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Investigation of secondary cooling design enhancements in thermally limited compact notebooks

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Abstract: Thermal design enhancements in a thermally limited compact notebook system are investigated in this paper. System temperature, power, and fan speed are characterized under a range of activity levels. A finite element model is developed, and validated against measurements. Design enhancements improve cooling with minimum intrusion to the existing mechanical design. A passive secondary heat pipe in the system reduces the CPU temperature by 5 °C, and improves the system performance through increased CPU + Graphics and Memory Controller Hub (GMCH) thermal design power (TDP) by 6.4%. When such a secondary heat pipe is considered with an integrated off-the-shelf Peltier cooler, the CPU temperature is only reduced by 2.3 °C and CPU+GMCH TDP is improved only by 4.9%. Although Peltier integration provides no benefit to thermals, it can be advantageous in generating small amount of thermoelectric power in conditions when the system is not executing thermally limited applications. Calculations suggest that a 10% increase in Seebeck coefficient and consequently a 5.5% increase in coefficient of performance (COP) of off-the-shelf thermoelectric materials can increase the TDP envelop by 7.1% using the Peltier-integrated secondary heat pipe scheme.

Key words: Thermal management, notebook systems, passive cooling, Peltier cooling

1. Introduction

Decreasing size and increasing device density, in accordance with Moore's law, pose thermal management challenges in the design of today's microelectronic systems. Undesired temperature levels constrain processor design, and have been proven to be a key limiter in performance, throttling, clock skew, leakage power, reliability, variability, and cooling costs for modern processors [1]. System thermal limit, i.e. the maximum power required to be dissipated by cooling system in a computer, also known as thermal design power or TDP, is about 80 W for low power mobile computers at present, and may increase in the future [2]. This corresponds to heat flux of between 57 W/cm^2 and 108 W/cm^2, which must be removed from the package through appropriate cooling techniques. Tightly packed configuration of components in compact ultrabooks, notebooks, and netbooks limits the free convection to be used as the main mode of heat transfer due to very little room for air within the chassis of these systems. Consequently, these systems are now provided with a combination of active and passive cooling

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solutions through the utilization of conduction plates (heat spreaders), heat pipes, fans, and heat exchangers to dissipate heat from hot components to the ambient.

As an alternate active cooling method, a DC voltage is applied to thermoelectric (TE) Peltier module's input to turn it into a heat pump. Most office systems do not run a TDP activity in daily use most of the time. When these applications do occur, maximum performance is typically desired from the computing platform. TE Peltier modules need to be activated on demand without exceeding the power budget, and should otherwise be turned off to avoid depleting precious battery charge in a mobile system. In addition, TE needs to be integrated using a carefully selected cooling design to minimize negative impact on the heat rejection path from its thermal resistance when it is not powered.

This study investigates cooling opportunities in a compact notebook system predisposed to an environment highly constrained in terms of size, temperature, and power. The main contributions of the work are: (i) A validated thermal simulation model of a thermally limited notebook system for investigating enhancements to the existing cooling solution with minimum change to the original mechanical design, (ii) derivation and verification of the near-optimal conditions for the integration of a secondary active and passive cooling solution in a selected real compact system with and without TE technology, (iii) projection and comparison of benefits from different cooling enhancements set forth in (ii).

2. Background

The amount of heat Q_C dissipated by a Peltier cooler can be expressed as a function of electrical current I passing through the interface and the Peltier coefficient Π of the material. In its simplest form it can be defined as

$$Q_C = f\ (\Pi\,, I)\ , \tag{1}$$

where

$$\Pi = \alpha\, T_C\,, \tag{2}$$

α is the Seebeck coefficient, and T_c is the temperature of the cold side of the module. Q_C can then be estimated by the energy balance equation at the controlled junction [3] as

$$Q_c = 2n\alpha I T_C - \frac{1}{2} I^2 \frac{2n\rho}{\gamma} - 2n\gamma k \Delta T \tag{3}$$

and

$$\gamma = \frac{A_e}{L}\ , \tag{4}$$

where A_e and L represent the cross-sectional area and length of a TE element. The power input to the module can be calculated as a product of supplied voltage and current as follows:

$$P_{in} = V I \tag{5}$$

The coefficient of performance for the TE module can be calculated by simply dividing (3) by (5):

$$COP = \frac{Q_c}{P_{in}} \tag{6}$$

Thermal cooling is of high research interest due to the requirement to bound maximum processor temperature under active operating conditions despite the continuous miniaturization of notebook systems. Tari et al. [4]

numerically investigated the heat loads on active and passive paths in a typical notebook system. A new component distribution was proposed in this work to utilize opportunistic spaces in the system to enable stand-alone passive cooling. Peltier cooling was first analyzed by Taylor et al. [3], where a TE module was introduced between heat sink and CPU. Application of TE refrigeration was reported to be limited, but it was projected that rigorous system level modelling could enable TE refrigeration in practice.

Litivinovitch et al. analyzed steady state cooling of hot-spots using Si and SiGe superlattice TE modules [5]. The temperature of the hotspot location was reduced by 4.5 °C, but several challenges were identified with integration in compact devices. In another study, by Gupta et al., a numerical Peltier model was developed with steady state and transient response for hotspot cooling [6]. Transient pulses effectively reduced the temperature of hot spots by 6–7 °C, while steady state current pulse reduced temperature across the device. Both [5] and [6] overlooked the possible challenges in physical integration and controlled operation of TE modules. Muhtaroğlu et al. introduced the idea of hybrid thermoelectric conversion in mobile computing for enhanced efficiency [7], which refers to the use of a TE module as cooler or power generator depending upon the instantaneous requirement of the system. A 10% theoretical improvement in system efficiency was projected using off-the-shelf TE modules. Taylor et al. [3] worked on Peltier cooling in desktop computers, but did not address the utilization of TE coolers in compact mobile computers, where thermal constraints are higher.

On-chip or in-package cooling solutions are costly and hard to implement; similarly chip power reduction is a major design effort that lasts months. A gap in the literature has thus been the empirical demonstration of integrating Peltier coolers at system level, and measurement of impact to system thermal performance. Another critical question for product teams has been about the additional cooling that can be achieved with minimum redesign effort for improved performance in increasingly popular notebooks of choice, which are small, thin, and thermally limited. Hence, the present study investigates fast in-system cooling solutions, with and without a TE component, through post-manufacturing analysis of microelectronic systems with consideration of minimum redesign cost.

3. System and methods

3.1. Target test system characterization

The selected notebook, a Toshiba Portégé R705-P25, was an office type, compact mobile computer. The details of mechanical and thermal characterization were presented previously [8]. Processor TDP of 35 W was shared between the CPU and GMCH in the same package. The maximum power dissipation of the full system totaled 65 W [9]. The characterization of the system began with the identification of hotspots through thermal imaging in open chassis conditions as shown in Figure 1. A nonintrusive, dual digital tachometer was used to measure the fan speed in the test system at every minute. Six different application scenarios, as reported in [8], were utilized for thermal, power, and fan speed characterization in the test system.

3.2. Finite element modelling of test system

Mechanical and thermal characterization data from the test system were used to build a model in ANSYS Icepak as shown in Figure 2. The meshing parameters and the resulting number of elements and nodes were previously reported in [8]. The heat source for thermal design conditions was assigned with a breakdown of 25 W inside the CPU die and 10 W inside the GMCH die, based on the specifications [10]. Another heat source of 1 W was defined inside the PCH [11]. The boundary conditions for computational domain were defined such that the model fluid was exposed to the external environment at 21 °C specified under ambient conditions of the simulation. All heat transfer options (conduction, convection, and radiation) were enabled in the simulation.

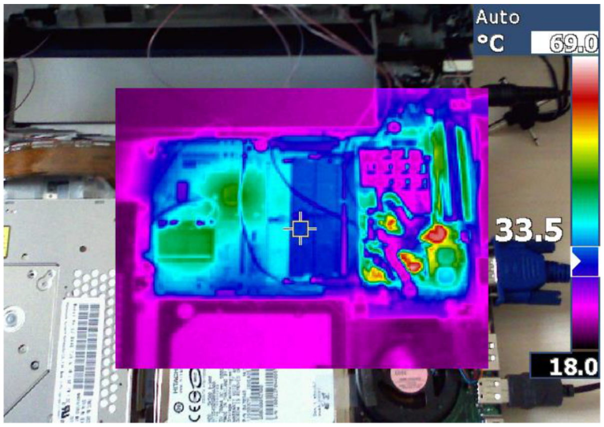

Figure 1. Thermal image of the test system in open chassis conditions.

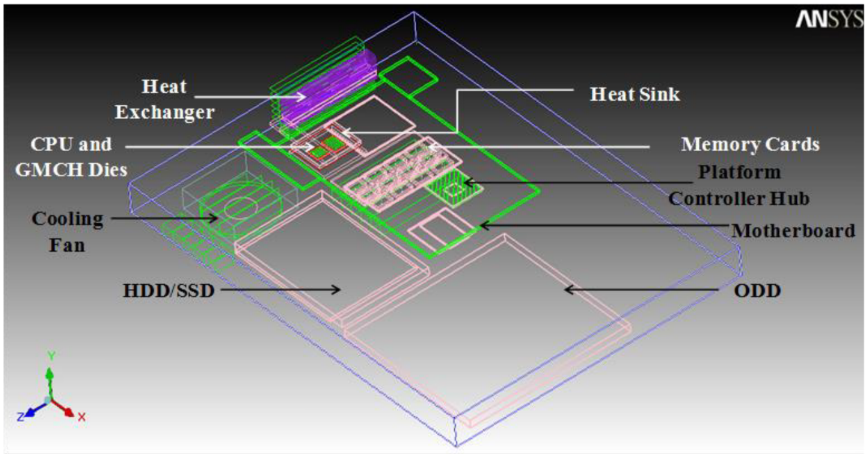

Figure 2. Modelling of test system in ANSYS Icepak.

3.3. Performance metrics and design enhancements

The secondary modifications in the system design targeted improvement of the thermal performance as measured by the following metrics:

1. Reduction in processor temperature at the component TDP specification condition,
2. Increased amount of component maximum thermal design power (TDP) that can be dissipated by the modified cooling solution without notably impacting the maximum attained processor temperature (and the fan speed).

3.3.1. Secondary heat pipe enhancement

The test system under consideration comes with a single heat pipe, which is placed on the heat spreader attached to the CPU+GMCH package, and dissipates heat from there to the ambient through a heat exchanger. With enough space available in the box, addition of a secondary heat pipe was considered as the first quick passive design enhancement, as shown in Figure 3. The improvement required no additional power. The enhancements were added to the model described in Section 3.2, and were verified by simulations.

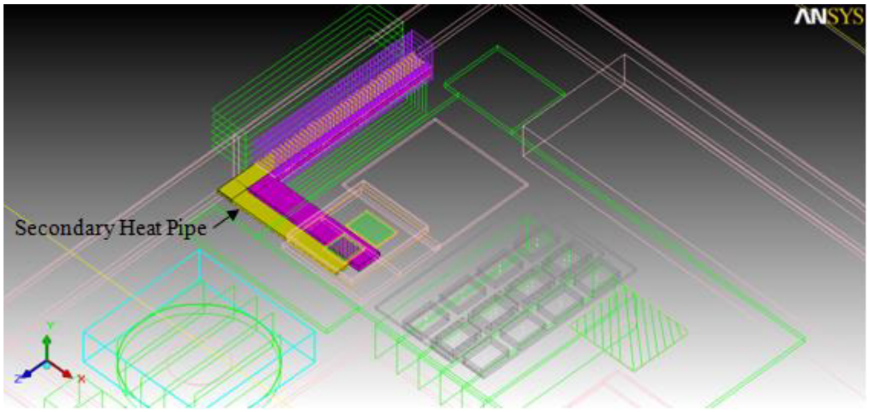

Figure 3. Secondary heat pipe in the test system (marked in yellow).

3.3.2. Secondary heat pipe + Peltier cooler enhancement

A simple model of an active Peltier cooler using three layers was constructed together with a secondary heat pipe to be integrated in the full system simulation. The material properties of the TE model are summarized in Table 1. Peltier coolers, when integrated to any application for cooling purpose, require a secondary solution that can dissipate heat from the hot side of the device. Hence, a Peltier cooler was first incorporated into the CPU side of CPU+GMCH package on top of the heat spreader next to the primary heat pipe, and the secondary heat pipe model was then connected to the top of the Peltier cooler (hot side) as shown in Figure 4.

Table 1. Material properties for Peltier cooler in Icepak.

Block Name	Material	Properties
TE Top Plate	Alumina Typical	k = 27 W/m-K
Bi_2Te_3	Bi_2Te_3 Solid Material	Density = 1890.2 kg/m^3 Specific Heat = 660 J/kg-k Orthotropic Conductivity 'W/m-K' kx= 0.026, ky = 0.0966, kz= 0.026
TE Bottom Plate	Alumina Typical	k= 27 W/m-K

4. Results and discussion

4.1. Measured temperature, power, and fan speed profile

The results from thermal, power, and fan speed measurements at all activity levels are summarized in Figure 5, which provided insight into the original system thermal design before enhancements. The temperature of each component in the system was directly related to CPU and GMCH temperatures since these were the dominant power dissipating parts. PWM fan control pushed the fan speed to the maximum observed, 5477 rpm, when the CPU temperature reached 100 °C. However, the overall range of fan speed throughout the characterization was 2200–5450 rpm.

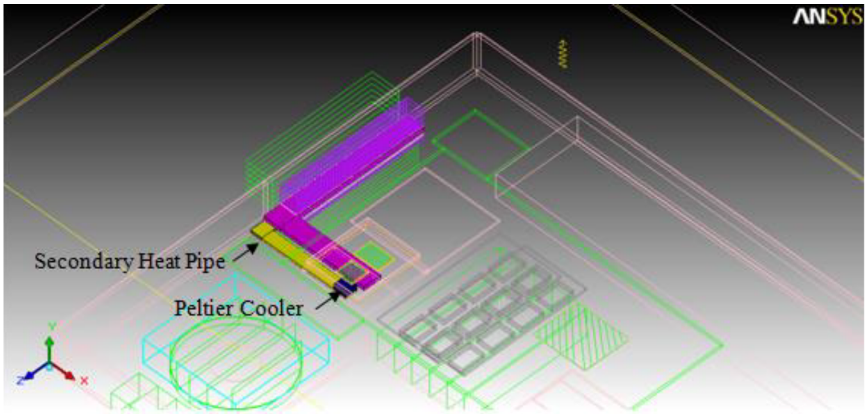

Figure 4. Secondary heat pipe in test system (shown in yellow) together with Peltier cooler (shown in dark blue).

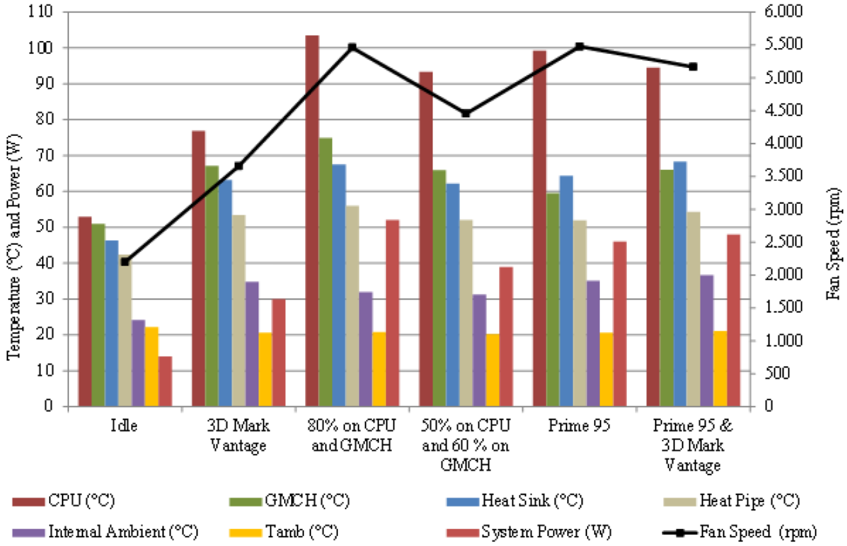

Figure 5. Results of thermal and power characterization and fan speed measurement.

On executing the system at higher activity, the CPU temperature reached 103.5 °C, which was very close to the maximum junction temperature of 105 °C. However, under low workload conditions, the CPU experienced temperatures between 50 °C and 94 °C, providing a good thermal budget within the system for safe operation. Although the system power delivery is designed for 65 W, the maximum power consumed by the system was 52 W throughout the characterization, providing a great amount of power headroom that can be supplied to the integrated Peltier cooler, especially in the cases when there is need for performance improvements.

4.2. Validation of finite element model

Temperature contours obtained as a result of thermal simulation show the heat dissipation path within the system in Figure 6. The heat in the system was concentrated around the microprocessor assembly and the cooling solution in the vicinity. While the maximum power consumed by the system was 52 W, it was evident from thermal imaging (Figure 1) that the CPU+GMCH assembly and PCH were the main contributors of heat within the system. It was assumed that the rest of the power was consumed by the other system components.

A thermal resistance network of the model is depicted in Figure 7, along with the temperature profile of the system heat dissipation path from CPU and GMCH surfaces to ambient. Measured and simulated values of temperatures were compared for maximum workload conditions and are presented in Table 2. Good correlation between measured and simulated values of temperature confirmed sufficient model health, which laid firm grounds for further enhancement to the system thermal design.

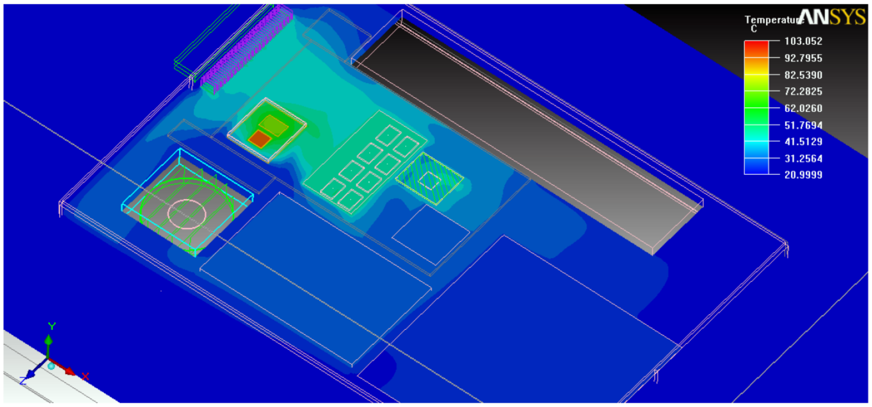

Figure 6. Test system simulation results at maximum workload conditions (80% on CPU and GMCH).

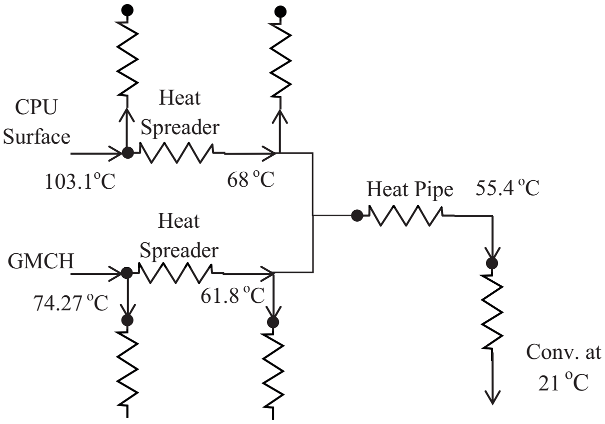

Figure 7. Thermal resistance network for test system with temperatures at selected components.

Table 2. Measured and simulated temperature profile without TE module at maximum workload conditions.

		Measured (°C)	Simulated (°C)
CPU	Thread 0	103.5	103.1
	Thread 1	103.5	
	Thread 2	96.8	
	Thread 3	97.4	
GMCH		74.9	74.27
Heat Spreader	CPU Side	67.6	68
	GMCH Side	65.4	61.8
Heat Pipe		56.1	55.4

4.3. Quantification of improvements by enhancements to system thermal design

The quantification of improvements by modifying system thermal design is relative to the base case as presented in Table 2. Impacts of all modifications are studied in terms of temperatures at key components within the system, and performance improvement through TDP envelop enlargement within temperature limits.

4.3.1. Impact of secondary heat pipe in the test system

The secondary heat pipe in the test system provided a significant decline in CPU temperature from 103.1 °C to 98.36 °C as shown in the cut-plane view of temperature profile in Figure 8. The thermal resistance network of the test system with the secondary heat pipe is presented in Figure 9. Table 3 summarizes the impact of the secondary heat pipe in the system with respect to the base case using the temperature profile of the test system at 35 W TDP, and possible improvements in TDP via scaling it to the maximum CPU temperature as in the base case. It was observed that the TDP value can be increased by 2.25 W without increasing the CPU temperature over 102.6 °C.

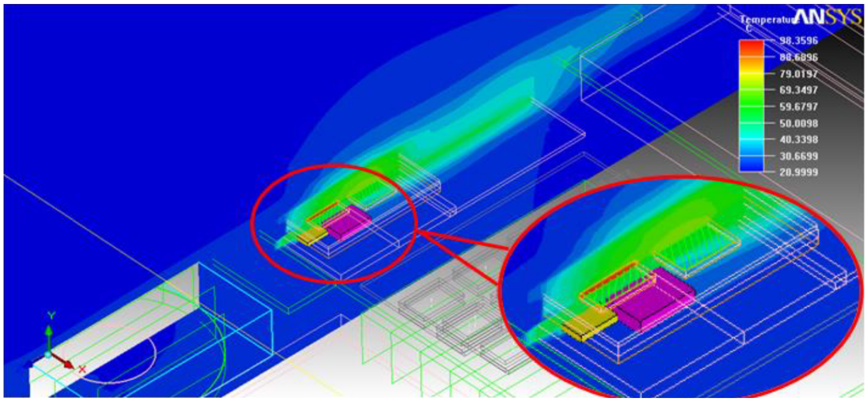

Figure 8. Temperature profile of test system with secondary heat pipe.

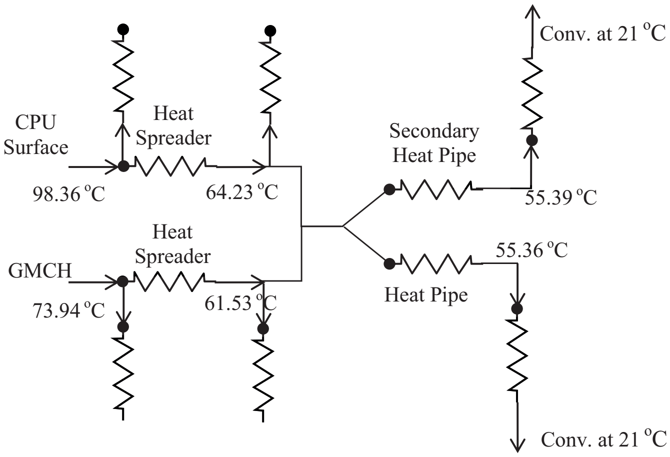

Figure 9. Temperature profile of test system with secondary heat pipe.

4.3.2. Impact of secondary heat pipe + Peltier cooler in the test system

Table 4 summarizes the temperature profile of the test system with the secondary heat pipe and Peltier cooler module at 35 W TDP, and possible improvements in TDP envelop. Power input to the TE module was 1.375 W.

CPU temperature dropped to 100.8 °C using the combined secondary heat pipe and Peltier cooler module as shown in Figure 10. The thermal resistance network of this configuration is outlined in Figure 11. Temperature of the uncontrolled side of the TE module was ∼32 °C, which corresponded to a heat dissipation of 4.2 W and a coefficient of performance value of 3.06 for the Peltier cooler. In terms of thermal headroom, the secondary heat pipe allowed an increase in TDP up to 36.7 W in the presence of the Peltier cooler.

Table 3. Impact of secondary heat pipe on the performance of the test system.

		Test System with Secondary Heat Pipe	
	Base Case	TDP 35W	TDP Scaled to 37.25 W
Temperature (°C)			
CPU	103.1	98.36	102.6
GMCH	74.27	73.94	77
Heat Sink (CPU)	68	64.23	66.46
Heat Sink (GMCH)	61.8	61.53	63.65
Heat Pipe	55.4	55.36	57.02
PCB	33.5	33.73	34.4
Sec Heat Pipe	-	55.39	57.06
Thermal Design Power (W)			
CPU TDP	25	25	26.5
GMCH TDP	10	10	10.75
Overall TDP	35	35	37.25
TDP Envelop Extension	-	-	2.25

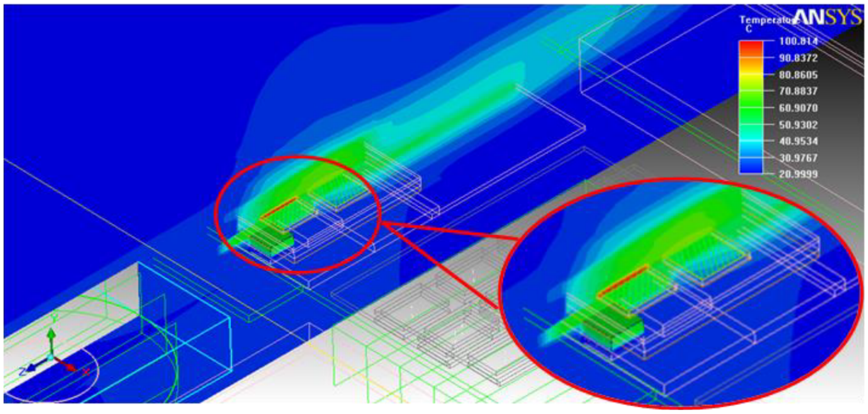

Figure 10. Temperature profile of the test system with combined secondary heat pipe and Peltier cooler modules.

Although the Peltier cooler coupled with the secondary heat pipe aided in decreasing the CPU temperature to 100.8 °C, the attained temperature was 2.44 °C higher than the test system with only the secondary heat pipe. Therefore, integration of a Peltier cooler into the enhanced cooling solution does not improve performance further and consumes power (degrading battery life). Hence, combined secondary heat pipe and Peltier cooling should only be considered if a CPU temperature less than 98.36 °C can be obtained. The analytical model based on Eqs. (1) to (6) of Section 2 was used to determine the COP of the Peltier cooler that would satisfy this condition. With the same amount of power supplied, it was found that the Peltier cooler needed to dissipate more than 4.4 W, which corresponded to a COP value of 3.23 for the TE module under consideration. The analytical model for Peltier cooling provided a metric for determining the change in junction temperature

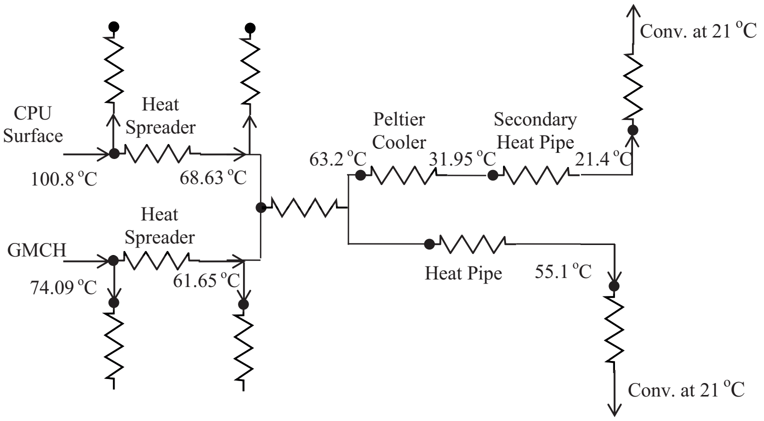

Figure 11. Thermal resistance network for test system with secondary heat pipe + Peltier cooler.

Table 4. Impact of secondary heat pipe on the performance of the test system.

		Test System with Secondary Heat Pipe + Peltier Cooler	
	Base Case	TDP 35W	TDP Scaled to 36.7 W
Temperature (°C)			
CPU	103.1	100.8	103.5
GMCH	74.27	74.09	75.53
Heat Sink (CPU)	68	68.63	69.72
Heat Sink (GMCH)	61.8	61.65	62.47
Hear Pipe	55.4	55.1	55.55
PCB	33.5	31.66	31.93
TE (cold side)	-	63.2	64.02
TE (hot side)	-	31.95	33.1
ΔT	-	31.25	30.92
Sec Heat Pipe	-	21.4	22.82
Thermal Design Power (W)			
CPU TDP	25	25	26.2
GMCH TDP	10	10	10.5
Overall TDP	35	35	36.7
TDP Envelop Extension	-	-	1.7

as a function of COP, which is

$$\frac{\text{Change in Junction Temperature}}{\text{Change in Coefficient of Performance}} = \frac{-\Delta T_j}{\Delta COP} \tag{7}$$

By using this metric, it was concluded that the junction temperature can be decreased up to 13 °C by a unit increase in COP of the Peltier cooler being used in the region of operation. Since COP is directly related to the cold side temperature and Seebeck coefficient (α) of the cooler, a ~4% decrease in the module's cold side or a ~10% increase in α can improve the COP by 5.5%, making the use of a combined secondary heat pipe and Peltier cooler feasible in the enhanced test system. A summary of results for maximum workload conditions is provided in Figure 12, describing the CPU temperature and performance improvement opportunities in the test system for all scenarios under consideration.

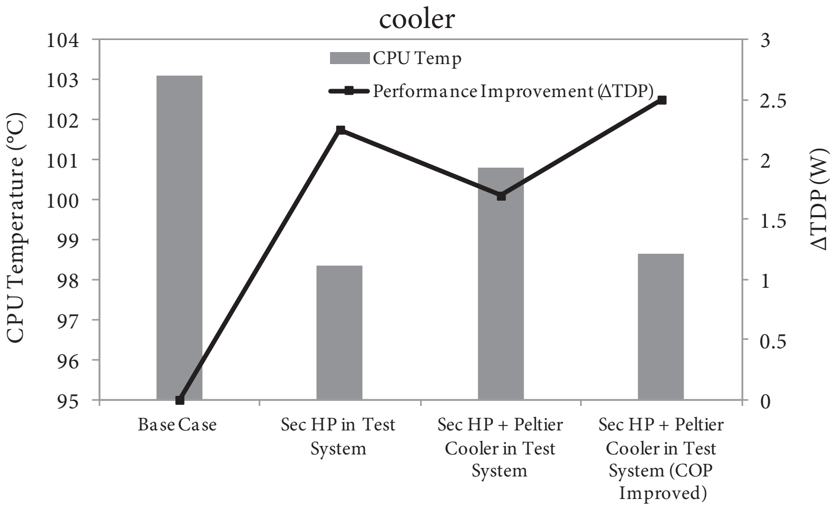

Figure 12. Performance improvement opportunities at maximum workload conditions.

5. Energy harvesting opportunity

The interest of authors in using a Peltier cooler in the system is due to the fact that it can also scavenge energy from waste heat of the microprocessor in hybrid mode of operation. We previously presented the opportunities of thermoelectric energy harvesting in the same test system without any substantial degradation in system performance [8]. A significant difference of approximately 22 °C was observed between the hot and cold side of the thermoelectric module when the system was operated close to maximum workload, resulting in a net power generation of 410.5 μW. The generated power scaled down to 60.5 μW when the system was idle. It was reported in previous work that maximum power density up to 4.27 mW/cm^3 can be generated in a carefully selected hotspot in the test system with off-the-shelf TE modules.

6. Conclusions

Thermal design enhancements in terms of passive, i.e. secondary heat pipe, and a combination of passive + active solutions have been analyzed to quantify their effect on CPU temperature and TDP improvements in a compact notebook system. The secondary heat pipe reduced the CPU temperature by ∼5 °C compared to the base case, and alternatively provided a 2.25 W enlargement in the TDP envelop at the original maximum temperature point. For the combined secondary heat pipe + Peltier cooler solution, CPU temperature was reduced by 2.3 °C and TDP envelop was alternatively improved by 1.7 W with a well-characterized off-the-shelf TE micro-module. A 10% improvement in the material's Seebeck coefficient causes its COP to increase by 5.5%, resulting in a net TDP improvement of 2.5 W or alternatively maintaining the CPU temperature at the minimum value recorded throughout the study, i.e. 98.36 °C for the original TDP. Since the addition of a passive or combined active + passive solution can increase the price and weight of the resulting system, an effort has been made to quantify the effects of these additions. The economies of scale suggest that the price significantly drops for large volume production; therefore, the cost of large volumes of heat pipes and Peltier coolers are estimated based on a coarse market study. The price of a single heat pipe is $10/part [12] and it is estimated to be $2.54/part for an order of 1,000,000 parts. Similarly, the price of a Peltier cooler is found to be $19.70/part [13], which is reduced to $8.82/part for an order of 1,000,000 parts. The weight of the type of heat pipe and Peltier cooler selected for this study is found to be 8 and 10 g, respectively. A summary of results including price per performance, i.e. price per TDP, and weight of the system is presented in Table 5. The normalized price per TDP decreases if the suggested modifications are employed in notebook systems on a large scale. Moreover, scaling of the cost/price to high volume could be even better than the projected values as there will be some nonlinearity associated due to the fact that most investment cost items in high volume manufacturing significantly fall with quantity and get compounded. It is evident that there is no significant increase in the weight of the notebook system with the proposed modifications in the system thermal design. It can be concluded that investing in a combined active + passive cooling solution and taking advantage of improved TE properties for cooling is a better strategy for performance improvement in such a thermally limited system, because this combination provides an opportunity to scavenge energy from waste heat of the processor, whenever Peltier refrigeration is not needed, which can then be used to enable independent low power circuits and sensors within the system, for example to aid in context aware computing efforts. On the other hand, in lack of improvements in technology to extend TE COP beyond what has been characterized in this work, integrating a secondary heat pipe only without the Peltier device optimizes performance per cost in pushing the thermal envelop. The work thus provides a methodological approach to improve the performance of a thermally limited computer system without changing the main building blocks and without modifying the mechanical shell.

Table 5. Analysis of price per performance and weight with modification in system thermal design.

Notebook system	Estimated Price in $ (Based on Coarse Market Study using 1,000,000 Units)	Price/TDP	Normalized Price/TDP	Weight (kg)	Normalized Weight
Baseline	650	18.57	1.00	1.5	1.000
Enhanced with HP	650 + 2.54	17.52	0.94	1.5 + 0.008	1.005
Enhanced with HP + Peltier Cooler	650 + 8.82 + 2.54	18.02	0.97	1.5 + 0.008 + 0.01	1.012

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