Enhancing Computer Heat Sink Design with Phase Change Thermal Energy Storage and Thermoelectric Generators

Literature Review

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Table of Contents

Abstract

Over the past forty years, computers have become progressively more powerful, and they now play a major part in many aspects of our lives, from communication to entertainment. However, as transistors size is reduced and performance is increased, heat flux is also increased. This necessitates an increase in cooling capability, as computer performance is lowered at higher operating temperatures to protect computer processors from temperature damage. Unfortunately, modern cooling solutions are either energy intensive, expensive, or do not utilize the heat generated by computers. To reduce the energy demand of cooling solutions, thermal energy storage systems can be used. These systems utilize either sensible, phase change, or thermochemical energy storage. Of these systems, phase change thermal energy storage is the optimal method for cooling CPUs as it has a higher energy storage density than sensible energy storage systems and is mechanically simpler to implement than thermochemical systems. Phase change materials (PCMs) can cool CPUs by changing phases, for example from a solid to a liquid, when the CPU reaches the PCMs melting point, thus storing heat as molecular kinetic energy. Devices that can be used to turn this heat back into electricity include thermoelectric, thermoacoustic, and Stirling engine-based generators. Thermoelectric devices are ideal for this task, as they are simple and have no moving parts, consist mainly of semiconductors that are cheap to produce, and are widely researched and thus constantly improved upon. With PCMs and thermoelectric generators working together, a computer cooling solution could cool a processor without the need for an external energy input while simultaneously generating electricity, effectively 'reusing' the heat the processor outputs.

Keywords: central processing unit (CPU), phase change material (PCM), heat storage, thermoelectric generator (TEG), wattage, voltage, processor temperature

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Literature Review

Computers play an ever-increasing role in the lives of people, and almost all of the major aspects of the modern world rely to some level on technology and, more specifically, on computers. Computer transistors have become smaller and smaller over the past 40 years, such that from 1980 to today the maximum transistor density has doubled every two years in accordance with Moore's law (Swamy & Satyanarayan, 2019). This has led to an incredible increase in performance, as transistors are the basic building block of all computer processors. Accordingly, with this decrease in transistor size, the heat flux of computer processors, or heat produced per unit area, has gone up significantly. This has resulted in the necessity of more complicated, expensive, and energy intensive cooling solutions, whereas the first computers were cooled completely passively (Chu et al., 2004). However, these solutions are often either expensive, complex, unreliable, or power intensive. For example, many higher-end computers use liquid cooling, but this requires energy for the constant pumping of a fluid, usually water. Other methods such as gas decompression cooling are also very complex and energy intensive (Chu et al., 2004). Even the most common cooling method, a finned heatsink cooled by a fan, requires additional energy to power the fan (Chu et al., 2004). To reduce this energy demand past studies have focused on improving the cooling ability of heat pipes, which operate by evaporating and condensing a liquid inside of a wicked tube. Today heat pipes can often be found in laptops. However, even though they can be used for laptop CPU cooling, they lack the cooling potential needed for desktop CPU applications, and like most cooling solutions release heat into the environment without every fully utilizing it (Wang et al., 2018).

Keeping a computer cool is essential, for multiple reasons. First, the hotter a computer chip gets, the lower its clock speed has to be, resulting in higher power consumption and lower computing power (Price et al., 2014). In fact, one study found that a CPU can complete 2.5 times more calculations per unit time at a temperature of -200°C than at 100°C (Chu et al., 2004). Secondly, CPUs are extremely complex and delicate devices, and even the slightest damage can have catastrophic results. As a result, temperature is a very important factor in the longevity of a computer chip, and a study found that for every degree Celsius below maximum operating temperature, the failure rate of a CPU decreased by 4% (Hosseinizadeh et al., 2011). Almost every modern computer contains a cooling system, but almost none of these cooling solutions reutilize the energy generated by the processors. This leaves a need for a computer cooling solution that not only effectively cools a computer, but also ‘recycles’ the heat that the computer processor emits. One method that can be used to cool a CPU is to store the heat that it generates, effectively removing the heat from the environment.

Storing Heat & Thermal Energy Storage Cooling

An important secondary effect that results from storing thermal energy is that in the immediate moment it cools the environment. This allows for the storage of thermal energy to be used as an alternative method of cooling. In fact, there have been previous studies that have used thermal energy storage systems in order to cool computer processors (Gharbi et al., 2017). Aside from cooling, the reasons for storing heat include seasonal energy storage, residential heating, heat island effect mediation, and electrical production. Importantly, thermal energy storage (TES) allows for the clean storage of large amount of energy for longer than solar panel and battery-based systems can manage (Erlund & Zevenhoven, 2018). There are multiple TES methods that can be used to cool a CPU, and these methods, as well as pros and cons of each, will be discussed next.

Sensible Energy Storage

The simplest method of storing thermal energy is sensible thermal energy storage. Sensible thermal energy storage occurs when an object is at a lower temperature than a heat source, and is then thermally connected to that heat source, allowing it to absorb thermal energy (Rao et al., 2018). Previous research has mainly focused on increasing the amount of energy that can be transferred to the sensible heat storage material. The reason for this is that sensible energy storage materials with higher energy storage densities, such as concrete, are usually fairly non-conductive and thus will not be able to absorb much energy on their own. An improved sensible energy storage design was created by Rao et al. in 2018, where they ran fins made of different metals through concrete which maintained the high energy density of concrete while simultaneously increasing the conductivity of the system, thus allowing it to absorb as more heat.

However, there is a major drawback to sensible energy storage: when absorbing the heat, thermal energy is not being transformed into another form of energy, and is instead simply being transferred to another object, and this makes it difficult to utilize in areas such as computer cooling because the design only works until thermal equilibrium is reached. Thus, sensible heat storage is more effective at storing energy than at cooling. A water loop and radiator-based computer cooling solution could be labeled a sensible energy storage system, as it involves the heating of water by running it over a hot plate connected to the CPU, and then removing that heat from the water by pumping the water through a radiator (Chu et al., 2014). Similarly to the water-cooling system, sensible energy storage also necessitates a complex and energy intensive design. As a result of its insufficient cooling abilities and complexity, it is not often used for computer cooling purposes. Other TES methods may be a better fit for computer cooling.

Phase Change Energy Storage

The second TES system that will be discussed is phase change energy storage. Phase change energy storage occurs when a phase change material absorbs heat which is used to loosen the bonds in the material, turning it into a liquid (Gharbi et al., 2017). This makes it useful for cooling, as the energy is converted into molecular kinetic energy, and thus the temperature of the material stays constant while changing phases, allowing it to act as a temperature stabilizer. If there is not a consistent heat source, the material eventually returns to a solid form and releases that heat that was originally absorbed. These two effects make it useful for both energy storage and cooling. Previous studies have focused mainly on the heat storage aspect of PCMs. In one review of such studies, the effect of storage angle, PCM type, and PCM additives was analyzed, showing that a broad range of studies have been done focused on improving the performance of PCMs (Kan et al., 2016). Additionally, a study completed at MIT focused on improving another aspect of PCMs, phase maintenance. In this study, the ability of the PCM to maintain its current phase was increased through the addition of ultraviolet activated microswitches, which triggered the phase change, so that the length of time for which the heat was stored could be controlled (Chandler, 2017). In the realm of PCM cooling, a research group studied the use of a PCM as an energy storage medium that simultaneously acts as a cooler, as well as the ability of internal fins to increase the thermal conductivity of the PCM (Hosseinizadeh et al., 2011). This leads to one of the main problems with phase change materials: their low thermal conductivity when compared to other energy storage mediums (Khan et al., 2018). This has been a focal point of many studies, which have focused on increasing the thermal conductivity of PCMs through the inclusion of additives such as metal nanoparticles or carbon-based particulates, with each of these proving to be highly effective (Khan et al., 2018). Despite the large amount of research done on improving PCMs, few studies have focused on how PCMs can be used for cooling. Despite this lack of research in the realm of PCM cooling, due to the characteristics of PCMs and the simplicity of the necessary systems, they are an optimal candidate for computer cooling solutions. However, there is yet another TES method that will be discussed.

Thermochemical Energy Storage

Thermochemical energy storage is the final and most complex method of thermal energy storage. Thermochemical energy storage occurs when heat is supplied to reactants, they endothermically react, and energy is stored in molecular and atomic bonds, or lack thereof (Erlund et al., 2018). The products of these reactions can be separated and stored separately, and when recombined the heat is released via an exothermic reaction. This makes thermochemical energy storage applicable to long term energy storage scenarios, as the products can be stored over long periods of time in a ready-to-react state. As a result, thermochemical energy storage is very useful in seasonal energy storage applications, as energy can be stored during summer, and the reactants recombined during winter. Previous studies have focused on how thermochemical systems can be built and optimized, in terms of material and design, to store energy when it is abundant, such as during the day, and release it when it is needed, such as during the night (Erlund et al., 2018). Many different chemicals can be used, and each reaction has a varying energy density and activation temperature (Erlund et al., 2018). However, there have not been many studies focused on using thermochemical energy storage for cooling. Due to the complexity of thermochemical energy storage systems, high energy input requirements of these systems, and lack of cooling ability, thermochemical energy storage is not useful in the area of computer cooling. Additionally, there still remains the question of how heat can be utilized.

Heat Utilization and Conversion

Thus far energy storage methods have been discussed, but not how that stored energy can be used. Indeed, much of the research on thermal energy storage and cooling lacks a method for heat extraction from the storage medium. One of the most useful types of energy, is electricity. Electricity is what is used to power computers, and as such a cycle can potentially be created where energy is stored by a PCM and is then turned back into electricity which is then used to return some power the computer. Thus, research done on turning heat into electricity is incredibly important, and in general it is often useful to turn heat into other types of energy.

Thermoelectric Generators

Thermoelectric generators are widely researched devices that can turn a temperature gradient into an electrical current. The fundamental effect that allows thermoelectric generators to generate electricity is the Seebeck effect, discovered in 1823 by Thomas Seebeck, which is the phenomenon of an electrical current occurring when there is a temperature gradient between two materials of different resistances (Teffah et al., 2018). The opposite of this is the Peltier effect, which dictates that an electric current run through two differently conductive materials results in a temperature difference (Teffah et al., 2018). Devices that utilize the Peltier effect can either be called Peltiers or thermoelectric coolers (TECs), while those that utilize the Seebeck effect are most commonly referred to as thermoelectric generators (TEGs). A large amount of research has been done on TEGs/TECs over the past sixty years, and this has resulted in the efficiency of these devices quickly increasing. While in 1960, the maximum heat-to-electricity conversion rate was around 5% with a TEG, today it is closer to 20% (Teffah et al., 2018). This makes the devices much more useful than they were 60 years ago. A key improvement that has led to this increase in efficiency is the use of semiconductors in these devices. Modern-day thermoelectric devices do not consist of electrically connected metal sheets but rather contain a grid of semiconductor units, similar to what is shown in Fig. 1 (Pourkiaei et al., 2019). Due to the use of semiconductors in computing, and to the fact that the semiconducting materials used are fairly simple to produce, the cost of these devices has remained relatively stable.

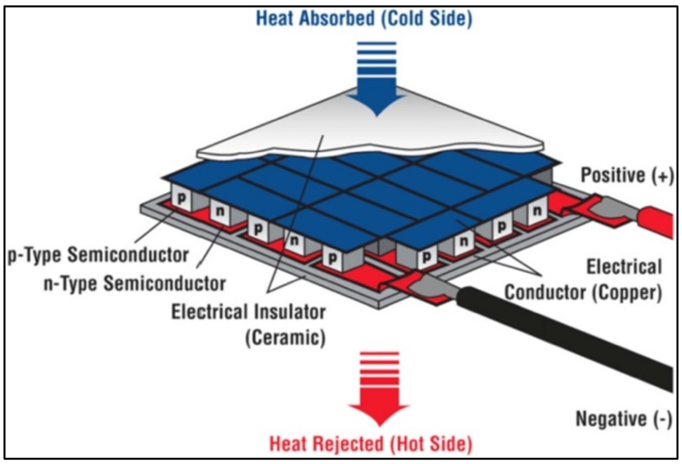

Fig. 1. A diagram that shows the structure of most thermoelectric devices (Pourkiaei et al., 2019)

As a result of this increase in efficiency, these devices are used to generate power in a range of applications. For example, one research group decided to focus on using thermoelectric generators in combination with PCMs used as an intermediary heatsink material to generate electricity from body heat, thus creating a generator that can be used to power small devices such as pacemakers and personal communication devices (Lee et al., 2019). On the other hand, thermoelectric devices have also been used in larger scale applications, such as in NASA's Cassini craft, which utilizes heat generated by the radioactive decay of plutonium to power its electronic components (NASA, 2018).

Additionally, Peltier's are broadly available for applications such as refrigeration and cryogenic storage and are relatively inexpensive due to improvements in semiconductor manufacturing. However, there is still much research to be done on how these devices can be used as effective coolers and generators for computers. For example, one study showed that when TEGs are combined with TECs, the TEGs turn heat into electricity, and then the TECs are used to turn this electricity back into a heat difference, a heatsink can be created capable of cooling a CPU using only CPU heat as an energy source (Teffah et al., 2018). Another study focused on how different types of semiconductors can be used, what their benefits and drawbacks are, and what changes can be made to the structure of the devices themselves in order to improve performance (Pourkiaei et al., 2019). Altogether, the combined ability to generate power and cool makes TEGs/TECs highly useful devices for computer energy generation. There are also other methods of turning heat into electricity that should also be considered, as even today thermoelectric devices have a relatively low real world conversion efficiency of only ~10%.

Thermophotovoltaics

One of these alternative methods is thermophotovoltaics. These devices consist of a heat source, an infrared radiation lens/emitter, and a thermophotovoltaic cell (Yang et al., 2013). When the heat source gets to extreme temperatures, it begins to emit large amounts of IR (infrared) radiation, and then photovoltaic cells turn this IR radiation into electricity. One benefit of these devices is that they have a higher efficiency compared to devices such as thermoelectric generators, and still maintain the noiselessness and low failure rate of thermoelectric generators due to their lack of moving parts. Past research has focused on improving these devices via the addition of heat recuperators which allow more of the heat to be turned into IR radiation, and thus into electricity, while also reducing temperature differences which can increase the failure rate of the system (Yang et al., 2013). However, due to the inherent nature of thermophotovoltaics, they do not possess the benefit of being reversible, unlike thermoelectric devices. This makes them useful for generating electricity from heat, but not for generating a heat difference from electricity. Additionally, as the heat source often requires a fuel, such as hydrocarbons, that burns at a very high temperature in order to emit the correct spectrum of radiation, this technology is not useful for generating electricity at temperatures that computer processors are able to produce. There is another method of turning heat into electricity that operates at CPU-like temperatures that is also more efficient than thermoelectric devices.

Stirling Engine Generators

The last method of turning heat into electricity discussed here is Stirling engine generators. These devices consist of a Stirling engine that utilizes the expansion and contraction of a working fluid due to a temperature difference to create mechanical motion, which is then converted into electrical energy via a generator (de la Bat et al., 2020). These devices often require lower temperature differences than thermophotovoltaics and have a higher conversion efficiency when compared to thermoelectric generators. In one study, when using a free-piston Stirling engine developed at Stellenbosch University, and a 600ºC hot plate, the resulting power was over 100 W at peak (de la Bat et al., 2020). Other studies have focused on finding out how free-piston Stirling engines can best be modeled, as this is useful for determining where the engines should be used (de la Bat et al., 2020). Stirling engines are traditionally labelled to be external combustion engines, however, they are often capable of operating on processes other than combustion, as all they require is a temperature difference. They are versatile and can be adjusted to operate at the range of temperatures produced by CPUs, and the mechanical motion can efficiently be turned into electrical potential through the use of a simple generator. An important drawback of these engines is that they are not noiseless and contain many moving parts. This, coupled with their production cost and complexness, makes them less useful for computer cooling applications and more useful for large scale waste heat recuperation in industrial scenarios. However, for any heatsink to work well, the heat first needs to be transferred from the CPU to the heatsink.

Thermal Interface Materials

Another factor that impacts a computer cooling systems performance is the thermal interface material (TIM) used. There are two places in which thermal interface materials are typically used. Oftentimes, a TIM will be used inside of the CPU die, which includes a covering that goes over the actual silicon, that transfers heat from the silicon to the integrated heat spreader (Swamy & Satyanarayan, 2019). TIMs are also used in order to convey heat from the integrated heat spreader of a CPU to the heatsink. Thus, TIMs can have a large impact on the temperature of a CPU, as if heat cannot be transferred, no matter how quickly a cooling system can dissipate that heat, it will never get from the CPU to that cooling system, and the CPU will overheat. The majority of research on TIMs has focused on what different materials can be used in order to fabricate a more effective TIM with a higher heat flux (Swamy & Satyanarayan, 2019). However, TIMs are often not the limiting point of a cooling solution, with the actual heatsink being the limitation instead. Thus, most common, and cheap TIMs are effective enough for modern computing solutions, and when they are not, more expensive but still readily available TIMs such as “liquid metal” (gallium) based TIMs can be used.

Conclusion

In following with all of the information and research previously discussed, one main knowledge gap can be identified. This is that the combination of a thermal energy storage and utilization system is left almost completely unresearched. Such a system would have the benefit of being able to generate electricity even when the computer is no longer running and would be completely energy self-sufficient. It would also fill the gap for an all-in-one solution to utilize computer waste heat. Such a system would be able to generate electricity, while also storing heat for other applications if needed. PCMs are the optimal TES candidate for such a system, and PCMs such as waxes are capable of storing large amounts of energy, while being cheap and non-toxic. Such a design could also be constructed without any moving parts, reducing its failure rate when compared to conventional water-cooling loops or fan-based systems. Thus, a joint PCM-TEG system would be simple, reliable, inexpensive, and useful.

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