Design and Optimization of 3D Printed Air-Cooled Heat Sinks Based on Genetic Algorithms

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***Abstract*— Enhancing power density and reliability of power electronics is extremely important in power electronics applications. One of the key challenges in the design process is to design the optimum heat sink. In this paper, an algorithm is proposed to design air-cooled heat sinks using genetic algorithm (GA) and finite element analysis (FEA) simulations. While the GA generates a population of candidate heat sinks in each iteration, FEA simulations are used to evaluate the fitness function of each. The fitness function considered in this paper is the maximum junction temperature of the semiconductor devices. With an approach that prefers "survival of the fittest", a heat sink providing better performance than the conventional heat sinks is obtained. The simulation and experimental evaluations of the optimized air-cooled heat sink are also included in the paper.**

Keywords—Thermal management, Genetic Algorithm, 3D Printing, Forced-air Cooled Heat sink, Power density, 3-phase inverter design

I. Introduction

In the literature, many different air-cooled heat sink designs with complex geometries have been proposed. In [1], a 3D printed air-cooled heat sink design methodology is introduced using topology optimization where a gradient-based optimizer coupled with FEA simulation is utilized. The predefined design domain is meshed into small elements which are assigned either solid or fluid material, based on the density variable γ. The objective function is used to optimize γ to achieve the best performance. Similar methods are also found in [2-3]. An additive method is proposed in [4] by imitating the growth of a tree, the 2D pattern of the heat sink cross-section is designed starting from the baseplate. The pattern grows by adding branches to the geometry from previous iteration. There is a "Growth Tolerance Criteria" defined by the percentage of the thermal performance improvement. The optimization is terminated when either the designed "branch" reaches the boundary, or no additional improvement can be achieved by adding elements. In [5], a "Subtractive Design Methodology" has been used for either "Unrestricted Removal" or "Top Surface Removal" to optimize a predesigned fin structure heat sink. A 3D printed heat sink with monolithic structures is built in [6]. Wavy channel structure heat sinks are printed and tested with different design parameters in [7]. A mesh heat sink for a larger surface area is printed in [8]. Although the different approaches have been introduced in variety of papers, either the heat source information or the heat convection coefficients to the environment are simplified as fixed values with uniform distribution. These approximations can simplify the boundary conditions and reduce the computation efforts; however, they also reduce the evaluation accuracy. Moreover, when dealing with the presence of several discrete semiconductor die, device layout on the surface of direct bonded copper (DBC) impacts the temperature profile. Although the approximation simplifies the design process, it does not produce the most optimal solution.

In this paper, a GA-based heat sink optimization method is described that considers the device losses and the DBC design without oversimplification of the heat sink models. The developed algorithm can be used to design a heat sink for any power conversion application as long as device geometries and losses are known. The complex geometries for the optimized heat sinks can be manufactured using 3D printing technologies. The authors of this paper have demonstrated 3D printed liquid heat sinks and GA-based optimization techniques in previous papers [9-10].

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II. Heat Sink Design Approach

A machine learning based design approach with self-evolution capability is proposed. This approach optimizes the maximum junction temperature of the bare semiconductor die on the heat sink. Due to the high non-continuity of the solution space and the non-convex objective function and constraints of the problem, Gradient or Hessian based algorithms are not suitable. Instead, genetic algorithm (GA), a population-based algorithm is used. GA is an evolutionary algorithm that uses fitness functions to evaluate the population of solutions and modifies the unwanted solutions through crossover and mutation to converge to the final solution. The fitness functions in this approach are evaluated based on thermal Finite Element Analysis (FEA) simulation results to evaluate the thermal performance of the heat sinks as they provide superior temperature estimates when compared to approximate thermal models.

The resulting automated design process is computationally intensive due to the co-simulation of GA and FEA using different software packages, MATLAB and COMSOL, respectively. One iteration of the optimization may take hours. As the computational power of personal computers increases, the time it takes for each iteration will get shorter.

For automation purposes, the FEA simulation commands that are executed in COMSOL are directly invoked from the algorithms implemented in MATLAB. The design process (Fig. 1) is automated and does not require additional supervision.

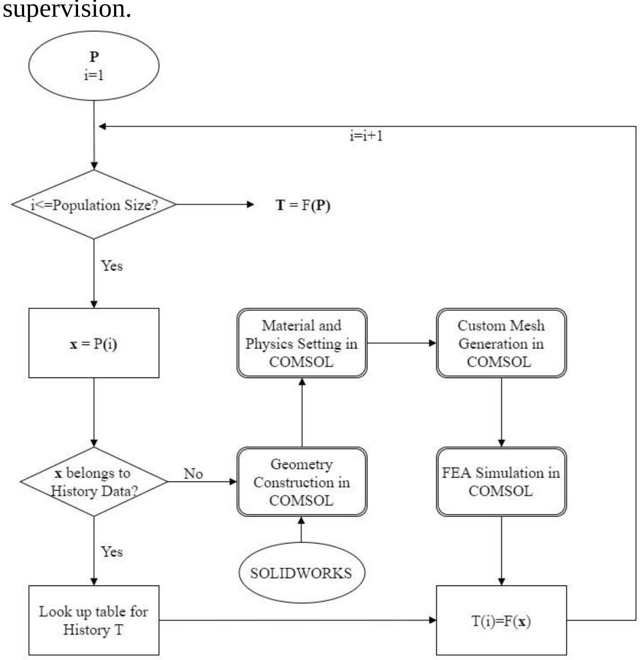

Fig. 1. Proposed automatic iteration loop

III. Hardware Description

The proposed design approach is applied to a case study of a 50 kW three-phase inverter with a 1000 V DC link. The direct bonded copper (DBC) substrate for one switch is designed to handle 1000 V DC link voltage for a 50 kW inverter. The designed DBC board is shown in Fig. 2 with five bare semiconductor die of 1700 V/34 A SiC MOSFETs and three of 1700 V/50 A SiC Schottky diodes.

The DBC design is created in SOLIDWORKS and its geometry is imported to COMSOL by MATLAB for evaluation of each individual heat sink design. For this study, the power density is constrained to 100W/in³, and the design goal is to minimize the maximum junction temperature of the semiconductor devices.

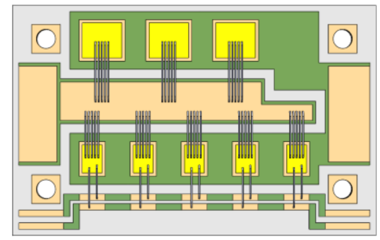

Fig. 2. Designed DBC for a switch in the phase-leg module

The heat sinks are designed for each switch (MOSFET and diode) and are packaged in a phase leg as shown in Fig. 3. The basic structures of the phase leg, including the DBC, semiconductor devices, extraction fan and other components except the heat sink blocks, are drawn in SOLIDWORKS before the initialization step in the GA. Each switch in the phase leg is represented by a DBC substrate with bare MOSFETs and diodes, attached to an optimized heat sink, and is placed facing each other. Based on the predesigned structure shown in Fig. 3, the volume of the heat sink is defined to be 36mm×57mm×27mm, so that the power density of the inverter will not exceed the design constraint.

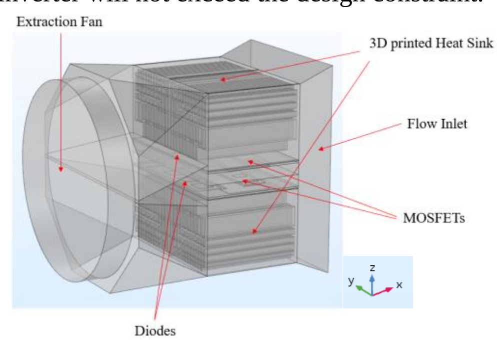

Fig. 1. Phase leg module geometry

The flow rate in this module is determined by the selected fan curve and the pressure drop in the module, as is shown in Fig. 4. The gray curve in Fig. 4 is obtained from the data sheet of the selected fan and the blue curve is the pressure drop curve of the designed heat sink. The pressure drop curve depends on the design of the heat sink.

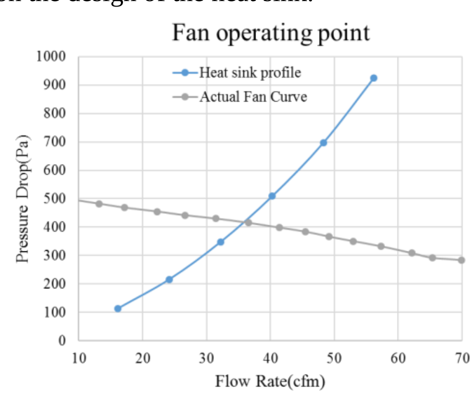

Fig. 2. Flow rate of the power module

The flow rate of the operating point is then determined at the crossing point of curves. Since the flow rate and junction temperature are directly related, the pressure drop of the designed heat sink is not separately optimized. Instead, only the maximum junction temperature is considered.

IV. Genetic Algorithm Approach

In the proposed design process, GA uses a population size of 21 in each iteration. The maximum number of iterations is set to 150, running through five steps: Initialization, Evaluation and Selection, Crossover and Mutation, Reproduction, and Second-Stage Perturbation.

- Initialization

Initialization step creates random 2D extruded structure heat sink candidates that form the first generation of population in GA. The 2D extruded structure considers only the cross-section of the heat sink in the yz-plane for optimization purposes (as is shown in Fig. 5). The heat sink is built by extruding the cross-section developed in the x-direction. For the design case-study, the available design area in the yz-plane is 57mm×27mm.

The design area is divided into a 4×9 array of cells as shown in Fig. 5 where the size for each cell is 7mm×7mm.

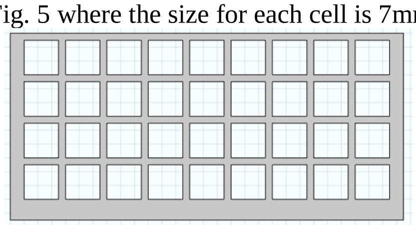

Fig. 5. Empty template of the heat sink cross-section

As shown in Fig. 6, nine possible types of cell patterns are considered in this version, numbered as 1-9. One of these patterns will fill each of the empty cells in Fig 5.

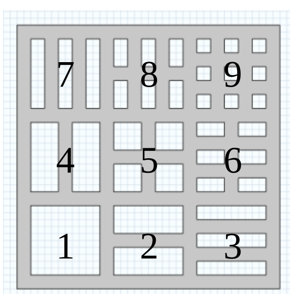

Fig. 6. Type of cell patterns

The individual cells of the heat sink in Fig 5 are initialized with a number indicating the cell pattern chosen. The 4×9 matrix of numbers is treated as a “cell distribution chromosome” in the GA. A solution space size around 10^{33} is created with this chromosome. A secondary smaller 3×9 matrix, named “wall-layout chromosome”, is created to determine the existence of the connected walls between any two vertical adjacent cells. Each entry in the matrix is 0 or 1, with 0 representing the absence of wall and 1 representing the converse case. The presence of a wall indicates separation of 2 adjacent cells. Design examples are presented in Fig. 7 for illustration. The case on the left is built by a wall-layout chromosome (0,0,0)’ applying on a cell distribution chromosome (7,4,6,7)’. And the right one presents the individual with chromosomes (7,7,7,6)’ and (0,1,0)’.

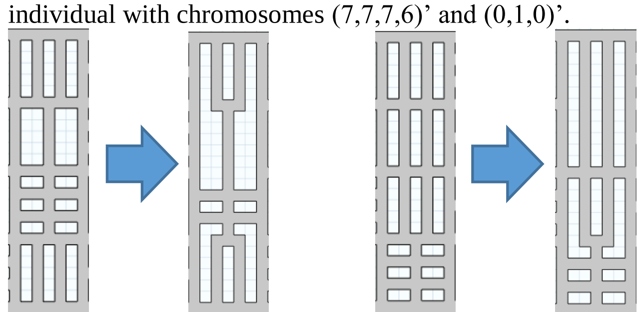

Fig. 7. Examples of “wall-layout chromosome”

Inclusion of the additional chromosome can generate greater variety with a larger solution space size around 10^{42}. The combination of two chromosomes forms the DNA of one individual. Each DNA in the population represents one heat sink cross-section geometry. A one-to-one mapping from DNAs to heat sink patterns is constructed based on this proposed method.

Two design cases are shown in Fig. 8 with two chromosomes each. The first one is a special case that allows the cell model heat sink representing a fin-shape heat sink. The second pattern is a random generated individual.

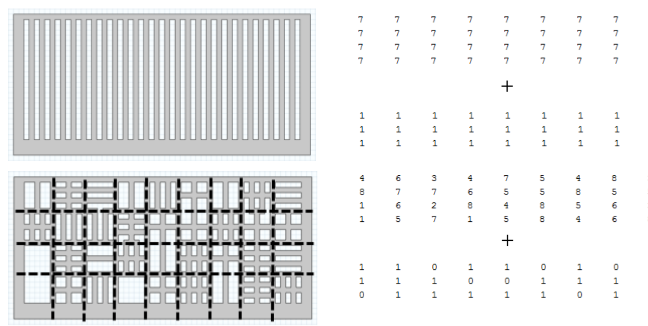

Fig. 8 Design examples of the cross-section pattern and corresponding DNA

Based on the designed cross-section, a heat sink block is created by extending the pattern to the third dimension, as shown by the red arrow in Fig. 9.

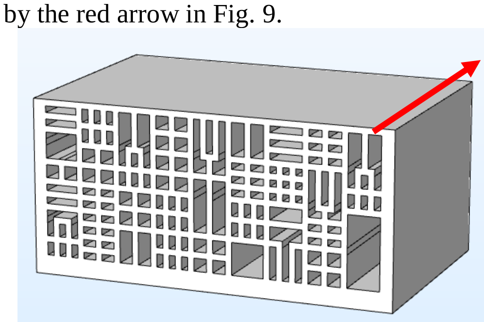

Fig. 9. Random created air-cooled heat sink in COMSOL

By assembling the heat sinks with the imported parts from SOLIDWORKS, the phase leg geometry, as shown in Fig. 3, is constructed in COMSOL. This approach creates the initial population for the GA.

- Evaluation

Temperature profiles of each individual in the population is evaluated based on FEA simulation using COMSOL. A coupled FEA stationary solver including heat transfer and flow dynamic is used. Settings of the model are described as follows:

The material for each domain is set by the default properties built in COMSOL, except the thermal conductivity of the 3D printed Aluminum which is set using the data in [11].

The physics parameters then are set, per the design spec and the data sheet. The initial temperature, ambient temperature and the inlet air temperature are all set to be 28.2°C. The loss of the inverter is estimated as 290W per phase leg. That is 27W loss for each MOSFET and 3.5W for each diode. Thermal interface material is applied between the DBC and the heat sink, with a thermal conductivity of 0.8 W/mK and a thickness of 100 μm. Outlet of the extraction fan is assigned based on the flow rate vs. pressure curve shown in Fig. 4 and the inlet is set to be free flow. The type of flow, either laminar or turbulence is determined based on the flow dynamic theory. Reynolds number of the system is calculated to be larger than 2000. Thus, it is necessary to use the weakly compressible turbulence flow.

After the physics setting, finite element mesh grids are built. To save the computation time, custom meshes are generated to achieve a higher computation speed without sacrificing the simulation accuracy, as shown in Fig. 10. The number of custom mesh elements is around five to ten times smaller than the default.

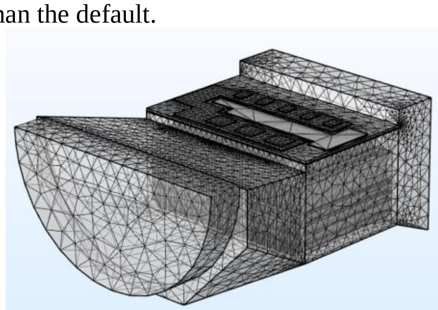

Fig. 10. Half of the geometry with a custom mesh grid

The computation time for each individual varies from 2 to 10 minutes by using a six-core workstation with 3.5 GHz processors and 40GB of RAM. Based on the temperature profile of the simulated result, the maximum junction temperature is reported back to the algorithm in MATLAB.

Previously mentioned steps can be represented by an evaluation function *E(X)=T* where *X* is the DNA (heat sink solution) of each individual and the output, *T* is the maximum junction temperature. For a population of 21 individuals, a list of 21 *T*s is Obtained.

- Selection

16 survivors of the population are picked based on their fitness score, five lowest scorers are eliminated. The fitness function is defined below.

$$f(i) = 1/\left(\frac{\alpha T}{T_{limit}} + \frac{(1-\alpha)R(i)}{21}\right) \tag{1}$$

Where T_{limit} is the maximum allowed junction temperature and $R(i)$ is the rank of the individual in the population. α is a weight factor changing with each iteration and it controls the rate of convergence. A higher fitness score means a lower maximum junction temperature and better performance; therefore, the chance of survivMal is higher. This selection follows the "survival of the fittest" rule. The division of the individual *i*'s fitness score over the sum of all the scores defines the survival possibility, *s(i)*, for that individual as shown in equation (2).

$$s(i) = \frac{f(i)}{\sum_{j=1}^{N} f(j)} \tag{2}$$

- Crossover and mutation

The 16 survivors in the mating pool are divided into eight couples. Each couple will go through crossover and produce two individuals to replace them in the next generation. Based on a pre-defined probability, the crossover can happen by randomly selecting and exchanging the values at each matrix position between the couples. If the crossover does not happen, the parents will remain and become the candidates in the next generation directly. Mutations may also occur during the crossover by changing an entry in the matrix representing the cell distribution DNA or the wall-layout DNA. The probability of mutation is a function of the rate of convergence. A higher probability enables the algorithm to reach a global minima, while a lower probability can increase the rate of convergence.

- Recombination

Besides the 16 offsprings from the previous generation, five more individuals are selected. Elitism operator is proposed here to make sure the best individual of the previous generation will always survive and be identically copied into the next generation. Additional four newly generated individuals are introduced. This is a migration operator to prevent the premature convergence of the system. The new population to be used in the next iteration of the GA will consist of the 16 new-born heat sink candidates that inherit genetic information from the parents' generation, four newly generated heat sink candidates, and one of the best heat sink candidates of the previous generation.

- Second-stage perturbation

After convergence of the genetic algorithm, heat sink candidates with the high fitness scores are picked as the optimization objects for the second stage. Cells in each heat sink are randomly selected and changed. The thickness of the wall and the position are modified as well to improve the fitness scores. After each iteration of the second-stage optimization, the heat sink candidates with the lowest fitness scores are replaced with the better ones and the process is repeated until the best result is obtained.

V. Case Study

For this case, after a computation time of in total 135 hours, the simulation results converge to the heat sink shown in Fig 11 with a maximum junction temperature of 106.29 °C.

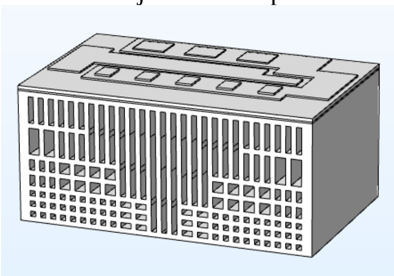

Fig. 11. The first stage optimized heat sink

Based on the results of the first stage, the second-stage optimized heat sink is developed. As shown in Fig. 12, the thickness of walls in the center decreases and other small modifications have implemented. As a result, a lower maximum junction temperature of 104.02 °C is achieved.

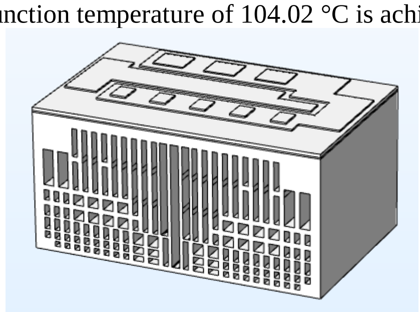

Fig. 12. The second stage optimized heat sink

Following the method described in Fig. 4, the flow rate of the fan is estimated around 42 cfm at the cross point. Fig. 13 shows temperature profile change in vertical direction.

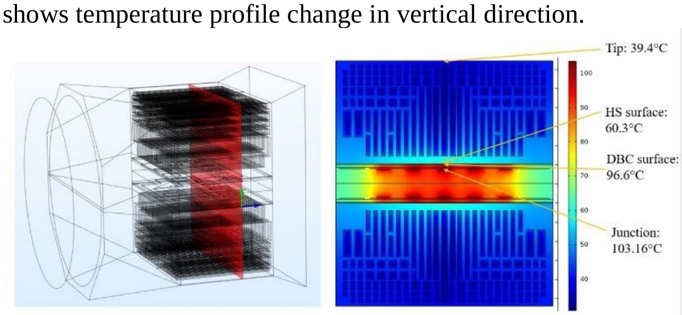

Fig. 13 Thermal profile plot of vertical cut plane

Based on the profile, a steady state thermal equivalent circuit (TEC) is derived as shown in Fig. 14. Values of each thermal resistance are listed as well.

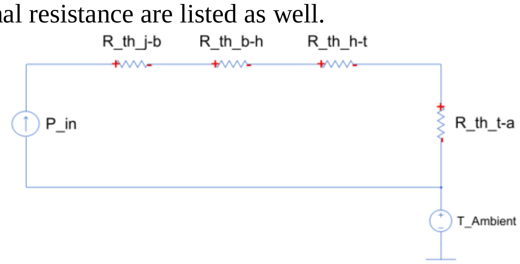

Fig. 14. Thermal Equivalent circuit

Thermal resistance value for each component can be calculated based on the temperature profile of the cut plane. The parameters of the TEC are listed in Table I.

TABLE I
Parameters of the TEC

Label	Description	Value
P_in	Total input power of power devices	290W
R_th_j-b	Junction to DBC surface TR	0.0226 °C/W
R_th_b-h	DBC surface to HS surface TR	0.125 °C/W
R_th_h-t	HS surface to Tip TR	0.0721 °C/W
R_th_t-a	Tip to Ambient TR	0.0386 °C/W
T_Ambient	Ambient temperature	28.2 °C

The temperature profile of each device is tested according to the horizontal cut plane in Fig. 15. The maximum junction temperature of the bare semiconductor die is 104.2°C, and the temperature variation among the MOSFETs is about 10%.

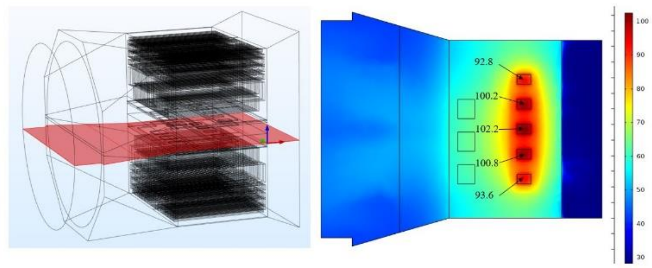

Fig. 15. Thermal profile plots of horizontal cut plane

VI. Experimental Verification

Fig. 16 shows the 3D printed heat sink compared to a penny. The overall volume of this 3D printed part is 36mm×57mm×27mm.

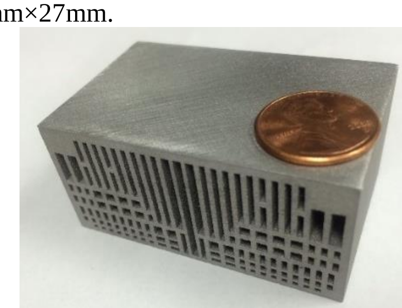

Fig. 16. 3D printed Aluminum air-cooled heat sink

The package of one switch is shown in Fig. 17. DBC is mounted on the ground surface of heat sink with a thermal grease layer placed in between. DC buses, wire-bonds, gate signal and other connections are assembled.

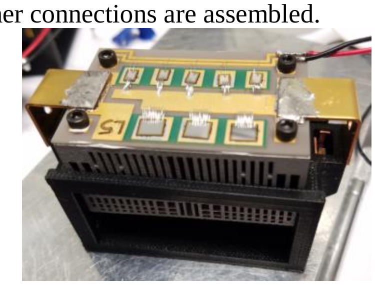

Fig. 17. 3D printed package of one switch position

A phase-leg module consisting of two switch packages, outside package for stress relief, mechanical support and air duct is designed and 3D printed correspondingly, as shown in Fig. 18.

Fig. 18. Phase leg module of air-cooled phase leg

The flow profile is measured at different locations in the outlet channel of the module. Those data are compared with the simulation flow profile. As shown in Fig. 19, the average output flow velocity for each location is obtained in COMSOL and compared with test data, as shown in Fig. 20.

Fig. 19 Simulated air flow profile

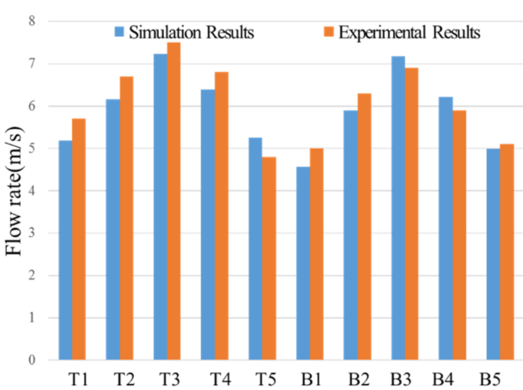

Fig. 20 Flow rate comparison

This comparison verifies the validation of the flow simulation. The average outlet flow velocity is 5.2 m/s.

Another thermal verification is carried out based on the energy balance equation, as shown in the equation below:

$$\int \rho \cdot A \cdot v \cdot Cp \cdot \Delta T \cdot dt = \int P \cdot dt \quad (3)$$

Where ρ is the density of the flow; A is the cross-section area of the flow channel; v is the average velocity of the flow; Cp is the heat capacity of the flow; ΔT is the average temperature rise between the inlet and outlet and P is the total power dissipation from devices.

All parameters in this equation are related to the air flow profile except for the temperature rise ΔT. The calculated average temperature rise of the outlet flow is 12.5°C. The experimental measurement shows an inlet temperature of 27.5°C, and an outlet temperature of 39.4°C on average. The temperature rise measured in the experiment is 11.9°C.

The actual junction temperature of the module then can be estimated based on the simulation results to be around 100°C. That is far below the maximum allowed operation temperature.

VII. Conclusion

In this paper, an algorithm is developed to optimize the design of heat sinks based on GA and FEA simulations. This algorithm provides means to automate heat sink designs in different applications. Compared to the existing design algorithms for the heat sink in literature, the proposed algorithm allows for a higher degree of freedom through inclusion of complex shapes.

VIII. Acknowlegegment

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