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Thermal Analysis of Heat Sinks with Metal 3 D Printer

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Master of Science in Mechanical Engineering, Texas A&M University, College Station, TX Grad: 08/2007

Bachelor of Science in Mechanical Engineering, Korea University, Seoul, Korea Grad: 02/2004

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WORK EXPERIENCE Texas A&M University Assistant Professor of Instruction College Station, TX 09/2017 – present

Texas A&M University Research Assistant Professor College Station, TX 09/2014 – 08/2017

Texas A&M University Technical Lab Manager College Station, TX 01/2014 – 08/2014 •Maintained lab equipments and supplies inventory at shared service facility in the department of Mechanical Engineering and provided technical support and training

Texas A&M University Instructor College Station, TX 06/2014 – 08/2014

A.O. Smith Corporation Technology Center Mechanical Engineering Intern Milwaukee, WI 05/2013 – 12/2013 •Evaluated efficiency improvement of thermoelectric devices in electric water heaters •Developed heat recovery modules based on heat pipe-heat exchanger

UW-Milwaukee Teaching Assistant and Lab Manager Milwaukee, WI 01/2012 – 05/2013 •Maintained lab equipments and developed methods of lab experimentation for mechanical experimentation class •Taught experimental methods for engineering problem solving and computerized programming environment based on LabVIEW

UW-Milwaukee Research Assistant Milwaukee, WI 08/2009 – 12/2011 •Nanomaterials synthesis and analysis using Raman spectroscopy, scanning electron microscopy, and X-ray diffraction •Developed nanomaterials for anode electrodes in lithium ion batteries and performed the electrochemical characteristics using electrochemical impedance spectroscopy and battery test equipments

Advanced Test Concepts (ATC), Inc Research Engineer Indianapolis, IN 03/2008 – 01/2009 •Led a product development team for new product development •Designed and conducted leak testing of various mechanical components for the seal integrity •Performed mechanical design for new products using SolidWorks •Designed experiments and conducted data acquisition measurement via a LabVIEW-based leak measurement system

Korean Army Helicopter dispatcher Chungnam, Korea 04/1999 – 06/2001 •Managed flight plans of 40 helicopters supervising 8 assistants •Analyzed and evaluated meteorological information for the safety of flight •Maintained no accidents for 2 years; elected best helicopter unit

TEACHING • MEEN 461, Heat Transfer • MEEN 464, Heat Transfer Laboratory • MEEN 345, Fluid Mechanics Laboratory • MEEN 401, Introduction to Mechanical Engineering Design Studio • MEEN 402, Intermediate Design Studio • MEEN 404, Engineering Laboratory Studio • MEEN 315, Principle of Thermodynamics

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PUBLICATIONS 1. H. Kim, X. Huang, I. Guo, S. Cui, Z. Wen, J. Chen, Novel hybrid Si film/highly branched graphene nanosheets for anode materials in lithium-ion batteries, Journal of Physics D: Applied Physics, 52(34), 2019 2. Y. G. Nam, M. Hummod, H. Kim, A.A Polycarpou, Electrode architecture of carbon-coated silicon nanowires through magnesiothermic reduction for lithium-ion batteries. MRS Communications, 7(4), 867-872, 2017 3. H. Kim, X. Huang, Z. Wen, S. Cui, X. Guo, J. Chen, Novel hybrid Si film/carbon nanofiber for anode materials in lithium-ion batteries. Journal of Materials Chemistry A., 2015 4. S. Ci, S. Mao, Y. Hou, S. Cui, H. Kim, R. Ren, Z. Wen, and J. Chen, Rational design of mesoporous NiFe-alloy-based hybrids for oxygen conversion electrocatalysis. Journal of Materials Chemistry A, 3(15), pp.7986-7993, 2015 5. H. Kim, X. Huang, X. Guo, Z. Wen, S. Cui, J. Chen, Novel hybrid carbon nanofiber/highly branched graphene nanosheet for anode materials in lithium-ion batteries. ACS Applied Materials Interfaces. 6(21), 18590-18596, 2014 6. Wen, Z., Lu, G., Cui, S., Kim, H., Ci, S., Jiang, J., Hurley, P. T., Chen, J. Rational design of carbon network cross-linked Si–SiC hollow nanosphere as anode of lithium-ion batteries. Nanoscale, 6(1), 342-351, 2014 7. K. H. Yu, G. H. Lu, Z. H. Wen, H. Kim, Y. Y. Qian, E. Andrew, S. Mao, and J. H. Chen, "Hierarchical Vertically-Oriented Graphene as a Catalytic Counter Electrode in Dye-Sensitized Solar Cells," Journal of Materials Chemistry. 1, 188-193, 2013 8. Wen, Z., Lu, G., Mao, S., H. Kim, Cui, S., Yu, K., Huang,X., Hurley,P, Mao,O., and Chen, J., "Silicon nanotube anode for lithium-ion batteries." Electrochemistry Communications, 29, 67-70. 2013 9. S. Mao, Z. H. Wen, H. Kim, G. H. Lu, P. Hurley, and J. H. Chen, "A General Approach to One-Pot Fabrication of Crumpled Graphene-Based Nanohybrids for Energy Applications," ACS Nano. 6(8), 7505-7513, 2012 10. Z. H. Wen, X. C. Wang, S. Mao, Z. Bo, H. Kim, S. M. Cui, G. H. Lu, X. L. Feng, and J. H. Chen, "Crumpled Nitrogen-Doped Graphene Nanosheets with Ultrahigh Pore Volume for High-performance Supercapacitor," Advanced Materials.24(41), 5610-5616, 2012 11. H. Kim, Z. H. Wen, K. H. Yu, O. Mao, and J. H. Chen, "Straightforward Fabrication of Highly Branched Graphene Nanosheet Array for Li-ion Battery Anode," Journal of Materials Chemistry. 22(31), 15514-15518, 2012 12. Bo, Z., Wen, Z., Kim, H., Lu, G., Yu, K., and Chen, J., "One-step fabrication and capacitive behavior of electrochemical double layer capacitor electrodes using vertically-oriented graphene directly grown on metal," Carbon, 50(12), 4379-4387, 2012. 13. Z. H. Wen, S. M. Cui, H. Kim, S. Mao, K. H. Yu, G. H. Lu, H. H. Pu, O. Mao, and J. H. Chen, "Binding Sn-Based Nanoparticles on Graphene as Anode of Lithium Ions Batteries," Journal of Materials Chemistry. 22(8), 3300-3306, 2012 14. K. H. Yu, G. H. Lu, K. H. Chen, S. Mao, H. Kim, and J. H. Chen, "Controllable Photoelectron Transfer in CdSe Nanocrystal-Carbon Nanotube Hybrid Structures," Nanoscale. 4(3), 742-746, 2012. 15. K. H. Yu, G. H. Lu, S. Mao, H. Kim, and J. H. Chen, "Selective Deposition of CdSe Nanoparticles on Reduced Graphene Oxide to Understand Photoinduced Charge Transfer in Hybrid Nanostructures," ACS Applied Materials & Interfaces. 3(7), 2703-2709, 2011 16. H. Peng, H. Kim, D. Luo, M. Marquez, Z. Cheng, "Low-frequency ac electro-flow-focusing microfluidic emulsification, " Applied Physics Letters. 96, 174103, 2010 17. H. Kim, D. Luo, D. Link, D. Weitz,M. Marquez, Z. Cheng, "Controlled production of emulsion drops using an electric field in a flow focusing microfluidic device,"Applied Physics Letters. 91,133106, 2007

Heat Transfer Laboratory:

Thermal Analysis of Heat Sinks with Metal 3 D Printer

Introduction

A heat sink is widely used in electronics and mechanical devices, to effectively transfer the thermal energy from the heated medium to the surroundings using an extended surface. The thermal analysis of fins is one of the most important subject matters, coupling conduction and convection problems in heat transfer course. A very few publications have been reported on the design of heat sinks for laboratory class, focusing on the machining process [1], [2]. This paper serves as a guideline for the heat sinks experiment using a 3D metal printer for the undergraduate heat transfer laboratory course. The laboratory described here does not follow the typical laboratory format in the sense that it does not provide step-by-step instructions of laboratory procedures, equipment operation, or data analysis technique.

A heat transfer laboratory on performing thermal analysis of heat sinks was designed. Students developed an experimental plan on how to proceed the experiment for achieving the thermal analysis of heat sinks. The materials and equipment for the experiment were provided including a selection of heat sinks made using metal 3 D printers, heat source simulators, temperature measuring devices, and wind tunnels. From this laboratory, students reinforced problem-solving skills and applied the knowledge in heat transfer to the real-world problems. Furthermore, they learned to choose or design heat sinks that meet the cooling requirements for a particular application. Students are given the following project statement to accomplish the laboratory.

Project Statement

A common failure mode of electronics is overheating. Generally, this is caused by the lack of adequate cooling and improper layout of components. One effective and common method of cooling electronic devices is the use of heat sinks. A heat sink is a device to promote the heat transfer from one medium to another using extended surfaces. Heat from the electronics is absorbed and transmitted to the heat sink fins, which are cooled by natural or forced convection. The performance of heat sinks is often presented as a plot of thermal resistance of the heat sinks versus a variable airflow. From this information, engineers are able to choose heat sinks that meet the cooling requirements for a particular application. The objective of this project is to evaluate a heat sink which is cooled by natural convection and forced convection. Consider a device (aluminum block of 1.75″ by 1.75″) dissipating 20 W. The device must be maintained at 45 °C or less to prevent failure. A set of heat sinks will be provided. You will choose a heat sink with the desired size, geometry, the number of fins and material. The thermal performance test will be conducted in a wind tunnel. A cartridge heater is inserted into the aluminum block to simulate a heated device. The power supplied to the cartridge heater is measured with the watt meter. Attach thermocouples at the desired location of the heat sink. Mount the heat sink to the aluminum block. This laboratory requires you to write a report that includes the following results: (1) discuss about the feasibility of using the heat sink without a fan; (2) determine the minimum velocity of the air by the windtunnel to avoid overheating of the device; (3) provide a plot of thermal resistance of the heat sink in function of wind velocity; and (4) suggest a way to further optimize the heat sink taking into consideration the main constraints to the design of the heat sinks which are cost and size.

Materials

- Heat sinks built using metal 3D printer
- Heat source or aluminum block with cartridge heater insert, simulating a processor
- Cartridge heater
- Power Supply
- Watt meter
- Thermocouples for flat surface contact and bead type thermocouples
- Aluminum tape for thermocouple attachment
- LabVIEW based Data Acquisition Device (DAQ)
- Thermal interface material (TIM)
- Heat sink mounting hardware
- Windtunnel

Experimental Method

Students were asked to develop the experimental methods. The following is the representative experimental procedure developed by students. Stainless steel heat sinks were produced with metal 3D printer (Desktop Metal®) as shown in Fig. 1(a). A cartridge heater was inserted to an aluminum block to simulate an electronic device, dissipating heat at a constant rate. The power supplied to the heater was measured by the watt meter. The top surface of the block was coated with a very thin layer of thermal compound to minimize the thermal contact resistance between the heat sink and simulator. A flat surface-thermocouples was placed on the top side of the block. Subsequently, a heat sink was mounted on the top of the block and fastened with a custom designed clamp to ensure good contact at the interface and secure the heat sink against the wind. The assembly was installed inside the windtunnel and additional thermocouples were placed on the side surfaces of the aluminum block, which were then insulated with foam insulation tape to ensure that heat is mainly conducted to the heat sink. The complete assembly before installing the thermocouples is shown in Fig. 1(b). Thermocouples were connected to NI-9213 cDAQ (National Instruments™) based on LabVIEW for data recording. The power to the heater was set at 20 W. The initial test was conducted with no forced air. If the temperature of the aluminum block exceeded 45 ℃, the device was considered damaged due to overheating. Subsequently, the heat sinks under forced convection was conducted. The temperatures were monitored at various wind velocities to determine the minimum required wind velocity, preventing the overheating. The wind velocity was measured using a pitot tube.

Thermal Analysis

The following includes the representative data and analysis of a plate heat sink conducted by students. First, the temperature response of the aluminum block was monitored under natural convection to determine if it is feasible to use the heat sink without force convection. The heater was turned on and kept at constant power of 20 W. After a short period of the temperature measurement, students confirmed that the temperature of the simulator exceeded the maximum allowable temperature of 45 ℃ threshold at which it operates without failure. The convection heat transfer coefficient, h under natural convection was not high enough to prevent the overheating. Therefore, it implied that the heat sink alone was not capable of preventing overheating under natural convection and it should be used under forced convection.

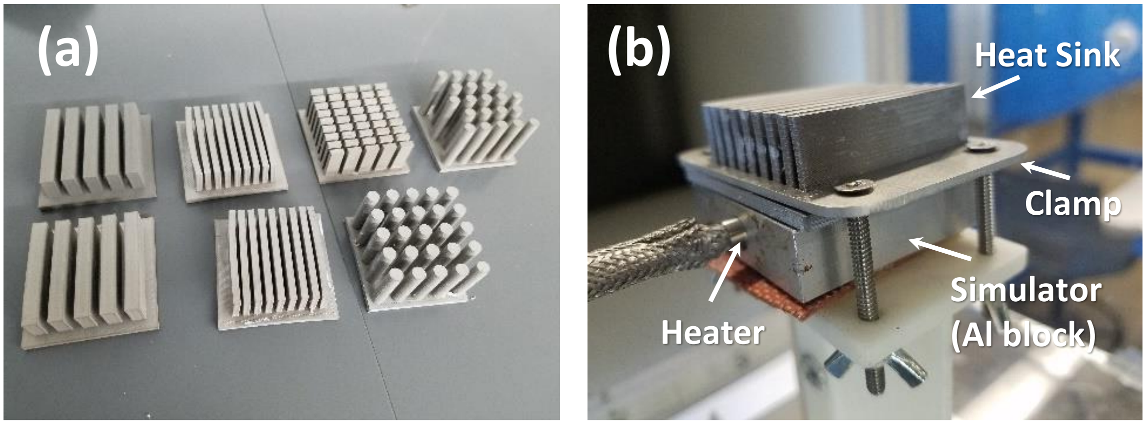

Figure 1. (a) A selection of heat sinks produced using metal 3D printer. All units are made of stainless steel and have the same mass, but different fin configurations. (b) Experimental set-up of heat sink assembly. After installing the thermocouples, the side of the simulator were insulated with foam insulation tape (not shown in the image).

A thermal resistance model of the simulator-heat sink system can be constructed as shown in Fig. 2. Under steady-state condition, the thermal resistance of the simulator-heat sink system is calculated using the following equation [3]:

$$R_{heat\ sink} = \frac{T_S - T_\infty}{q} \qquad \text{Eq. (1)}$$

, where T_S is the average surface temperature of the simulator, T_∞ is the air temperature in the test section and q is the power supplied to the heater. The heat transfer problem is simplified as one-dimensional heat conduction that is normal to the wind direction. Additionally, the temperature at the base of the heat sink is assumed to be the same as the temperature of the simulator for simplicity. That is, the thermal resistance of the thermal interface material is neglected.

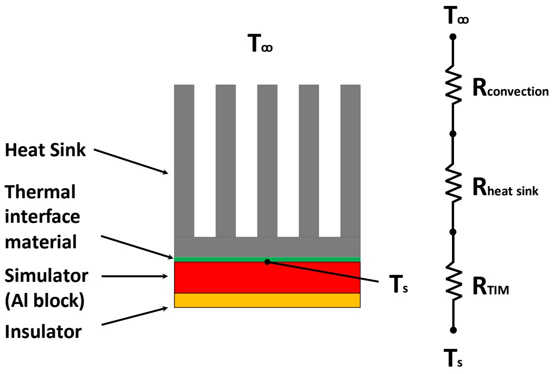

Figure 2. Thermal resistance network of heat sink assembly.

The steady state temperature of the simulator was measured at various wind velocities as shown in Table 1 to determine the minimum required wind velocity to avoid damaging the simulator. In Fig. 3, it was determined that the temperature of the simulator remained below 45 °C when the wind velocity was about 7 m/s or higher. The thermal resistance of the heat sinks decreased as the wind velocity increased. It was noted that the thermal resistance of the heat sinks in Equation (1) includes the thermal resistance by convection, which was supported by the observation of decreasing $R_{heat\ sink}$ with increasing wind velocity.

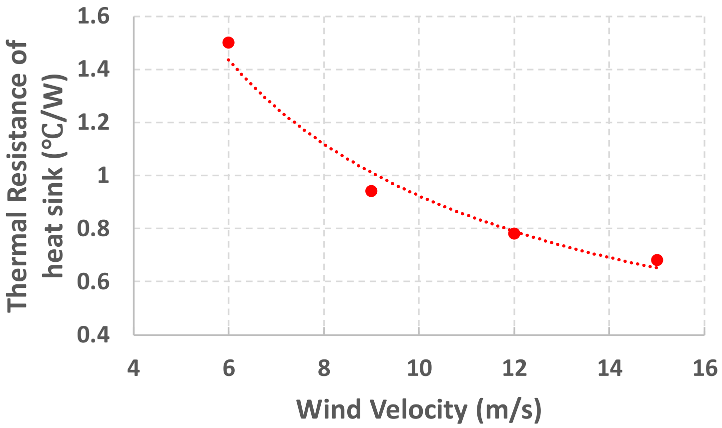

Figure 3. Thermal resistance of a heat sink at various wind velocity

Wind velocity (m/s)	Simulator Temperature (℃)	Overheating?	Resistance (℃/W)
0	> 50	Yes	N/A
6	48.0	Yes	1.50
9	36.8	No	0.94
12	33.6	No	0.78
15	31.7	No	0.68

Table 1. steady-state temperature and thermal resistance of the simulator at various wind velocities.

Students discussed about further optimizations of heat sinks by using a heat sink material with higher thermal conductivity, forming staggered fins using a larger number of fins, and fabricating a slender fin geometry. In addition, they suggested to use a TIM with higher thermal conductivity, polish the base of the heat sinks, and press the heat sinks against the simulator with clamps for smaller thermal contact resistances.

Conclusions

The experiment on the thermal performance of heat sinks made using metal 3D printer enabled students to learn to define the problem, construct a hypothesis and experimental procedure, and evaluate the thermal performance of heat sinks. Students successfully demonstrated the ability to select and build heat sinks that meet the cooling requirements for a particular application.

Future Works

The main learning outcomes of this experiment include knowledge of scientific and experimental concepts, correct use of instruments, data analysis skills, experimental design and technical writing skills. These learning outcomes will be assessed through laboratory reports. In addition, students' satisfaction and engagement will be assessed using the course evaluation form.
To assess the impact of the experiment on students' learning, I will conduct a randomized controlled trial. The sessions will be randomly assigned to a treatment condition and a control condition. In the treatment condition, students are required to complete the experiment per this paper. In the control condition, students will participate in the traditional heat sink experiment without designing components.

The laboratory can be further expanded to a design-oriented experiment: students may design and build their own heat sink using a metal 3 D printer. The design parameters of a heat sink include the size, geometry, material, number of fins and fin arrangement. They have to provide justifications for their design decisions with analytical methods. The main constraints to the design of heat sinks are size and material cost. Taking one step further, heat sinks may be built in conjunction with heat pipes and integrated fan. Students need to develop an experimental plan on how to proceed the experiment. The results of thermal performance of students' heat sinks can be compared to determine the optimal design of heat sinks.

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