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Development of vapour chamber-based VGA thermal module

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Abstract

Purpose – The purpose of this paper is to describe how a traditional metal base plate is replaced with a vapour chamber, a two-phase flow heat transfer module with high heat transfer efficiency, to effectively reduce the temperature of heat sources as graphic processing unit (GPU) of smaller area and higher power.

Design/methodology/approach – As a first step, the nature of flow field of a vapour chamber-based thermal module with heat sink is simulated and analysed through computational numerical method. Second, a sample is prepared according to the theoretical results and the performance of thermal modules is tested together with thermal performance experiment.

Findings – The results show that when the fin height from vapour chamber top to fan bottom area is more than 3 mm and not more than 8 mm, the vapour chamber-based thermal module can achieve the optimum heat dissipation and the maximum heat flux may exceed 90 W/cm^2. Also, when copper fins are 3 mm in height, 0.2 mm in thickness, 53 in number and spaced out 1.0 mm apart, the optimum total thermal resistance of a vapour chamber-based thermal module is 0.28 °C/W.

Originality/value – The Sapphire Atomic HD3870 of Video Graphics Array module for AMD RV670XT using MicroLoops vapour chamber has greater thermal performance than the AMD reference dual slot thermal module. So, AMD latest GPU is considered to be the vapour chamber thermal cooler to solve the higher power consumption.

Keywords Vapourization, Vapour pressure, Heat transfer, Thermal resistance
Paper type Research paper

Nomenclature

k	thermal conductivity, W/m°C
Q	total heat transfer rate, Watt
R	thermal resistance, °C /W
R_t	total thermal resistance, °C /W
T	temperature, °C
T_d	lower central surface temperature of vapour chamber, °C
T_u	mean upper surface temperature of vapour chamber, °C

Subscripts

a	ambient
h	heat source

Introduction

Taiwan is the largest thermal module manufacturing base in the world. In Taiwan, development and application of thermal modules are always the index of the development of the new microelectronic module cooling technology. Traditionally, Video Graphics Array (VGA) thermal module is only heat sink and fan to dissipate the heat capacity from Graphic Process Unit (GPU). Its total thermal resistance is usually over 0.6 °C/W not adjust high heat

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capacity; In recent years, technical development related with the application of two-phase flow heat transfer (Wang, 2007a) assembly to thermal modules has become mature and heat pipe-based two-phase flow heat transfer module is one of the best choices. The heat pipe-based thermal module using in the notebook has an optimum total thermal resistance value of 0.25 °C/W (Nguyen *et al.*, 2000; Legierski and Wiecek, 2001). Wang *et al.* (2007) and Wang (2008a) used a aluminium heat sink with embedded two and four heat pipes of 6-mm diameter; they can carry 36 and 48 per cent of the total dissipated heat capacity from Central Process Unit (CPU) and the total thermal resistance is under 0.24 °C/W. Thus, using a two-phase heat transferring device heat pipe as the VGA thermal module is the method to solve the high heat flux above 30 W/cm^2. This VGA heat pipe thermal module has the same thermal performance as like as embedded heat pipes heat sink module using in the CPU (Wang, 2007a). However, it is a limited region for lowering the spreading thermal resistance of the base plate. Hsieh *et al.* (2008) showed a heat removal capacity of 220 W/cm^2 with a thermal spreading resistance of 0.2 °C/W for a vapour chamber heat spreader. The vapour chamber can reduce the spreading resistances sufficiently by its excellent lateral spreading effect (Chen *et al.*, 2009). Nowadays, the vapour chamber replaces the embedded heat pipes using in the VGA thermal module for lowering the spreading of thermal resistance. (Wang, 2007b, 2008b). Wang (2007b, 2008b) analysed that the total thermal resistance of vapour chamber thermal module is more lower than embedded two pair of heat pipes. Wei (2008) pointed that the integration of a vapour chamber yields a further improvement; the cooling performance is improved by 20 per cent with a 20 per cent weight reduction application in high-performance servers. In conclusion, the next generation VGA thermal module is the vapour chamber thermal module.

Sapphire Atomic HD3870 for AMD RV670XT DDR4 original PCB utilizes MicroLoops vapour chamber to employ single-slot vapour chamber thermal module as shown in Figure 1. The dimensions of vapour chamber are 89.2 × 88.8 × 3 mm^3. The fan performances are 14 mmAq of maximum pressure and 10CFM of maximum flow rate. The total thermal resistance of Sapphire Atomic HD3870 is 0.37 °C/W with aluminium fins. From the official web browser testing data, Sapphire's Atomic Edition HD 3870 adjust the clocks (Default is 825 MHz Core and 1200 MHz Memory) in order to detect the maximum stable clock frequency using ATI Tool and AMD over clocking software. The final over clocks are 864 MHz Core (5 per cent over clock) and 1,251 MHz Memory (4 per cent over clock) and the temperature is under 90 °C. The reference PCB design clocks are 777 MHz/1,126 MHz and the over clocks are 11 per cent for both

Figure 1.
Sapphire Atomic HD3870

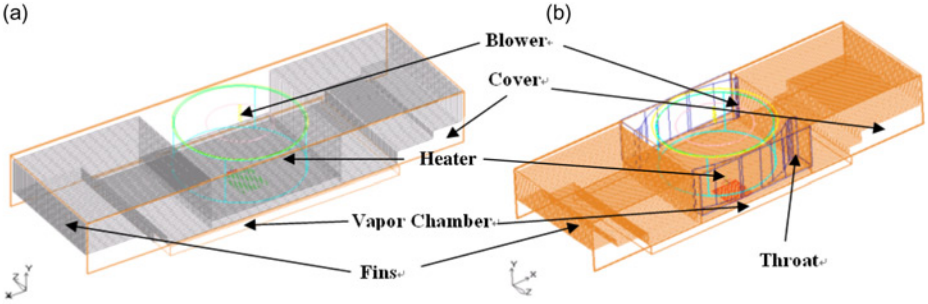
memory and core. For a single-slot cooler, its thermal performance is better than the reference design HD 3870 with a dual-slot cooler with fan performance of P_{max} 26 mm Aq and Q_{max} 22CFM and total thermal resistance 0.44 °C/W with copper fins.

It is known from the above description that, a thermal module in which two-phase flow heat transfer module (heat pipe, vapour chamber) is used as base plate represents a better thermal performance than traditional single-solid phase thermal modules (copper and aluminium base plate) because it can effectively reduces the base plate thermal resistance. In this paper, the thermal performance experiment is conducted with actual VGA's thermal module mass products and it is discovered through the comparison that the total thermal resistance value of thermal modules composed of embedded four heat pipes (TM40) are much higher than the one of vapour chamber-based thermal modules. Therefore, the thermal modules in which a vapour chamber is used as the base plate can be applied to medium- or high-grade VGA products.

Analysis method

Vapour chambers manufactured by Taiwan MicroLoops Corp. have been produced and applied to single-slot thermal modules for HD3870 VGA in a large scale, achieved optimum thermal performance and its total thermal resistance is below 0.37 °C/W. Therefore, in this paper, vapour chambers manufactured by Taiwan MicroLoops Corp. used on dual-slot VGA thermal modules are chosen to achieve a better thermal performance. At present, for a existing VGA thermal module, its thermal performance is measured by using an analytic method of thermal resistance test and thermal modules are improved or the advantage of other products of the same types are incorporated according to the engineering personnel's experience in VGA thermal module design and basic theory. Then, modification is further made through many experiments testing activities. This repeated sample costs and time taken for waiting for sample preparation does not comply with cost-efficiency in present era when market competition is fierce and science and technology are rapidly developing. In view of this point, by applying computer-aided design (CAD) and analytical software tools (Icepak), it is possible to reduce much cost of manufacture and rapidly design VGA thermal modules or improve the thermal performance of existing modules within a short period. Thermal flow field of thermal modules is simulated by numerical analysis, comparison is drawn between the simulation results and data obtained from thermal performance experiment to ensure that the error between the values and the results obtained from experiments is the allowable range. And error analysis method is adopted to confirm the error range of theoretical values.

Numerical analysis is a subject belonging to computational fluid dynamics (CFD), in which fluid mechanics, discrete mathematics, numerical method and computer technology are integrated. Icepak commercial electronic heat transfer analysis software developed by American Fluent Inc. is adopted in this paper. The process of numerical simulation analysis adopted in the paper can be divided into pre-processing, numerical solving and post-processing. The simulation analytical model is as shown in Figure 2 and the overall dimension is $210 \times 93 \times 34$ mm. The entire analytical model is established by utilizing file conversion skill between CAD and CFD. In this model, the size of heat source for simulation GPU is 16×16 mm and input power is 200 W. The overall size of vapour chamber is $135 \times 72 \times 4$ mm and its thermo physical property can be entered as shown in Table I. The size of the centrifugal fan is $90 \times 25\,\mathrm{mm}^3$, rotational speed is 4500 RPM, air volume flow is 17CFM and static pressure is 26 mmAq. The material of fins can be aluminium or copper and its dimension is as shown in Table II. The fins' length and fins' width are 208 and 91 mm, respectively. The



Notes: (a) No throat of cover; and (b) with throat of cover

Figure 2.
3-D numerical model

Heat flux (W/cm^2)	K (W/mk)
8.6	350
17.2	529
25.8	632
34.4	667
43.0	675
51.6	686
60.2	800
68.8	694
77.4	706
86.0	719
94.6	725
103.2	739

Table I.
Effective thermal conductivity of vapour chamber

Thickness (mm)	0.2	0.2	0.2	0.2
Pitch (mm)	0.6	1.0	1.2	1.4
Count	79	53	46	40

Table II.
Dimensions of fins

range of fin dimension above vapour chambers may be 0-9 mm. The interior of plastics housing for thermal modules can be divided into a structure with a throat and a structure without a throat. A throat functions as forcing air to flow towards two sides at pressurized condition. Figure 3 is the schematic diagram of this process of numerical

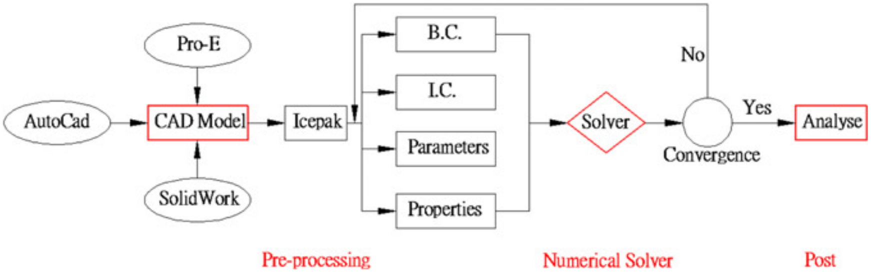


Figure 3.
Schematic diagram

simulation analysis adopted in the paper. It can be divided into pre-processing, numerical solving and post-processing. With regard to pre-processing, first of all, a geometrical model is established for 3D VGA thermal module. Generally, in order to reduce computation grid elements and time taken for simulation and solving, some minor characteristics without influence or with a little influence will be ignored when establishing 3D geometrical model. And input the boundary conditions and thermophysical properties, which the ambient temperature is set to 25 °C, turbulent model is the k-ε two-equations, the grid pattern is non-structural one and the entire simulation analysis type is steady state. For the entire module, about 1,500 thousands grid elements are used, iterations is about 1,000 and it will take about 24 h to simulate every scenario.

The temperature of thermal modules is measured at different position and different input power together with thermal performance experiment for vapour chamber-based thermal module. On the other hand, thermal resistance analytical method is utilized to represent the thermal performance of VGA thermal modules. Thermal resistance is commonly used to evaluate thermal performance of thermal modules and also an important parameter in thermal module design. The larger the total thermal resistance is, poorer the thermal performance of thermal modules is, and higher the temperature of heat source is. Thermal resistance is defined as follows:

$$Q = \frac{\Delta T}{R}, \tag{1}$$

where R is the thermal resistance (°C/W), ΔT is temperature difference (°C), Q is the input power (Watt).

The vapour chamber is supplied by Taiwan Microloops Corp. and assembled with machined fins, plastics housing and fan to form a sample of VGA thermal module. Figure 4 is the structural model of thermal performance experiment. The heat source for simulation GPU is a heated copper block 36.5 × 25.5 × 11 mm and the area of heat source is 16 × 16 mm. An electrical heating tube is provided copper block and a T-type thermocouple is embedded to measure the temperature of heat source (T_h). There are six thermocouples attached to the centre of the lower surface of vapour chamber and five points along the diagonal of the upper surface of vapour chamber, measuring the temperatures at the centre of the lower surface of the vapour chamber (T_d) and the average temperature of the upper surface of the vapour chamber (T_u). A thermocouple is placed on the top of the fan to measure the ambient temperature (T_a). The digital power supply for this experiment is mainly used to supply power required for simulated heat source and cooling fans. This power supply unit has two output ports, which can be connected in series or parallel. The maximum output current and voltage

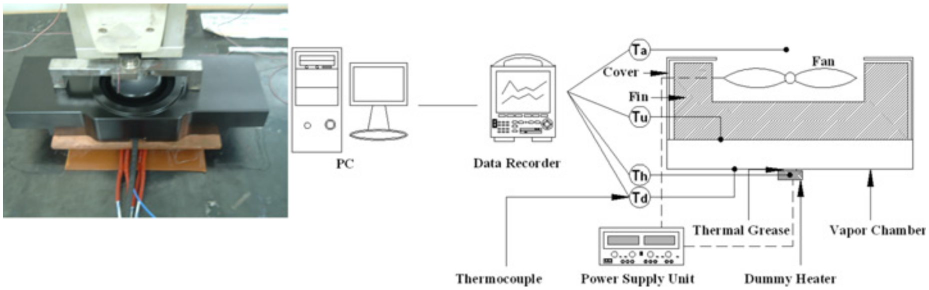


Figure 4.
Vapour chamber-based thermal module experimental equipment

of each output port are 6A and 30V, respectively. The measurement error is ±(0.5 per cent + 2 digits). The data recorder is the product manufactured by Yokogawa Company, data are sampled via 30 channels and RS232 communication gateway is used to connect with PC. This device is mainly used to record the temperature values at various thermocouple locations inside thermal modules and the measurement error is ±1 per cent. Thermocouple of type T is used and its measurement error is ±0.5 °C. This junction is placed the measurement position and another end is fixed to the data recorder to measure temperature.

The upper and lower copper cover for vapour chamber are made from C1100 oxygen-free copper, wick structure inside the chamber is composed of copper wire mesh with uniform mesh spacer and copper wall, which are tightly structured by utilizing diffusion bounding without any soldering materials, and operating fluid is pure water containing a low-oxygen content. A pressure of about 9 to 11 $\mathrm{Kg/cm^2}$ is applied upon the fixture fixing thermal module with simulated heat source during experiment to control and maintain thermal contact resistance of the system. A group of commercially available medium- and high-grade VGA and heat pipe-based thermal module named TM40 embedded four 6-mm heat pipes are specially chosen for the experiment, as shown in Figure 5. The thermal performance experiments are conducted upon them and the results obtained from TM40 is compared with the results obtained from vapour chamber-based thermal module to demonstrate the difference between thermal performance of vapour chamber-based thermal module and the one of embedded four heat pipes thermal module.

The procedures of the experiment introduced in the paper are as follows:

(1) Set up the equipments and calibrate instruments and thermocouples.

(2) Apply thermal grease on the surface of simulated heat source uniformly.

(3) Fix the thermal module on the fixtures.

(4) Turn on the fan and maintain input voltage at 12 V.

(5) Adjust the pressure applied upon the fixture to stabilize thermal contact resistance.

(6) Adjust the voltage and current of the power supply unit till the heating power of the simulated heat source is 40 W.

(7) Record the steady-state temperature value by using a data recorder.

(8) Repeat Step 6 to adjust the heating power to 60, 80, 100, 120, 140, 160, 180, 200, 220 and 240 W in order.

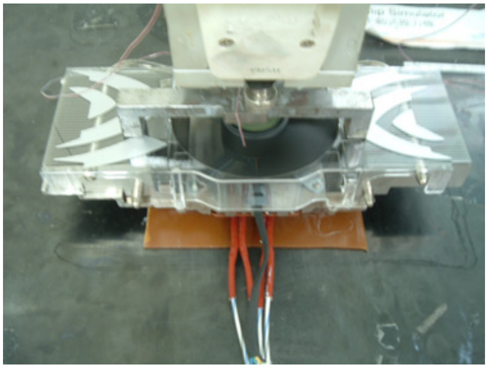


Figure 5.
TM40 thermal module experimental equipment

Certain error necessarily exists between the data measured during the experiment, value deriving from experimental data and actual values due to artificial operation and limitation of accuracy of experimental apparatus. For this reason, it is necessary to take account of experimental error to create confidence of experiments before analysing experimental results. The concept of propagation of error is introduced to calculate experimental error and fundamental functional relations for propagation of error. During the experiment, various items of thermal resistances are utilized to analyse the heat transfer characteristics of various pars of thermal modules. A thermal resistance belongs to derived variable and includes temperature and heating power, which are measured with experimental instruments. The error of experimental instruments is propagated to the result value during deduction and thus become the error of thermal resistance value. An error is represented with a relative error and the maximum relative error of thermal resistance defined is within 5 per cent.

Results and discussions

Figure 6 shows that the comparison between the simulated results and experimental results of the vapour chamber-based thermal module with 53 copper fins with a thickness of 0.2 mm and spacing of 1.0 mm at heating power of 40-240 W, fin height above vapour chamber of 3 mm. The maximum temperature of heat source is 91.78 °C for the experimental results at heating power of 240 W. The maximum temperature of heat source is 101.78 °C for the simulated results at heating power of 240 W. There is maximum error about 9.9 per cent between them. The average error is under 2.5 per

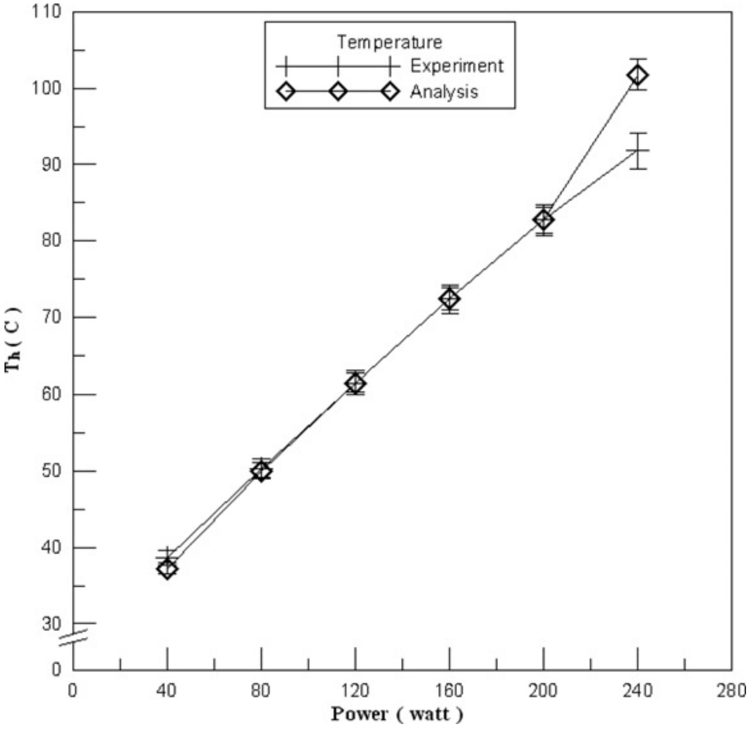
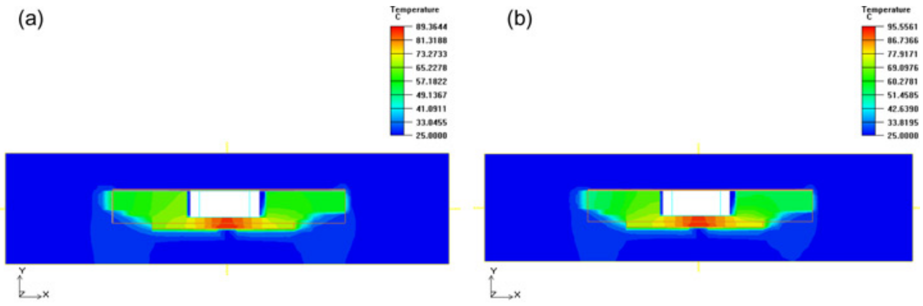


Figure 6.
Relationships of the temperature of 53 copper fins having a thickness of 0.2 mm and spacing of 1.0 mm (fin height below fans is 3 mm) with total input power for experimental and analysis results

cent between simulated results and experimental results. These show that the simulated results are in good agreement with the experimental results. The curve of simulated temperature of heat source is consistent with curve of experimental temperature of heat source, verifying that the experimental method and simulated analysis used in this article are valid.

The comparison is drawn between temperature profile along central section of *Z* planar heat source of vapour chamber-based thermal module with copper fins and aluminium fins at heating power of 200 W, plastics housing without throat mechanism, fin height above vapour chamber of 3 mm, fin thickness of 0.2 mm, fin pitch of 1.4 mm and fin number of 40 in Figure 7. For copper fins, the maximum temperature of heat source is 89.4 °C and total thermal resistance value of thermal module is 0.322 °C/W. For aluminium fins, the maximum temperature of heat source is 95.6 °C and total thermal resistance value of thermal module is 0.353 °C/W. These show that a vapour chamber-based thermal module with copper fins has the better thermal performance than aluminium fins and the temperature difference of their heat sources is 6.2 °C. This is because copper fins can rapidly dissipate heat from a vapour chamber-based to ambient atmosphere. It is known from Figure 7(a) that vapour chamber-based thermal module with copper fins transfers heat capacity rapidly.

In Figure 8, comparison is drawn between thermal performance of vapour chamber-based thermal module with different fin spacing at copper fin thickness of 0.2 mm, fin height above vapour chamber of 3 mm, heating power of 200 W and without throat mechanism. The highest temperature of the heat source is 89.4 °C and total thermal resistance value is 0.322 °C/W of a thermal module with 40 fins spacing by 1.4 mm. The highest temperature of the heat source is 86.0 °C and total thermal resistance value is 0.305 °C/W of a thermal module with 46 fins spacing by 1.2 mm. The highest temperature of the heat source is 81.3 °C and total thermal resistance value is 0.282 °C/W a thermal module with 53 fins spacing by 1.0 mm. The highest temperature of the heat source is 81.9 °C and total thermal resistance value is 0.285 °C/W a thermal module with 79 fins spacing by 0.6 mm. Thus, it can be known that, when fin spacing is smaller above 1.0 mm and heat source temperature is lower, a vapour chamber-based thermal module will reach a minimum total thermal resistance of 0.282 °C/W. This is because, when fin spacing is 1.0 mm, the fan can achieve the highest cooling efficiency and rapidly dissipate heat from 53 fins, whereas when fin spacing is 0.6 mm, flow resistance is excessive high and fan efficiency is weakened so that it cannot dissipate heat from 79 fins and total thermal resistance rise up slightly.



Notes: (a) Cu fins with vapour chamber; and (b) Al fins with vapour chamber

Figure 7.
Temperature distributions of *Z* cutting plane at the central heat source

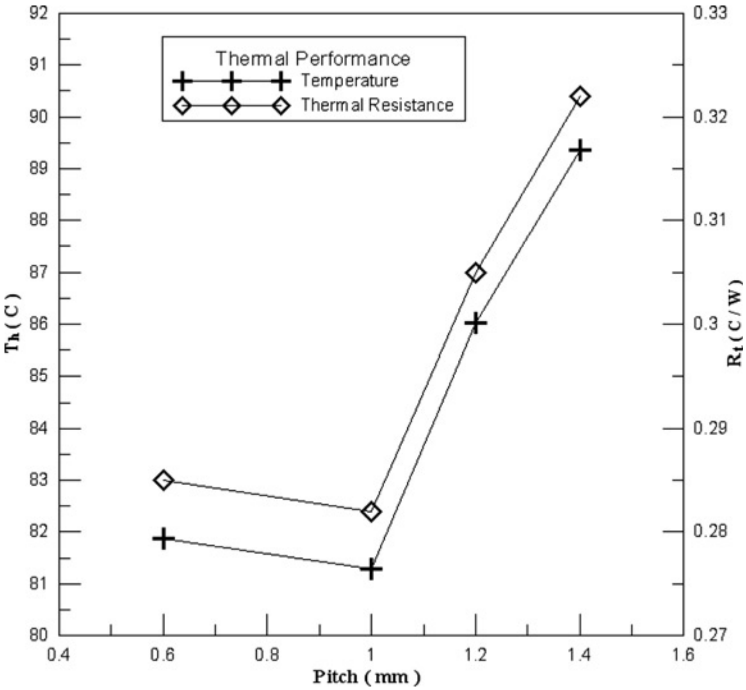


Figure 8.
Relationships of *Z*-plane temperature distributions (left *Y*-axis) and total thermal resistance (right *Y*-axis) with different fin pitch

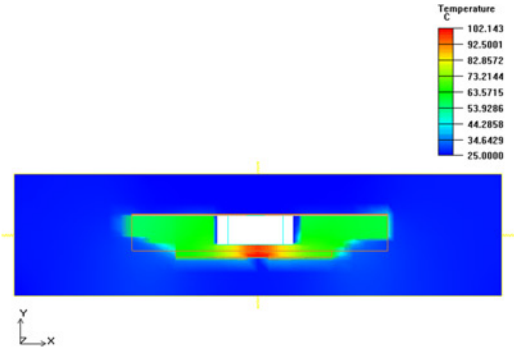


Figure 9.
Z-plane temperature distributions of Cu fins pitch 1.0 mm with Cu base

The temperature distribution of full-copper heat sink thermal module for traditional VGA is as shown in Figure 9 and the fins are 0.2 mm in thickness, 53 in number and spaced by an interval of 1.0 mm. It may be known from Figure 9 that the temperature of the heat source is 102.1 °C and total thermal resistance is 0.386 °C/W. The temperature of its heat source is much higher than the one of vapour chamber-based thermal module of 20.8 °C. This is because a vapour chamber as a two-phase flow heat transfer module can rapidly diffuse heat capacity from a heat source with a small area to plane *X-Y*, effectively reduce base plate thermal resistance and lower the temperature of a heat source. Especially, the higher the heating power is, the better the thermal efficiency is, and therefore the total thermal resistance of vapour chamber-based thermal module can be lower than the one full-copper thermal module. The

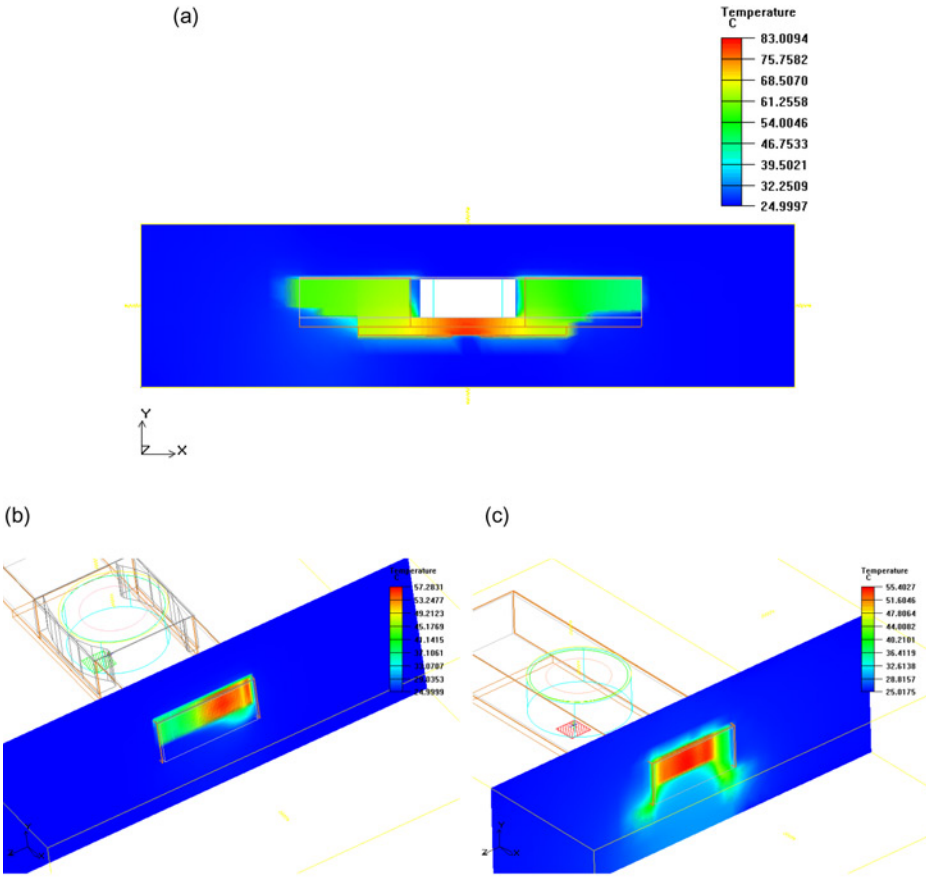


Figure 10.
Z-plane temperature distributions of Cu fins pitch 1.0 mm with vapour chamber

Notes: (a) At the central heat source with throat; (b) at the exhaust with throat; and (c) at the exhaust no throat

temperature distribution of a thermal module with and without a throat structure inside plastics housing is as shown in Figure 10. It is known from this figure that the temperature of the heat source is 83.0 °C and total thermal resistance is 0.290 °C/W. The temperature difference of heat source is 1.7 °C higher than the one without a throat structure. It can be known from Figure 10(c) that the fin temperature with a throat become non-uniform, which leads to a higher temperature of the heat source, and therefore the total thermal resistance value, is higher than the one of a thermal module without a throat structure.

The height of fins from the top of vapour chamber to fan bottom can vary in the range from 0 to 9 mm. These fins are closest to the heat source and fan and it is necessary to take account of their effect upon air flow and temperature field. The vapour chamber-based thermal module shown in Figure 11 is the one with 53 copper fins with a thickness of 0.2 mm and spacing of 1.0 mm, and without a throat. The relationship between heating power and temperature of heat source at different fin height is drawn and the slopes of curves can be assumed as a thermal resistance value

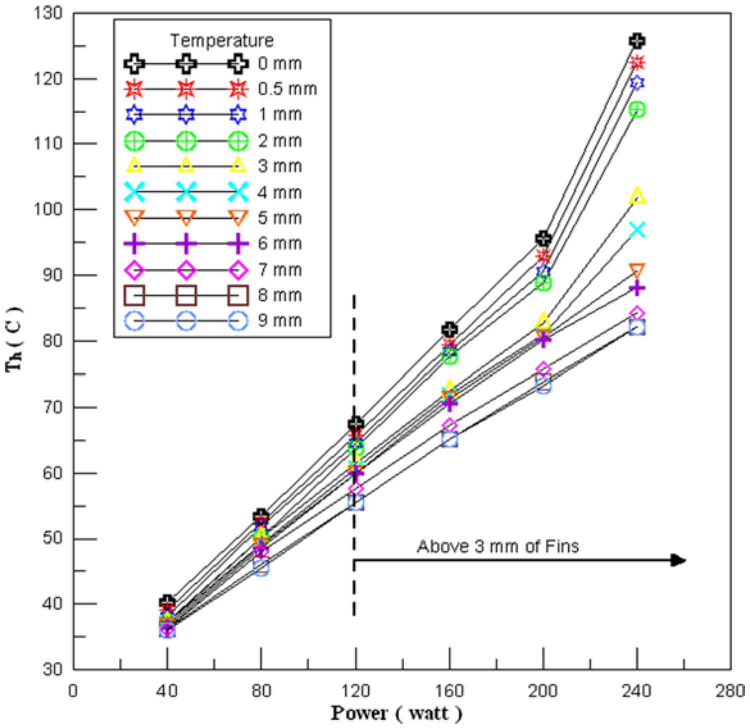


Figure 11.
Relationships of the temperature of different fins height with total input power

in this figure. It may be seen from the figure that, as heating power rises up, the temperature of a heat source will rise up continuously. The curve for the vapour chamber thermal module without fins (0 mm) above vapour chamber is the biggest and the one of curve 9 mm is the smallest. When a heating power is 40-80 W, the temperature of heat source differs slightly and is below 55 °C. When the heating power is 120-200 W, the temperature of a heat source for c curve 0, 0.5, 1 and 2 mm begins to rise sharply up to 90 °C and the temperature of curve 3-9 mm rise up slightly and are below 85 °C. When the heating power reaches 240 W, the temperature of the heat source for curve 2 mm will exceed 110 °C. This is because fins below fans function as guiding air flow adding area of heat dissipation, force air to flow towards two sides and enhance forced convection of fins at the bottom.

The relationship between heating power and total thermal resistance of a vapour chamber-based thermal module with 53 copper fins having a thickness of 0.2 mm and spacing of 1.0 mm (fin height below fans is 3 mm) and without throat mechanism, and TM40 are as shown in Figure 12. The vapour chamber curve in this figure shows that, when the heating power is 200 W, the corresponding thermal resistance is 0.275 °C/W and heat source temperature is 83.1 °C. Comparing these values with the total thermal resistance of 0.282 °C/W and heat source temperature of 81.3 °C obtained from simulation analysis, the error is below 3 per cent, showing that the result of numerical simulation analysis adopted in this paper is correct. We measured thermal performance of TM40 and vapour chamber-based thermal modules by using the same experimental equipments. It can be known from the figure that, when the heating power is less than 80 W, the total thermal resistance of TM40 is small; however when

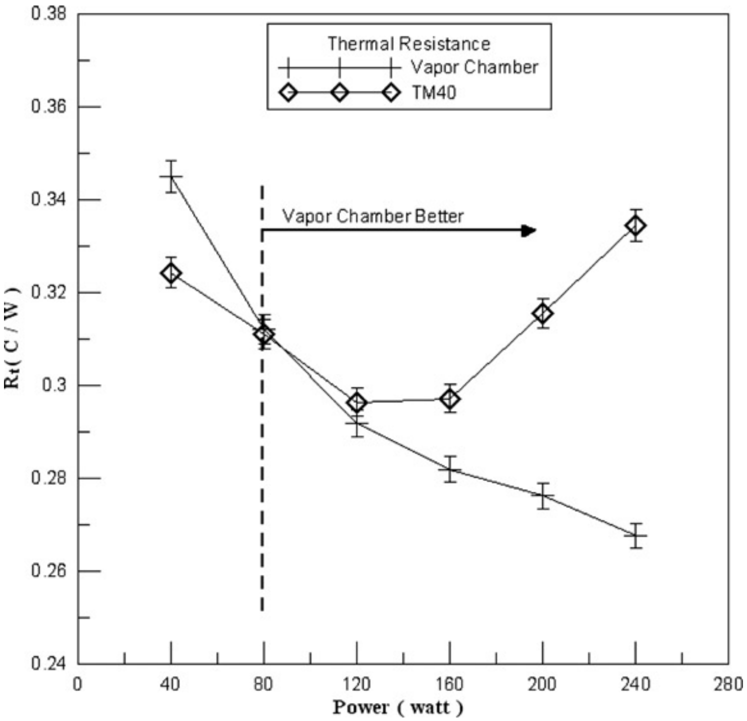


Figure 12.
Relationships of the total thermal resistances of vapour chamber-based thermal module and TM40 thermal module with total input power

the heating power is 80 W up to 240 W, the total thermal resistance of vapour chamber-based thermal module is lower than the one of TM40. When the heating power is 140 W, the TM40 has the minimum total thermal resistance value of 0.295 °C/W. When the heating power is 240 W, the vapour chamber-based thermal module reaches the minimum total thermal resistance of 0.265 °C/W. Therefore, a vapour chamber-based thermal module is much better than TM40 thermal module composed of embedded four heat pipes of 6-mm diameter with regard to thermal performance.

Conclusions

In this paper, vapour chamber-based thermal module is analysed at high heat flux GPU and without changing fan performance through CFD simulation and thermal performance of a thermal module sample is measured together with thermal resistance analysis and thermal performance experiment. The simulation analytical results and experimental data show that the error of the total thermal resistance value is within 5 per cent for a VGA thermal module with 53 copper fins having a thickness of 0.2 mm and spacing of 1.0 mm (fin height below fans is 3 mm) and without a throat mechanism. Therefore, the thermal performance of vapour chamber-based thermal module can be accurately simulated and analysed by applying the method introduced in this paper.

The fin height from vapour chamber top to fan bottom area is at least 3 mm. If so, the vapour chamber-based thermal module can achieve the optimum thermal performance and the critical heat flux may exceed 90 W/cm^2. The thermal performance of a thermal module TM40 for commercially available VGA is measured. The measurement result shows that, when the heating power is 40-240 W, the total thermal resistance presents a smile curve. When the heating power is 140 W, the minimum total thermal resistance of TM40 is 0.295 °C/W observed; whereas when the heating power is 40-240 W, the total thermal resistance of the vapour chamber-based thermal module introduced in this paper will decrease with heating power rise. When the heating power is 240 W, the minimum total thermal resistance of 0.265 °C/W is observed. Therefore, the vapour chamber-based thermal module introduced in this paper is able to cope with future GPU with high heat flux of more than 40 W/cm^2.

References

Chen, Y.-S., Chien, K.-H., Hung, T.-C., Wang, C.-C., Feng, Y.-M. and Pei, B.-S. (2009), "Numerical simulation of a heat sink embedded with a vapor chamber and calculation of effective thermal conductivity of a vapor chamber", *Applied Thermal Engineering*, Vol. 29 No. 13, pp. 2655-64.

Hsieh, S.-S., Lee, R.-Y., Shyu, J.-C. and Chen, S.-W. (2008), "Thermal performance of flat vapor chamber heat spreader", *Energy Conversion and Management*, Vol. 49 No. 6, pp. 1774-84.

Legierski, J. and Wiecek, B. (2001), "Steady state analysis of cooling electronic circuits using heat pipes", *IEEE Transactions on Components and Packing Technology*, Vol. 24 No. 4.

Nguyen, T., Mochizuki, M., Mashiko, K., Saito, Y., Sauciuc, I. and Boggs, R. (2000), "Advanced cooling system using miniature heat pipes in mobile PC", *IEEE Transactions on Components and Packing Technology*, Vol. 23 No. 1.

Wang, J.-C. (2007a), "The investigation of thermal performance of two-phase thermal module", PhD thesis, National Taiwan University ME, available at: www.cetd.com.tw/ec/thesisDetail.aspx?etdun=U0001-1107200710561200; http://etds.ncl.edu.tw/theabs/site/sh/detail_result.jsp

Wang, J.-C. (2007b), "Investigation of vapor chamber VGA thermal module", *Taiwan Ansys/Fluent User Conference*, available at: www.cadmen.com/sec_page/news/2009_ansys_conference/list.html

Wang, J.-C. (2008a), "Novel thermal resistance network analysis of heat sink with embedded heat pipes", *Jordan Journal of Mechanical and Industrial Engineering*, Vol. 2 No. 1, pp. 23-30.

Wang, J.-C. (2008b), "The best thermal performance design for the vapor chamber thermal module", *Taiwan Thermal Manager Associate and Technology Conference*, No. 9, pp. 24-35, available at: www.thermal.org.tw/Publication/publication-more.asp?Btfiysa

Wang, J.-C., Huang, H.-S. and Chen, S.-L. (2007), "Experimental investigations of thermal resistance of a heat sink with horizontal embedded heat pipes", *International Communication in Heat and Mass Transfer*, Vol. 34 No. 8, pp. 958-70.

Wei, J. (2008), "Challenges in cooling design of CPU packages for high-performance servers", *Heat Transfer Engineering*, Vol. 29 No. 2, pp. 178-87.

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