Journal of Advanced Research Design

Journal homepage:
https://akademiabaru.com/submit/index.php/ard
ISSN: 2289-7984

Heat Flow in Computer Casing

Goh Chee Qiang[1] , Nor Azwadi Che Sidik[1,*]

[1] Faculty of Mechanical Engineering, University Teknologi Malaysia, UTM Skudai, Johor, Malaysia

ARTICLE INFO

Article history:
Received 27 May 2020
Received in revised form 30 October 2020
Accepted 17 November 2020
Available online 27 November 2020

Keywords:
Heat flow profile; computer casing; computational fluid dynamic software

ABSTRACT

The purpose of this study was to investigate the heat flow profile inside a computer casing. Through this study, we can also identify which form factor was more efficient in cooling capability. The performance of Advanced Technology Extended (ATX) and its purposed successor, Balanced Technology Extended (BTX) were compared in this study. Simulations were conducted using ANSYS 12, a Computational Fluid Dynamic (CFD) software. Results obtained from the simulation were compared with values in the datasheet to identify its validity. It was discovered that there were more chaos region in the flow profile for ATX form factor. In contrast, BTX form factor yielded a straighter flow profile. Based on the result, we can conclude that BTX form factor had better cooling capability compared to its predecessor, ATX. This was due to the improvement of layout made in the BTX form factor. With this change, it enabled BTX form factor to be used with more advanced components which dissipate more amount of heat. In addition, this also improved the acoustic performance of BTX as the change reduces the number of the fan needed to just one unit for BTX. All together, these advantages made BTX form factor a need for today's computing world.

1. Introduction

A poor thermal management system is directly related to poor reliability. This is because poor thermal management only lead to high temperature among the components inside, resulting poor performance. Even worst, this will cause the components to break down due to overexpose in thermal stress. According to past study, a 2°C increment at a threshold temperature would cause 10 % decrease of the fatigue life of the package [1]. Also, it is stated that the temperature of chips could not exceed 105°C and that of PCBs should be less than 90°C [2].

Besides the ability to determine the thermal performance of PC system, form factor also can determine other parameters such as the expandability and interchangeable of parts, etc. In order to be able to sustain the heat dissipated by the component during the time, the proper form factor design was necessary. This is the reason why world's leading processor manufacturer, Intel introduced the Advanced Technology Extended (ATX) form factor in the late 1994 to replace its predecessor, the AT form factor.

* *Corresponding author.*
E-mail address: azwadi@semarakilmu.com.my

ATX form factor still is very popular among all users currently. Unfortunately, there is a lot of case regarding intermittent shutdown of new PC recently. Based on statistic of past study, majority of the failure is caused by temperature issue. The pie chart for the failure mechanisms of electrical components is shown in Figure 1 below. Again, the reliability of ATX form factor was to support newly released hardware. To overcome this, Intel then released the successor for the current ATX form factor, the Balanced Technology Extended (BTX). BTX was introduced to public in late 2004. BTX utilized cost-effective engineering and design strategies for power dissipation, structural integrity, acoustic performance [7] and motherboard design [4] into a scalable form factor according to Foxconn FTC Technology Inc[3].

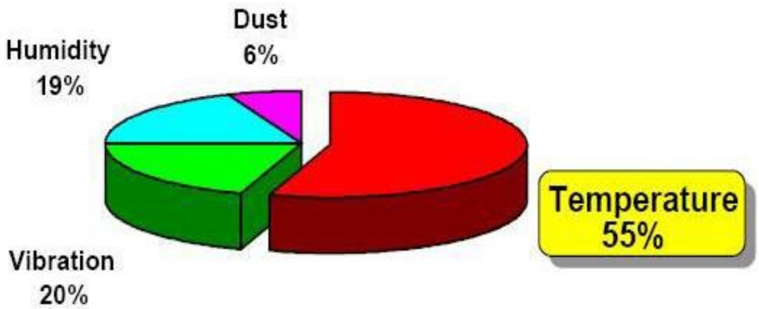

Fig. 1. Type of source for electrical component failure

Although BTX is one of the effective way to reduce heat emitted, but it is not popular among customers. A lot of people still prefer to use other methods to solve the heat emitted problem. Such methods are using liquid cooling, adding extra fan and others [3]. Besides that, it is to be known that BTX does not have backward compatibility with its predecessor, ATX. This forces the user to change the motherboard of their computer if they decided to change their casing to the BTX one. Furthermore, there is only narrow range of the key product for BTX such as motherboard and power supply unit (PSU) offered in the market. Lastly, it is to be known that BTX casing also is more expensive compared to ATX [2,3].

2. Methodology

The heat flow profile in the casing was analyzed using computational fluid dynamics (CFD), which is a numerical method that involves the use of computer to obtain the solutions. The CFD software that was utilized in this research is ANSYS Icepak 12. FLUENT was the solver used by this software to solve the problem.

In order to determine the convective heat transfer rate [5,6], distribution of few variables along the flow field must be known beforehand so to determine the rate of heat transfer at various locations in the flow field. These variables were the pressure (P), velocity vector (V) and the temperature (T). To determine these variables, several principles such as the conservation of mass, conservation of momentum (Newton's law) and lastly the conservation of energy (first law of thermodynamics) were used. It is to be known that these three principles were not just applied in CFD in order to find the heat transfer profile, but they are applicable in any fluid flow as these three principles are the basic.

Generally, the use of these three conservation principles were adequate to analyze most of the present engineering problems. The application of these principles led to three of the most basic equation in convective heat transfer [5]. These equations are the continuity, Navier-Stokes and the

Journal of Advanced Research Design
Volume 74 Issue 1 (2020) 1-14

energy equation. Basically, these are the methodologies to determine the heat transfer rate [10] in various flow fields. The flowchart to conduct this research is shown in Figure 2.

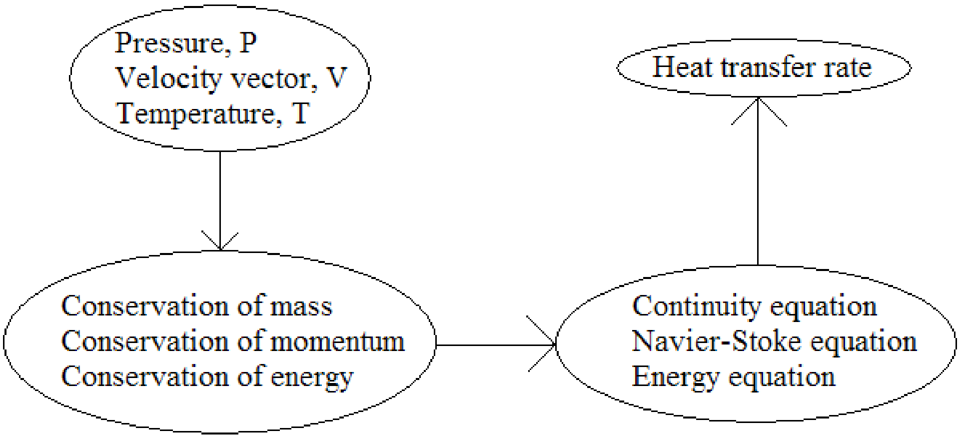

Fig. 2. Flow chart to determine heat transfer rate

2.1 The Continuity Equation

As discussed previously, the equation for convective heat transfer was derived based on few principles. In this section, the continuity equation was derived based on the conservation of mass principle. Consider a differential volume of element with side length of Δx, Δy and Δz as shown in Figure 3.

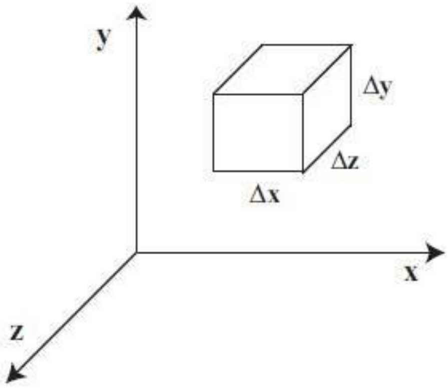

Fig. 3. A differential volume element used to derived Continuity equation

2.2 The Navier-Stokes Equation

The Navier-Stokes equation was derived based on the principle of conservation of momentum. Applying the same control volume as shown in the same Figure 3, differences between the rates of momentum leave and enter the element was also considered. The differences was equal to the net force acting on this control volume in their respective directions. This net force arose due to the pressure and shear force that acted on the faces of the element.

The Navier-Stokes equation is derived based on constant fluid properties. Hence, these (Navier-Stokes) equations can be solved independently with the energy equation to give the pressure and velocity distribution of the flow field. This was due to the set of equation and not dependent with the temperature field. Beside rectangular coordinate, the Navier-Stokes equation can also be expressed in other coordinate form, e.g. cylindrical coordinate.

2.3 The Energy Equation

It is stated that the continuity and Navier-Stokes equation were used to obtain the velocity and pressure distribution of the flow. Meanwhile, the energy equation was used to determine the temperature field which can be used to deduce the heat transfer rate.

To derive the energy equation, consider flow through a control volume with length of dx, dy and dz at each sides respectively. For steady flow, the energy equation turns to be in the form of Eq. (1),

$$h'_{out} + KE'_{out} - h'_{in} - KE'_{in} = \Delta q' + \Delta w' \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \tag{1}$$

This equation shows that the net rate of heat transfer and work done on the control volume were equivalent to the difference between the rate enthalpy and kinetic energy entering and leaving the control volume.

Figure 4 below considers the flow of fluid, and the sum of enthalpy flow in and out of the control volume.

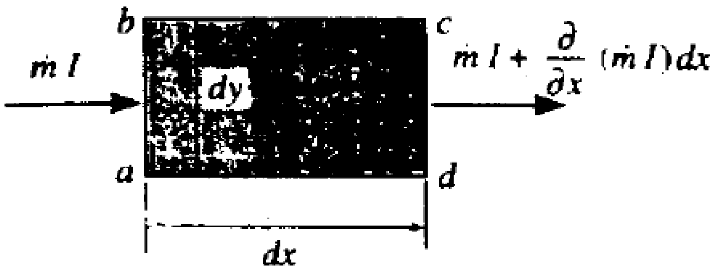

Fig. 4. Flow in and out of control volume

For the right hand side, the first term would be the heat transfer term. Again, consider the control volume as shown in Figure 5 below. Heat transfer in and out of the control volume by the sake of conduction. In the figure below, only the x direction of the heat transfer was considered. However in practical, heat transfer in both x and y direction may occur. The calculation of the heat transfer in both the direction must be done separately.

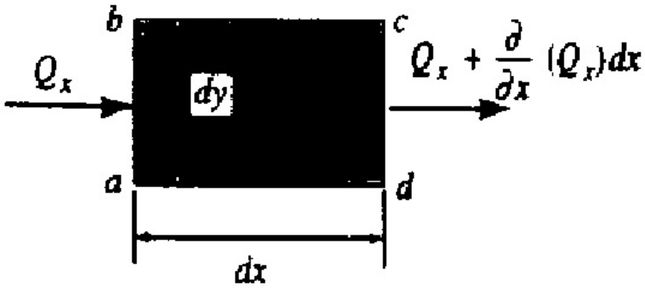

Fig. 5. Heat transfer on the control volume

As the name implies, it informs that the work done by the fluid on the control volume that is caused by the force. This force was due to the stress (normal and shear) on the surface of the control volume. Consider the control volume moving in the fluid which is at rest. The state of stress at the control volume will be the same as shown in Figure 6 below.

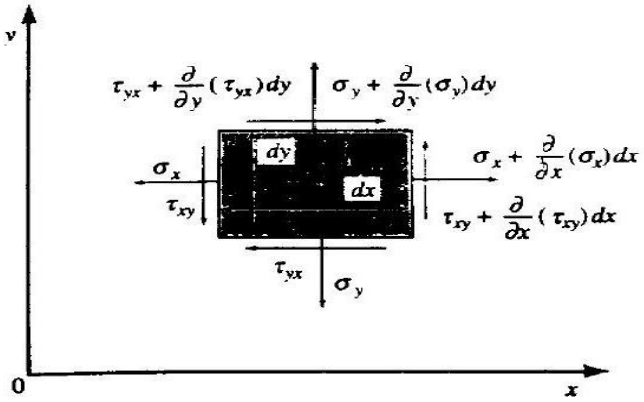

Fig. 6. State of stress on the control volume

3. Results and Discussion

Generally, the results can be classified into two categories which include: temperature and velocity profile respectively. As the name implies, these results tell about the distribution of temperature and flow velocity profile, which is used to determine which form factor provided better cooling solution.

3.1 Temperature Profile of ATX Form Factor

Figure 7 shows the temperature distribution of the ATX form factor. From the figure, we can see that the hottest part inside the casing was the Central Processing Unit (CPU), which is about 120°C. This was followed by the Graphic Processing Unit (GPU) at 110°C. The GPU lies inside the VGA card. The temperature of the motherboard which is the VGA card is located and recorded at 100°C averagely. This was mainly due to the heat transferred from the heatsink of the VGA card to the surface of the motherboard [4,11] at the particular area.

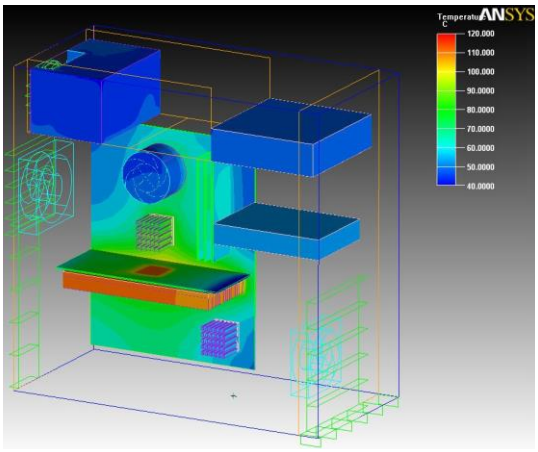

Fig. 7. Temperature profile of ATX form factor

Further looking into the temperature profile within the VGA assembly as shown in Figure 8 below, the chip of the assembly had the highest temperature, around 110°C. Upon further away from the chip, the temperature values started to decline.

This was mainly due to the high power consumption of the GPU (200 W). Furthermore, the GPU used in this setup had only passive heatsink, which was less efficient compared to the active one that was used frequently to cool down the high-power consumption GPU.

In addition, the material of the heatsink was assumed to be aluminum in this case as a result from failure to determine the material used. Fortunately, the maximum core temperature of the GPU based on the datasheet was said to be 110°C. In other words, that is the highest temperature level in the reality.

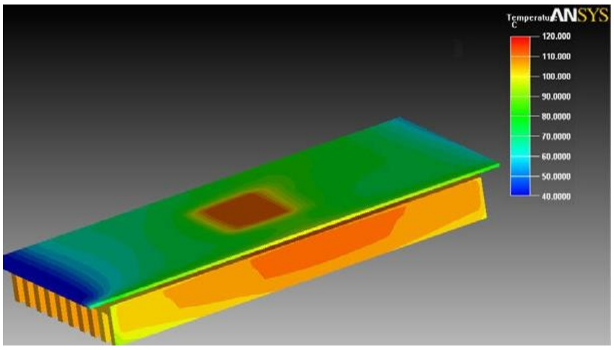

Fig. 8. Surface temperature for VGA card used in ATX form factor

The CPU (not shown) is the component which has second highest temperature. Referring to Figure 9, the chip itself carries surface temperature of 120°C. We can observe that the maximum temperature value was slightly higher compared to the value at the datasheet that was around 100°C. This is due to the simplification done in order to reduce the computation time (The original Heatsink fan is shown at the right side).

By comparing the figures, the simplification process has led the number of fins in the heatsink to be reduced. In addition, the base of the actual heatsink assembly was made of copper and the rest of the part was extruded Aluminum. However in this case, the whole assembly was modeled by using extruded Aluminum. As a result, the heatsink became less efficient as the surface area and the thermal conductivity [8] was reduced.

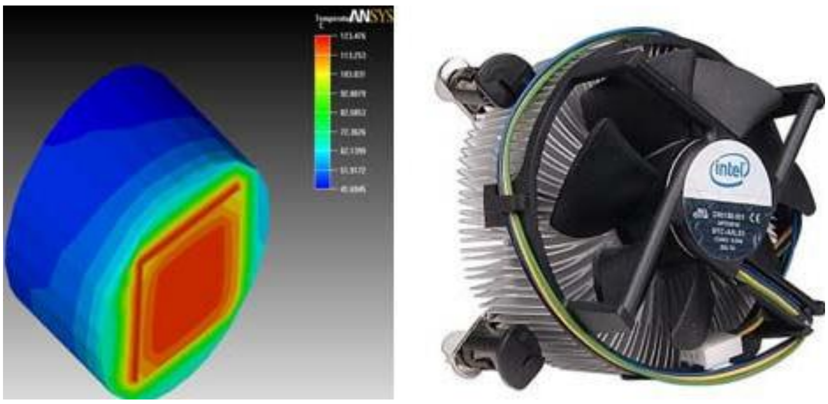

Fig. 9. Surface temperature of CPU heatsink assembly of ATX (left) and actual CPU heatsink fan assembly (right)

To further reduce the temperature, third party cooler can be used instead of the original heatsink. We know that the original cooler was designed only to be used under normal conditions. It has the ability to cool the processor in full load condition. However, the temperature value would be very high and might reduce the life of the component. This is the reason why a lot of hardware enthusiast who like to overclock (An operation which done to increase the clock of the processor higher than the original value) their processor uses these third party coolers.

Next, the temperature profile of the motherboard assembly shows that temperature was 65°C at major area of the motherboard. The surface temperature profile for the Northbridge and Southbridge inside the ATX form factor is shown in Figure 10 and 11.

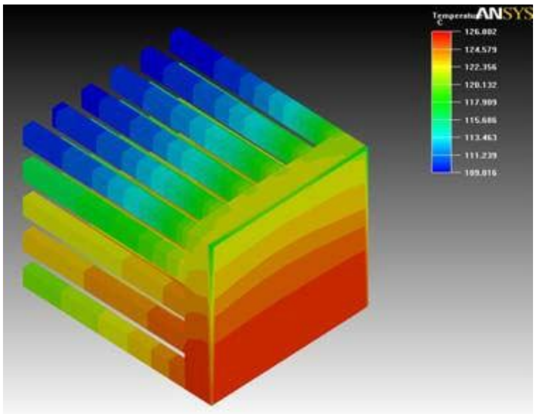

Fig. 10. Surface temperature for Northbridge assembly used in ATX

By observing Figure 10, we can see that there is uneven temperature distribution at the surface of the chip. That is the bottom part consists of higher temperature, while the upper part is lower. The main factor that contributes to this was the arrangement of ATX that situated the Northbridge near the VGA card (refer to Figure 7). In addition, we know that VGA card dissipated the most amount of heat as it was the hottest component in the PC [12].

Beside the chip, the fins also pose a very high temperature, which was 75°C being the lowest temperature. This was mainly caused by all the heat been transferred directly to the heatsink surface as contact resistance was neglected in this study. On the other hand, phase change material was used as the interface material to reduce the contact resistance. However, contact resistance could not be eliminated totally.

Meanwhile in Figure 11, it can be observed that the overall temperature of the Southbridge assembly was much lower compared to Northbridge. The chip recorded surface temperature of 70°C averagely, which was almost the same as the value stated in the datasheet. This incident was due to the power consumption of Southbridge was far lower compared to Northbridge.

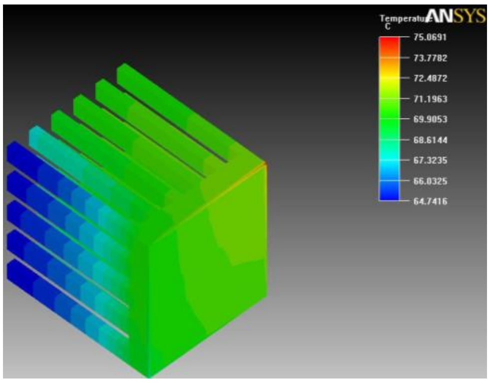

Fig. 11. Surface temperature for Southbridge assembly used in ATX

From both figures, the location where the chip was located has the highest temperature. This is because this was where the heat source was generated. In addition, the temperature distribution shown above was calculated based on the Thermal Design Power (TDP), which meant that the power dissipated rating in this case was under maximum load condition.

As distance from the chip increased, value of surface temperature started to decline. The difference in the temperature is called the temperature gradient. By comparing Figure 10 and 11, we can see the temperature gradient of Northbridge assembly was higher. This was expected as the heat at the fin on the heatsink was absorbed by air from the cooling solution for the CPU or processor.

The next components to discuss is the Dual In-line Memory Module (DIMM). From Figure 7, we can conclude that the DIMM temperature fall between the ranges of 70 - 80°C. This temperature was acceptable for normal use as the worst case temperature was about 90°C. As lower temperature may prolong lifetime of one component, effort to lower the temperature still had be done. One of the most common methods is by installing heat spreader on the DIMM. The heat spreader can remove the heat from the chip more effectively by conduction. Furthermore, it can increase the surface area that exposed to the surrounding air (refer to Figure 12), thus enabling air to be convected more efficiently. Besides using heat spreader, some manufacturers also used fan to cool down their DIMM. Some of the typical DIMM in the market are shown in Figure 12 below.

Fig. 12. Few types of DIMM with its own cooling solution

3.2 Temperature Profile of BTX Form Factor

Figure 13 shows the temperature profile for the BTX form factor. We can observe that the highest temperature was located at the GPU,

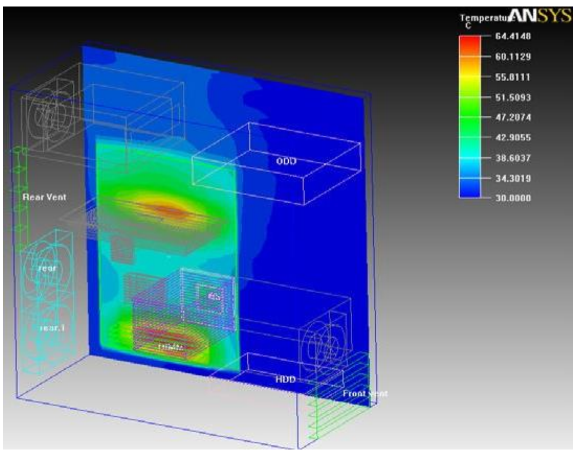

Fig. 13. Temperature profile of BTX form factor

For the case of BTX form factor, the temperature distribution on the surface of the VGA card is shown in Figure 14 below. The surface temperature of the card had the value of 110°C maximum. Since the same card was used for analysis, the same heat was transferred from the card. However, difference in the cooling solution resulted in different temperature distribution.

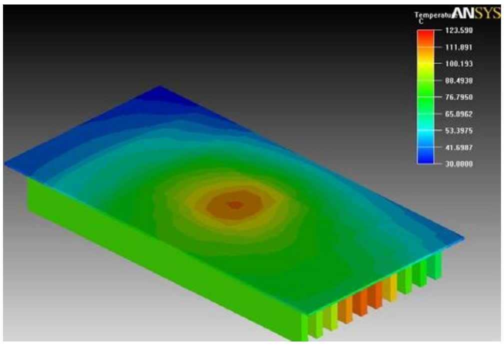

Fig. 14. Surface temperature for VGA card used in BTX form factor

Unlike ATX form factor, the temperature distribution of BTX [9] varied in the direction perpendicular to the longitudinal axis of the card itself. This was an expected result as the zone with the lower surface temperature was further away from location where the heat source is located. On the other hand, the flow which was parallel to the longitudinal axis of the card drew heat uniformly in the direction perpendicular to it, as a result this phenomenon occured.

Figure 15 shows the surface temperature for the CPU and its heat sink assembly. The highest temperature was at the surface of the chip, which is about 47°C. The value of temperature decreased as distance moving further from the chip. Despite that, the fins' temperature was slightly higher than the ambient temperature. That was about 34°C.

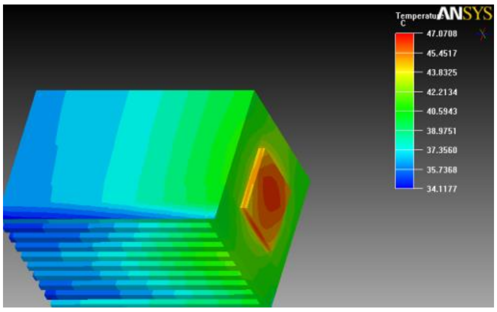

Fig. 15. Surface temperature for CPU heatsink used in BTX form factor

The main reason that contributed to this condition was the cooling system used. By looking at the figure, the heatsink used in BTX system was certainly much larger compared to the ATX one. Thus, there was a larger area which allowed more heat to be convected by the air as flow passed thru it. Furthermore, the air has higher velocity accompanied by lower temperature, an ideal condition to enhance the heat transfer.

As air is directly taken from environment, it is for sure much colder since it hasn't expose to any heat sources. Next, the higher velocity of air which resulted from the use of Support Retention Module (SRM) also was one of the factors that leads to more efficient cooling. Together, this can lower the temperature for both the heatsink and the CPU itself.

The surface temperature of chipset of the BTX form factor is shown below in Figure 16. We can conclude that the temperature gradient was very low as there was almost no difference between temperature of chip and heatsink. In addition, the thermal conductivity was already constant as the same material been used for the numerical simulation. As a result, the heat flux will be very low due to the temperature gradient according to Fourier's law of conduction.

In overall, the temperature of the Northbridge was still lower for the case of BTX. In addition, compensation had been done to overcome the low heat flux phenomenon; that is by applying higher surface area in the heatsink. This was the reason why the heatsink used in the BTX geometry is much larger.

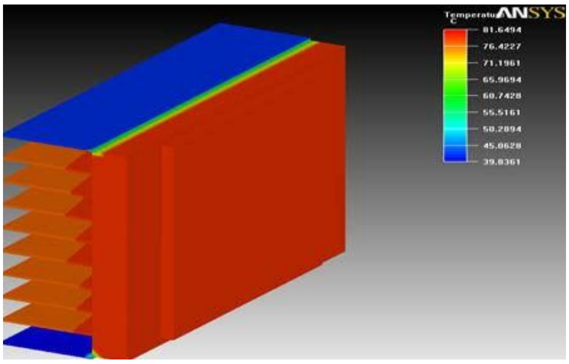

Fig. 16. Surface temperature for Northbridge assembly used in BTX

The Southbridge is the only component in BTX that is comprised of higher surface temperature compared to the ATX form factor. In Figure 17 is the surface temperature profile for the BTX Southbridge assembly. It can be observed that the similar profile obtained for the Southbridge and Northbridge assembly. This meant that both North and South bridge(s) have low heat flux which contributed to high surface temperature at the chip as well at the heatsink.

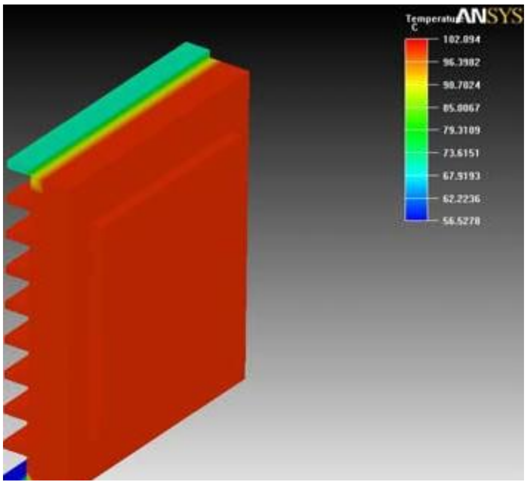

Fig. 17. Surface temperature for Southbridge assembly used in BTX

In the figure, we can see that the highest temperature at the Southbridge assembly was about 80°C. The main factor that caused this to happen was the reduction in surface area of the heatsink. Recalled the heatsink assembly of the ATX, which is taller. This is a vital criterion which can determine the quantity of heat flux.

Besides, the location of the assembly also influences the surface temperature of the assembly. By comparing Figure 7 and 13, it can be seen that Southbridge assembly in ATX form factor can receive colder air compared to the BTX which received air at much higher temperature. This can be justified by the point in which the air received by the Southbridge assembly in ATX form factor can be considered direct from the ambient environment, thus having ambient temperature.

However, in the arrangement of BTX form factor, Southbridge assembly received the air that already absorbed heat from the previous object it flows through (CPU, Northbridge etc). As a result, the air temperature rose higher as it reached the Southbridge.

Looking at the temperature on the motherboard, the location where the DIMM was situated had the highest temperature value. This was obvious as most of the heat from the DIMM conduct to the motherboard rather than transferred to the surrounding air by convection. Similar to ATX, these temperature rise may be caused by the absence of heat spreader.

Hard Disk Drive (HDD) used in the BTX system presented the peak temperature of 40°C. This can be justified when the position of the HDD was changed in the BTX form factor, which was from the rack at the bottom part of the casing compared to the traditional ATX form factor that situated the drive at the middle section. This modification had allowed the HDD to received cool air that draw directly from the ambient. As a result, this produced a large temperature gradient between the surface of the HDD and the air. Thus enabling higher heat transfer rate.

Finally, surface temperature of 45°C was detected for the Optical Disk Drive (ODD) for the case of BTX form factor. This result is reasonable as the location of the ODD was placed at the top part of the casing which there was no air flow. It is interesting to know that why the ODD was still been placed at this particular area whereas the ventilation is poor.

There are few reasons why the ODD was placed in this way. The first one is regarding the size of the ODD. ODD has the size of about 5.25", this meant that they needed a larger area to be placed. The main point was due to ergonomic issue. ODD is the device where users place their disc in. In other words, it need to have easy access all the time. As a result, placing ODD in the area which eases to be reached was more desirable.

By comparing both Table 1 and 2, we can observe that most components in the BTX form factor possess lower temperature. Thus, we can concluded that the BTX form factor do provide more efficient cooling to the hardware. The layout of the BTX is the key that allows it to have such criterion. Figure 18 and 19 show the flow velocity magnitude inside the casing which was obtained from the simulation for both ATX and BTX.

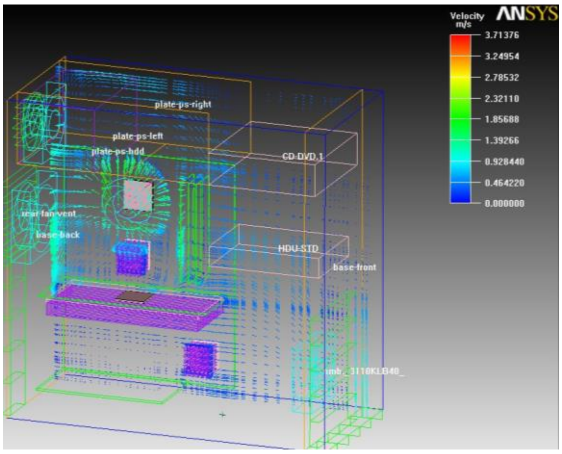

Fig. 18. Velocity magnitudes in ATX form factor

We can note that the velocity magnitude in the BTX form factor was much straighter than ATX. Besides, velocity magnitude in the BTX form factor was also higher, about 8 m/s compared to ATX which had only about 4 m/s. This higher velocity was the most vital part that led to the efficient cooling of BTX.

Table 1
Power consumption and maximum temperature of components in ATX form factor

Component	Power consumption (W)	Maximum temperature (°C)
CPU	75	120
GPU & VGA Card	200	110
DIMM	8	80
Northbridge	15	126
Southbridge	5	75
Hard Disk Drive (HDD)	20	45
Optical Disk Drive (ODD)	5	35

Table 2
Power consumption and maximum temperature of components in BTX form factor

Component	Power consumption (W)	Maximum temperature (°C)
CPU	75	47
GPU & VGA Card	200	110
DIMM	8	73
Northbridge	15	81
Southbridge	5	80
Hard Disk Drive (HDD)	20	40
Optical Disk Drive (ODD)	5	40

There were few factors that allowed the high velocity magnitude in the BTX form factor. The first factor was the unidirectional flow of air in the casing. In BTX, there were no fans installed at other place inside the casing except the front and back of the casing as shown in Figure 19. Hence, this allowed the air flow in one direction only as the face of the fans is parallel to each other.

On the other hand, the flow in ATX form factor seemed to be in various directions. The most significant factor that contributed to this is the fan on the heatsink assembly of the CPU that generated omnidirectional flow around it. Omnidirectional flow means flow that occurred in all direction, similar to the propagation of sound wave. This flow tends to distort the flow by creating a vacuum at the area where more than one flow which was in the opposite direction. Therefore, the velocity magnitude reduced.

The next factor that contributed to the high velocity magnitude was the arrangement of components on the motherboard. In ATX, the arrangement of the components was in various orientations. Starting with the DIMM that was arranged in the way with which its longitudinal axis was perpendicular to the air flow direction. This would cause the airflow to be blocked by the height of the DIMM itself.

However in the BTX system, DIMM was placed with its longitudinal axis parallel to the airflow. By using this arrangement, the longitudinal axis of the DIMM now become the channel which enhances the airflow instead of blocking it. Besides, this also allowed heat to be drawn more easily from the surface of the DIMM, where the chips for the module were located.

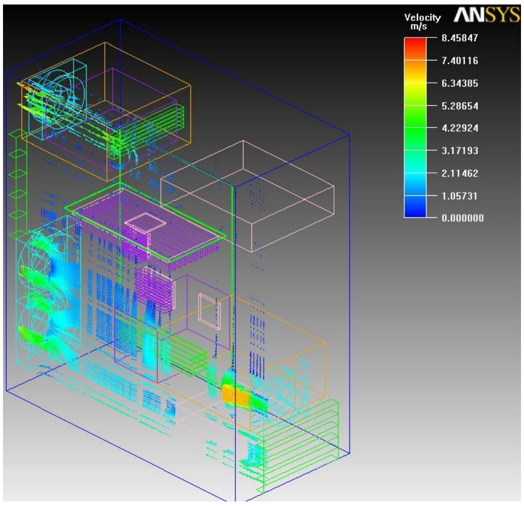

Fig. 19. Velocity magnitudes in BTX form factor

In addition to high velocity magnitude, the arrangement of the components does make BTX more efficient in cooling. BTX arrangement was based on the quantity of heat dissipated from each of the components. Theoretically, CPU, Northbridge and Southbridge consume the most amount of power. That's the reason why they were arranged together in one line. Furthermore, the location of that particular line is collinear with the SRM, which provided cool air to the entire components in the casing.

However, this theory doesn't seem logic because the component which consumes the most power was the VGA card instead of CPU, Northbridge and Southbridge. This is due to BTX form factor was introduced back in 2005. During that time, technology was not advanced like today. Even the most advanced VGA card only consumed about 30 W of power.

Fortunately in this study, the VGA card had the power rating of 200 W. From the numerical simulation, the temperature obtained was slightly higher than the maximum allowable temperature in the datasheet. However, when recalling that the power rating used in this study was based on the maximum power dissipated, which was rarely reaching the normal condition. As a consequence, the result obtained was useable because it was at the worst condition.

4. Conclusions

From this study, the main conclusion we can make is that BTX form factor provided better thermal solution to the components inside the casing. By modifying the layout of the motherboard, the location of components mounted to it had been realigned based on the power consumption of the respective components. Therefore, component which consumes the largest amount of power will be given priority to be cooled down.

Another advantage of BTX form factor was the velocity of the air produced. In this study, the maximum velocity obtained for BTX was about 8.45 m/s. In contrast, the ATX form factor only had 3.71 m/s. As a result, this contributed to the improvement of cooling capabilities for BTX form factor. This advantage resulted from the rearrangement of layout of the BTX motherboard.

Next, we can conclude that the heat flow profile in the BTX form factor was more in a linear path. In contrast, there was a lot of chaos region in the ATX form factor. The rising of this chaos was due to the layout of ATX motherboard which formed blockage for the flow. Besides, the CPU heatsink used in the ATX form factor also transferred hot air to nearby components such as RAM and Northbridge.

Finally, the GPU which draws the most power, also one of the hottest components lies in the PC. This was followed by the CPU. As such, cooling of such components must be given priority to avoid damage by overheating.

Acknowledgement
The author would like to acknowledge Faculty of Mechanical Engineering, University Teknologi Malaysia, UTM for the support given in conducting this research.

References
[1] Misra, Krishna B. Reliability analysis and prediction: A methodology oriented treatment. Elsevier, 2012.
[2] Mulgaonker, S., B. Chambers, M. Mahalingam, G. Ganesan, V. Hause, and H. Berg. "Thermal performance limits of the QFP family." *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A* 17, no. 4 (1994): 573-582. https://doi.org/10.1109/95.335044
[3] Wang, Yaxiong, Yinshan Feng, Robert Dong, and Phil Chou. "Investigation of CPU thermal solution designs for BTX desktop system." In *Twenty-Third Annual IEEE Semiconductor Thermal Measurement and Management Symposium*, pp. 24-29. IEEE, 2007. https://doi.org/10.1109/STHERM.2007.352388
[4] Ng, Kar Mun, and Ketan R. Shah. "Motherboard heat transfer modeling methodology." In *Conference on High Density Microsystem Design and Packaging and Component Failure Analysis, 2006. HDP'06.* pp. 43-48. IEEE, 2006. https://doi.org/10.1109/HDP.2006.1707563
[5] Oosthuizen, Patrick H., and David Naylor. "An introduction to convective heat transfer analysis." *(No Title)* (1999).
[6] Bergman, Theodore L., Adrienne S. Lavine, Frank P. Incropera, and David P. DeWitt. *Introduction to heat transfer*. John Wiley & Sons, 2011.
[7] Scott, Mueller. *Upgrading and repairing PCs*. Pearson Education India, 2010.
[8] Yunus, A., M. John, and J. Afshin. *THERMAL FLUID SCIENCES*. Second. Ny, Ny: Mcgraw Hill, 2004.
[9] Smith, Will. *Maximum PC Guide to Building a Dream PC*. Que Publishing, 2004.
[10] Cheng, Hsien-Chie, Wen-Hwa Chen, and Hwa-Fa Cheng. "Theoretical and experimental characterization of heat dissipation in a board-level microelectronic component." *Applied Thermal Engineering* 28, no. 5-6 (2008): 575-588. https://doi.org/10.1016/j.applthermaleng.2007.04.013
[11] Suwa, Tohru, and Hamid Hadim. "Multidisciplinary placement optimization of heat generating electronic components on a printed circuit board in an enclosure." *IEEE Transactions on Components and Packaging Technologies* 30, no. 3 (2007): 402-410. https://doi.org/10.1109/TCAPT.2007.901674
[12] Singh, Pratap, and Puligandla Viswanadham. *Failure modes and mechanisms in electronic packages*. Springer Science & Business Media, 1997.