VERSATILE DESKTOP EXPERIMENT MODULE (DEMo) ON HEAT TRANSFER

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The junior-level Heat Transfer class is the first course in conduction in 1-D and 2-D systems (Cartesian, cylindrical, and spherical coordinates); conduction through composite walls; evaluation of resistances; heat transfer enhancement using fins; convective heat transfer (laminar and turbulent flow, flow past immersed bodies and tube banks); overall heat transfer coefficient; and heat exchanger design. The current text for this course is Incropera and DeWitt's *Fundamentals of Heat and Mass Transfer*.[1] It should be noted that this work was first presented and published in the 2009 ASEE conference proceedings as paper # AC 2009-1609.[2]

The main course objective is to provide junior-level undergraduate students with fundamental knowledge of heat transfer in chemical engineering processes and process equipment. Special emphasis is given to the economics of heat exchanger design and heat recovery.

It is assumed that students entering the class are proficient in:

- *Manipulating units in their solitary form or with Δchanges such as ΔT,*
- *Performing mass and energy balances,*
- *Drawing flow profiles and calculating flow in rectangular and cylindrical geometries, and*
- *Physically interpreting a derivative and solving linear ordinary differential equations.*

Throughout the course, students learn and demonstrate the tools, skills, and knowledge to:

- *Distinguish between and apply mathematical models for the three mechanisms of heat flow (conduction, convection, and radiation).*
- *Draw temperature profiles and describe heat flow given system geometry, medium, and direction of temperature gradients.*
- *Calculate rates of heat transfer and analyze data to determine heat flow in various geometries, in media, and in common heat exchangers.*
- *Identity types of heat exchangers, evaluate heat transfer efficiencies, and size and select heat exchangers for specific applications.*

Desktop Experiment Modules (DEMos) can augment understanding at multiple points in the Heat Transfer course. They are versatile, inexpensive, and portable experiments positioned on student desks throughout a classroom. They are superior to instructor-led demonstrations because:

1) *each student can closely examine and manipulate the apparatus,*
2) *student teams can progress through experiment discovery at their own learning pace, and*
3) *all learning styles are stimulated to maximize understanding of important fundamental concepts.*

The DEMo approach has been successfully implemented with two previous DEMo experiments in an Introduction to Chemical Engineering course. The experiments were Charged Up on Electrophoresis and Brewing with Bioreactors, and were disseminated via ASEE *Proceedings* publications and a website resource.[3-5] Other chemical engineering programs have adopted these experiments.[6] Since these hands-on ex-

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periences do not require dedicated lab space, students have a simple yet unique experience to link into their evolving understanding of chemical engineering principles. As a result, these learning tools also serve as vibrant, hands-on experiments with high school students.

This latest Desktop Experiment Module focuses on demonstrating heat transfer concepts. The DEMo is versatile so that it can be incorporated into any existing chemical engineering Heat Transfer course as either a quick, illustrative example during a traditional lecture or as a mini experiment to demonstrate conduction through various materials or convection. While there is latitude in the equipment purchased for these DEMos, if an IR surface thermometer is purchased, it serves as an illustrative example of radiative heat transfer as well.

Advantages of this hands-on experience include that it is not dependent on the availability of lab space and that students have a unique experience to link into their evolving understanding of chemical engineering heat transfer concepts. An instructor can chose to focus on one or more of the following topics when they adapt this experiment: 1-D steady-state conduction, composite systems, contact resistance, thermal energy generation, heat diffusion equation and boundary conditions, fins, convective heat transfer, and many other applications. Coupling the demonstrations with exercise problems in which students must look up properties, assess thicknesses of materials, etc., also adds practical grounding to homework assignments. Course materials including a supply list, example exercises, and experimental procedures are discussed and are available for instructor use via a website.[5]

DESKTOP EXPERIMENT MODULE

A supply list is provided first such that the materials referenced below are familiar to the reader.

Supplies and Setting Up

These supplies will need to be ordered some time in advance. Total cost for 10 stations is about $650.

For each team of students (~2 students per team):

- *Coffee cup warmer [any brand is fine, but avoid high edges around the hot plate. Mr. Coffee brand is ~$10]*
- *CPU passive heat sink with fan [example is Thermaltake P4 Spark II CPU Cooler for Socket 478 (Item #: 6634928, Mfr. Part#: A1584) ~$7]*
- *CPU passive heat sink without a fan (no forced convection) [Example is Northbridge Chipset Passive Heat Sink (Item #: 7037826, Mfr. Part#: ZM- NB32K) ~$3]*
- *Silicone-base heat sink compound [RadioShack has this or Dow sometimes offers samples, ~$3]*
- *Rods of aluminum, copper, steel [1.5 inches in diameter, cut to 1 inch sections, Example is Speedy Metals Online, <www.speedymetals.com>]*
- *Blocks of wood, Styrofoam, glass, drywall [cut to the same size, 3" square, can obtain from hardware store]*
- *Fisher Brand infrared thermometer [Cat #15 077 966, resolution is 0.1°C, accuracy ±1°C]*
- *9 volt batteries*
- *9 volt battery adaptor [obtain from RadioShack]*

For the classroom (or laboratory):

- *Extension cords with power strips*
- *Paper towels for wiping up heat sink compound*
- *Extra batteries*

1-Dimensional Conduction:

Heat transfer is illustrated through use of a coffee cup warmer plate and surface IR thermometer. By examining the warmer as a heat source on a wall of a material, 1-D conduction can be quickly illustrated on each student's desk. Thermal conductivity of different materials can be demonstrated as well. Problems can be set up in which the students have to back calculate to determine the thermal conductivity of the material from the two surface temperatures and distance information. Further, composite systems can be examined via wood, Styrofoam, and drywall sandwich blocks.

The choice of materials is such that it spans a wide range of thermal conductivities as demonstrated in Table 1.[1, 7]

Experimental Procedure:

1. *Turn on mug warmer with the block of material positioned on top and allow the system to heat up for 15 minutes.*
2. *Check the temperature at the top surface of the material three times at 30-second intervals to ensure the system has reached steady-state.*
3. *Check the temperature at the surface of the mug warmer once the system has reached steady-state. Note that this may be greater than the steady-state temperature of the mug warmer when exposed only to convection in the air.*
4. *Replace with new blocks of material allowing it to equilibrate between temperature readings.*

TABLE 1
Suggested Materials and Their Thermal Conductivities

Material	Thermal Conductivity $\left(\frac{W}{m \cdot K}\right)$
Polystyrene (R-12)	0.027
Softwood (Fir)	0.12
Plaster board	0.17
Polycarbonate	0.21
Firebrick	1.0
High Density Carbon Steel	60.5
Aluminum Alloy 2024	177
Copper	401

Analysis:

The heat diffusion equation for 1-D, steady-state conduction with constant thermal conductivity is as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)=0\Rightarrow\frac{\partial^2 T}{\partial x^2}=0 \qquad (1)$$

The general solution is as follows:

$$T(x)=C_1x+C_2 \qquad (2)$$

Boundary conditions are determined from the student's experiment. The following example uses data for a polycarbonate block 1 cm thick. Polycarbonate was chosen because its glass transition temperature is about 150 °C and therefore it won't soften or melt on the mug warmer surface.

$$T(0)=T_{w.s}\Rightarrow T(0)=122\,^{\circ}C \qquad (3)$$

$$T(L)=T_{p.s}\Rightarrow T(0.01m)=88.8\,^{\circ}C \qquad (4)$$

The particular solution is in symbolic and numeric form:

$$T(x)=\frac{T_{p,s}-T_{w,s}}{L}x+T_{w,s}$$

$$T_{polycarb}(x)=\left(-3320\frac{^{\circ}C}{m}\right)x+122\,^{\circ}C \qquad (5)$$

Students will obtain a different temperature profile for each material they study and can then use Fourier's Law to determine the conduction heat transfer flux.

$$q_x^{''}=-k\frac{dT}{dx}=\frac{k}{L}\left(T_{w,s}-T_{p,s}\right) \qquad (6)$$

By providing the thermal conductivity, k, or the heat flux, $q_x^{''}$, it is possible to calculate the other parameter. Alternatively, students could determine heat flux from the steady-state heat generation experiment outlined below.

$$q_x^{''}=\frac{0.21\frac{W}{m\cdot k}}{0.01m}\left(122^{\circ}C-88.8\,^{\circ}C\right)=697\frac{W}{m^2} \qquad (7)$$

1-Dimensional Conduction Through Composite Systems

Steady-state heat conduction through layers of materials can be accomplished as well by stacking the materials provided in Table 1. The analysis is similar to that outlined above.

1-Dimensional Conduction with Contact Resistance

Contact resistance can be demonstrated by using a high thermal conductivity fluid in between the mug warmer and the material block from Table 1. A silicone-base heat sink compound is easy to obtain and, when used, it can be assumed to represent "perfect contact" between the warmer surface and the material block. Comparison with the system outlined above (which has air in the gap between the warmer and the material block) enables the student to back out the resistance due to thermal contact resistance. With access to wood or the metals with a rough edge from cutting vs. a smooth edge after cutting, this can also be illustrated.

$$q_{x,compound}^{''}=\frac{0.21\frac{W}{m\cdot k}}{0.01m}\left(122\,^{\circ}C-93.1\,^{\circ}C\right)=607\frac{W}{m^2} \qquad (8)$$

Obtaining the total thermal contact resistance for the case with and the case without heat sink compound is:

$$R_{t,c}^{''}=\frac{122\,^{\circ}C-88.8\,^{\circ}C}{697\frac{W}{m^2}}=0.04763\frac{^{\circ}C\cdot m^2}{W} \qquad (9a)$$

$$R_{t,c,compound}^{''}=\frac{122\,^{\circ}C-93.1\,^{\circ}C}{6o7\frac{W}{m^2}}=0.04761\frac{^{\circ}C\cdot m^2}{W} \qquad (9b)$$

$$R_{t,c}^{''}-R_{t,c,compound}^{''}= \qquad (10)$$

$$0.04763\frac{^{\circ}C\cdot m^2}{W}-0.04761\frac{^{\circ}C\cdot m^2}{W}=2.15*10^{-5}\frac{^{\circ}C\cdot m^2}{W}$$

As demonstrated, in this case of a smooth polymer surface, thermal contact resistance can be neglected as it is a couple of order of magnitudes smaller than the thermal resistance associated with the material. Rough metal blocks are good illustrators of how poor physical contact between two materials can impede flow of thermal energy.

Heat Generation Analysis

Heat generation can be considered by expanding the system boundaries to include the electrical resistance heating in the plate warmer. Solution of the heat diffusion equation with constant flux from an electrical heater can be explored via either transient heat generation or steady-state heat generation.

Transient Heat Generation

The transient nature of electrical resistance heat generation can be illustrated by simply having the students measure the temperature of the plate warmer with the IR thermometer from when it is turned on until it reaches steady-state. A sample experimental procedure is given and data is provided in Figure 1 for two experiments. If students are too hasty in ending the experiment, they may miss reaching the true steady-state temperature, which in this case is approximately 122 °C.

Experimental Procedure:

1. *Take initial temperature reading of plate warmer before turned on and record its initial temperature at time 0.*
2. *Turn on the plate warmer and begin stopwatch at the same time.*
3. *At 15-second intervals, take a temperature reading of the plate warmer using the infrared thermometer. Make sure to measure at the same location for each reading.*

4. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

Analysis:

The spatial variations in temperature are not considered in this case, so the heat diffusion equation is just:

$$\dot{q} = \rho C_p \frac{dT}{dt} \tag{11}$$

Assuming that heat generation, $\dot{q}$, is constant, the solution to this differential equation is:

$$T(t) = \frac{\dot{q}}{\rho C_p} t + C_1 \tag{12}$$

Using the initial condition that the temperature of the mug warmer was initially at 22.3 ˚C, it is possible to solve for the constant of integration.

$$T(t)0 = 22.3\,^{o}C = 0 + C_1 \Rightarrow C_1 = 22.3\,^{o}C \tag{13}$$

Therefore the particular temperature distribution expression is as follows and can be compared to the data fitted by a linear trend line with a fixed y-intercept of the initial mug warmer temperature.

$$T(t) = \frac{\dot{q}}{\rho C_p} t + 22.3\,^{o}C \Leftrightarrow T(t) = \left(0.2646 \frac{^{o}C}{s}\right) t + 22.3\,^{o}C \tag{14}$$

By taking apart one of the mug warmers, it can be ascertained that the plate is primarily aluminum, which has a density of $\rho = 2702 \frac{kg}{m^3}$ and a heat capacity of $C_p = 903 \frac{J}{kg \cdot K}$. Heat generation can then be obtained:

$$\dot{q} = 646{,}000 \frac{W}{m^3} \tag{15}$$

It can be valuable to discuss with students the case in which, when constant power is supplied to the mug warmer and this translates into constant heat generation from the mug warmer, why the data is curved. Most students will deduce that convection from the surface is being neglected and that this contribution only gets greater as the temperature increases.

Steady-State Heat Generation

It is possible to determine the steady-state heat generation by performing an energy balance at the surface of the mug warmer. The students will need to consider that all heat generated by the plate is being convected away from the mug warmer and will also need to obtain a valid convective heat transfer coefficient for convection from the surface of the mug warmer.

Since heat generation is usually expressed as a volumetric generation rate $\left(W/_{m^3} \right)$, it is important to pay attention to units. Further, electrical heat generation can be estimated via Joule heating in the mug warmer's heating coil, which has an electrical resistance, R_e, and a current, I. So

$$\dot{q} = \frac{I^2 R_e}{V} \text{ and } q'' = \dot{q}L [=] \frac{W}{m^2} \tag{16}$$

Energy Balance at the Mug Warmer Surface:

Energy generated in the plate = energy convected away from plate

$$\dot{q}L = h\left(T_{w,s} - T_{ambient}\right) \tag{17}$$

While convective heat transfer coefficients can be determined more rigorously, for this exercise, it is fine to use $h = 5 \frac{W}{m^2 \cdot K}$. The thickness of the mug warmer's heating coil has to be assumed from the thickness of the unit in use, but L=0.01m is realistic. The students can easily measure the ambient air temperature, and the surface temperature of the mug warmer at steady-state was already obtained. Therefore:

$$\dot{q} = \frac{h\left(T_{w,s} - T_{ambient}\right)}{L} = \frac{5 \frac{W}{m^2 \cdot K}\left(122\,^{o}C - 22\,^{o}C\right)}{0.01m} = 50{,}000 \frac{W}{m^3} \tag{18}$$

Heat flux is then:

$$q'' = \dot{q}L = 50{,}000 \frac{W}{m^3} \cdot 0.01m = 500 \frac{W}{m^2} \tag{19}$$

Using the well-known electrical relation for Power, P:

$$P = V \cdot I [=] \text{Volts} \cdot \text{Amperes} [=] \frac{J}{C} \cdot \frac{C}{s} = \text{Watts} \tag{20}$$

The current can be calculated from the information typically provided on the mug warmer unit.

$$I = \frac{P}{V_{AC}} = \frac{17W}{120V_{AC}} = 0.142A \tag{21}$$

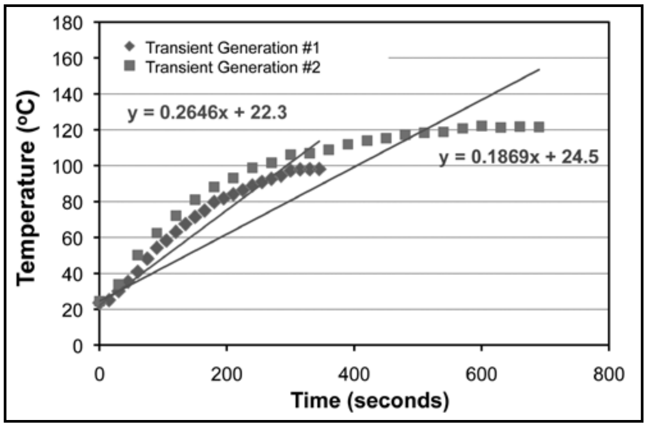

Figure 1. *Transient heating of the mug warmer demonstrating transient heat generation.*

And the electrical resistance can then be obtained through the volume, v, of the warmer plate:

$$\dot{q} = \frac{I^2 R_e}{v} = 50{,}000\frac{W}{m^3} = \frac{\left(0.142\frac{C}{s}\right)^2 R_e}{0.01m\cdot\pi\cdot\left(0.045m\right)^2} \tag{22}$$

$$R_e = 158\frac{J\cdot s}{C^2} = 158\Omega \tag{23}$$

Thermal Contact Resistance

Thermal contact resistance can also be illustrated using a coffee mug on the plate warmer. By adding an empty cup at room temperature to the fully heated plate warmer, the students can observe the transient heating of the cup. If transient heating has already been covered, however, it is possible to have the student set up the experiment and then conduct lecture or other class activities until the system reaches steady-state. This typically takes about 15 minutes.

Experimental Procedure:

1. *Allow the plate warmer to heat up and reach steady-state (about 15 minutes to T_{ss}≈120 ˚C).*
2. *Measure initial temperature of the empty mug inside the cup pointing the IR thermometer at the bottom center surface.*
3. *Place the coffee cup on the mug warmer and start the stopwatch.*
4. *At 15-second intervals, record the temperature of the bottom inside surface of the mug.*
5. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

Analysis:

Since two thermal resistances exist between the surface of the mug warmer and the bottom surface of the coffee cup, it is not possible to isolate the thermal contact resistance from the ceramic mug's resistance. It can be a valuable exercise, however, to ask students to determine from tables the thermal conductivity (and thus calculate thermal resistance) of the coffee mug itself. Depending on whether fired clay or rock is chosen, the thermal conductivity is usually between 1.3 and 2.15 $W/_{mK}$.[1] Estimating the thickness of the bottom of the cup to be 0.5 cm, the thermal resistance of the cup can be determined to be (per unit area):

$$\frac{L}{k} = \frac{0.05m}{1.7\,W/_{mK}} = 0.029m^2K/_{W} \tag{24}$$

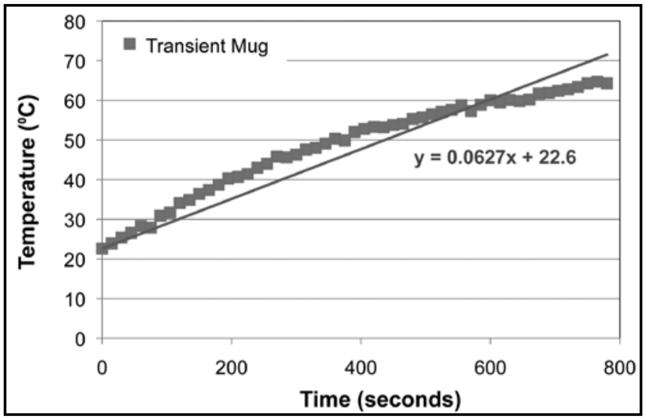

Figure 2. *Transient heating of a standard coffee mug on a preheated mug warmer.*

Using the heat transfer rate obtained from the steady-state heat generation example, one can then solve for the thermal contact resistance:

$$q_x'' = \frac{T_{w,s} - T_{m,s}}{\frac{L_m}{k_m} + R_{t,c}''} = \frac{122\,^\circ C - 75^\circ C}{0{,}029\frac{m^2K}{W} + R_{t,c}''} = 500\frac{W}{m^2}$$

$$R_{t,c}'' = 0.065\frac{m^2K}{W} \tag{25}$$

This thermal contact resistance is substantial and is the reason that the mug warmer is not able to heat coffee or any liquids to boiling despite its high surface temperature of ≈12 ˚C at steady-state. As demonstrated in Figure 2, the inside surface of the coffee mug remains below 70 ˚C. It can be beneficial to reinforce to the students that reducing thermal contact resistance can be accomplished using contact grease or increasing surface contact between the mug and the warming plate.

Heat Transfer from Extended Surfaces (Fins)

CPU passive heat sinks are excellent small examples of fins. Smaller ones fit nicely onto the coffee mug warmer and have copper bases for increased conduction away from the processor. The text by Incropera and DeWitt has a number of example problems using passive heat sinks that help reinforce what the students observe.[1]

Experimental Procedure:

1. *Allow the plate warmer to heat up and reach steady-state (about 15 minutes to reach T_{ss} ≈120 ˚C).*
2. *Measure initial temperature reading of fin tip and record this as time 0.*
3. *Place the CPU passive heat sink on the mug warmer and start the stopwatch.*
4. *At 15-second intervals, record the temperatures of the same fin tip or, alternatively, allow the system to reach equilibrium while class lecture / discussions continue.*
5. *Continue to take readings until the mug warmer temperature is constant for 45 seconds and reaches steady-state.*

Analysis:

Time-dependent fin-temperature expressions are not typically a part of undergraduate Heat Transfer courses. Therefore a rigorous analysis of the data in Figure 3 is not included here. It would be ideal to be able to determine temperature as a function of position, but this is not possible with the IR thermometers used in this experiment. This system can, however, still be used as an illustrative visual aid when discussing heat transfer from fins. Most CPU heat sink fins are of uniform cross-sectional area and the following equations are valid for this geometry. The tip is assumed to experience convective heat transfer and so the steady-state, position-dependent temperature distribution with this boundary condition is:

$$T(x) = T_{\infty,\text{ambient}} + \left(T_{w,s} - T_{\infty,\text{ambient}}\right)\frac{\cosh m(L-x) + \frac{h}{mk}\sinh m(L-x)}{\cosh mL + \frac{h}{mk}\sinh mL} \tag{26}$$

and the steady-state fin heat transfer rate is:

$$q_{\text{fin}} = M\frac{\sinh mL + \frac{h}{mk}\cosh mL}{\cosh mL + \frac{h}{mk}\sinh mL} \tag{27}$$

where $m = \sqrt{\frac{hp}{kA_c}}$ and $M = \left(T_{w,s} - T_{\infty,\text{ambient}}\right)\sqrt{hpkA_c}$ and p = fin perimeter while A_c = fin cross sectional area.

Convection

Convection can be included by using a CPU fan on top of a passive CPU heat sink. Most fans are 3 Pin, 9V, or 12V, which can be connected directly to a 9V battery adapter (can be purchased from RadioShack) by splicing together the red wires and the black wires and ignoring the yellow (control) wire. A 12V fan will simply run at a lower speed on a 9V battery. Videos from YouTube are particularly good at demonstrating external flow past rods or fins.[8]

This section covered demonstrations and student experiments for steady-state, 1-D conduction in both a composite system and considering contact resistance, heat generation from both a transient and steady-state perspective, and heat transfer from fins with and without forced convection. Some demonstrations are relatively quick (5 to 8 minutes) while others involving transient temperature changes can take 15 to 20 minutes to complete. Since the same basic materials are used throughout the course to illustrate the different concepts, student familiarity with the tools increases and thus the students' efficiency at conducting experiments increases through the semester. The advantage of repeatedly using the same system to illustrate different aspects of thermal energy flow is apparent when the students begin integrating concepts into a coherent framework.[9]

CONCLUSIONS

A versatile hotplate conduction and convection system is outlined as a Desktop Experiment Module. These DEMos can be useful tools to introduce students to heat transfer concepts in a complementary fashion to the traditional Heat Transfer lecture course. This article briefly discussed the course structure and content as well as the straightforward desktop experiments, which utilized inexpensive supplies to demonstrate thermal energy motion in solid materials, fins, convective heat transfer from solid surfaces, and radiation. Advantages of this hands-on experience include that it is not dependent on the availability of lab space and students have a unique experience to link into their evolving understanding of chemical engineering concepts. A supply list, instructional procedure, and lab mats were briefly discussed; full versions are available for instructor use upon request.

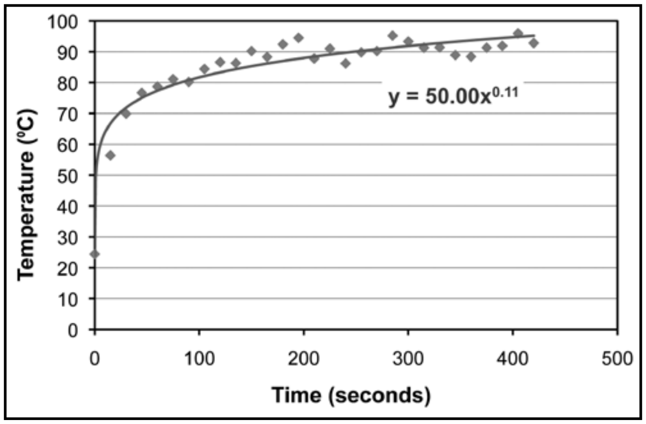

Figure 3. *Transient heating of a heat sink fin with time. The variability in temperature at steady-state is likely due to the difficulty reading temperatures at the same fin location.*

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