrm{P}|}\min_{s\in S}\sqrt{\sum_{k=1}^{M} | f_k(r_i) - f_k(s)|^2} \qquad (13)$$

Figures 15 and 16 show graph of performance indices with respect to *Spacing* (SP) and *Seven Point Average Distance* (SPAD). The results show that PIs can be used to determine the correct value of inertia, correction factor and number of iteration (generation). In this case, we conclude that using an iteration of 300 and inertia of 0.8 and Correction factor of 0.4 are suitable for producing a better optimality of Pareto front. Table 2 shows the optimized value of the design variables using PSO technique of multi objective for current heat sink design. Results show that with PSO acts as an optimization tool in searching a better heat sink performance. Result shows that the new optimal design had increased heat dissipation by 23.8 watt and reduction of size by 22.98 cm^2 from the original specifications while using 0.8 as inertia and 0.4 as correction factor.

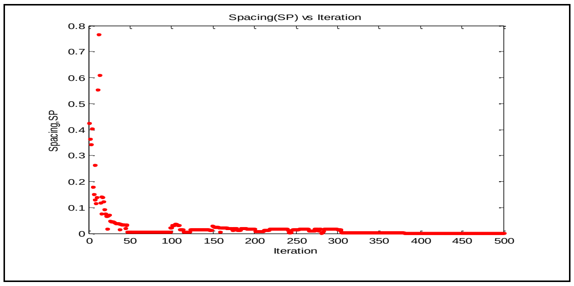


Figure 15 Graph spacing (SP) vs iteration

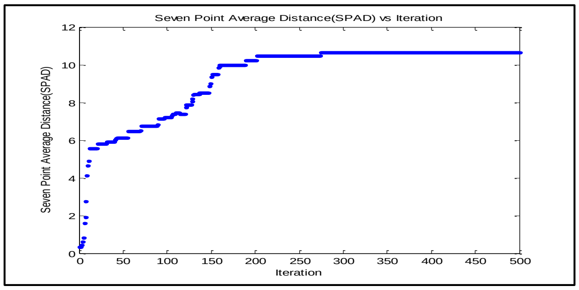


Figure 16 Seven point average distance (SPAD) vs iteration

Table 2 Comparison of heat sink design (multi objective)

Parameter	**Heat Sink***(Number of Fins, n=50)*	
	Current Design	***New Design***
Length of area 1, x_1(cm)	1.3	1.06
Length of area 2, x_2(cm)	1.8	1.36
Fin thickness, t (cm)	0.1	0.01
Heat Dissipation, (watt)	30	53.80 (79.3% increased)
Size of Heat Sink (cm2)	84.64	61.66 (27.15% decreased)

■4.0 CONCLUSIONS

This paper proposed a new optimal dimension of heat sink design using particle swarm optimization method. Presented results demonstrate high heat dissipation under various sets of constraint parameters for single and multi objective approaches. Furthermore, the effect of design variables as well as PSO parameters for the optimum result was suggested. The proposed variables have been analyzed and can be used for further analysis in order to produce a suitable heat sink dimension with heat dissipation increased by 79.33% and size of heat sink reduced about 27.15%.

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