

Genetic Algorithm Design of a 3D Printed Heat Sink

Tong Wu¹, Burak Ozpineci^{1,2}, Curtis Ayers²

wut1@ornl.gov, burak@ornl.gov, ayerscw@ornl.gov

¹Bredesen Center
The University of Tennessee
Knoxville, TN 37996 USA

²Power Electronics and Electric Machinery
Research Center
Oak Ridge National Laboratory
Knoxville, TN 37932 USA

Abstract— In this paper, a genetic algorithm- (GA-) based approach is discussed for designing heat sinks based on total heat generation and dissipation for a pre-specified size and shape. This approach combines random iteration processes and genetic algorithms with finite element analysis (FEA) to design the optimized heat sink. With an approach that prefers “survival of the fittest”, a more powerful heat sink can be designed which can cool power electronics more efficiently. Some of the resulting designs can only be 3D printed due to their complexity. In addition to describing the methodology, this paper also includes comparisons of different cases to evaluate the performance of the newly designed heat sink compared to commercially available heat sinks.

Keywords— Thermal management, Genetic Algorithm, 3D Printing, Liquid Cooled Heat sink, Cold Plate

I. INTRODUCTION

Electric vehicle (EV) sales have been increasing exponentially [1] and so is the importance of higher power density, more efficient electric drive systems for EVs [2]. The developments in the power semiconductor technology have recently shown significant improvements in the power density especially with the use of silicon carbide power devices. Further improvements can be achieved using better optimized more compact heat sinks that allow intimate cooling of power devices. The advances in 3D printing of aluminum allow newer approaches for heat sink designs. Even though this paper focuses on heat sink for electric vehicles, the proposed approach can be used for designing heat exchangers for any application both air and liquid-cooled systems, including dual phase systems.

The conventional manufacturing processes, such as

milling, drilling, and casting have limitations for constructing one-piece heat sinks with internal complex shapes and geometries and multi-piece heat sinks are prone to leaks. Using 3D printing technology, it is possible to manufacture one-piece heat sinks with complex internal structures with no additional cost for complexity. Instead of drilling and milling a whole block where material is subtracted, 3D printing adds layers of material to build parts. 3D metal printing is available by melting metal powder with laser or fine e-beam to build parts layer by layer following a computer generated design [3]. Similar technology has already been used by Oak Ridge National Laboratory (ORNL) to build the first 50% 3D printed inverter with a 3D printed heat sink and power module package resulting in a high efficiency inverter with a compact design [4].

Based on the total heat generation, heat distribution pre-specified size, shape, and liquid flow amount, a unique and better performance heat sink can be designed automatically using genetic algorithms (GA). Previous GA applications in power electronics literature have focused on switching time optimization [5-7] and in control of power converters [8].

II. CONVENTIONAL HEAT SINK DESIGNS

Over the past several decades, plenty of work has been done in designing and optimizing heat sinks for multiple purposes. Normally, a mathematic model is built to simplify and calculate the heat transfer ability. The model depends on the structure and material being used and can be complicated to derive. Take an air-cooling heat sink optimization from [9] as an example:

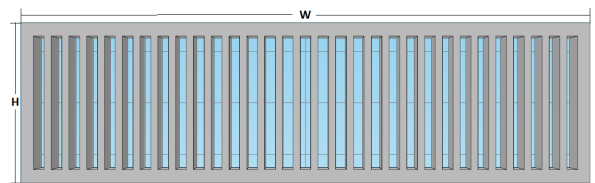


Fig. 1. A finned heat sink for optimization

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

a) First, the basic structure is pre-specified, in this case, a finned heat sink shown in Fig. 1. For a given size and operating conditions, the optimization goal is to maximize the total heat dissipation rate.

b) Then, make an initial guess for the plate-to-plate (fin-to-fin) distance to determine the channel spacing (S) and the Rayleigh number (Ra_s) by

$$S = p - th_c \quad (1)$$

$$Ra_s = \frac{gs^3\beta(T_s - T_\infty)}{\nu\alpha} \quad (2)$$

where p is the pressure drop, th_c is the fin thickness, T_s is maximum junction temperature, T_∞ is ambient temperature, g is gravity constant, k, ν, α, β are properties of the coolant.

c) The average Nusselt number ($\overline{Nu}_s$) and the average heat transfer coefficient ($\bar{h}$) are calculated based on (1) and (2)

$$\overline{Nu}_s = Ra_s S (1 - e^{\frac{-35L}{Ra_s S}^{0.75/24L}}) \quad (3)$$

$$\bar{h} = \frac{\overline{Nu}_s}{S} \quad (4)$$

Calculating the heat transfer coefficient for an open channel flow

$$q_{plate} = 2\bar{h}LW(T_s - T_\infty) \quad (5)$$

for a single plate results in the total heat transfer rate

$$q_{total} = Nq_{plate} \quad (6)$$

d) Based on the calculations above, iterations are used to come up with a design with the maximum total heat transfer and best performance.

The steps described above can be summarized in a flow

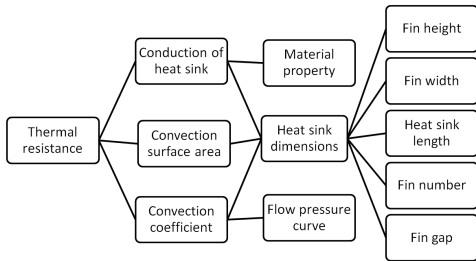


Fig. 2. Design process flow chart of air-cooled heat sink

chart shown as Fig. 2.

The approach is easy to implement, and the primary goal of the design is to decrease the thermal resistance in the equivalent circuit; however, several drawbacks should be noticed here. First, the overall design freedom is limited, because of the type of heat sink is predefined. Moreover, the optimization accuracy is not high enough, due to the approximations in mathematic analytical model. Finally, the

heat sink is designed based on the thermal resistance only. This is a general approach, without considering unique thermal distribution for different power conversion systems sacrificing the efficiency of the heat sink.

Several other ways of designing heat sinks exist, for example, the Entropy Generation Minimization Method [10] uses the effects of thermal resistance in combination with pressure drop to evaluate the entropy generation and comes up with a mathematic model for optimization. However, the same limitations apply here as the previously mentioned approach.

Overall, conventional heat sink designing processes mentioned above are powerful for simple heat sink shapes where the thermal modeling equations are typically known or are simple to derive. The heat sink structures are pre-selected by designers and the optimization calculations are completed on these structures without considering the actual heat distribution.

Automotive manufacturers have developed complex heat sinks to cool their electric drive technologies spending a lot of time and money to come up with analytical models and then optimizing them.

In this paper, a new process will be shown to design liquid-cooled heat sinks without empirical principles and analytical models but focusing on FEA modeling of power devices and heat sinks. The developed algorithm can be applied to any application or any condition as long as the maximum allowed heat sink size, device and system loss characteristics, and the coolant information is supplied. The resulting heat sinks are automatically generated and are typically complex structures. Overall, the new design process is expected to dramatically reduce the heat sink design cycle time and improve the thermal performance of the power electronics systems.

III. THERMAL EQUIVALENT CIRCUIT

A. Heat Transfer Path

A typical heat transfer path for a liquid-cooled system is shown as Fig. 3. The heat generated by the devices transfer through the thermal grease to the heat sink body, heat up the contact surface and transfer heat to the cooling media. Then the heat is moved away by the liquid to be dissipated.

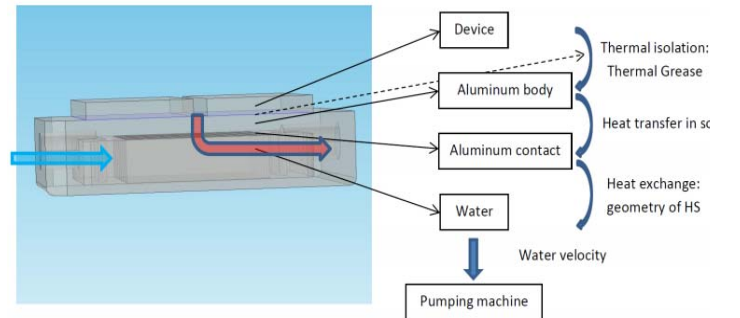


Fig. 3. Heat transfer path of liquid-cooled heat sink

B. Steady State Thermal Equivalent Circuit

Based on the analysis of heat transfer path, a thermal equivalent circuit is shown as Fig. 4.

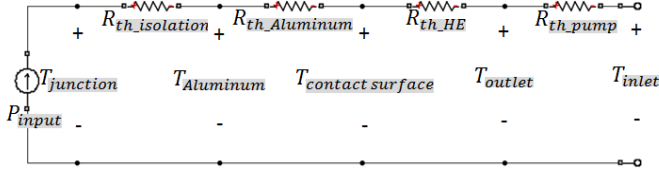


Fig. 4. Steady state thermal equivalent circuit

At steady state, the equivalent voltage on each node represents the corresponding steady state temperature.

Based on this circuit, several conclusions can be made using the energy conversion and the junction temperature equations below:

$$T_{outlet} = T_{inlet} + R_{th_pump} \times P_{input} \quad (13)$$

$$T_{junction} = T_{inlet} + (R_{th_isolation} + R_{th_Aluminum} + R_{th_HE} + R_{th_pump}) \times P_{input} \quad (14)$$

As shown above, the junction temperature could be reduced for the same operating conditions by:

- Reducing $R_{th_isolation}$ or eliminating the thermal grease
- Reducing $R_{th_Aluminum}$, by improving thermal conductivity. $R = \frac{1}{\sigma} \cdot \frac{l}{A}$, where $\frac{l}{A}$ is fixed for the given size and the σ represents the thermal conductivity. This paper will consider bulk Aluminum for design optimization. 3D printed metal technology can eventually result in higher thermal conductivity low-cost heat sinks but this is not within the scope of this paper.
- Reducing R_{th_pump} by increasing the liquid inlet speed. However, this will increase power consumption and levels of acoustic noise and pressure drop.
- Decreasing T_{inlet} which will again introduce higher cooling costs.

Besides the approaches above, the only viable option that will not increase the cost of the system is reducing the R_{th_HE} , which can be achieved by designing a better performing heat sink.

To evaluate and show the improvement of the heat sink designed in this paper, a commercially available comparison model is introduced in this section. The corresponding FEA simulation model and the working environment are also stated.

A. Comparison heat sink

A commercial heat sink, Lytron's standard tubed CP15 is selected for comparison purposes. It is an aluminum-based heat sink, with copper tubes shown in Fig. 5 and is a typical heat sink used in the Power Electronics and Electric Machinery Research Center labs for applications such as the SiC MOSFET based inverter for wireless charging built by ORNL PEEM group [11]. The inlet and outlet tubes are connected to the pump which allows a liquid flow loop with the fixed inlet temperature and inlet velocity.



Fig. 5. Lytron heat sink for the SiC MOSFET based inverter

B. Finite element analysis model

Based on the actually dimension measurements of the heat sink in Fig. 5, a FEA simulation model is built as shown in Fig. 6. The body is made of Aluminum 6061, the tube is made by copper, and the liquid inside is assumed to be water. All materials are defined by the material library built in COMSOL. The active area is in the middle of the flat surface. The dimensions of the heat sink are $86mm \times 64mm \times 8mm$. Based on the measurement of the

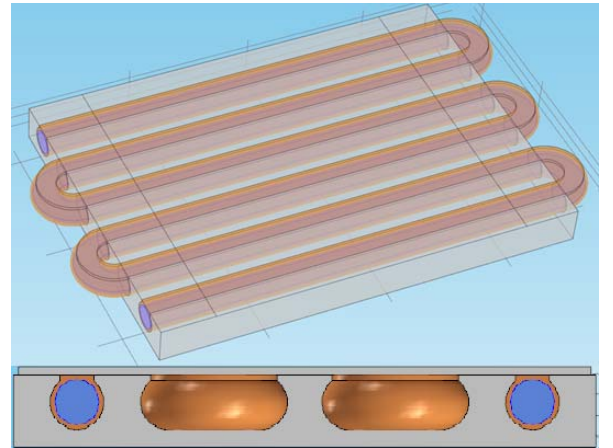


Fig. 6. COMSOL commercial heat sink model and the cross section of the copper tube

dimensions, the copper weight is estimated to be $56.1 \text{ cm}^3 \times \text{cm}^3/\text{cm}^3 = 502\text{g}$ and the aluminum weight is: $292.5 \text{ cm}^3 \times \text{cm}^3/\text{cm}^3 = 790\text{g}$ with a total weight of 1292g.

C. Parameter, environment and assumption

The models are simulated in COMSOL for 3D stationary conjugate heat transfer ignoring the radiation to the environment whose contribution is negligible compared with the conjugate heat transfer.

Case one simulates a large heat source on the heat sink assuming a SiC MOSFET H-bridge based inverter module with a baseplate. The heat source is defined to be $64\text{mm} \times 64\text{mm} \times 1\text{mm}$ and the total power dissipation is assumed to be 2 kW. The ambient temperature is the room temperature 20°C and the inlet water is set to be laminar flow with a velocity of 0.036L/s and temperature of 20°C .

Case two simulates an H-Bridge inverter with four separate die instead of using a baseplate. This case simulates four individual devices on a heat sink rather than on one module. To dissipate the heat generated by four power electronics components, instead of using the base plate, thermal interface material is placed as an isolation layer between chips and heat sink. This topology is the most common design for the commercial electric vehicle drive system [12]. Four chips are sparsely placed on the surface of the heat sink and each of them generates power 250W that is a total 1000W power loss. The flow parameters are the same as the first case.

V. Genetic Algorithm Approach

Genetic algorithm (GA) is known as a solution space searching algorithm that imitates the process of natural evolution following the rule of “the survival of the fittest”. After iterations, the optimized object evolves automatically based on the selection rules and the fitness function. Finally, a desired solution is obtained by exploring a large space of random solutions to find the optimum solution efficiently instead searching for every possibility [13].

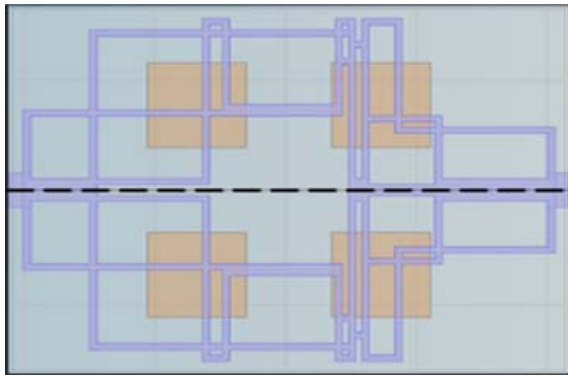


Fig. 8. Symmetric geometry approach

The proposed approach uses an algorithm that combines a newly developed random walking process and genetic algorithms to design the heat sink. First, to save computation time, it is assumed that the system is horizontally symmetrical, so the algorithm only focuses on half of the heat sink, shown in Fig. 8.

The overall process is a self-evolution process containing two stages. The first stage is a fundamental genetic algorithm iteration based on the fitness function to select the targets for the second stage. The second stage then, acts a perturbation function on targets to optimize for better individuals. The proposed process then replaces the targets by the better ones and repeats the same steps until the given number of iterations or the goal is reached.

A. First stage genetic algorithm approach

First stage GA has four steps that are iterated: Initialization, Evaluation and Selection, Crossover and Mutation, and Reproduction.

1) Initialize Population: Generated by the random walking process which randomly digs flow channels inside the aluminum block creating a heat sink automatically. Random walking process, which is implemented in steps with random direction and distance, is used for creating increased variety of different geometries within the heat sink. The process works like mining and digging tunnels underground. Before digging, each model contains a given size of aluminum heat sink block with inlet and outlet locations predefined and a heat source attached. Then, starting from the inlet, two to ten random water channels are formed, randomly with the walking process and are merged at the outlet of the heat sink. Each channel is represented as an $n \times 2$ matrix, as shown in Fig. 9 with first row being the starting point or the inlet which is designated to start at a location between (1, 1) and (1, 10). n is the number of the turns (changes in direction or elbows) the channel has and the matrix presents where these turns occur. For example, in the matrix in Fig. 9, 15 turns are generated starting from location (1, 5), going horizontal first to (1, 10); continuing from (1, 10) and going vertical (down) two points to (3, 10). The same process is repeated until the channel reaches the end point (outlet) which is at (80, 5). The rows in Fig. 10

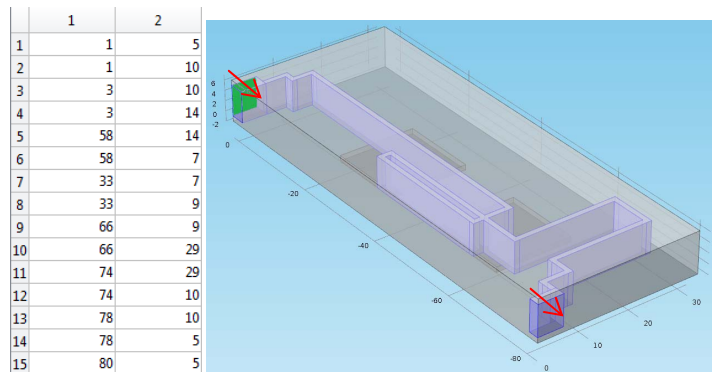


Fig. 9. Channel matrix and the generated channel

represent each heat sink solution, where the columns represent starting points for each channels. “[]” means there are no channels starting from that point. The numbers in the cells represent the $n \times 2$ matrices representing the channels starting from that point. 15 rows in Fig. 10 form an initial solution population of 15.

'Start from(1,1)'	'Start from(1,2)'	'Start from(1,3)'	'Start from(1,4)'	'Start from(1,5)'	'Start from(1,6)'	'Start from(1,7)'	'Start from(1,8)'	'Start from(1,9)'	'Start from(1,10)'
24x2 double	[1,21,1,31,1,31...	7x2 double		27x2 double	27x2 double	7x2 double	8x2 double	27x2 double	12x2 double
			6x2 double	17x2 double					
12x2 double		14x2 double	7x2 double			18x2 double	[1,81,1,78,1,78...		7x2 double
				14x2 double				[1,9,79,9,80,9]	
[1,1,1,29,77,29...		7x2 double					9x2 double	23x2 double	
9x2 double	7x2 double	7x2 double	13x2 double	8x2 double	60x2 double	10x2 double	7x2 double	9x2 double	11x2 double
						21x2 double	9x2 double	23x2 double	11x2 double
				[1,5,77,5,80,5]		21x2 double			11x2 double
	33x2 double			27x2 double		15x2 double	12x2 double		[1,10,1,30,21,30...
29x2 double	7x2 double	16x2 double	7x2 double	9x2 double	[1,6,1,1,45,1,45...				14x2 double
33x2 double	10x2 double	37x2 double	9x2 double	[1,5,1,9,39,9,39...	7x2 double	36x2 double	7x2 double	37x2 double	[1,10,1,27,78,27...
12x2 double	[1,2,79,2,80,2]	10x2 double	26x2 double	11x2 double	6x2 double	12x2 double	[1,9,1,28,25,28...	9x2 double	11x2 double
37x2 double	14x2 double			33x2 double	[1,6,1,3,71,3,71...	7x2 double	7x2 double	[1,9,1,7,63,7,63...	9x2 double
	20x2 double	[1,3,1,27,6,27,6...				10x2 double		15x2 double	
[1,1,79,1,80,1]	35x2 double		[1,4,1,23,19,23...			10x2 double			31x2 double

Fig. 10. Initial generation matrix cells

2) Evaluation and Selection: Each individual in the population is evaluated under the same boundary conditions. The maximum heat sink (shown as junction temperature in Fig. 4) temperature and the inlet force (defining the pressure drop) are calculated using COMSOL finite element simulation. A fitness score (cost function) is set as a function of the heat sink temperature rise along with the inlet force

$$Fitness = \Delta T + F_{inlet}/2^\gamma \quad (15)$$

where γ is a weight factor between the temperature and the force causing pressure drop (defined as force instead of pressure because of the variation of the inlet opening for different solutions) and can be varied depending on the application. If the importance of the inlet force is higher than the temperature rise, a relatively small γ can be used. In the opposite condition a relatively large γ can be used. In this paper, γ is selected as 0, so that the importance of the force index is around 3% of the temperature.

The individual solutions are then ranked from high to low in a decreasing order of the fitness scores. The individual (i)'s survival possibility equals to the value of $(Rank(i)/Sum(rank))^\alpha$, where α is the control factor for the convergence speed. At the beginning, α is small so that the convergence speed is slow to generate a larger variety of solution; at the end, α is higher to ensure the presence of the “good” individuals. The higher possibility means a higher possibility to be selected for the next round. Generally, the individual with lower temperature rise and an acceptable inlet force will be more likely to survive, that is, it will have a higher survival possibility. This selection process follows the “survival of the fittest” rule. For our example, for a population of 21, 6 of them will be eliminated and 15 survivors will go to the next step.

3) Crossover and Mutation: 15 survivors (surviving solutions) are evenly split into 5 groups. Each group contains 3 survivors and will go through crossover and produce three individuals to replace them as the next generation. Crossover is implemented by exchanging the

channel matrix cells (chromosome) between pairs of group members. After crossover, if some of the newborns contain less than 2 channels, they will be replaced by a newly generated solution. This process ensures that all the surviving individuals are qualified and at the same time, better distributes the chromosomes. Also, during the crossover, mutations may happen, which means the parts of channels are randomly changed. The possibility of a mutation is a function of the convergence level. A high convergence level will bring a larger possibility of mutation to prevent the premature convergence and being stuck in a local minimum instead of a global one.

4) Reproduction: The new population is formed by 15 new-born individuals inheriting genetic information from the ancestors' generations, 5 new randomly generated individuals, and one of the best individuals from the previous generation. This will be used for the next iteration of GA. The algorithm will run until the target temperature is achieved or the maximum iteration number is reached.

The overall process of GA is shown as Fig. 11 and the convergence plot is shown in Fig. 12.

The steps shown in Fig. 12 demonstrate the evolution

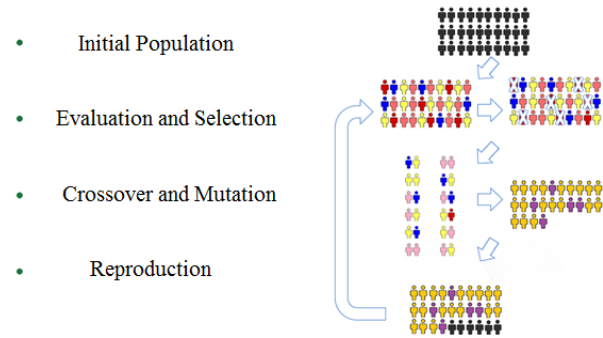


Fig. 11. The overall GA approach

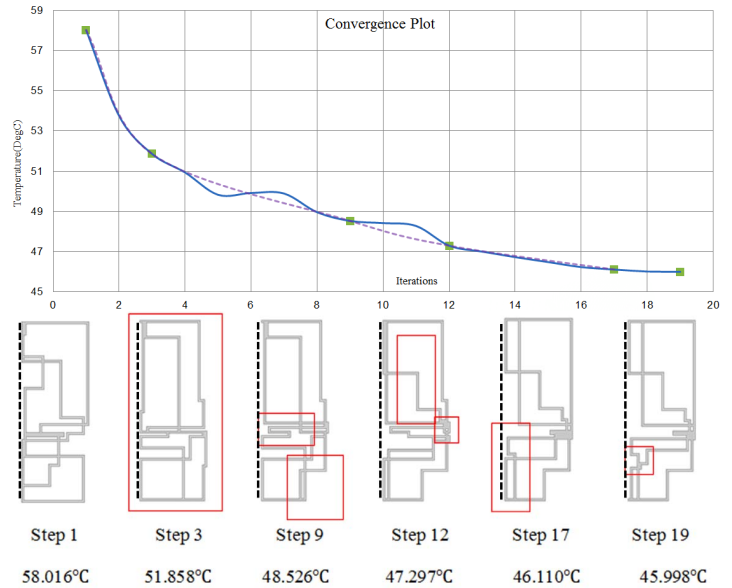


Fig. 12. Convergence plot and the evolved individuals

process. Between steps 1 and 3, a total new geometry is generated by the algorithm and the system temperature drops a significant seven degrees. The transitions from Step 3 to 12 are mostly carried out by crossover. After Step 12, the possibility of the mutation increases and some small changes can be observed from Step 17 to Step 19 due to the mutation. The overall convergence plot trend is shown by the purple dashed line which is an exponentially decrease. For this example, in 19 iterations, the minimum temperature of the heat sink is decreased by 12 degrees for the same load and the same size heat sink.

B. Second stage genetic algorithm approach

After the iterations in the first stage, several “pretty good” geometries of heat sink survive in the final population. Based on the results from the first stage, second stage optimization is applied. The second stage is a perturbation function of the optimized geometries and it includes Translation, Connection, Creation, and Deletion steps shown as Fig. 13 below for a three channel heat sink design:

Each type of perturbation can be applied up to 3 times for each individual (solution):

The Translation perturbation is performed as in Fig. 13(a) by randomly selecting parts of a channel and translating (moving) it to another position and still keeping the connections to other parts. In this case, three parts (two horizontal and one vertical), one per channel have been translated.

The Creation perturbation is performed as Fig. 13(b) by selecting points beyond the original channels and connecting them to the nearest channels.

The Connection perturbation randomly picks a possible short cut two parallel channels and connects them directly as

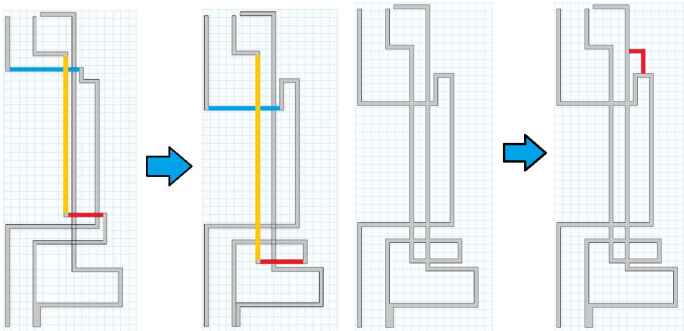


Fig. 13(a). Translation

Fig. 13(b). Creation

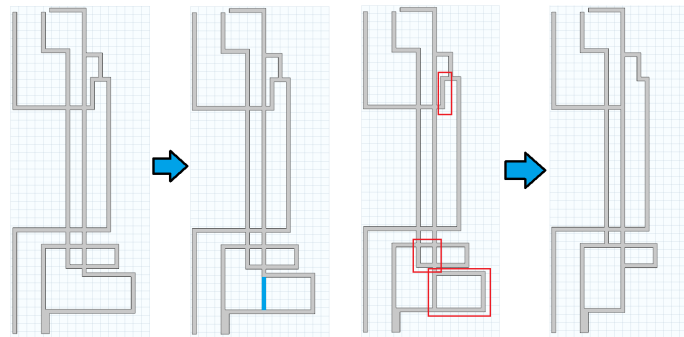


Fig. 13(c). Connection

Fig. 13(d). Deletion

Fig. 13. Perturbations

shown in Fig. 13(c).

The Deletion perturbation picks a random point on the existing channel and deletes the potentially blocked or circulating channels around this point.

After the first iteration of the second stage optimization, the worst performing individuals are replaced with the better ones and the process is repeated until a stable group of individuals is obtained.

VI. Simulation Results

A. Case one, large plate heat source:

1) Commercial Simulation

The commercial heat sink is simulated in COMSOL as shown in Fig. 14 which also shows the resulting temperature distribution. The inlet water was set to have a velocity of 0.036L/s and a temperature of 20°C. For a total power of 2kW applied uniformly to the large plate heat source, the max junction temperature on the heat sink is 53.78°C, which is a temperature rise of 33.78°C. The corresponding inlet force, which is the integral of the pressure drop of the inlet, is 0.56N. Applying the fitness function (15), the fitness value is $33.78 + 0.56 = 34.34$.

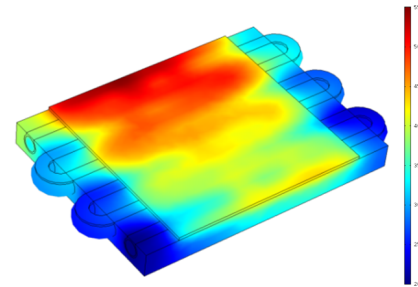


Fig. 14. Commercial large heat source heat sink performance

2) 1st stage optimization

After the first stage of the algorithm is applied, the solution in Fig. 15 is obtained with the same temperature scale as in Fig. 14 using the same load and flow parameters as in the commercial heat sink simulation. The resulting max junction temperature is 49.21°C which is a 29.21°C rise

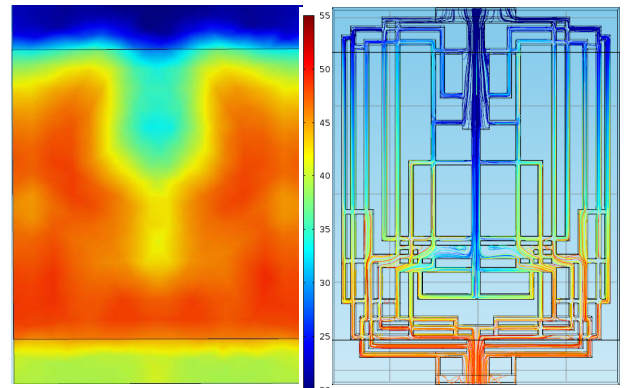


Fig. 15. 1st stage optimized heat sink

in temperature with an inlet force of 0.58N. Applying the fitness function (15), the fitness value is $29.21 + 0.58 = 29.79$ which is lower than the commercial case since this solution has a lower temperature and lower inlet force performance.

3) 2nd stage optimization

Applying the second stage optimization algorithm, the resulting solution in Fig. 16 is obtained. In this case, the max temperature is 47.92°C, with a temperature rise of 27.92°C and an inlet force of 0.55N corresponding to a fitness value is $27.92 + 0.55 = 28.47$. Both the temperature and the force are lower than the commercial unit. The heat sink is composed only by aluminum and the total weight is $315.5 \text{ cm}^3 \times 2.7 \text{ g/cm}^3 = 852 \text{ g}$.

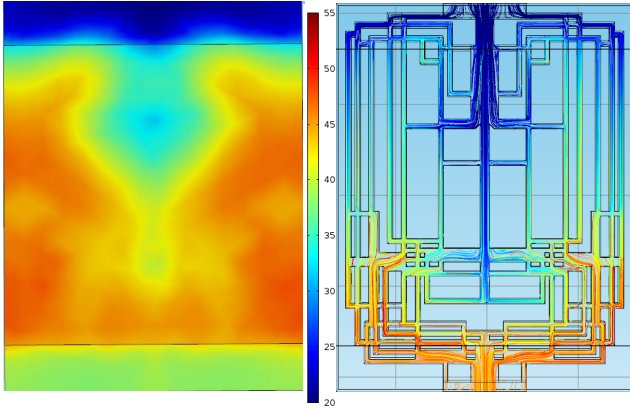


Fig. 16. 2nd stage optimized heat sink

4) Analysis

The fitness values for the commercial heat sink and the GA designed unit after the first and second stage optimization are 34.34, 29.79, and 28.47 showing 13.3% and 17.1% improvements compared with the commercial heat sink. Moreover, the weight is about 2/3 of the commercial one and better performance is obtained even with no copper. Based on the heat distribution plots, it is clear to see that the optimized heat sink evenly distributes the heat avoiding possible heat spots leading to lower heat sink temperatures.

It is interesting to note that the algorithm decided to design the channels to bring the cooler water to the bottom half (closer to the outlet) of the heat sink preventing the water to circulate in the upper half and warming up. On the bottom half (closer to the bottom half), however, it decided to insert more channels to take full advantage of any cooler water coming directly from the inlet. In addition, it can be noted that the vertical channels are more or less uniformly distributed. After the second optimization, several channels are deleted and others are created in the upper half. This strategy which is already built into the algorithm, distributes colder water to the lower half, bringing a more uniform temperature distribution.

B. Case two, distributed heat sources:

1) Commercial Simulation

The same commercial heat sink is used in this case with four distributed heat sources with each generating 250W loss for a total of 1 kW. The devices are evenly placed on the surface of the heat sink. The simulation results are shown in Fig. 17. The max junction temperature is 53.02°C, with a temperature rise of 33.02°C and an inlet force of 0.56N. Applying the fitness function (15), the fitness value is $33.02 + 0.56 = 33.58$.

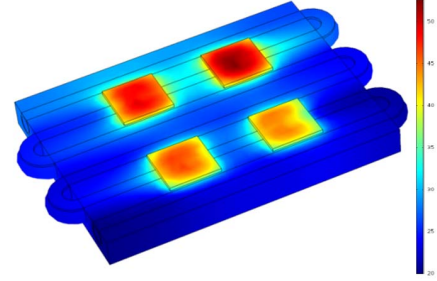


Fig. 17. Commercial separated heat source heat sink performance

2) 1st stage optimization

After the first stage of the algorithm developed in this paper, the solution obtained is shown in Fig. 18 with the same temperature scale as in Fig 17 using the same load and flow parameters as in the commercial heat sink simulation. The resulting max junction temperature is 46.1°C, which is a 26.1°C rise in temperature with an inlet force of 1.63N and a fitness score of $26.1 + 1.63 = 27.73$.

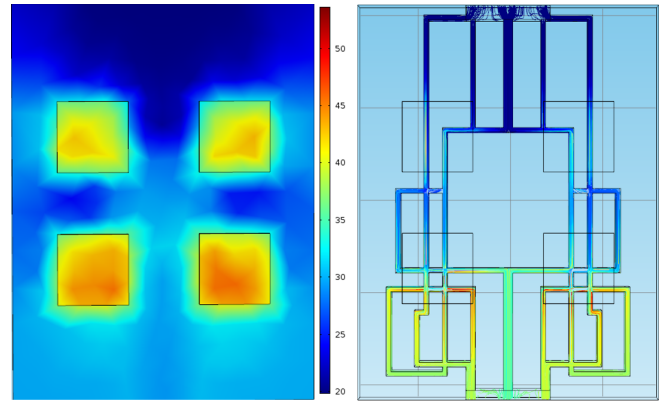


Fig. 18. 1st stage optimized heat sink

3) 2nd stage optimization

Applying the second stage optimization, the solution in Fig. 19 is obtained. It is interesting to note that the algorithm designed bypass channels to the right of the upper right heat source and the left of the upper left heat source to bypass these and send cooler water to the lower heat sources. The

result is a heat sink temperature of 44.85 °C with a temperature rise of 24.85°C and an inlet force of 1.3N. The fitness value then becomes $24.85 + 1.3 = 26.15$ and the weight of the heat sink is calculated to be $383.3\text{cm}^3 \times 2.7\text{g/cm}^3 = 1035\text{g}$.

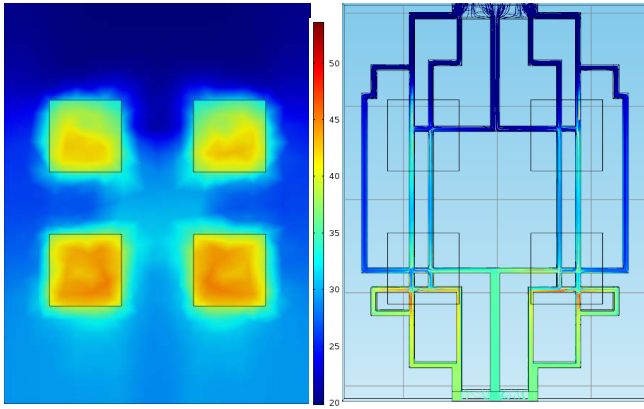


Fig. 19. 2nd stage optimized heat sink

4) Analysis

The fitness values for the commercial heat sink and the GA designed unit after the first and second stage optimization are 33.85, 27.73, and 26.15 showing 18.1% and 22.8% improvements compared with the commercial heat sink. The overall strategy of the algorithm is balancing the temperatures of the upper and lower halves of the heat sink. A relatively fast flow bypasses the upper heat sources and brings cooler water (as indicated by a darker streamline in Fig. 19) to the lower half. Concentrating the cooler liquid in “#” shaped channels under the lower half heat sources result in a slower speed flow and larger heat exchange surface. This increases the heat transfer rate at the lower half and ensures that the local temperature stays balanced. However, at the same time, the inlet force is sacrificed. The designer has to pick the relative importance of junction temperature and the inlet force (which is proportional to the pressure drop) through the use of γ . For a smaller γ , with a more importance on pressure drop, a different solution would be obtained.

Evaluating the results for both cases, it can be observed that the algorithm is trying to evenly distribute the heat throughout the heat sink. To avoid, water being heated up when flowing under the upper half heat sources, two different strategies are implemented. A uniform distribution is developed in the first case and more simplified and concentrated channels are used in the second case. Overall, the strategies ensure the even temperature distribution. Actually, the maximum junction temperature difference between upper and lower parts is about 1°C compared with the commercial case, which is about 10°C.

Also, comparing the weight of the optimized heat sink with the commercial one, a 16% to 30% reduction is observed for both cases.

VII. CONCLUSION

A genetic algorithm optimization process is developed in this paper. Several simulation comparisons are shown and more than 15% improvement in thermal performance is observed. The algorithm approach provides an automatic way for a unique and better heat sink design without the need for complicated analytical models. Comparing with the common optimization methods in the literature, the proposed algorithm allows for a higher degree of freedom.

In this paper, the volume of the heat sink to be optimized was pre-specified. Instead, if a target heat sink temperature is selected, the algorithm can be designed to optimize the size of the heat sink, increasing the power density of power conversion systems. This will be a part of the future work

VIII. REFERENCES

- [1] Z. Wang and R. Paranjape, “An evaluation of electric vehicle penetration under demand response in a multi-agent based simulation,” *Electrical Power and Energy Conference (EPEC)*, 12-14 Nov. 2014, pp. 220 - 225
- [2] D.S. Gautam; F. Musavi; D. Wager; M. Edington, “A comparison of thermal vs. patterns used for thermal management in power converter,” *Energy Conversion Congress and Exposition (ECCE)*, 15-19 Sept. 2013, pp. 2214 – 2218
- [3] T. A. Burruss, “Evaluation of 2004 Toyota Prius hybrid electric drive system,” Oak Ridge National Laboratory, Oak Ridge, TN, USA, Tech. Rep. ORNL/TM-2006/423, May 2006
- [4] Michael Molitch-Hou (2014) Oak Ridge National Lab controls 3D printed metal at the microscale, available at: <http://3dprintingindustry.com/2014/10/16/oak-ridge-national-lab-controls-3d-printed-metal-microscale/>
- [5] M. Chinthavali, C. Ayers, S. Campbell, R. Wiles, B. Ozpineci, “A 10-kW SiC inverter with a novel printed metal power module with integrated cooling using additive manufacturing,” *Wide Bandgap Power Devices and Applications (WiPDA)*, 13-15 Oct. 2014, pp. 48 – 54
- [6] B. Ozpineci, J. O. P. Pinto, and L. M. Tolbert, “Pulse width optimization in a pulse density modulated high frequency ac-ac converter using genetic algorithms,” 2001 IEEE International Conference, Arizona, USA, Oct. 2001, pp. 1924-1929
- [7] B. Ozpineci; L.M. Tolbert; J.N. Chiasson, “Harmonic optimization of multilevel converters using genetic algorithms,” *Power Electronics Specialists Conference, IEEE 35th Annual*, 20-25 June 2004, pp. 3911 – 3916.
- [8] M. J. Schutten, D. A. Torrey, “Genetic algorithms for control of power converters,” *Conference Proceedings of IEEE Power Electronics Specialists Conference*, 1995, pp. 1321-1326
- [9] W. R. Hambrgen “Optimal finned heat sinks”. WRL research report 86/4. Available at: <http://www.hpl.hp.com/techreports/Compaq-DEC/WRL-86-4.pdf>
- [10] W. A. Khan, M. M. Yovanovich, and J. R. Culham, “Optimization of microchannel heat sinks using entropy generation minimization method,” *Semiconductor Thermal Measurement and Management Symposium*, 14-16 March 2006, pp. 78 - 86
- [11] O. Onar, M. Chinthavali, S. Campbell, N. Puqi, C.P. White, J. M. Miller, “A SiC MOSFET based inverter for wireless power transfer applications,” *Applied Power Electronics Conference and Exposition (APEC)*, 16-20 March 2014, pp. 1690 - 1696
- [12] T. A. Burruss, “Evaluation of the 2010 Toyota Prius hybrid synergy drive system,” U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, USA
- [13] W. Banzhaf, P. Nordin, R. Keller, F. Francone, “Genetic Programming – An Introduction”. San Francisco, CA: Morgan Kaufmann. ISBN 978-1558605107