

## **Development of a Laboratory Curriculum Devoted to the Thermal Management of Electronics**

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### **Introduction**

Effective cooling of electronics has emerged as a challenging and constraining problem of the new 21<sup>st</sup> century. The economic market demands ever faster computer clock speeds while at the same time smaller physical enclosures. Computers, cell phones, and even automotive electronic systems are becoming smaller and smaller. Since computer chip heat fluxes (the rate of heat transfer per unit area) increase with increasing clock speeds and decreasing chip sizes, these demands have led to skyrocketing heat flux removal demands. At the same time, current technology allows a maximum junction (chip surface) temperature typically of no more than 125° C<sup>1</sup> – a value that continues to decrease. Above this maximum temperature, the life of the chip decreases in length significantly. The challenges posed by ever-increasing chip heat fluxes, smaller enclosures, and stricter performance and reliability standards have made thermal management of electronics a key technology in the continued development of 21<sup>st</sup> century microelectronic systems<sup>2</sup>. Indeed, thermal management of systems that will most likely be developed in the next several years cannot be done with the current state of technology<sup>3</sup>.

In the early 1960's, heat removal rates ranged typically from 0.1 to 0.3 W<sup>2</sup>. The Semiconductor Industry Association estimates that rates for 3.5 GHz chips used in servers and workstations will reach 160W in 2006<sup>4</sup>. Air cooling is the most common technique used to cool electronics. Innovative air cooling techniques allowed heat dissipation rates of 60-70 W by the late 1990s<sup>2</sup>. However, the point has been reached when many industries have had to look to high-capacity cooling technologies rather than air cooling. One high-capacity cooling technology, liquid cooling, has been used for many years by such companies as Cray (using immersion in liquid nitrogen) and IBM and Honeywell (in their water-cooled mainframes). Technologies receiving a lot of interest include liquid cooling using microchannel heat exchangers or microchannels etched into silicon, heat pipes (already used heavily in laptops and many non-electronics applications) and thermo-electric devices. Whatever the methodology, cooling must be a part of an integrated, chip-to-system design<sup>1</sup>.

Who will perform this research and develop these new designs? While undergraduate mechanical engineering curricula include a class on heat transfer, the cooling of electronics typically receives little or no attention. Most industrial work in this area is performed by engineers with advanced degrees and significant training on-the-job. Some universities (such as Stanford and Maryland) offer classes on electronics cooling at the graduate level. Only a few universities (such as San Jose State, Purdue, Minnesota, and UC Berkeley), offer classes specifically devoted to thermal

management of electronics for undergraduates or jointly for graduate and undergraduate students. Fewer still have a laboratory devoted to thermal management of electronics at the undergraduate level.

The need for engineers equipped to handle electronics cooling problems is especially significant in the Silicon Valley where San Jose State University is located. This need will only increase as industries look to these engineers to provide them with innovative cooling mechanisms. Therefore, a laboratory curriculum devoted to the thermal management of electronics that will be used exclusively at the undergraduate level is under development with funding from the National Science Foundation. This curriculum will provide students with an understanding of current and emerging cooling technologies and appropriate experimental methods. It will have two main aspects. First, a laboratory is being developed that will be used in four classes taken by mechanical, electrical, and computer engineering students. Second, a new senior-level elective open to these students will be developed. This elective will focus on an overview of the problem, air-cooling technologies, computational design methodologies, Jedec standards, and emerging technologies, including cooling of nano-scale devices. It will include both lecture and a significant laboratory component.

The laboratory, once completed, will include six experiments plus computational capabilities. Experiments will focus on 1) temperature measurement methods, including uncertainty, 2) chassis impedance and fan performance, 3) thermal resistance measurements in an air-cooled computer, 4) heat transfer coefficient determination using liquid crystal thermography, 5) liquid cooling using microchannel heat exchangers, and 6) heat pipes. These experiments and commercial computational fluid dynamics (CFD) capabilities will provide students with a broad overview of techniques and technologies used in industry. These experiments and capabilities will be described below, followed by sections describing the new elective and how the experiments will be incorporated into both the new and existing classes.

## **1. Temperature Measurement**

Engineers working in the thermal area must have a good understanding of how to take accurate temperature measurements and their uncertainty. Heat transfer classes typically focus on the theory, and students are left to learn experimental methodologies on-the-job. Unfortunately, this practice leaves many engineers with an inadequate understanding experiment design and data interpretation. The laboratory session will provide an overview of temperature measurement, how to calibrate temperature measurement devices, and how to calculate temperature measurement uncertainty and to estimate its value for different devices.

The lecture before this laboratory session will include a discussion of the performance of common temperature measurement devices including thermocouples, RTDs (resistance temperature devices), and thermistors, including their uncertainty. In the lab experiment, students will calibrate two different thermocouples using a constant temperature bath. One thermocouple will be connected to a National Instruments data acquisition system with a terminal block that includes an isothermal block as a reference junction. The other thermocouple will be connected to a voltmeter and will use an ice-point reference junction. Students will develop calibration curves and calculate both bias (fixed) and precision (random) errors in their temperature

measurements. The magnitude of the random error can be defined using a 95% confidence interval for the temperature readings at a given temperature (approximately forty readings will be taken for this calculation).

## **2. Chassis Impedance and Fan Curves**

Since most systems are currently cooled using air, it is important that students understand the relationship between fan performance, chassis impedance, and system thermal performance. Students must be able to read fan curves and understand how their chassis impedance will affect the rate of air flow. The second proposed experiment, therefore, involves the measurement of system impedance and fan volumetric flow rates over a wide air flow range using an AMCA 210-99 Airflow Test Chamber from Airflow Measurement Systems. Several chassis for a variety of applications will be acquired from manufacturers for this experiment.

## **3. Thermal Resistance Measurements in a Computer**

One of the most basic experiments in electronics cooling is the measurement of one-dimensional thermal resistances in a computer. Electronic packages are typically rated in terms of their thermal resistance, maximum allowable junction (chip surface), and power dissipation. In this first experiment students will measure junction, case, and air temperatures for a known power dissipation.

A thermal test chip (containing heating resistors and diode temperature sensors) will be acquired. (Another possibility is to use a typical computer chip and treat it as a diode-- see JEDEC standard JESD51-1 and/or MilStd 750 Method 3101.) A heat sink will be placed on the case to aid in heat transfer. The case and air temperatures will be measured using thermocouples. With an estimate of heat conducted through the package leads to the printed circuit board and an estimate of contact resistance between the chip and heat sink, the students can use the measured temperatures to find the total value of resistance to heat flow from the chip to the air as well as the junction-to-case resistance. They will compare these values to theoretical values calculated analytically and the manufacturer-specified junction-to-case resistance. The students will perform this experiment for four different cases: 1) no fans (natural convection), 2) two fans in series, 3) two fans in parallel, 4) two fans in series with high impedance (extra circuit boards added to cause a larger pressure drop through the case). With fan and chassis impedance curves provided, the students can also determine the effect of air flow rate on thermal performance. Three systems will be constructed to allow students to work in groups of four or less. In a more advanced version of this experiment, students will examine the effect of heat sink geometry on heat removal rates.

## **4. Liquid Crystal Thermography System**

Development of accurate heat transfer coefficients is of primary importance in making accurate heat transfer predictions. Liquid crystal thermography (LCT) has emerged as an effective method to acquire a detailed temperature map from which local and average heat transfer coefficients can be determined. LCT has the advantages of allowing extremely high spatial resolution and good accuracy in addition to being non-invasive. LCT is applied using either a steady-state or transient

method. An overview of this method can be found in Baughn<sup>5</sup>. The steady-state method requires the application of a constant surface heat flux to the object, usually applied through a foil heater or more recently through radiant heating. Knowing  $q''$  (the surface heat flux), the heat transfer coefficient can be found using  $h = q'' / (T_{\text{surface}} - T_{\infty})$ . This method has been applied in a variety of applications including turbine blades<sup>6</sup>, impinging jets<sup>7</sup>, pin fins<sup>8</sup>, and channel flow with diamond-shaped elements<sup>9</sup>. Several institutions have used LCT at the undergraduate level. The author has used a modification of transient LCT in an NSF RUI project at Baylor University. A. Anderson developed an LCT system at Union College for undergraduate heat transfer instruction through an NSF ILI Grant. She uses the system in two lab exercises that focus on temperature measurement techniques and the effects of thermal wakes on downstream components in an array of electronic components. She reports an increased student interest in heat transfer and a better understanding of temperature measurement methods<sup>10</sup>.

In the experiments to be developed for this laboratory, students will use the steady-state method to determine local heat transfer coefficients for several geometries. A gold foil and power supply will be used to heat the surfaces that will be placed in a wind tunnel. The images will be recorded using a color video camera, and image processing will be performed using a Matlab Liquid Crystal Image Processing Toolbox developed at the Air Force Academy<sup>11</sup>.

In the existing undergraduate heat transfer class ME 114, students will examine flow over a flat plate under laminar, turbulent, and mixed flow regimes and will compare their results to the expected analytical results. In the second experiment, to be used in the new elective, shapes similar in geometry to computer chips will be placed on the flat plate, and the students will look at the effect of the wakes on the heat transfer from the surfaces to which they are attached. This experiment will be used as a demonstration in the electronics cooling class taken by electrical and computer engineering students. Through these experiments, students will learn about flat plate heat transfer and the effect of surface geometry on heat transfer including recirculation zones and reattachment. They also will gain a better understanding of experimental methods, image analysis, and calibration.

## **5. Microchannel Heat Transfer**

Microchannel heat exchangers have become increasingly popular for situations where fans and heat sinks cannot provide sufficient heat removal. Microchannels are tiny channels (from several micrometers up to a few millimeters, depending on the application) through which liquid flows, removing many times more heat than larger channels. As the trend towards miniaturization continues, they will become more and more important. Palm<sup>12</sup> has published a review of the microchannel research to date.

In this experiment, students will determine heat transfer coefficients in microchannel heat exchangers and compare them to theory. An open-loop cycle consisting of two tanks, a pump, and a microchannel heat exchanger is being used to analyze the performance of the microchannel heat exchanger. The working fluid is water. The channels in this experiment range from 0.2 to 0.4 mm. A resistance heater provides a known heat flux  $q''$ . The fluid temperatures at the inlet and exit of the microchannels are measured. The microchannel surface temperature is determined using small thermocouples placed in holes that allow the thermocouple to be placed just above

the inside surface of the microchannel. (The thermocouples cannot be placed on the actual surface because they would impede flow.) The actual surface temperature can be determined from the measured temperature just above the surface by using Fourier's law of conduction in one dimension,  $q'' = k (T_{measured} - T_{surface}) / L$  where  $q''$ ,  $k$ , and  $L$  (the distance from the small thermocouple to the surface) are all known. The fluid temperature at a given location can be found using  $T_{fluid}(x) = T_{inlet} + (q'' P / \dot{m} c_p) x$ , where  $P$  the outside perimeter of the entire microchannel,  $\dot{m}$  the mass flow rate of the fluid,  $c_p$  the specific heat of the fluid, and  $x$  the distance from the microchannel inlet. After the fluid temperature at a given location has been determined, heat transfer coefficients can be calculated using  $h(x) = q'' / (T_{surface} - T_{fluid}(x))$ .

Once the students determine experimental values of  $h$ , they will compare them with classical theory to determine if classical theory is valid even in these very small diameters and to determine the effect of experimental uncertainty on results.

## **6. Heat Pipes**

In recent years, heat pipes have arisen as a popular method of heat removal in electronics for cases where high heat fluxes or confined spaces make air cooling difficult (see for example references 13, 14, 15, 16). The two experiments under development will introduce students to how heat pipes work and the high heat removal rates that they can effect. In the first experiment, the evaporator section of a cylindrical heat pipe will be placed in hot water, and the condenser section will be placed in a wind tunnel. The section in between the water tank and the wind tunnel will be well insulated. Thermocouples will be used to measure the air and condenser surface temperatures in several locations. Using Nusselt number correlations for external flow over a cylinder and the measured temperatures, the heat removal rate can be measured. A copper rod of similar dimensions will be examined in the same way so that students can compare the heat pipe performance to the copper rod. Students will then examine a real application of heat pipes. An old laptop that includes a heat pipe will be acquired and instrumented so that students can measure the thermal performance in an actual system. Both experiments will be included in the same lab period as two different stations. Having different stations will give students an understanding of both how heat pipes work and how they are used in application and will also keep the number of students per experiment low.

## **7. Computational Analysis**

Computational modeling is becoming more and more important as a design tool. Most companies involved with electronic packaging employ a commercial computer package to assist in system design. No education into electronics cooling will be complete without an introduction to one of more of these packages along with a discussion of their strengths and weaknesses and associated uncertainty. Therefore, Flotherm, one of the predominant electronics cooling CFD (computational fluid dynamics) packages will be introduced to the students in the undergraduate heat transfer class with greater coverage in the new elective. Flotherm has been placed on all of the computers in the main computer laboratory. A high-speed computer has also purchased so students can perform independent study and senior design projects that use this package. Larger models can take over a day to converge, so it is important to have dedicated computers for this purpose.

### **New Elective: Thermal Management of Electronics Laboratory**

In the third year of the grant period, a new senior-level elective will be instituted. This elective will be open to mechanical and aerospace engineering students who have completed the undergraduate heat transfer class ME 114 and electrical and computer engineering students who have completed the electronics cooling course ME/CHE 109. It will cover an overview of the problem, air cooling, computer modeling, fundamental convection issues, Jedec standards, and emerging technologies (see Table 1). It will include two hours lecture and three hours lab per week. This course will provide students with a comprehensive understanding of the cooling of electronics as well as experimental methods. The students completing this class will be uniquely situated to begin jobs in thermal management in a variety of Silicon Valley industries.

The emerging technologies will include a two-week segment on nano-scale heat transfer. In a recent textbook published on MEMS design and manufacture<sup>17</sup>, T. R. Hsu outlined the fundamentals of thermofluid analyses in sub-micrometer, or nano scales. The transmission of thermal energy in solids at the nano scale is dominated by the “mean free path” (MFP) and the “Mean free time” (MFT) associated with the traveling energy-carrying quanta in the solid. The quanta that contain thermal energy varies with materials, for example, phonons for dielectric and

Table 1 An overview of the lecture topics and laboratory experiments to be included in the new elective

General Category	Lecture Topics	Experiments	Time
Introduction	1. Overview of the industry and the thermal management problem	None	1 Week
Air Cooling	1. Fan performance and its effect on the system 2. Air cooling with heat sinks	1. Development of fan and chassis impedance curves 2. Measurement of 1-D thermal resistance	3 Weeks
Jedec Standards	1. Jedec Standards	See #2 above.	1 Week
Computer Methods	1. Accurate development of CFD models and analysis of results	1. Flotherm tutorial and project	2 Weeks
Fundamental Convection Issues	1. Effect of geometry and turbulence intensity on heat transfer coefficients	1. Use of liquid crystal thermography to measure $h$ in wakes of bluff bodies	2 Weeks
Emerging Technologies	1. Heat Pipes 2. Liquid Cooling 3. Thermo-electric cooling 4. Vapor-compression systems 5. Nano-scale heat transfer	1. Measurement of heat pipe performance 2. Measurement of heat transfer coefficients in microchannels over a range of Reynolds numbers 3. Tour of UC Berkeley's micro- and nano-scale property measurement lab (Dr. Majumdar)	6 Weeks

semiconducting materials and electrons for metals. Consequently, there is no possibility for a “steady state” thermofluid condition in any substance at the nano scale. The convective heat transfer that is required in the design and analysis of gas cooling of nano electronics systems must include the “rarefied gas dynamics” as the principal modeling tool. Furthermore, all pertinent thermo-physical properties are size-dependent in the sub-micrometer and nano scales, which further complicates the analysis. This fundamentally different thermofluid behavior for the cooling analysis for nano electronic systems will be introduced in this elective course with examples and illustrations as well as visitation of laboratories that are engaged in the measurements of thermophysical properties of materials at these scales. It is hoped that the introduction of these new concepts of nano electronic cooling in this course will stimulate student’s interest, and thus their motivation in further studies on this pertinent subject in follow-up courses and research at a graduate school.

### **Expected Outcomes**

Once this work has been implemented, all students graduating with a Mechanical Engineering Degree from SJSU will have an understanding of what the basic issues in the thermal management of electronics are as well as how to design and test a simple electronics cooling system. The students taking the new elective – as well as ME 145 Electronic Packaging and Design -- will enter the work force much more prepared to work on electronics cooling and packaging than their fellow graduates from other universities.

### **Evaluation Plan**

Once these new laboratory experiments have been developed, his laboratory curriculum will be evaluated through an analysis of the undergraduate heat transfer class ME 114 and the new elective. In the fall of the third year of the grant, the students in one lecture section of ME 114 will be randomly placed in five laboratory sections of 15 students each. Two sections will include the current group of four experiments and one computer project, and the other three will include three or four of the new experiments. A pre- and post-test will be given to the students at the beginning and end of the semester to gauge changes in student interest in heat transfer, their views that theoretical solutions model reality, and their interest in pursuing future classes or work in the area of electronics cooling. Scores of exam problems related to the lecture material covered by the lab experiments will also be compared. While all students will receive the same lecture material and should be able to complete all exam problems, the different lab groups will supplement different sets of information. If the lab experiments are increasing student understanding of heat transfer on the topics they cover, a statistical difference should be clear. A T-test will be performed to analyze both the pre- and post-test results and the exam scores to determine statistical significance.

Also in the third year, similar pre- and post-tests will be developed for the new elective to determine the effect that the class has on likeliness to pursue a career in thermal management of electronics and knowledge of basic electronics cooling subjects. The syllabus for the course will be sent to members of industry for their review and suggestions. All results for both ME 114 and the elective will be used to suggest and implement course improvements. These changes will be incorporated in the two semesters following the evaluations.

## **For More Information**

If you are interested in thermal management of electronics curricula and would like to trade information about lab experiments, projects, and course syllabi, please email Nicole Okamoto at [ndejong@email.sjsu.edu](mailto:ndejong@email.sjsu.edu) or telephone her at 408-924-4054. Compiled information will be placed on the project website at [http://enr.sjsu.edu/ndejong/Electronics\\_Cooling.htm](http://enr.sjsu.edu/ndejong/Electronics_Cooling.htm) for any to use.

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