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Waste Heat Recovery System Applied to a High-Performance Video Card

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ABSTRACT This paper presents results given by a waste heat recovery (WHR) system applied to a high-performance video card, as well as average energy generated per hour according to emulation of computer graphics requirements demanded by the user while the card is working. A WHR system includes three phases: (1) waste heat collection, (2) energy conversion and (3) signal conditioning. The analysis of the WHR system is presented. The emulation of waste heat has been generated using electrical resistors as if they were the main components that generate waste heat, mainly the GPU (graphics processing unit), and DDR3 memories. This WHR system has considered the MSI-R4850 video card as a reference, operation temperature of which has an overall range between 60°C – 90°C. Thermoelectric generator modules (TEG) are based on the Seebeck effect, and the thermoelectric array used is an important part of the WHR system, which has been constructed based on the locations of the main components to convert waste heat into electrical power. The waste heat recovery process has two treatments: First, once the operating conditions, per GPU and DDR3 memories have been emulated, the energy recovered is measured per component and whole WHR system; the second one measures energy recovered considering the output signal conditioning of the WHR system, which was converted to 5V output through a DC-DC boost converter, while the input voltage operates within a range (0.9V – 5V). The energy recovered may be applied to low-power electronic devices, which is a contribution to energy efficiency.

INDEX TERMS Energy efficiency, seebeck effect, thermoelectric generator, thermoelectricity, waste heat recovery system.

I. INTRODUCTION

The increasing demand for electricity around the world has diversified the generation technologies in their primary sources, to permit coverage of the projected worldwide demand according to World Energy Outlook 2015. According to the new policies scenario, global primary energy demand will increase by nearly one-third between 2013 and 2040 to reach 17 900 Mtoe [1] in a sustainable way. This electrical energy demand projection includes not only fossil fuel usage but also renewable and clean sources.

This work found waste heat generation sources in a high-performance video card, according to a framework for energy recovery assessment [2], mainly in the GPU process and DDR3 memories while they are working to collect the heat waste and generate electrical power; then, the energy can be used to recharge batteries or supply energy to low power electronic devices.

The current technologies and applications for low-temperature waste heat recovery [3] have been analyzed from two perspectives: the local waste heat recovery technology and global optimization of the energy flow network, where the main problems to face are: first, lack of global optimization methodology; second, distributed waste heat recovery is not feasible yet, due to high costs; third, the mismatches between the waste heat supply and demand [4].

One important tool related to certain waste heat recovery systems is the thermoelectric generator (TEG), used as a device to generate clean-energy [5]–[7]. Some studies show that a new model of a compact thermoelectric generator has been developed to improve the electric performance per unit volume and maximize the energy conversion efficiency [8].

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Additionally, material properties and thermal losses, which occur as conductive heat transfer, have been analyzed by a mathematical model to better understand the temperature-dependent performance of a thermoelectric generator, and some effects of its use [9]. In addition, a strong correlation between the thermoelectric generator (TEG) performance and system mass was concluded on the basis of the multi-objective optimization results of a thermoelectric (TE) device [10]. Further, a power processing architecture standpoint reveals the recovery of thermal energy waste by means of thermoelectric modules and arrays [11].

Experimental studies regarding thermal power generation conducted with thermoelectric modules (TEM) at various operating conditions [12] have also used constant flow heat in a specific period of time; the test system is just programmed to change the volumetric and temperature flow rates as independent experiments, but the inflows to the thermoelectric modules remain constant and do not oscillate as a function of time within each experiment [13]. The heat-flow of a video card oscillates according to the graphic's requirements of the application used.

On the other hand, there have also been experimental studies focused on the application of thermoelectric modules for power generation, using the waste heat generated from a central processing unit (CPU) [14] of a desktop computer, under certain conditions or processing requirements, derives from users' needs like different computer applications. This test system involves additional equipment as a cooling system that includes a miniature water pump and water holding tank, to be used in one side of the thermoelectric module to increase ΔT [15].

The research on the waste heat usage from a waste heat source was also studied integrating the non-uniformity of the surface temperature distribution [16]. Furthermore, an experimental and numerical study was carried out on waste heat collection at low temperature with 24 thermoelectric generators (TEGs) to convert heat from the exhaust pipe of a car into electrical power [17].

The continuous search for alternative energy sources for several applications has seen achievements in the health area, in which a pacemaker has as a power source, an energy harvester based on the use of thermoelectric energy as a primary source, when the circuit is enabled to start up from input voltages as low as 60mV. The maximum deliverable power load from the energy harvester is 130μW. Indeed, the circuit was designed in such a way that overload conditions are tolerated [18].

One of the great research effort concerning the use of a thermoelectric system as an application reference for waste heat recovery has been in the Internet of Things (IoT) [19], [20], where wireless sensor networks (WSNs) are generally powered by some batteries with limited energy. The temperature is one of the critical parameters being monitored in industrial processes. Industrial plants have lots of hot pipelines, equipment or walls can function as a thermal energy source; for example, a waste heat recovery system that functions as a thermal energy harvesting wireless sensor network (WSN) node for temperature monitoring in IoT was implemented, where the WSN node can work autonomously and monitor the temperature of the industrial equipment, contributing to the partial resolution of the batteries' limited energy [21].

In the transportation sector, there exist several applications mainly because a considerable part of the fuel energy in vehicles never reaches the wheels and converts entirely to waste heat. A waste heat recovery system applied to solving this problem reported that the maximum recovered electrical power from the thermoelectric generators (TEGs) reached 1 kW, which was transmitted to the electrical system of the heavy duty vehicle [22].

The main objectives of this work are as follows: first, the maximum generation of electrical power, given the waste heat generated by the GPU and the working DDR3 memories of a high-performance video card which are directly related to the demand for graphics processing by the user. This objective is pursued through a thermoelectric array using thermoelectric generators (TEGs) according to the most appropriate potential thermal locations in the video card. For this work, the video card thermal process was emulated.

In this paper, three phases are considered, first: waste heat collection, second: conversion of thermal power into electrical power, and third: signal conditioning to charging low power electronic devices.

II. THERMOELECTRIC TECHNOLOGY OVERVIEW

Thermoelectric generators (TEGs) are solid-state energy converter devices or semiconductor systems that rely on a phenomenon called the Seebeck effect [23]–[25], which converts heat directly into electrical power through temperature differences between its two ceramic plates for recovering waste heat, also called Seebeck generators.

Thermoelectric devices contain thermoelectric couples n-type and p- type semiconductor materials, such as suitably doped bismuth telluride, arranged as shown in Fig.1. Bismuth telluride (Bi_2Te_3), has been extensively used in the construction of thermoelectric modules and it is the best material for use in thermoelectric generators when the temperature of the heat source is moderate [26]. Thus, bismuth telluride material is constantly studied to improve its performance, due to its potential utility in power generation [27]. The thermoelectric elements are wired electrically in series and thermally in parallel.

The open circuit voltage (V_0) of a thermoelectric generator is proportional to the temperature difference across the thermoelectric generator, and is given by [28]:

$$V_0 = N\alpha_{pn}\Delta T_{TEG}. \quad (1)$$

where N is the number of semiconductor thermoelements, $\alpha_{pn}$is the Seebeck coefficient of the thermocouple, and ΔT is the temperature difference across the thermocouples in a TEG. Also α_{pn} is defined as below:

$$\alpha_{pn} = \alpha_p - \alpha_n. \quad (2)$$

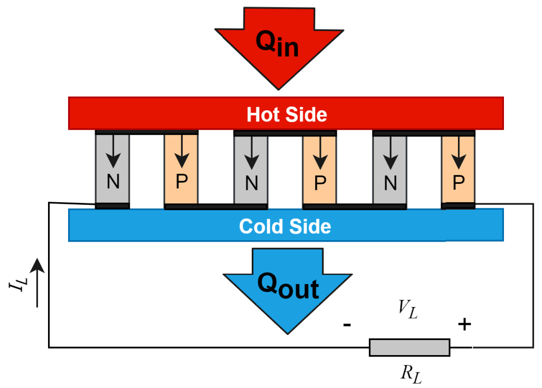


FIGURE 1. Representation of a TEG.

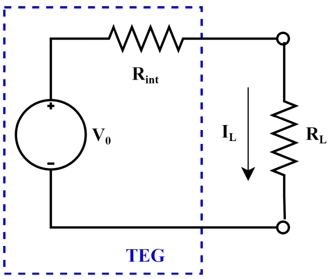


FIGURE 2. Electrical equivalent circuit of a TEG with a load.

where α_p and α_n are the Seebeck coefficients of p-type and n-type semiconductor, respectively; thus, ΔT_{TEG} is given by:

$$\Delta T_{TEG} = \Delta T \frac{K}{K + 2K_{int} + \frac{2\alpha^2 T_m}{R_{int}+R_L}} = \xi \Delta T. \quad (3)$$

K is the thermal conductivity of the ceramic plate, $T_m = (T_h + T_c)/2$ is the mean temperature, where K_{in} is the thermal conductance. The external temperature difference across the thermoelectric generator can be expressed as follows:

$$\Delta T = T_h - T_c. \quad (4)$$

The electrical equivalent circuit of a TEG with a load R_L is shown in Fig.2. When a load R_L is connected to the TEG, the output voltage V_L that arises across that load R_L, V_L, is less than V_0 and is a function of the load resistance R_L and the internal resistance R_{int} of the TEG. The output power P_L generated by a TEG to the load R_L may be calculated as [21]:

$$\begin{aligned} P_L &= I_L^2 R_L = \left(\frac{N\alpha_{pn}\xi\Delta T}{R_{int}+R_L}\right)^2 R_L \\ &= N^2\alpha_{pn}^2\xi^2\Delta T^2 \frac{R_L}{(R_{int}+R_L)^2}. \end{aligned} \quad (5)$$

where R_{int} is the internal resistance of the TEG. The maximum output power is delivered to an electrical load when that load is chosen to match the internal resistance of the TEG ($R_L = R_{int}$) as follows:

$$P_{Lmax} = \frac{N^2\alpha_{pn}^2\xi^2\Delta T^2}{4R_{int}}. \quad (6)$$

To maximize the power-generation efficiency of the TEG, the temperature differential between the hot and cold sides should be as large as possible.

III. WASTE HEAT RECOVERY SYSTEM ANALYSIS

The electronic components that generate more waste heat than others are the GPU and the DDR3 memories (2 blocks). Fig.3 shows the thermal flux generated by these electronic components, which is considered, as thermal power (P_{th}).

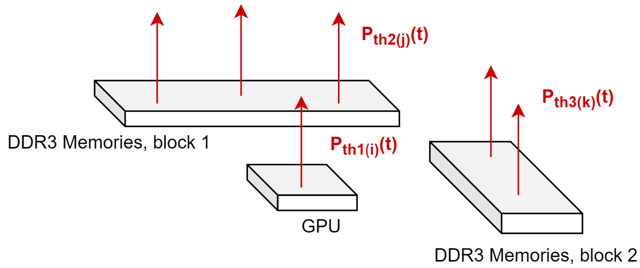


FIGURE 3. Schematic thermal power flow of GPU and DDR3 memories of the video card.

Thus, the sum of the thermal powers of a certain block of memories, or GPU results in the total thermal power generated by each component while it is working, as follows:

$$P_{th1}(t) = \sum_{i=1}^{n} P_{th1(i)}(t). \quad (7)$$

$$P_{th2}(t) = \sum_{j=1}^{n} P_{th2(j)}(t). \quad (8)$$

$$P_{th3}(t) = \sum_{k=1}^{n} P_{th3(k)}(t). \quad (9)$$

$$P_{th(Tot)}(t) = P_{th1}(t) + P_{th2}(t) + P_{th3}(t). \quad (10)$$

where $P_{th1} = GPU$ thermal power generation, $P_{th2} = DDR3$ memories(1) thermal power generation and $P_{th3} = DDR3$ memories(2) thermal power generation. To improve the heat distribution on the ceramic plate corresponding to T_h side of the TEG, and improve the waste heat collection, an aluminium plate was added, according to the dimensions of each component, the thermal conductivity of which is $220W/mK$ given a room temperature of $300K$ [29].

Heat transfer by conduction takes place across the interface between two material bodies in contact when at different temperatures, from regions of high temperature to regions of low temperature [30]. Heat flux from the surface of each electronic component (GPU and DDR3 memories blocks) to the surface of each aluminium plate, is shown in Fig.4.

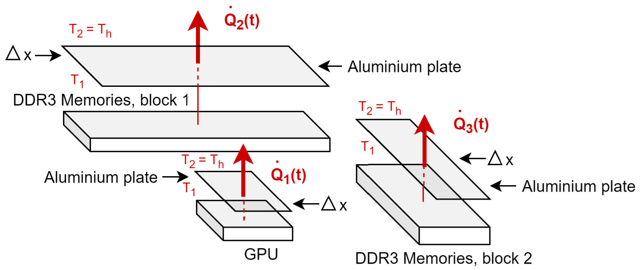


FIGURE 4. **Schematic heat flux of GPU and DDR3 memories across the aluminium plate.**

Heat flux for a one-dimensional steady system may be calculated as:

$$\dot{Q} = \lambda A \frac{T_1 - T_2}{\Delta x}. \tag{11}$$

where $\dot{Q}$ is the amount of heat transferred per unit area per unit time through the plate, λ is the thermal conductivity of the material of the plate, Δx is the plate thickness, A is the surface area of the plate, T_1 is the temperature of the surface of an electronic component(GPU and DDR3 memories), and T_2 is the temperature of the surface of the plate. Therefore, the equation that defines T_2 is:

$$T_2 = T_1 - \left[\frac{\Delta x \dot{Q}}{\lambda A}\right]. \tag{12}$$

Thus, T_2 corresponds to the highest external temperature (T_h) between the two ceramic plates of the TEG:

$$T_{2(i)} = T_{h(i)}. \tag{13}$$

Combining equations (5)-(12) and substituting T_h in order to calculate the output power P_L generated by a TEG to the load R_L:

$$\begin{aligned} P_L &= \left(\frac{N\alpha_{pn}\xi\left(\left[T_{1(i)} - \left|\frac{\Delta x_i \dot{Q}_i}{\lambda A_i}\right|\right] - T_c\right)}{R_{int}+R_L}\right)^2 R_L \\ &= N^2\alpha_{pn}^2\xi^2\left(\left[T_{1(i)} - \left|\frac{\Delta x_i \dot{Q}_i}{\lambda A_i}\right|\right] - T_c\right)^2 \frac{R_L}{(R_{int}+R_L)^2} \end{aligned} \tag{14}$$

Summing each output power $P_{L(i)}$ generated by TEG to the load R_L:

$$P_{L(Tot)} = \sum_{i=1}^{n} P_{L(i)}. \tag{15}$$

Combining equations (6)-(12) and substituting T_h, the maximum output power P_{Lmax} can be expressed as:

$$P_{Lmax} = \frac{N^2\alpha_{pn}^2\xi^2\left(\left[T_{1(i)} - \left|\frac{\Delta x_i \dot{Q}_i}{\lambda A_i}\right|\right] - T_c\right)^2}{4R_{int}}. \tag{16}$$

Summing each maximum output power $P_{Lmax(i)}$ to calculate the total maximum output power of the system:

$$P_{Lmax(Tot)} = \sum_{i=1}^{n} P_{Lmax(i)}. \tag{17}$$

The total maximum output power depicts the potential quantity per unit time (energy recovered [Er]) that would be obtained by the waste heat recovery system ideally.

IV. EXPERIMENT METHODOLOGY

A. EMULATION OF THE HIGH-PERFORMANCE VIDEO CARD

The reference video card used for this work is an MSI R4850, shown in Fig.5. The temperature range within which the video card works efficiently, i.e., within which the heat does not affect, diminish the performance or cause any damage to the microprocessor, DDR3 memories or other electronic components of the video card is (60°C – 90°C) according to data provided by the manufacturer.

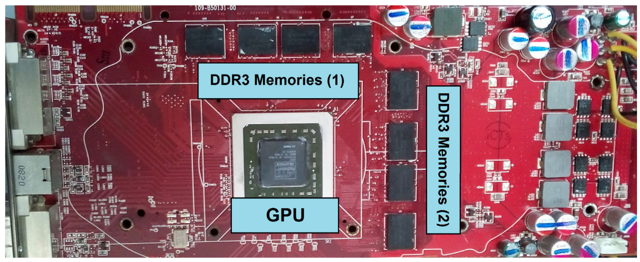


FIGURE 5. **Reference high performance video card.**

According to the thermovision image shown in Fig.6, the video card components that generate the highest waste heat, due to graphics processing demanded by the user, are the graphics processing unit (GPU) and the DDR3 memories (two blocks). Red and white spots in the thermovision image depict these electronic components, generating the highest waste heat, while the video card is working.

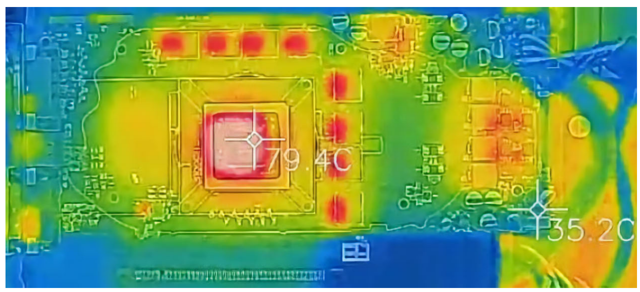


FIGURE 6. **Thermovision image of the video card when it is working.**

Once the video card electronic components that generate significant waste heat have been determined, the temperature data of each electronic component are acquired as a function of time. These data represent a very important input to configure the energy conversion system, because it is highly necessary to know the thermal behavior of the main electronics components that will be emulated through electrical resistors.

Fig.7 shows the temperature data correlation graph between the GPU and DDR3 memories when they start working, which have a strong linear association. Thus, according to the results of data acquisition, DDR3 memory blocks temperature is established up to 60°C, and GPU temperature is established up to 90°C. However, the increased temperature between GPU and DDR3 memories has a different velocity ratio.

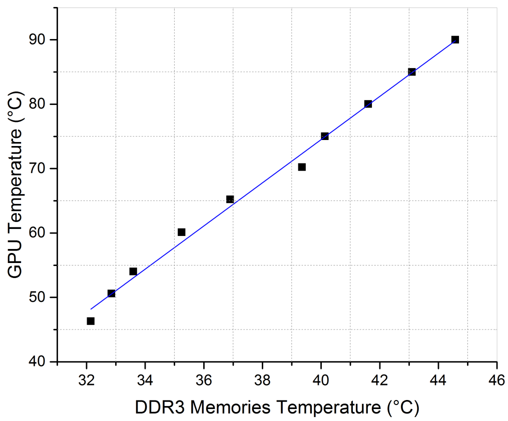
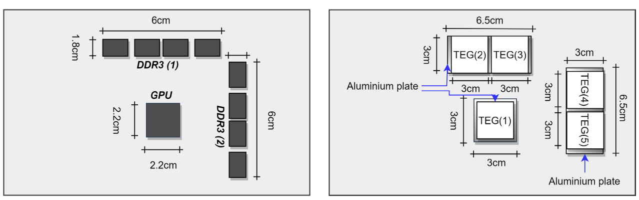


FIGURE 7. Correlation graph of temperatures GPU - DDR3 Memories.

B. TEST SYSTEM FOR WASTE HEAT RECOVERY

Geometric parameters of experimental setup (video card components and waste heat recovery system) are shown in Fig.8(a) and (b) respectively.

The WHR system consists of: (1) Waste heat collector: a thermal sheet, aluminium plate and thermal insulating materials, (2) Energy conversion: TEGs array (5 TEGs) with the standard heat sink and an electronic fan, (3) Signal conditioning: Boost DC-DC converter to $5V$.



(a) (b)

FIGURE 8. Geometric parameters of experimental setup (a)Video card components (b)Waste heat recovery system components.

Energy conversion from thermal power into electrical power is based on the temperature range (60°C – 90°C) determined previously, to determine the implementation of the thermoelectric array, five commercial thermoelectric generator modules TXL-127-03L from TXL Group were distributed in three blocks: the first is of 30*30mm, with just 1 TEG, which power input is the waste heat from GPU within a range of ΔT between (0 – 60°C); the second one consists of a pair of TEGs of 30*30mm each, and receives power input from the waste heat of the first block of DDR3 memories within a range of ΔT between (0 – 30°C); finally, the third one is a group of 2 TEGs of 30*30mm each, which corresponds to the second block of DDR3 memories within the same range of the first DDR3 memory block. As a result of this arrangement, the thermoelectric generator modules work in different operating conditions for temperature. The temperature of the thermal behavior emulation of the graphics processor unit and DDR3 memories has been measured, using LM35 temperature sensors, under steady state conditions when the computer is turned on, until a screensaver application is running, within range of temperature mentioned previously for a one hour working standard by the user. The 'cold' side of a module is normally the side of the module attached to the heat sink, and the 'hot' side of the module is the side attached to the aluminium plate which is the waste heat collector.

The TEGs array is configured electrically in series as shown in Fig.9, which includes a general-purpose diode of germanium that it is hooked up to one TEG module of the arrangement as a protection element against backflows, as well as low voltage consumption, besides a capacitor to keep a constant current flow.

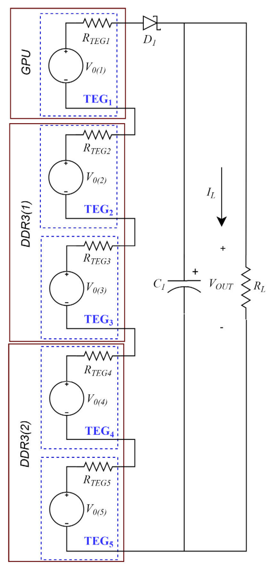


FIGURE 9. Energy conversion TEGs array: series configuration.

The hardware and materials of the WHR system consist of a personal computer running Matlab as data acquisition software and data logging unit, Arduino MEGA 2560 (microcontroller and electronic platform) as data acquisition card, LM35 temperature sensors, voltage sensors, aluminium plate, thermal sheet, thermal insulating material, five commercial TEG modules, TXL-127-03L from TXL Group in TEGs array, heat sink, standard electronic fan, and electric resistors with voltage controllers to emulate the thermal behavior of the video card (i.e., the temperature range of the electrical resistors that emulate GPU 60°C – 90°C) and the temperature range of the electrical resistors that emulate DDR3 memory blocks 30° – 60°C. A schematic diagram of the WHR system test is shown in Fig.10. The test system that includes a DC-DC boost converter to $5V$ is shown in Fig. 11.

The voltage measured in the load resistor is recorded by the Matlab data acquisition system. An LM35 sensor

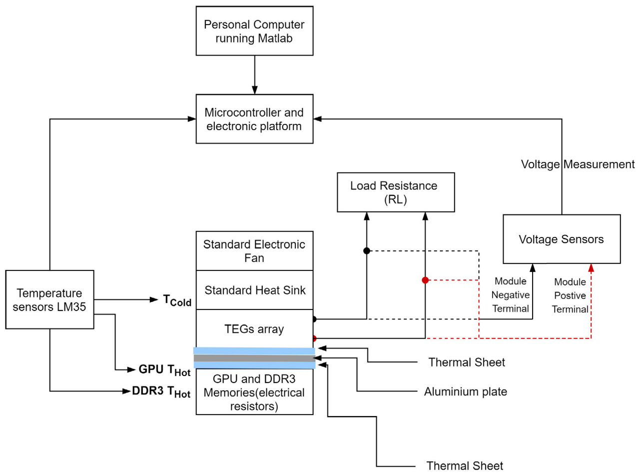


FIGURE 10. Schematic diagram of the test system for waste heat recovery.

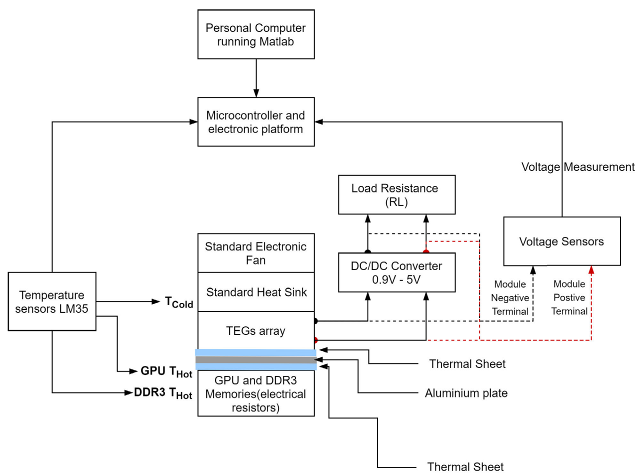


FIGURE 11. Schematic diagram of the test system for waste heat recovery with DC boost Converter.

measures the temperature of the standard heat sink, which is at approximately the same temperature as the cold side of the thermoelectric module, and the temperature of each electrical resistor, which emulates the thermal behavior of the electronic components at approximately the same temperature as the hot side of the thermoelectric module.

A set of experiments were undertaken using the experimental setup, with and without a DC-DC boost converter, as shown in Fig.12, and have also been conducted to determine maximum energy recovery from waste heat in the computer system for a one hour working standard by the user, just considering the video card hardware in both cases.

V. RESULTS AND DISCUSSION

A. POWER CURVE OF WASTE HEAT RECOVERED

The TEGs array's positive and negative terminals are connected to a variable load resistor (R_L), Which has been chosen to ensure the occurrence of maximum power transfer, while the emulation of the video card is operating within the same range of ΔT defined previously for the WHR system; data were thus acquired and recorded. According to these

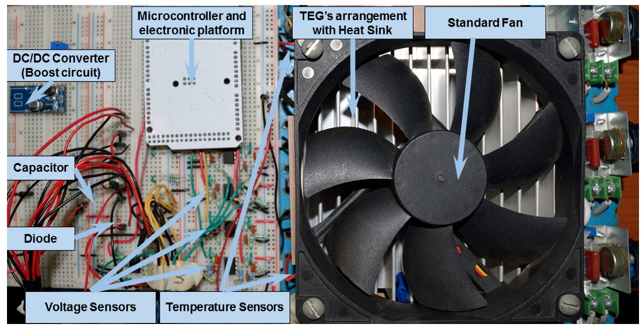


FIGURE 12. View of the experimental setup.

results, the load resistor to the first setup is established as $(R_L) = 40\Omega$ without DC-DC converter, a plot of the power output as a function of the maximum possible power, given the aforementioned conditions, which can be delivered to a load without DC-DC converter is shown in Fig.13. Finally, the last setup is established as $(R_L) = 1k\Omega$ as load resistor value with DC-DC converter.

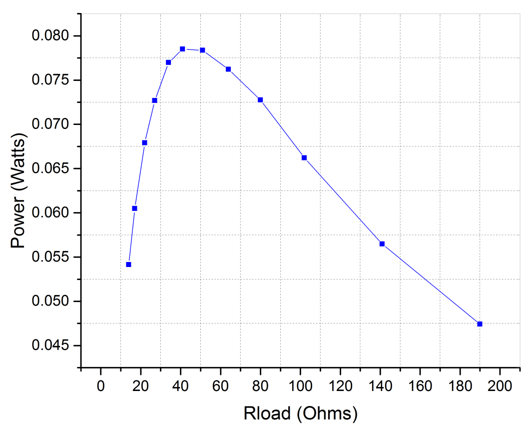


FIGURE 13. Output power as a function of load resistance.

B. ENERGY RECOVERED

For the first experiment set up, the parameters of the WHR system to convert the thermal power into electrical are measured and given in Table 1, where T_0 is the temperature of the standard heat sink, which is given as room temperature, T_1 is the temperature emulated of GPU, T_2 is the temperature emulated of DDR3 memories(1), T_3 is the temperature emulated of DDR3 memories(2), and V_{OUT}, I_{OUT} and P_{OUT} are the variables measured of the WHR system.

These parameters consider different temperature levels among electronic components that generate waste heat, due to the thermal behavior of these components which oscillate and are not constant values.

Least-squares data fitting method was used as a curve-fitting to obtain the best fit for the series of experimental data points [31].

The measurement data per main electronic component(GPU and DDR3 memories) is shown in the graphs 14 – 16 (a) and (b), respectively.

TABLE 1. Parameters of WHR system to the power conversion at different temperature levels.

T_0 $(°C)$	T_1 $(°C)$	T_2 $(°C)$	T_3 $(°C)$	V_{OUT} (mV)	I_{OUT} (mA)	P_{OUT} (mW)
29	90	59	60	1,924	48	93
29	80	54	57	1,834	46	84
30	71	50	50	1,022	26	26

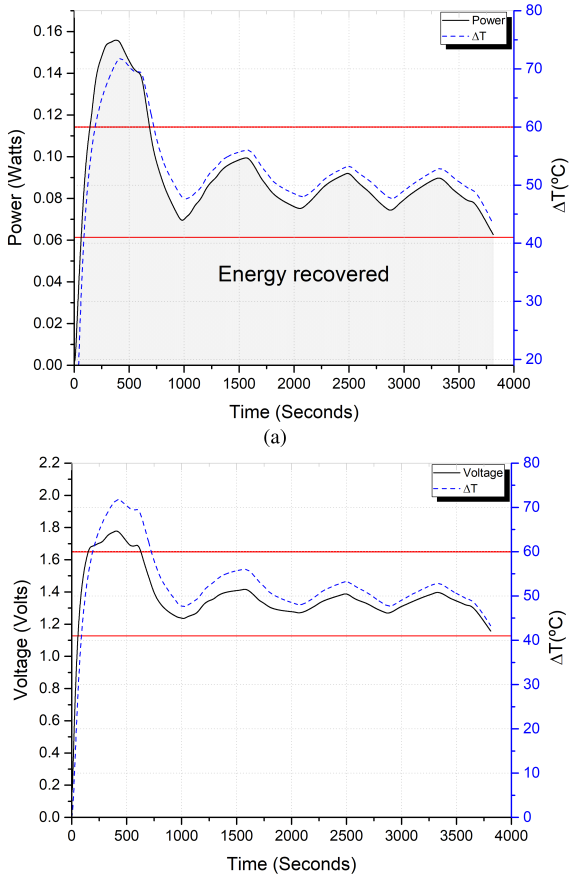


FIGURE 14. Results of the WHR system applied to emulation of the GPU for one hour, (a) power and ΔT as a function of time, (b) voltage, and ΔT as a function of time.

Energy recovered from each electronic component that generates waste heat of the video card (GPU and DDR3 memories) was calculated with the trapezoidal rule, which works by approximating the region under the graph of the function $P(t)$ as a trapezoid and calculating its area, during the established period (one hour). The power, voltage, and ΔT values as a function of time regarding the emulation of the GPU component, are shown in Fig. 14(a) and (b) respectively. The energy recovered depicts the region under the graph of the function $P(t)$, as is shown in Fig.14(a), which value is 334Wh. The ΔT range of the emulation of GPU, which was working for an hour, oscillates between (41°C – 60°C), while the process was stable; the maximum power reached was 99mW, whereas the maximum voltage reached in the same range of ΔT was 1.41V.

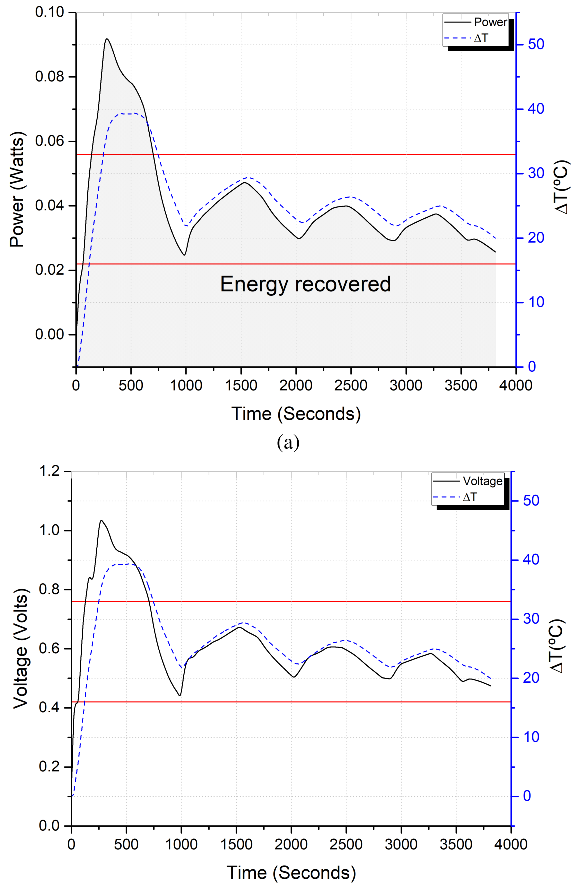


FIGURE 15. Results of the WHR system applied to emulation of the DDR3(1) memories for one hour, (a) power and ΔT as a function of time, (b) voltage, and ΔT as a function of time.

Regarding DDR3 memories block one, the power, voltage and ΔT values as a function of time, which are related to the emulation of this component are shown in Fig.15(a) and (b) correspondingly. The energy recovered depicts the region under the graph of the function $P(t)$ of this emulation, as is shown in Fig.15(a), which value is 152Wh. The ΔT range of the emulation of DDR3 memories block one, which was working during the same period, oscillates between (16°C – 33°C), while the process was stable; the maximum power reached was 47mW, whereas the maximum voltage reached in the same range of ΔT was 0.67V.

The power, voltage, and ΔT values as a function of time, regarding the emulation of DDR3 memories block two, are shown in Fig.16(a) and (b), accordingly. The energy recovered depicts the region under the graph of the function $P(t)$ of the DDR3 memories block two, as is shown in Fig.16(a), which value is 154Wh. The ΔT range of the emulation of DDR3 memories block two, which was working for an hour, oscillates between (16°C – 35°C), while the process was stable; the maximum power reached was 51mW, while the maximum voltage reached in the same range of ΔT was 0.72V.

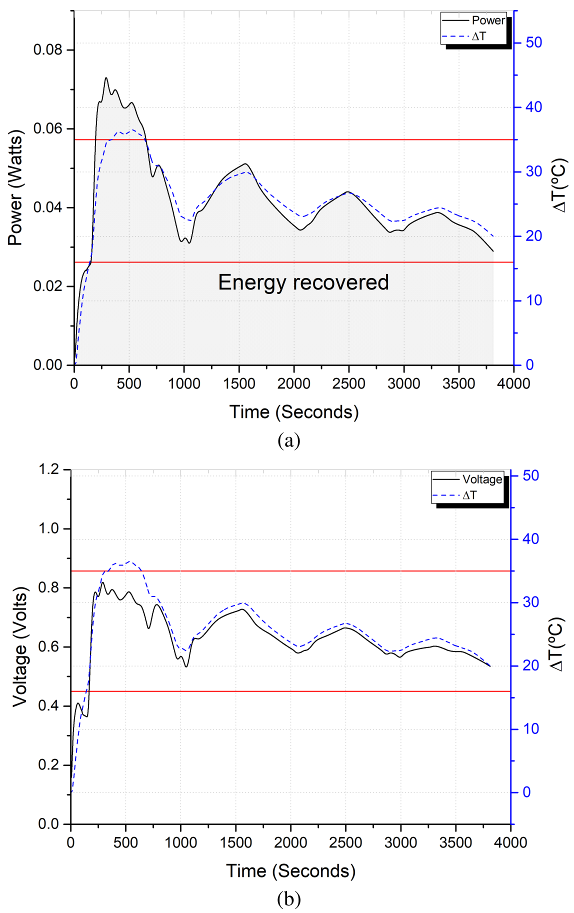


FIGURE 16. Results of the WHR system applied to emulation of the DDR3(2) memories for one hour, (a) power and ΔT as a function of time, (b) voltage, and ΔT as a function of time.

The second experiment set up has the objective of determining the energy recovered as a whole system, as well as conditioning the signal to 5V output. The parameters of the WHR system to convert thermal power into electrical are measured and given in Table 2, considering different levels of temperature among electronic components that generate waste heat according to their function. Where T_0 is the temperature of the standard heat sink, which is considered as room temperature, T_1 is the temperature emulated of GPU, T_2 is the temperature emulated of DDR3 memories(1), T_3 is the temperature emulated of DDR3 memories(2), and V_{OUT}, I_{OUT} and P_{OUT} are the variables measured of the WHR system to the output of DC-DC boost converter. The voltage and power values as a function of ΔT from the emulation of the whole WHR system with a DC-DC boost converter (5V signal output continuously) are shown in Fig.17(a) and (b) respectively. The energy recovered is represented by the region under the graph of the function $P(t)$ of the whole WHR system, as is shown in Fig. 17 (b), which value is 89Wh. Fig.17(a) depicts the voltage measured from the TEGs array and output of the DC-DC boost converter, which reached 5V whereas the voltage value is above 0.9V.

TABLE 2. Parameters of WHR system with dc–dc boost converter to the power conversion at different temperature levels.

T_0 $(^\circ C)$	T_1 $(^\circ C)$	T_2 $(^\circ C)$	T_3 $(^\circ C)$	V_{OUT} (mV)	I_{OUT} (mA)	P_{OUT} (mW)
28	90	58	58	4,987	5	25
28	80	55	55	4,976	4	24
28	72	49	50	3,797	3	14

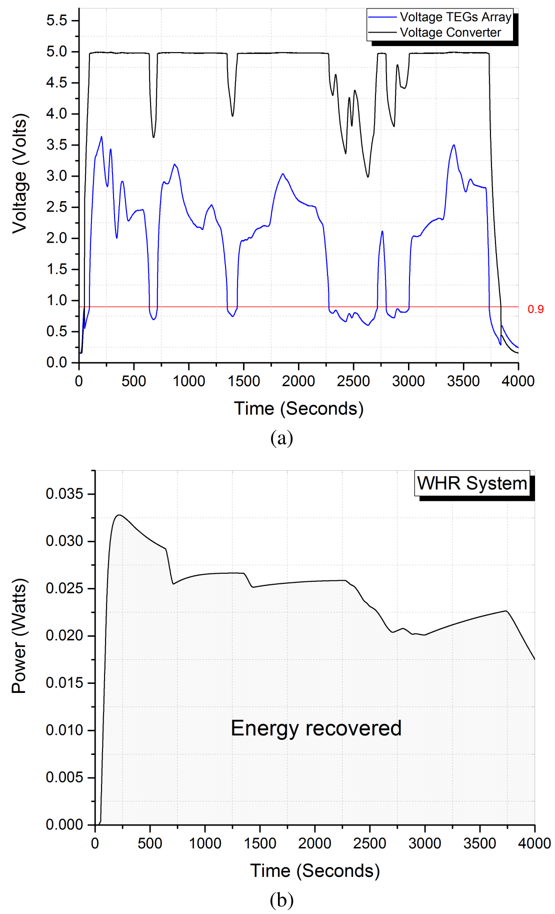


FIGURE 17. Results of the WHR system applied to emulation of the video card with dc–dc boost converter for one hour, (a) the voltage value of the TEGs array and the output converter simultaneously and (b) power.

C. ENERGY CONVERSION EFFICIENCY

Summing the energy recovered (Er) measured independently:

$$Er_{WHRS} = Er_{GPU} + Er_{DDR3(1)} + Er_{DDR3(2)}. \quad (18)$$

The energy recovered from the WHR system is 640Wh, relative to the total energy recovered, measured as a whole WHR system, which is 229Wh. Taking this data into account, it is possible to obtain the transfer energy efficiency of the WHR system, which is 36%. Based on this information, one of the following steps is to deeply investigate the losses generated in the process of recovered energy transfer, to reduce the gap as much as possible and maximize the transfer power to the load, per unit time (Er).

VI. CONCLUSION

Waste heat energy recovery from emulating a high-performance video card has been established as an alternative to charging low power electronic devices, given that there is No additional energy required for this purpose once it is implemented on the computer. This work is a basis to apply within a computer in the next step, which consists of modifying the devices that emit waste heat to include waste heat recovery systems as a component and improve their energy efficiency. The WHR process will show variations in terms of the quantity of energy recovered across time, mainly due to dependency on the graphics requirements demanded by the user, which gives a bigger or smaller differential of temperature. Results of energy generated from the waste heat recovery system were 229Wh, with an efficiency ($\eta = 36\%$) considering typical behavior and load resistance $R = 40\Omega$. Results of energy recovered considering DC boost converter were 89Wh with load resistance $R = 1k\Omega$. The contribution of this work consists of a potential advance in reducing a computer's energy consumption via increasing its energy efficiency with a waste heat recovery system. In addition to charging low power batteries, the energy recovered from the hardware can function as additional input power to the computer fan, input power for some electronic circuits according to their energy consumption, and so forth.

REFERENCES

[1] F. Birol, "World energy outlook 2015," *International Energy Agency*, vol. 1, no. 1, 2015.

[2] E. Woolley, Y. Luo, and A. Simeone, "Industrial waste heat recovery: A systematic approach," *Sustain. Energy Technol. Assessments*, vol. 29, pp. 50–59, Oct. 2018.

[3] H. Jouhara, N. Khordehgah, S. Almahmoud, B. Delpech, A. Chauhan, and S. A. Tassou, "Waste heat recovery technologies and applications," *Therm. Sci. Eng. Prog.*, vol. 6, pp. 268–289, Jun. 2018.

[4] Z. Xu, R. Wang, and C. Yang, "Perspectives for low-temperature waste heat recovery," *Energy*, vol. 176, pp. 1037–1043, Jun. 2019.

[5] J. Xie, C. Lee, and H. Feng, "Design, fabrication, and characterization of CMOS MEMS-based thermoelectric power generators," *J. Microelectromech. Syst.*, vol. 19, no. 2, pp. 317–324, Apr. 2010.

[6] D. Zabek and F. Morini, "Solid state generators and energy harvesters for waste heat recovery and thermal energy harvesting," *Ther. Sci. Eng. Prog.*, vol. 9, pp. 235–247, Mar. 2019.

[7] E. Kanimba and Z. Tian, "A new dimensionless number for thermoelectric generator performance," *Appl. Ther. Eng.*, vol. 152, pp. 858–864, Apr. 2019.

[8] T. Ming, W. Yang, X. Huang, Y. Wu, X. Li, and J. Liu, "Analytical and numerical investigation on a new compact thermoelectric generator," *Energy Convers. Manage.*, vol. 132, pp. 261–271, Jan. 2017.

[9] H. Lee, J. Sharp, D. Stokes, M. Pearson, and S. Priya, "Modeling and analysis of the effect of thermal losses on thermoelectric generator performance using effective properties," *Appl. Energy*, vol. 211, pp. 987–996, Feb. 2018.

[10] T. H. Kwan, X. Wu, and Q. Yao, "Thermoelectric device multi-objective optimization using a simultaneous TEG and TEC characterization," *Energy Convers. Manage.*, vol. 168, pp. 85–97, Jul. 2018.

[11] A. Petucco, S. Saggini, L. Corradini, and P. Mattavelli, "Analysis of power processing architectures for thermoelectric energy harvesting," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 4, no. 3, pp. 1036–1049, Sep. 2016.

[12] W.-H. Chen, C.-Y. Liao, C.-I. Hung, and W.-L. Huang, "Experimental study on thermoelectric modules for power generation at various operating conditions," *Energy*, vol. 45, no. 1, pp. 874–881, Sep. 2012.

[13] S. Mahmoudinezhad, A. Rezaniakolaei, and L. A. Rosendahl, "Experimental study on effect of operating conditions on thermoelectric power generation," *Energy Procedia*, vol. 142, pp. 558–563, Dec. 2017.

[14] C. Gould, N. Shammas, S. Grainger, and I. Taylor, "Thermoelectric technology: Micro-electrical and power generation properties," in *Proc. 2008 43rd Int. Universities Power Eng. Conf.*, Sep. 2008, pp. 1–5.

[15] C. Gould, N. Shammas, S. Grainger, and I. Taylor, "Thermoelectric cooling of microelectronic circuits and waste heat electrical power generation in a desktop personal computer," *Mater. Sci. Eng., B*, vol. 176, no. 4, pp. 316–325, Mar. 2011.

[16] Y. Zhou, S. Paul, and S. Bhunia, "Harvesting wasted heat in a microprocessor using thermoelectric generators: Modeling, analysis and measurement," in *Proc. Design, Autom. Test Eur.*, Mar. 2008, pp. 98–103.

[17] C.-T. Hsu, G.-Y. Huang, H.-S. Chu, B. Yu, and D.-J. Yao, "Experiments and simulations on low-temperature waste heat harvesting system by thermoelectric power generators," *Appl. Energy*, vol. 88, no. 4, pp. 1291–1297, Apr. 2011.

[18] M. Ashraf and N. Masoumi, "A thermal energy harvesting power supply with an internal startup circuit for pacemakers," *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.*, vol. 24, no. 1, pp. 26–37, Jan. 2016.

[19] Z. Hadas, L. Janak, and J. Smilek, "Virtual prototypes of energy harvesting systems for industrial applications," *Mech. Syst. Signal Process.*, vol. 110, pp. 152–164, Sep. 2018.

[20] H. Park, D. Lee, G. Park, S. Park, S. Khan, J. Kim, and W. Kim, "Energy harvesting using thermoelectricity for IoT (Internet of Things) and E-skin sensors," *J. Phys. Energy*, vol. 1, no. 4, Jul. 2019, Art. no. 042001.

[21] L. Hou, S. Tan, Z. Zhang, and N. W. Bergmann, "Thermal energy harvesting WSNs node for temperature monitoring in IIoT," *IEEE Access*, vol. 6, pp. 35243–35249, 2018.

[22] A. E. Risseh, H.-P. Nee, and C. Goupil, "Electrical power conditioning system for thermoelectric waste heat recovery in commercial vehicles," *IEEE Trans. Transp. Electrific.*, vol. 4, no. 2, pp. 548–562, Jun. 2018.

[23] L. E. Bell, "Cooling, heating, generating power, and recovering waste heat with thermoelectric systems," *Science*, vol. 321, no. 5895, pp. 1457–1461, Sep. 2008.

[24] G. J. Snyder and E. S. Toberer, "Complex thermoelectric materials," in *Materials for Sustainable Energy: A Collection of Peer-Reviewed Research and Review Articles From Nature Publishing Group*. Singapore: World Scientific, 2011, pp. 101–110.

[25] A. L. O. Maran, N. C. Henao, E. A. Silva, L. Schaeffer, and O. H. Ando, Jr., "Use of the seebeck effect for energy harvesting," *IEEE Latin Amer. Trans.*, vol. 14, no. 9, pp. 4106–4114, Sep. 2016.

[26] H. Goldsmid, "Bismuth telluride and its alloys as materials for thermoelectric generation," *Materials*, vol. 7, no. 4, pp. 2577–2592, Mar. 2014.

[27] L. Hu, H. Wu, T. Zhu, C. Fu, J. He, P. Ying, and X. Zhao, "Tuning multiscale microstructures to enhance thermoelectric performance of n-type bismuth-telluride-based solid solutions," *Adv. Energy Mater.*, vol. 5, no. 17, Sep. 2015, Art. no. 1500411.

[28] S. Dalola, M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli, and A. Taroni, "Characterization of thermoelectric modules for powering autonomous sensors," *IEEE Trans. Instrum. Meas.*, vol. 58, no. 1, pp. 99–107, Jan. 2009.

[29] T. W. Clyne, "4.7 thermal and electrical conduction in metal matrix composites," Tech. Rep., 2018.

[30] S. Kakaç, Y. Yener, and C. P. Naveira-Cotta, *Heat Conduction*. Boca Raton, FL, USA: CRC Press, 2018.

[31] J. R. Hauser, *Numerical Methods for Nonlinear Engineering Models*. Springer, 2009.

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