Thermoelectric cooling of microelectronic circuits and waste heat electrical power generation in a desktop personal computer

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Abstract:

Thermoelectric cooling and micro-power generation from waste heat within a standard desktop computer has been demonstrated. A thermoelectric test system has been designed and constructed, with typical test results presented for thermoelectric cooling and micro-power generation when the computer is executing a number of different applications. A thermoelectric module, operating as a heat pump, can lower the operating temperature of the computer's microprocessor and graphics processor to temperatures below ambient conditions. A small amount of electrical power, typically in the micro-watt or milli-watt range, can be generated by a thermoelectric module attached to the outside of the computer's standard heat sink assembly, when a secondary heat sink is attached to the other side of the thermoelectric module. Maximum electrical power can be generated by the thermoelectric module when a water-cooled heat sink is used as the secondary heat sink, as this produces the greatest temperature difference between both sides of the module.

Keywords: Thermoelectric; Peltier; Cooling; Micro-power generation; Seebeck

1. Introduction

This paper demonstrates the practical application of thermoelectricity for cooling and micro-power generation in a standard personal computer. A brief overview of thermoelectric technology is given, highlighting how the technology can be used to solve thermal problems in microelectronic circuits. The paper then describes a test system that has been designed to measure the temperature of the microprocessor and graphics processor in a standard desktop computer. The standard forced-air cooled system, comprising of a heat sink and electronic fan, and various thermoelectric solutions have been evaluated, with typical test results presented. The potential for electrical power generation from waste heat is also investigated and the paper draws conclusions on the effectiveness of the thermoelectric cooling and power generation system.

2. Overview of thermoelectric technology

The application of thermoelectric technology to cool microelectronic circuits is not new. It has been established for some time that the technology can be used in cooling, heating and micro-power generation applications, and can offer some distinct advantages over other technologies. For example, in cooling or refrigeration, the technology does not require any chlorofluorocarbons or other fluid that may need to be replaced; can achieve temperature control to within ±0.1◦C; is electrically quiet in operation; the modules are relatively small in size and weight; and do not import dust or other particles which may cause an electrical short circuit [1].

A standard thermoelectric module utilises the Seebeck, Peltier and Thomson effects and can operate as a heat pump, providing heating or cooling of an object connected to one side of the module if a DC current is applied to the module terminals. Alternatively, a module can generate a small amount of electrical power if a temperature difference is maintained between two terminals [1]. Historically, the motivation for using thermoelectric modules to cool microelectronic integrated circuits in the computer industry has been to increase their clock speed below ambient temperatures, which can be advantageous in some situations [2,3]. As integrated circuit power and power density continue to increase, the computer industry may begin to approach the limit of forced-air cooled systems and will need to find alternative solutions [2]. Thermoelectric technology has been highlighted as a possible solution to these problems

[4], and there is evidence of ongoing research into cooling the whole of a microprocessor with a thermoelectric module, and focus on cooling microprocessor 'hot spots' using embedded micro thermoelectric devices incorporated into the microprocessor die [5].

Thermoelectric power generation from waste heat in a computer system has received less attention, although some work has been done in this field with the application of 'heat spreaders' to produce a self-powered thermoelectric cooling system [6–9].

3. Test system

A thermoelectric test system has been designed and constructed that is suitable for experimentation in thermoelectric cooling and thermoelectric power generation. The hardware consists of a personal computer running National Instruments LabView data acquisition software; National Instruments USB-6211 data acquisition card; TC-08 Pico Technology thermocouple data logging unit; Supercool PR-59 PID control unit; and a number of K-type thermocouples. A schematic diagram of the test system for thermoelectric cooling is shown in Fig. 1. The test system for thermoelectric power generation is discussed later in this paper.

The computer's microprocessor is normally cooled using a heat sink and electronic fan assembly, mounted on top of the microprocessor, that provides forced air cooling. A thermoelectric module has been mounted in-between the computer's microprocessor and various heat sink and electronic fan assemblies in order to evaluate the effectiveness of different thermoelectric cooling solutions. For thermoelectric cooling, the temperature of the 'hot' and 'cold' sides of a thermoelectric module is of great interest. The 'cold' side of a module is normally the side of the module attached to the object to be cooled, in this case the computer microprocessor, and the 'hot' side of the module is the side attached to the heat sink. In practice, it is very difficult to measure the temperature of the hot and cold sides of a thermoelectric module, as it is important that the module lies flush with the object to be cooled and the heat sink in order to achieve good thermal conductivity. In order to overcome this problem, the temperature of the microprocessor was measured by a K-type thermocouple attached onto the side of the microprocessor. The microprocessor temperature is considered to be at approximately the same temperature as the cold side of the thermoelectric module, and is referred to as T_{Cold} in the experiments. Similarly, the temperature of the heat sink was measured using a K-type thermocouple attached onto the side of the heat sink. The temperature of the heat sink is at approximately the same temperature as the hot side of the thermoelectric module, and is referred to as T_{Hot} in the experiments.

The K-type thermocouples are connected to a Pico Technology TC-08 thermocouple data logger that converts the thermocouple

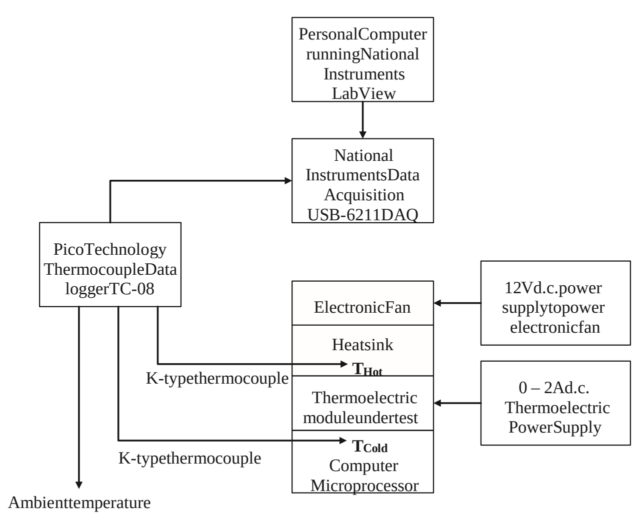

Fig. 1. Schematic diagram of the test system for thermoelectric cooling.

output into temperature in degrees centigrade. The temperature of each thermocouple is then recorded by a personal computer running a National Instruments LabView program.

The thermoelectric module is powered by a 0A to 2A d.c. input current that is supplied by an external power supply. The standard heat sink and electronic fan assembly is powered by the computer's internal power supply. Where the standard heat sink and electronic fan has been replaced with a different heat sink and electronic fan assembly, the electronic fan has been powered by an external 12V d.c. power supply.

4. Thermoelectric cooling modules

Two thermoelectric modules have been evaluated for thermoelectric cooling. The Supercool PE-192-1420-1118 (Module A) is a cascaded design, similar to two thermoelectric modules stacked on top of each other. The module has 34 thermoelectric couples, with a maximum thermoelectric input current and voltage of 6.7A and 15.6V, and a maximum heat pump capacity (Q_C) of 39.9W [10]. The Melcor CP1.4-127-045L (Module B) is a single stage device, and has 127 thermoelectric couples, a maximum thermoelectric input current and voltage of 8.5A and 15.4V, and a maximum heat pump capacity of 72W [11].

5. Experiment methodology

The cooling performance of the standard heat sink and electronic fan assemblies used to provide forced-air cooling of an Intel Pentium 4 1.8GHz microprocessor and Radeon 7500 graphics processor have been evaluated along with a number of thermoelectric solutions.

The computer's microprocessor is normally cooled using a heat sink and electronic fan assembly. A schematic diagram of the standard heat sink and electronic fan assembly, mounted onto the microprocessor, is shown in Fig. 2. The standard heat sink measures 83mm×69mm×35mm (length, width, height), and the electronic fan 83mm×69mm×21mm.

The graphics processor is cooled using a different heat sink and electronic fan assembly, and is significantly smaller in size, with the heat sink measuring 45mm×45mm×10mm. The electronic fan is fabricated inside the heat sink and forms part of the heat sink itself, and is shown in Fig. 3.

The temperature of the microprocessor and graphics processor has been measured, using K-type thermocouples, under steady state conditions when the computer is idle and only displaying the desktop environment; when a screensaver application is running; a PowerPoint presentation is displayed; and when the computer is running a graphically intensive computer game. These four operating conditions are typical of the demands placed on a personal computer, and present a range of low and high mathematical computation and graphical requirements for the computer system.

The standard microprocessor heat sink and electronic fan assembly was then removed, and a thermoelectric module

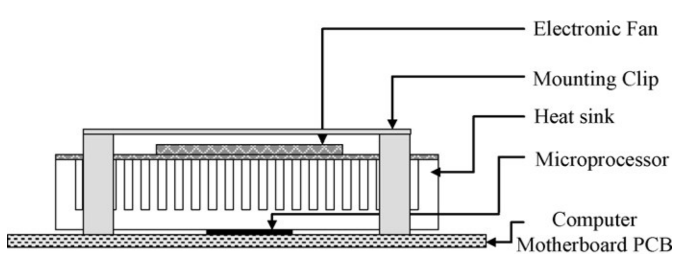

Fig. 2. Schematic diagram of the standard heat sink and electronic fan assembly mounted onto the microprocessor.

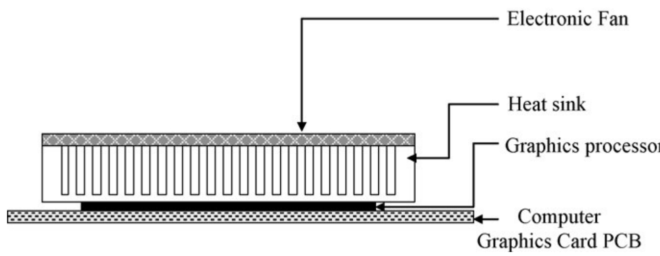

Fig. 3. Schematic diagram of the standard heat sink and electronic fan assembly mounted onto the graphics processor.

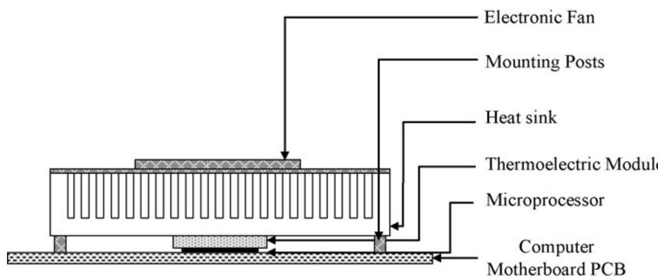

Fig. 4. Thermoelectric module mounted in-between the microprocessor and standard heat sink assembly.

mounted onto the microprocessor. The standard heat sink and electronic fan assembly was then mounted on top of the thermoelectric module, as shown in Fig. 4. The 'cold' side of the thermoelectric module was attached to the microprocessor, and the 'hot' side of the module attached to the standard computer heat sink and electronic fan assembly, with two K-type thermocouples located as showninFig.1.Thermalpastewasappliedonbothsidesofthethermoelectric module to ensure good thermal conductivity between surfaces, and mounting posts were used on each corner of the heat sink, secured between the PC base and the heat sink, to ensure the assembly held the thermoelectric module under compression.

The thermoelectric input current was varied from 0.0A to 2A in 0.5A steps, with the temperature of the microprocessor and the 'hot' side of the thermoelectric module recorded. The 'cold' side of the thermoelectric module is assumed to be at the same temperature as the microprocessor case temperature, and the difference between the hot 'T_{Hot}; and cold 'T_{Cold}' sides of the module called T, found by:

$$T = THot - TCold \qquad (1)$$

measured in◦C.

The experiment was repeated so that results could be obtained for both thermoelectric modules under test.

The standard heat sink and electronic fan assembly was then replaced with a smaller heat sink and electronic fan assembly designed for use with thermoelectric modules. The Thermo Electric TDEX6015/TH heat sink measures 60mm×60mm×15mm, and the electronic fan 60mm×60mm×25mm. The experiment was repeated for both thermoelectric modules.

The Thermo Electric TDEX6015/TH heat sink and electronic fan was then replaced with a Melcor LI201 water cooled heat sink and RS M200-S-SUB miniature water pump. A water-cooled heat sink reduces the temperature of the microprocessor by circulating water through the heat sink using the water pump. As the water passes through the heat sink, heat is transferred from the heat sink to the water and carried away, in this case to an external container that circulates the water back into the system. A schematic diagram of the test system is shown in Fig. 5, and Fig. 6 shows the water-cooled heat sink assembly.

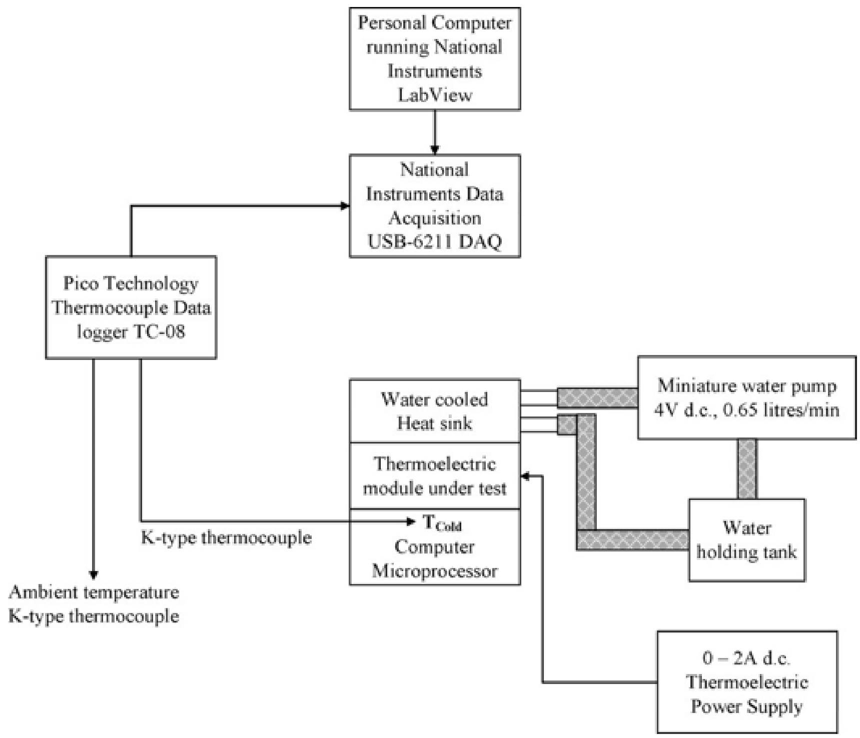

Fig. 5. Schematic diagram of the water cooled heat sink test system.

Further tests have been conducted using the Supercool Proportional Integral Derivative (PID) controller to maintain the temperature of the microprocessor at a preset level of 10◦C, 20◦C, 30◦C and 40◦C.

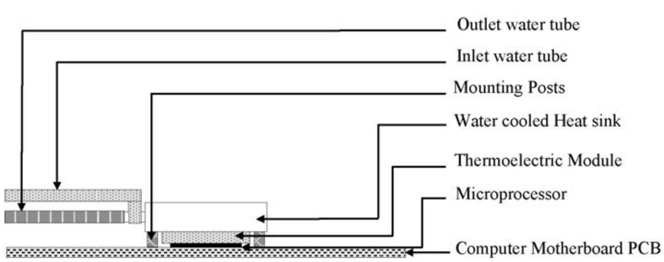

Fig. 6. Schematic diagram of the water-cooled heat sink assembly.

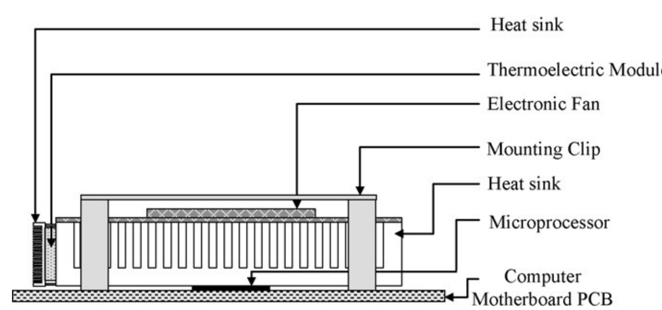

Fig. 8. Schematic diagram of the thermoelectric power generation assembly.

The PID controller varies the thermoelectric input current to the thermoelectric module in order to control the temperature of the thermoelectric module's cold side. As the output of the PID controller is an input current and voltage to the thermoelectric module, the thermoelectric input power to the thermoelectric module can be found by:

$$\text{Thermoelectric input power} = V_{in} \times I_{in} \qquad (2)$$

measured in Watts; where V_{in} is the voltage input to the thermoelectric module from the PID controller, and I_{in} is the current input to the thermoelectric module from the PID controller. The PID controller replaces the 0–2A thermoelectric power supply used in the earlier tests, and an extra thermocouple is attached to the side of the microprocessor in order to provide a reference temperature to the PID controller.

Experiments have also been conducted to demonstrate thermoelectric power generation from waste heat in the computer system. The test system is similar to the one used for thermoelectric cooling, but this time the standard heat sink and electronic fan assembly is mounted directly onto the microprocessor. A thermoelectric module has been attached onto one side of the standard heat sink, and a Thermo Electric Devices TDEX6015 heat sink is attached to the other side of the thermoelectric module. It should be noted
that the hot side of the thermoelectric module, T_{Hot}, for thermoelectric power generation is normally associated with the side of the thermoelectric module that is attached to the heat source, in this case the microprocessor heat sink. The cold side of the module, T_{Cold}, is the side of the module attached to the second heat sink.

The thermoelectric module's positive and negative terminals are connected to a 2 load resistor (RL) that has been chosen to ensure maximum power transfer can occur. The voltage and current measured in the load resistor is recorded by the LabView data acquisition system. The K-type thermocouples measure the temperature of the standard heat sink, which is at approximately the same temperature as the hot side of the thermoelectric module; and the temperature of the second heat sink, which is at approximately the same temperature as the cold side of the thermoelectric module. The experiment set-up is shown in Fig. 7, and the power generation assembly in Fig. 8.

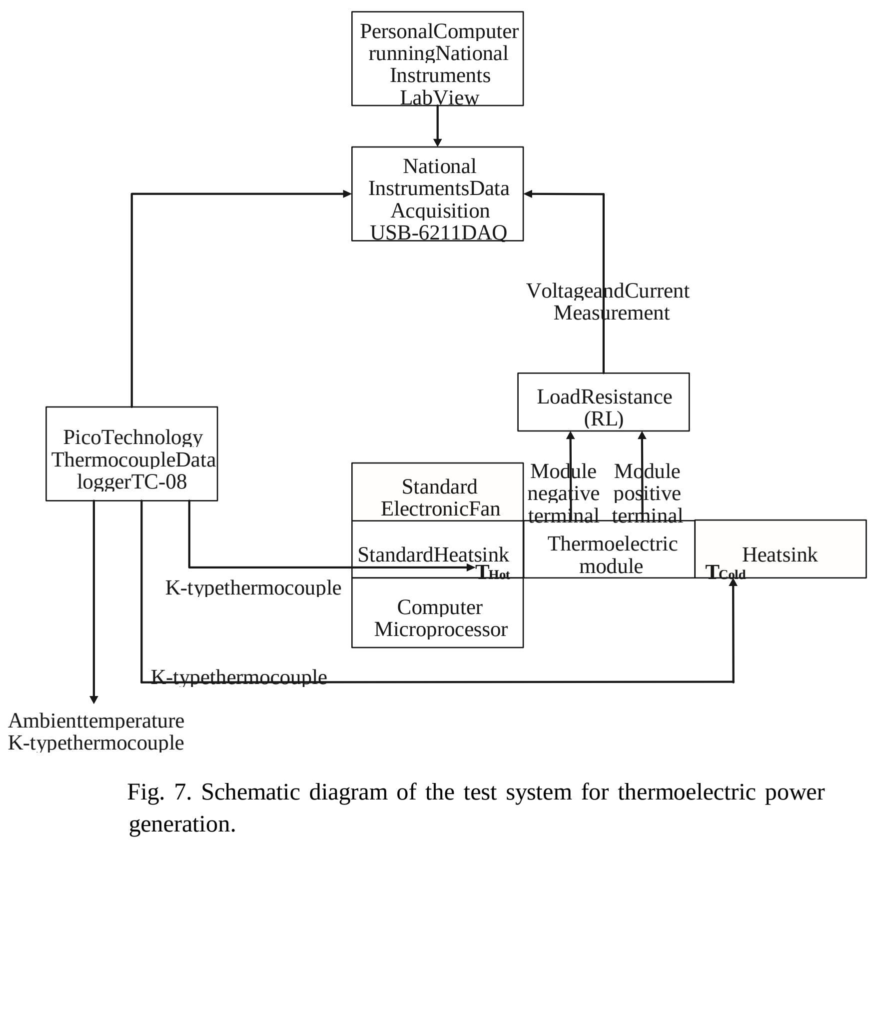

Fig. 7. Schematic diagram of the test system for thermoelectric power generation.

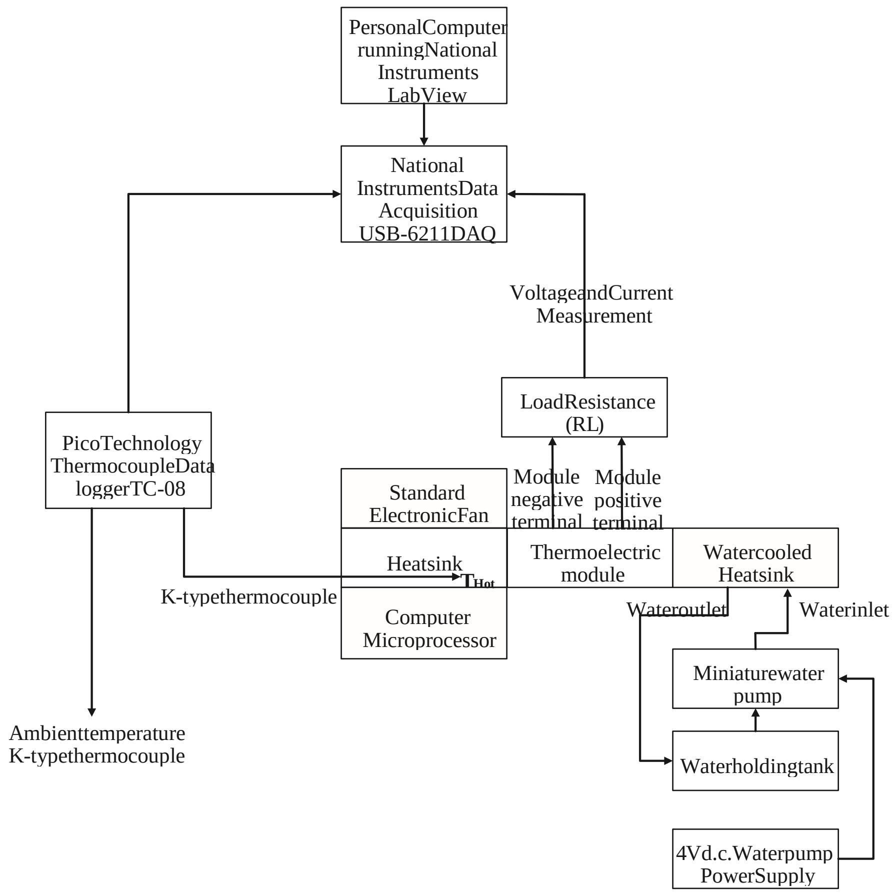

Fig. 9. Schematic diagram of the water cooled test system for thermoelectric power generation.

6. Thermoelectric power generation modules

Two thermoelectric modules have been evaluated for thermoelectric power generation. Although not specifically designed for thermoelectric power generation, they can be used in this configuration and are sufficient to demonstrate the concept of thermoelectric power generation. The Melcor CP2-31-10L (Module C) has 31 thermoelectric couples and measures 30mm×30mm×5.6mm. The Supercool PE-127-10-13-UK (Module D) has 10 thermoelectric couples and measures 30mm×30mm×3.6mm. These modules were chosen for their relatively small size, as there is limited space to mount a thermoelectric module inside the desktop computer without redesigning the internal layout.

The TDEX6015 heat sink was then replaced with a water-cooled heat sink and the experiment repeated. The test system with the water-cooled heat sink is shown in Fig. 9, and the power generation assembly in Fig. 10. 7. Results

7.1. Thermoelectric cooling

Using the standard heat sink and electronic fan assemblies, the temperature of the microprocessor and graphics processor have been measured for the four computer operating conditions, with the results shown in Fig. 11. The results highlight how the standard system maintains the temperature of each integrated circuit between 33◦C and 45◦C dependent on the application the computer is running.

When the computer is in a steady state condition, the microprocessor temperature is typically 33◦C, approximately 7◦C above ambient temperature. When the screensaver is activated, the temperature of the microprocessor rises to 40◦C; this increase in temperature is not unexpected, as the microprocessor is now performing more tasks in order to display the screensaver on the computers monitor. Similarly, when the computer is running a computer game program, the microprocessor temperature increases from 33◦C to 45◦C. Interestingly, the execution of a PowerPoint presentation does not significantly increase the temperature of the microprocessor from steady state conditions. The graphics processor operates at a slightly higher temperature than the microprocessor at 38◦C under steady state conditions, rising to 42◦C when the screensaver is activated.

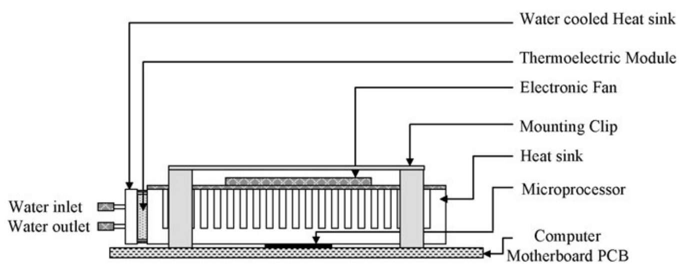

Fig. 10. Schematic diagram of the water cooled thermoelectric power generation assembly.

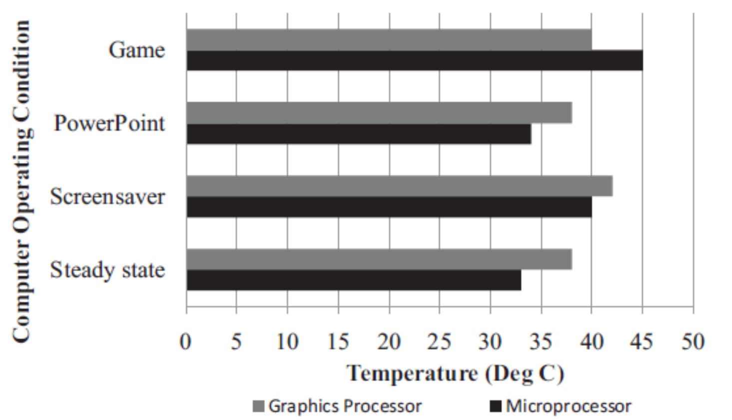

Fig. 11. Microprocessor and graphics processor temperature with standard heat sink and fan assemblies.

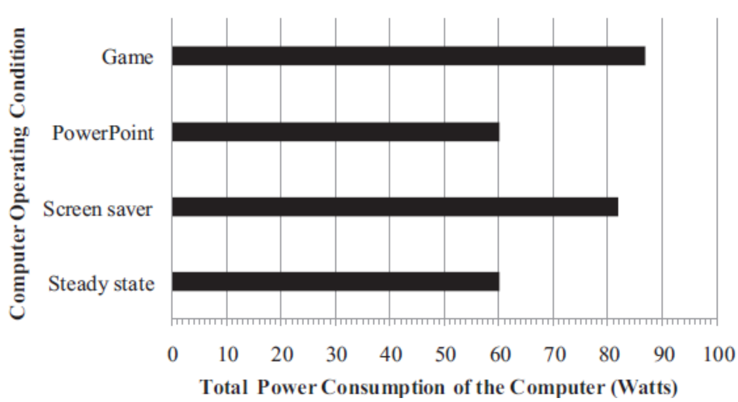

Fig. 12. Total power consumption of the computer in each of the four operating conditions.

The total electrical power consumption of the computer has been measured under the four operating conditions, using a plugin energy monitor inserted between the incoming 240V AC power socket and the computer's AC plug. It can be seen in Fig. 12, that the computer uses approximately 60W of electrical power under steady state conditions, rising to 87W when the game program is running. The electronic fan mounted onto the standard heat sink assembly operates from an internal d.c. supply of 12V at 0.16A, which is an electrical power consumption of 1.92W.

The standard heat sink and electronic fan assembly was then replaced by different thermoelectric solutions. Initially, module A was mounted between the microprocessor and the standard heat sink and fan assembly. The results of this test can be seen in Fig. 13 and Table 1. The thermoelectric module does reduce the temperature of the microprocessor when electrical power is applied to the module's input terminals. However, it should be noted that if no electrical power is applied to the module, the introduction of the module between the microprocessor and the standard heat sink assembly causes the steady state temperature of the microprocessor to increase. Without the thermoelectric module, the temperature of the microprocessor was 33◦C under steady state conditions. With the introduction of the module, the temperature has risen to 40◦C. This is not unexpected as the module will increase the thermal load of the system, and the heat sink and electronic fan are no longer in direct contact with the microprocessor.

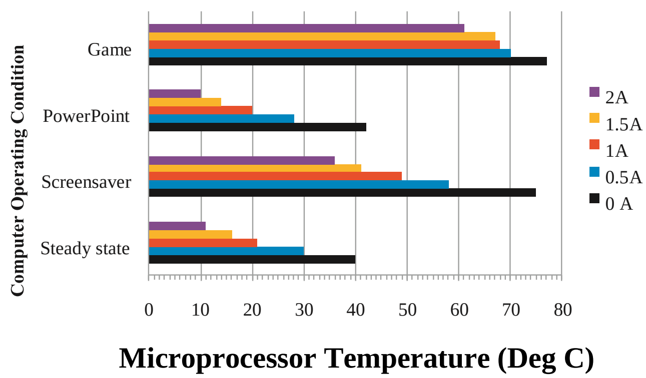

Fig. 13. Thermoelectric module A with standard heat sink and fan.

When the computer is in a steady state condition, and electrical power is applied to the thermoelectric module, the temperature of the microprocessor has reduced to 11◦C with a thermoelectric input current of 2A, and is significantly below the ambient temperature of 23◦C. Running the PowerPoint presentation does not significantly affect the temperature of the microprocessor. In contrast, with a thermoelectric input current between 0.5A and 2A, the microprocessor temperature rises to a higher temperature than observed using only the heat sink and fan assembly when the computer game is running. In this situation, without increasing the thermoelectric input current further, the thermoelectric module has reached a point where it cannot transfer the heat sufficiently from the 'cold' side of the module, attached to the microprocessor, to the module's 'hot' side, where the heat can be rejected by the heat sink and electronic fan into the atmosphere. This results in an increase in temperature of the 'cold' side of the module and will eventually lead to the module no longer functioning satisfactorily as a heat pump. Furthermore, the difference in temperature observed between the 'hot' and 'cold' sides of the module (T) can be seen to be negative when the computer game is running, highlighting that the 'cold' side of the module is now at a higher temperature than the 'hot' side of the module.

If the thermoelectric input current is increased from its current level, it may be possible to reduce the temperature of the microprocessor further when the game program is running. The thermoelectric input current range of 0.5–2A was chosen to ensure the microprocessor stayed within its temperature specification limits as it was cooled by the thermoelectric module. The manufacturer datasheet for the Intel Pentium 4 1.8GHz microprocessor specifies an absolute maximum case temperature range of between 5◦C and 77◦C [12]. If the thermoelectric input current is increased above 2A in order to achieve lower microprocessor temperatures when the computer is running the game program, it is important to ensure this does not result in the microprocessor temperature goingbelowthelowerspecificationlimitof5◦Cwhenthecomputer returns to a steady state condition.

The standard heat sink and electronic fan was then replaced with a Thermo Electric Devices TDEX6015/TH heat sink and electronic

Table 1
Thermoelectric module A with standard heat sink and fan.

Thermoelectric input current	0 A	0.5 A	1 A	1.5 A	2 A
Thermoelectric module	ΔT	ΔT	ΔT	ΔT	ΔT
Steady state	−9 °C	2 °C	11 °C	18 °C	26 °C
Screensaver	−42 °C	−24 °C	−10 °C	−3 °C	8 °C
Power point	−11 °C	1 °C	12 °C	18 °C	27 °C
Game	−44 °C	−37 °C	−33 °C	−24 °C	−16 °C

Table 2
Thermoelectric module A with TDEX6015/TH.

Thermoelectric input current	0 A	0.5 A	1 A	1.5 A	2 A
Thermoelectric module	ΔT	ΔT	ΔT	ΔT	ΔT
Steady state	−10 °C	3 °C	13 °C	22 °C	30 °C
Screensaver	−37 °C	−19 °C	−10 °C	−2 °C	10 °C
Power point	−12 °C	3 °C	12 °C	21 °C	30 °C
Game	−4 °C	−20 °C	−20 °C	−18 °C	−10 °C

fan assembly, with typical test results shown in Fig. 14 and Table 2. The TDEX6015/TH heat sink is relatively small in size and measures 60mm×60mm×15mm, and is smaller than the standard microprocessor heat sink which measures 83mm×69mm×35mm. There is limited space around the microprocessor to mount a new heat sink, and therefore the placement and choice of heat sink is limited. The TDEX6015/TH electronic fan operates from a 12V at 0.13A d.c. supply, which is an electrical power consumption of
1.56W.

Replacing the standard heat sink has, in most cases, improved the system performance. With a thermoelectric input current of 0.5A, the steady state temperature of the microprocessor is now 26◦C instead of 30◦C, an improvement on the temperature observed earlier with the module and standard heat sink assembly. As the thermoelectric input current increases to 2A, the temperature of the microprocessor is similar using either of the two heat sink and fan assemblies.

Replacing the TDEX6015/TH heat sink and electronic fan with a Melcor LI201 water cooled heat sink and RS M200-S-SUB miniature water pump further improves the performance of the thermoelectric system. A water cooled heat sink reduces the temperature of the microprocessor by circulating water through the heat sink using the water pump. As the water passes through the heat sink, heat is transferred from the heat sink to the water and carried away, in this case to an external container that circulates the water back into the system. The results of these tests are shown in Fig. 15, where

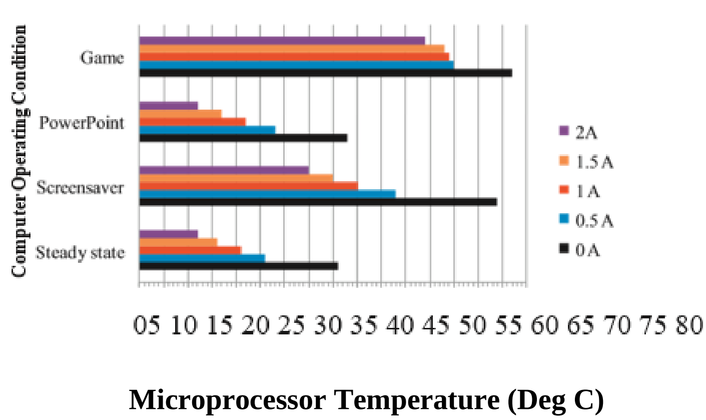

Fig. 14. Thermoelectric module A with TDEX6015/TH.

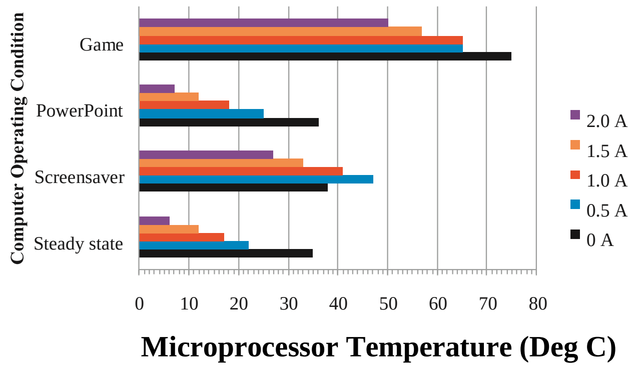

Fig. 15. Thermoelectric module A with LI201 water cooled heat sink.

it can be seen that with a thermoelectric input current of 2A, the temperature of the microprocessor has now been cooled to 6◦C when the computer is in the steady state condition, very close to the microprocessor lower temperature specification limit of 5◦C [12].

Comparing the results with the standard system, the temperature of the microprocessor is now at a lower level in three of the four computer operating conditions. Running the computer game still raises the temperature of the microprocessor to 50◦C with a thermoelectric input current of 2A, which is 5◦C above the temperature achieved by the standard system.

As noted earlier, increasing the thermoelectric input current above 2A when the computer game is running would lower the microprocessor temperature below 50◦C, but this is likely to result in the microprocessor being cooled below 5◦C when the computer is in a steady state condition. One solution is to vary the thermoelectric input current, instead of maintaining a fixed value, increasing the current above 2A when required, and then reducing it in order to maintain a desired microprocessor temperature.

In order to evaluate the performance of the thermoelectric cooling system on the graphics processor, a smaller thermoelectric module had to be used due to the physical size constraints imposed by the graphic card’s design. A Supercool PE-127-10-13-UK thermoelectric module was attached between the graphics processor and the Melcor LI201 water cooled heat sink. This module is only 30mm×30mm×5.6mm in size and has 10 thermoelectric couples. A thermoelectric input current of 1A and 2A was used in this test, with the results shown in Fig. 16.

The temperature of the graphics processor has been reduced by using the thermoelectric module, with a temperature of 26◦C measured when the computer is running the screensaver application. The standard cooling system achieved a higher temperature of 42◦C under the same test conditions.

7.2. Thermoelectric temperature control

Temperature control of a thermoelectric module can be achieved by designing appropriate control electronics in order to control the thermoelectric input current. A common method is to use a Proportional Integral Derivative (PID) controller. Experiments have been conducted using the Supercool PR-59 PID controller to maintain the temperature of the microprocessor at 10◦C, 20◦C,

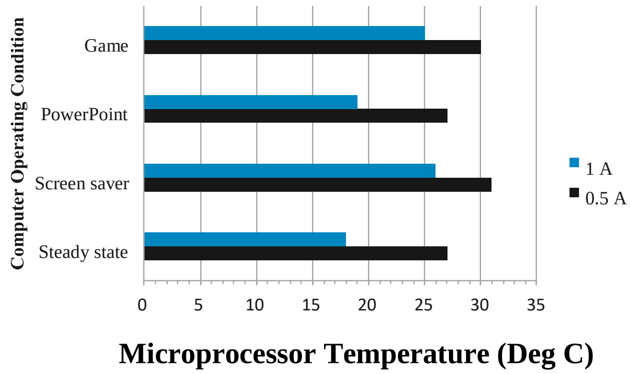

Fig. 16. Thermoelectric cooling of the graphics processor.

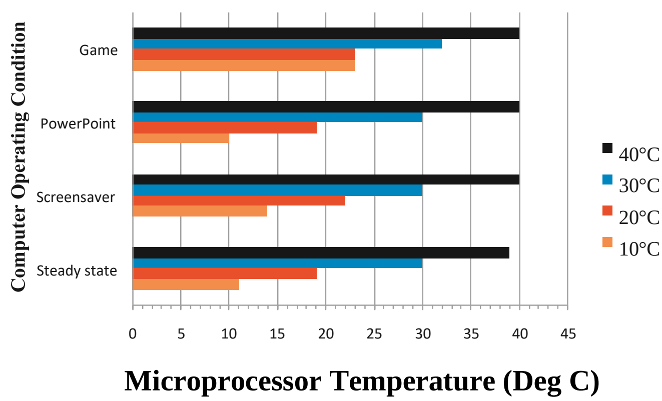

Fig. 17. Temperature control using thermoelectric module A, LI201 water cooled heat sink and PR-59 PID controller.

30◦C and 40◦C [13]. These four temperature settings demonstrate how a thermoelectric module can cool the microprocessor below ambient temperature and heat the microprocessor to a specific temperature. If the polarity of the thermoelectric input current is reversed, the module will now operate as a thermoelectric heater, resulting in the 'cold' side of the module increasing in temperature.

The power supply used to provide power to the thermoelectric module has a maximum output current and voltage of 5A and 20V. As module A and module B have a maximum input voltage of approximately 15V, the thermoelectric input voltage was limited to 14V. Therefore, the maximum thermoelectric input power is limited to 70W in these experiments.

The results for module A, fitted to the Melcor LI201 water cooled heat sink and RS M200-S-SUB water pump are shown in Fig. 17 and Table 3. The thermoelectric input current and voltage was recorded throughout the test and can be used to calculate the thermoelectric input power using Eq. (2). Using the PID controller, the thermoelectric module successfully maintains the set-point temperature under most of the operating conditions.

Under steady state conditions, the temperature of the microprocessor can be maintained at approximately 10◦C, 20◦C, 30◦C and 40◦C. The thermoelectric input power is typically 33W in order to maintain the temperature of the microprocessor at approximately 10◦C, reducing to 1W at 40◦C. Maintaining the temperature of the microprocessor at 40◦C requires the thermoelectric module to operate as a thermoelectric 'heater'. In this situation, the PID controller reverses the polarity of the thermoelectric input current and the temperature of the 'cold' side of the thermoelectric module can be seen to increase. Once the microprocessor temperature has reached the set-point of 40◦C, it only requires a small thermoelectric input power of 1W to maintain this temperature, as it is above the ambient temperature of 25◦C.

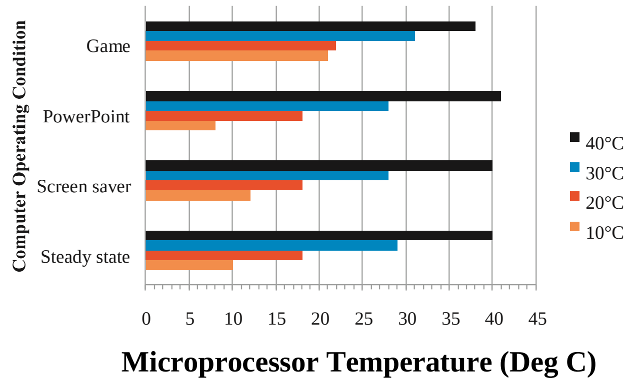

Fig. 18. Temperature control using thermoelectric module B, LI201 water cooled heat sink and PR-59 PID controller.

When the computer game program is running, the thermoelectric module successfully lowers the temperature of the microprocessor to 23◦C with a thermoelectric input power of 70W, which is significantly below the temperature observed using the standard system.

Further tests have been conducted using module B, with the results shown in Fig. 18 and Table 4. This module successfully cools the microprocessor to the set-point temperature at 20◦C, 30◦C and 40◦C under all the computer operating conditions. With a set-point temperature of 10◦C, the microprocessor is cooled to 21◦C when the computer game is running, which is the lowest temperature achieved in all the tests.

7.3. Thermoelectric power generation

The standard heat sink and fan assembly was then re-mounted onto the microprocessor, and thermoelectric module C (Melcor CP2-31-10L)wasattachedtotheoutsideofthemicroprocessorheat sink, with the other side of the module mounted onto the Thermo ElectricDevicesTDEX6015heatsink.Inthisarrangement,thewaste heat from the microprocessor will generate a small amount of electrical power when the thermoelectric module has a temperature difference maintained between the ‘hot’ and ‘cold’ sides of the module. It should be noted that the hot side of the thermoelectric module,T_{Hot},forthermoelectricpowergenerationisnormallyassociated with the side of the thermoelectric module that is attached to the heat source, in this case the microprocessor heat sink. The cold side of the module, T_{Cold}, is the side of the module attached to the TDEX6015 heat sink. The output terminals of the thermo- electric module were connected to a 2 resistive load (RL). This value of load resistance was chosen to ensure maximum power transfer would occur. Previous work has demonstrated that maximum power generation occurs with a resistive load of 2 with this module [14].

Table 3
Temperature control using thermoelectric module A, LI201 water cooled heat sink and PR-59 PID controller.

Set-point temp	10◦C	20◦C	30◦C	40◦C
Thermoelectric input power	Typ input power	Typ input power	Typ input power	Typ input power
Steady state	33 W	21 W	8 W	1 W
Screensaver	53 W	45 W	35 W	23 W
PowerPoint	33 W	20 W	9 W	1 W
Game	70 W	68 W	59 W	50 W

Table 4
Temperature control using thermoelectric module B, LI201 water cooled heat sink and PR-59 PID controller.

Set-point temp	10 °C	20 °C	30 °C	40 °C
Thermoelectric input power	Typ input power	Typ input power	Typ input power	Typ input power
Steady state	52 W	38 W	13 W	5 W
Screensaver	70 W	70 W	54 W	34 W
PowerPoint	70 W	57 W	37 W	8 W
Game	70 W	70 W	70 W	50 W

Table 5
Thermoelectric power generation, module C and D, and TDEX6015.

	Thermoelectric module C, ΔT temp.	Ambient temp.	Thermoelectric Module D, ΔT temp.	Ambient temp.
Steady state	0.4 °C	22 °C	0.7 °C	23 °C
Screensaver	3.0 °C	22 °C	2.0 °C	22 °C
PowerPoint	0.6 °C	22 °C	0.7 °C	23 °C
Game	6.0 °C	23 °C	2.5 °C	23 °C

electric module were connected to a 2 resistive load (RL). This value of load resistance was chosen to ensure maximum power transfer would occur. Previous work has demonstrated that maximum power generation occurs with a resistive load of 2 with this module [14].

The thermoelectric output power generated by the thermoelectric module was measured for the four computer operating conditions, with typical test results presented in Fig. 19 and Table 5. The ‘Peak’ electrical power is the highest recorded power generated by the thermoelectric module during the test. The ‘Typical’ electrical power is the average power generated when the thermoelectric module has reached a stable power output. A thermoelectric module will generate the highest electrical power output when the largest temperature difference occurs between both sides of the module. This often happens when the hot side of the module rapidly increases in temperature, and the cold side of the module is maintained at a lower temperature. Over time, if the cold side of the module cannot reject all of the temperature pumped from the hot side, often due to insufficient thermal capability of the heat sink assembly, the temperature of the cold side will increase and reduce the temperature difference between both sides of the module. Overtime, the temperature difference between the hot and cold sides of the module will stabilise, and a stable or typical electrical power is generated at the load.

The electrical power generated by thermoelectric module C is within the micro-watt range. If the computer is in a steady state condition or executing the PowerPoint presentation, the typical power generated in the resistive load is relatively small at 0.3–0.4W. The power generated by the module is low due to the very small temperature difference achieved between the ‘hot’ and ‘cold’ sides of the module. As the computer is executing more demanding applications, i.e. the screensaver and game program, the electrical power generated by the thermoelectric module increases but is still within the micro-watt range. Higher electrical power levels have been achieved using module D (Supercool PE127-10-13-UK), although the power generated is still within the micro-watt range. The results for module C and D are shown in Fig. 19 and Table 5.

Replacing the TDEX6015 heat sink with the Melcor LI201 water cooled heat sink and RS M200-S-SUB water pump significantly improves the power generated by the thermoelectric module.

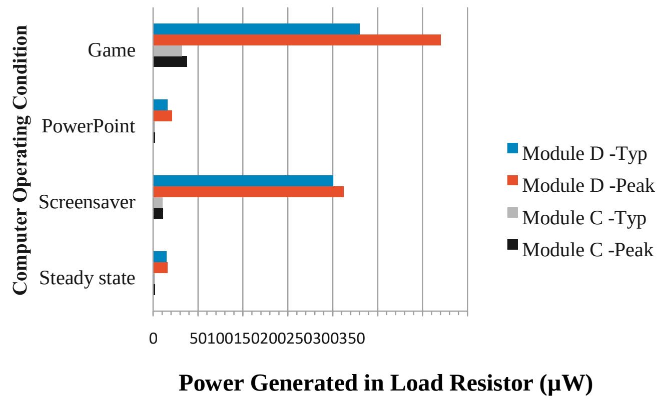

Fig. 20. Thermoelectric power generation, modules C and D, and water cooled heat sink.

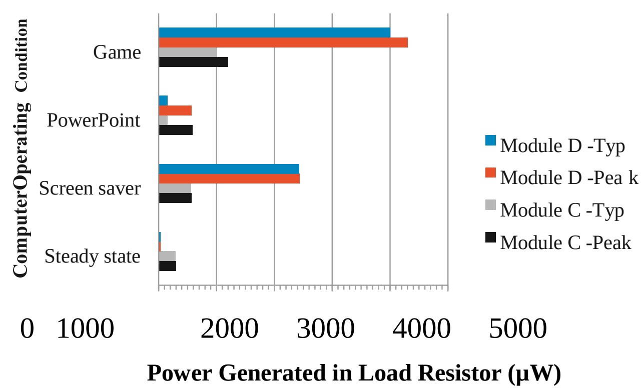

Fig. 19. Thermoelectric power generation, modules C and D, and TDEX6015.

Using module C, the electrical power generated in the resistive load is now in the milli-watt range when the computer game is running. This is not unexpected, as the increased performance of the heat sink will produce a greater temperature difference between the ‘hot’ and ‘cold’ sides of the module. In this case, the electrical power supplied to the water pump was 2W, and would require more power to operate than the power generated by the thermoelectric module. However, if the water pump was already present in the system, or thermoelectric cooling was implemented using a water cooled heat sink, the power generated by the thermoelectric module would be of benefit to the overall system. The test was repeated using module D, and it can be seen that higher power levels are generated in the resistive load with this module, with a

typical power generated in the load of 4mW when the computer game is running. The results for module C and D with the water cooled heat sink are shown in Fig. 20.

8. Discussion

The experiment results demonstrate that thermoelectric modules can successfully lower the operating temperature of the computer’s microprocessor and graphics processor. The thermoelectric modules used were not chosen or optimised for their thermoelectric coefficient of performance (COP), but are sufficient to demonstrate the concept of thermoelectric cooling. Using thermoelectric modules that are operating at their maximum COP may improve the overall performance of the system. It has been shown that the type of heat sink used does have an effect on the overall performance of the thermoelectric cooling system. Replacing the standard heat sink and electronic fan assembly with a Thermo Electric Devices TDEX6015/TH heat sink and fan improves the performance of the thermoelectric solution, with lower microprocessor temperatures achieved. Using a water cooled heat sink further improves the performance of the system, and under steady state conditions and a thermoelectric input current of 2A, the temperature of the microprocessor has now been reduced to 6◦C. With a thermoelectric input current range of 0.5–2A, the computer game is the only operating condition where the standard system achieves better cooling performance.

Controlling the thermoelectric input current, by adding the Supercool PR-59 PID controller to the system, demonstrates how a

thermoelectric module can maintain the temperature of the microprocessor to a pre-set level. The thermoelectric solution maintains the set-point temperature under most of the computer operating conditions using the PID controller. The microprocessor temperature can be controlled at approximately 10◦C, 20◦C, 30◦C and 40◦C when the computer is in a steady state condition, running the PowerPoint presentation or screensaver application. Although the temperature of the microprocessor does not reach 10◦C when the computer game is running, the temperature has been significantly reduced to 21◦C, and is a now at a much lower temperature than observed when using the standard cooling system.

Overall, the experiment results demonstrate that thermoelectric cooling of the microprocessor and graphics processor has been successfully achieved. Using a water cooled heat sink and PID controller to vary the thermoelectric input current achieves the best results.

Mounting a thermoelectric module onto the outside of the standard heat sink and electronic fan assembly enables a small amount of electrical power, typically in the microwatt range, to be generated if a Thermo Electric Devices TDEX6015 heat sink, without an electronic fan, is attached to the other side of the thermoelectric module. The Supercool PE-127-10-13-UK thermoelectric module generates a peak power of 320W using a 2 load resistor (RL), higher than observed when using the Melcor CP2-31-10L which generates a peak power of 38W under the same test conditions. Higher power levels can be generated if the TDEX6015 heat sink is replaced with a Melcor LI201 water cooled heat sink mounted onto the cold side of the thermoelectric module. The peak power generated in the load resistor (RL) rises to 4.2mW with the Supercool module, and 1.2mW using the Melcor module. It should be noted that using the water cooled heat sink and water pump does consume electrical power, in contrast to using the TDEX6015 heat sink in the previous test, which requires no external power as cooling is achieved through natural convection only.

Although the electrical power generated by a thermoelectric module is very small, it can be accumulated and stored in capacitors or super capacitors for future use. Connecting two or more thermoelectric modules in series or parallel will also increase the overall voltage or current produced by the modules. Another technique often implemented is to increase the thermoelectric output voltage by using charge pump capacitors or DC to DC converters [1]. The electrical power generated could be used to recharge batteries and potentially power an electronic fan or water pump. Further investigation into the power requirements of individual electronic circuits within the computer system needs to be conducted in order to identify how this electrical power generated by the thermoelectric module could be used.

9. Conclusions

Thermo electric cooling and electrical power generation within a standard desktop computer has been demonstrated. Replacing the standard forced-air cooled systems, used to cool the microprocessor and graphics processor, with a thermoelectric solution enables lower integrated circuit operating temperatures to be obtained. It is also possible to cool the microprocessor and graphics processor to temperatures below ambient conditions.

The waste heat created by integrated circuits within the computer system can be utilised to generate electrical power. Attaching a thermoelectric module onto the outside of the standard heat sink assembly, with a secondary heat sink attached to the other side of the thermoelectric module, in order to create a temperature difference between both sides of the module, generates a small amount of electrical power that is typically in the milli-watt or micro-watt range. Maximum electrical power can be generated by the thermoelectric module when a water cooled heat sink is used as the secondary heat sink, as this produces the greatest temperature difference between both sides of the module. Although the electrical power generated by a thermoelectric module is relatively small, it can be stored in capacitors or super capacitors for future use, charge batteries or power other electronic devices in the computer system.

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