Design and Use of a Standalone TCS/Computer System
For Teaching Thermal Behavior

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While the modern desktop computer used by students today is a valuable analytical and computational tool, it is rarely studied in the classroom as a thermal system. In order to effectively study such a potentially complex system however, there are difficulties that must be overcome. The most tangible difficulty concerns the cost and complexity of instrumenting and controlling the computer while still retaining its original thermal behavior. On a more abstract level are difficulties regarding an effective approach to the concepts that would be meaningful to mechanical engineering technology students in an associate’s degree program.

A system called the Thermal Computing System (TCS) was designed and installed in a desktop computer to provide a simple, very low cost solution to the first difficulty. It allows students to observe, test, and record in real-time the thermal behavior and effects of individual components and parameters of the same desktop computer in which it is installed. However, the question of how to effectively use this TCS/computer to teach potentially complex heat transfer concepts to sophomore engineering technology students remains.

This paper first summarizes the design and behavior of the TCS/computer that makes straightforward and inexpensive exploration of a desktop computer’s thermal behavior possible. It then proposes a pedagogical approach to the exploration of thermal systems such as this that would be appropriate in a 2-year engineering technology program.

TCS/Computer Design

To present a viable computer project to a class for laboratory-based analysis, the computer should be both generic and inexpensive. An older system of modest speed and capability was selected. This system began its life as a basic circa mid-1990s desktop IBM clone containing a 166 megahertz Pentium 1 processor, 2.8 GB hard drive, Verge video card, 12X CD drive, and a 250W power supply. Software consisted of the basics as well; Microsoft Windows 98 II and Office. In a previous life it had been a student-access computer on campus.

To convert this computer into an effective teaching tool the project had the following constraints. First, data acquisition hardware couldn’t cost significantly more than the computer itself (which was free). Naturally this eliminated all known commercial DAQ packages. Secondly, potential software for data display and storage must have minimal cost, RAM, and hard drive storage requirements, primarily as a result of the platform chosen. Additionally, an infinitesimal learning
curve was required since students had not yet taken courses where more-sophisticated commercial packages would be presented. This meant LabView and its commercial analogues were out of the question. Finally, computer component performance had to be controllable, with mechanisms to deliberately manipulate internal functions such as processor loads and component cooling rates. Together these constraints drove the design of the TCS/computer system summarized below. A complete detailed description is presented in a separate paper\textsuperscript{1}.

The TCS hardware package was designed to fit inside the computer’s original CD drive box. It measures 8 internal computer temperatures and is controlled using Visual Basic 6.0, all at a cost of less than $50. A summary of its mechanical design, electronics and software design, and thermocouple placement is discussed below. Additionally, the computer was equipped with a rear flap-door installed over the power supply ventilation fan to provide control of the computer’s overall cooling-air flow rate. This flap-door allows the air flow rate to be regulated from 100\% (unobstructed) down to 2\% of its original design value.

Mechanical design of the TCS package itself is straightforward. After removal of the original CD drive’s components a thin acrylic mounting plate is installed to provide structural support for two circuit boards in a stacked arrangement, a small ventilation fan to insure isolation from any thermal contributions from the computer itself, the original I/O sockets, and a toggle switch to manually control the CPU fan. The resulting system, shown schematically in Figure 1, is placed back into its slot within the computer frame. The slot immediately below the CD box is then isolated and used to provide inlet air to the box, with exhaust ventilation out the front. Figure 2 shows a front view of the final installation.

![Figure 1 – TCS Package (schematic)](image-url)
The electrical design contains many unique features that are described in detail in a separate paper. Visual Basic is used to provide a simple, user-friendly operator interface where data storage and display options are controlled and the central processing unit (CPU) and graphics processing unit (GPU) loads can be controlled. The CPU and GPU loads are controlled using separate software benchmarks, or “benches”, that will push these devices to their maximum designed capability, thereby consuming 100% of their designed power. This allows their individual contributions to component temperature and thermal loading to be tested.

To complete the system eight type-K thermocouples are placed in selected locations within the computer. These locations are; an inlet air port, the GPU chip surface, the hard drive case surface (directly over the platter bearing), the power supply air inlet grill, the power supply fan outlet grill, and the CPU sub-system assembly. The layout is shown schematically for clarity in Figure 3. The CPU sub-system received special attention. Here three thermocouples are used; one at the interface between the CPU and the heat sink, another at the interface between the heat sink and the CPU fan (imbedded in the tip of a heat sink fin), and the third directly above the fan inlet. All thermocouples used to measure surface or interface temperatures use Techspray® heat sink compound to insure good thermal conductivity. All air-sensing thermocouples are placed 1/4 inch from the nearest surface to minimize unintended movement or contact.
After installation, the complete TCS/computer system was tested and its performance verified. The following test plan was implemented, with Figure 4 graphically showing the data collected. Immediately following the computer system startup the TCS package was activated. After approximately 50 seconds (data point 10) the CPU fan was turned off and the CPU and GPU benches were activated. Five hundred seventy seconds (9 minutes 30 seconds) later (data point 113) the CPU fan was reactivated and the benches turned off so the system could return to its normal steady-state condition. Data for all components were collected every 5 seconds for a total of 13 minutes. In this particular test the run was terminated prior to a complete return to the true steady-state condition. All components and functions (benches, data storage and display) performed as expected with full data retrieval achieved.

The performance of individual components is discussed first, followed by the overall system.
Behavior of Individual Components

Using Excel to display all thermocouple inputs as a function of time, examination begins with the behavior of the computer’s individual components; the hard drive, GPU, power supply, and CPU/sink/fan sub-system.

In the case of the hard drive, data points up to and including number 113 indicate that there is virtually no temperature increase over time once its operating temperature of 90 degrees Fahrenheit is reached, as might be expected. Notice however, that a small but noticeable rise in temperature beyond point 113 coincides with reactivation of the CPU fan. This indicates that additional thermal energy reaches the hard drive from elsewhere in the computer, likely due to increased air circulation from hotter components, rather than from internal sources.
In the case of the GPU there is a gradual increase in temperature from 110 degrees Fahrenheit to approximately 118 F, followed by a relatively steady-state period that also ends when the CPU fan is reactivated. The contribution of the GPU bench to its increase in temperature may or may not be real and would require additional testing. From this test run, at least, the only clear behavioral trend appears to be that GPU temperature is significantly affected by the heat generation and air flow behavior of nearby components.

Examination of the power supply reveals little if any temperature increase directly attributable to the device itself, as measured by the difference between PS inlet and PS outlet temperatures. Although it is rated at 250W it is unlikely to be taxed to such an extent by the system it powers. Other test runs, not documented here, indicate that if the flap-door is fully closed, such that only 2% of the designed air flow rate is allowed, the temperature difference between inlet and outlet is more significant. Even under these conditions, however, the inlet/outlet temperature difference is still relatively minor compared to the overall system temperature difference.

Finally, examination of the CPU/sink/fan sub-system data reveals a more complex behavior. Prior to deactivation of the fan, the temperature of components in this sub-system indicates the sub-system quickly reaches a steady-state condition, with only small temperature differences between the three thermocouple locations. Once the fan is deactivated, however, all temperatures in the sub-system immediately begin to climb towards a significantly higher steady-state condition characterized by large positional temperature differences. In the interest of component longevity this second steady-state condition was not fully reached. Never-the-less, it is clear that its behavior changes significantly with changes in forced air flow rate. Then, when the fan is reactivated temperatures immediately begin returning to their original steady-state values. Also, due to the fact that the CPU bench was activated at the same time the fan was deactivated, its contribution to temperature rise is unknown, although it is thought to be minimal.

Behavior of the Overall System

From the system standpoint examination of the computer inlet and power supply outlet air temperatures is most important since together they indicate the total amount of thermal energy being removed from the system.

As shown in Figure 4, there is a consistent 7 to 8 degree temperature difference between these two locations, up to data point 113. After the CPU fan is reactivated this difference increases slightly as the excess energy that accumulated in the area of the CPU is dissipated. The stability of the temperature difference is an indication that the computer’s overall cooling system has ample capacity to handle a range of component behaviors. A test that measures inlet/outlet temperature difference as a function of air flow rate would further explore this system performance aspect.

In the context of a complete computer system then, the overall cooling system has its own behavioral characteristics that can be substantially separated from those of its internal
components. This distinction between component performance and overall system performance can be leveraged when determining the best method for meaningful classroom implementation.

Classroom Implementation

The difficulty in using this system effectively as a teaching tool for sophomore engineering technology students centers on the approach to, and depth of the mathematics used in its analysis. Engineering technology students in particular, may have difficulty applying Reynolds numbers, Nusselt numbers, or generalized resistance networks as mechanisms for understanding the thermal behavior of a system such as this. So, while students definitely need exposure to thermal concepts, the graduated approach presented below will hopefully prove helpful when presenting the fundamental heat generation and transfer concepts involved. Student assessment and outcomes evaluating this approach will be presented with this paper at the upcoming conference.

Pedagogy

The overall goal is to impart a sound understanding of the fundamentals of heat generation and transfer, and how they are all related in a recognizably self-contained system such as a desktop computer. An examination and experimentation sequence that might achieve this goal involves starting with the overall system and working progressively inwards towards the CPU sub-system. In this way students begin by exploring the most fundamental aspect of all systems; energy input minus energy output equals energy remaining (1st Law). Then the concepts of heat generation, and conductive and convective transfer mechanisms can be added while examining the hard drive, power supply, GPU, and finally the CPU sub-system. Transient behavior can also be examined, or at least presented in an understandable context, using this approach. Mechanisms that minimize the mathematical workload typically associated with this progression include assigning students the task of researching rated performance rather than relying on theoretical analysis, and applying order-of-magnitude approximations based on published component specifications for power consumption and efficiency.

The Experimental Progression

An initial experiment that explores the basics of the overall system would be to measure delta T as a function of air flow rate using the flap-door, with delta T being the difference between computer inlet and power supply outlet temperatures. Adjustment or modification of other parameters within the computer is therefore not necessary and would likely confuse this most-basic analysis. Students should conclude with the fact that delta T is inversely related to air flow rate, yet the steady-state power into the system must still equal power out of the system. Therefore, the first law of thermodynamics works in real-world systems such as computers, and not just textbooks.

At the next level would come analysis of the individual components, starting with the hard drive and the graphics processing unit (GPU). At this level Newton’s law of cooling would be applied
to heat generating solids. Since the hard drive is not a thermally controllable device, analysis of this device would be limited to delta T versus the convective coefficient $h$, with the power supply flap-door and computer case covers available as mechanisms for controlling convection flow rates in its immediate vicinity. When exploring the GPU the “video bench” feature mentioned above can be used to separately control heat generation rate. This additional control variable allows a more analytical approach to be presented when determining delta T versus $h$ for various air flow rates. Published performance values would replace mathematical analysis of the heat generation rate, thereby reinforcing the practical approach to thermal behavior emphasized in an engineering technology curriculum.

For the next level of examination, the combination of devices and heat transfer mechanisms present in the CPU sub-system would be presented. These combined devices and mechanisms include an essentially one-sided thermal source (the CPU), a solid-to-air finned cooling device (the heat sink), and a controllable fan. Control of the variables of CPU load using the CPU bench, air flow rate through the heat sink fins using the CPU fan switch, and overall flow rate of cooling air through the computer using the flap-door is available to provide a range of experimental versatility. An experimental (versus analytical) approach to investigating the mechanisms of combined conductive and convective heat transfer is still emphasized so that any mathematical analysis discussed can be kept in perspective.

Finally, for the sharper students that are typically not challenged by the average lab exercise, the topic of transient behavior could also be explored. Note that in the above test run, the data exhibited a glimpse into this category of behavior after the fan for the CPU sub-system was reactivated. After a delay of approximately 50 seconds an increase in the system delta T can be observed, indicating a pulse of higher temperature air was working its way through the computer. While experiments to quantify this behavior would be relatively straightforward, even a qualitative examination could be useful in exposing students to these heat transfer concepts.

Conclusion

The TCS/computer system was built to enhance engineering technology students’ understanding of the thermal concepts and behavior associated with familiar systems such as computers. It contains several components that can be used to investigate thermal behavior and includes temperature recording instrumentation of the major computer components, user-friendly software, and independent control of various power consumption and air flow variables. Using this system as an instructional tool, many aspects of a typical modern computer can be examined, both analytically and experimentally, to present and reinforce a systems perspective of heat transfer concepts.

Additionally, the TCS/computer system enables presentation of fundamental heat generation and transfer concepts in a logical, progressive manner that can strengthen conceptual understanding of potentially complex mathematical relationships in an experimental fashion that is more appropriate
in an engineering technology environment. This is especially important when heat transfer concepts are not taught in any other mechanical engineering technology class at the Bachelors level. Discussion of both the usefulness of the TCS, and of the success of this approach will be presented along with this paper in June.

Bibliography: