# THERMAL MANAGERMENT OF HIGH POWER MEMORY MODULE FOR SERVER PLATFORMS

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## ABSTRACT

This paper demonstrates an approach for thermal solution development of high power memory module for computer system platforms. A lumped thermal resistance equation is adopted to consider the coupling between register/buffer and DRAMs. Comprehensive thermal analysis is done to characterize the thermal resistances under various memory thermal conditions in different system configurations. Memory thermal gap is identified and addressed with efficient and low cost thermal solutions such as full DIMM heat spreader (FDHS). Structural consideration is further discussed to address FDHS air gap risk related to height differences between DRAM and register/buffer packages. The thermal solution development approach is applicable to memory modules such as registered DIMM (RDIMM) or fully buffered DIMM (FBD).

**KEY WORDS**: memory module, DRAM, DIMM, thermal management, heatspreader

## INTRODUCTION

With the higher demand for faster speed and larger capacity memory technology, not only the power in each DRAM (Dynamic Random Access Memory) device increases but also the number of DRAM devices on DIMM (Dual In-line Memory Module) increases. Higher power becomes a common trend for future high-end server systems [1]. Therefore, thermally efficient, cost-effective and mechanically reliable thermal managements are required to ensure the satisfactory memory operation with lower thermal budget on memory sub-system. Unlike single device module, with multiple devices placed on DIMM, the complexity of thermal performance assessment and thermal solution design are inevitable. In this work, a commercial numerical simulation tool, Flotherm® [2], is used to conduct the CFD and thermal analysis. Steady state thermal models can be developed to simulate the forced convection condition in server application. Through the parametric study, thermal resistance sensitivities under different flow and DIMM pitch can be determined. At given DIMM power and DIMM local boundary conditions, using engineering approach, the hottest device junction temperature and the module cooling capability can be predicted. When memory can not meet the cooling target, heatspeaders are considered as the main low-cost cooling solutions for high power memory module. By considering the trade-offs between flow and thermal impedance, an optimal heatspreader thickness is recommended after a DOE analysis. Structure analysis with ABAQUS® [3] is further performed, with proper selection of thermal interface material compressibility, to assess risk of air gap between packages and heatspreader. With the low cost thermal management, the cooling capability of high power memory module can be improved significantly.

## THERMAL CHRACTERIZATION

Figure 1 illustrates the memory module example in high end server application. The device on the middle of each DIMM card could be advanced memory buffer (AMB) or register package. The other devices on the module are DRAMs packages. Thermal characterization becomes complicated because of the thermal interactions not only among different types of components on the DIMM, but also between any two adjacent DIMM cards.

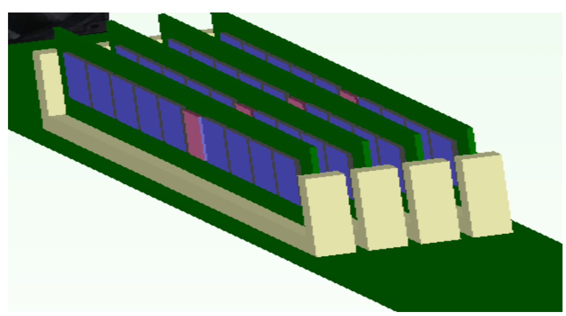

Figure 1: A typical multi-component DIMM module in high-end server application

This work will be focused on register DIMM (RDIMM). All the modeling and analysis that will be introduced later are based on DDR3 Register DIMM.

### Thermal analysis approach

Module level thermal analysis procedure can be described by three major steps:

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First, CFD model is built in Flotherm to represent the thermally critical cards in a numerical wind tunnel environment. One full DIMM sits in the center with two adjacent DIMMs by the side. The two adjacent DIMMs are simplified as two half DIMMs with symmetrical boundary conditions to save the computation grids. The DIMM pitch and channel top bypass are constrained by the specified system design. Air flows in from one end. In server application the air velocity typically varies from 1 to 4m/s depending on the fan operation mode. The ambient temperature at memory local can be obtained by system level thermal simulation. Most of the pre-heat at DIMM inlet is from CPU. Through parametric study, the resistance sensitivity to the inlet flow and DIMM pitch can be extracted for trend analysis.

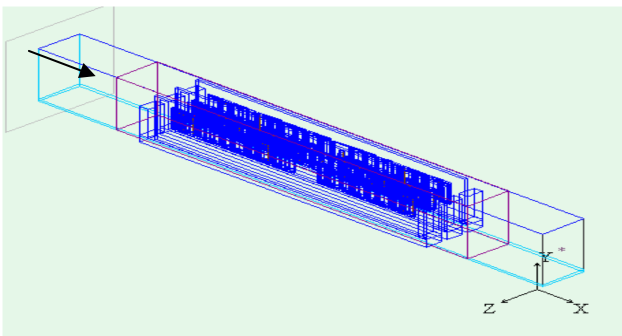



Figure 2: CFD model in Flotherm

In the second step, by superposition, six thermal resistances can be obtained at any given boundary conditions. The six thermal resistances include the device self-heating resistances, spreading heating resistances and adjacent heating resistances. The junction temperatures of DRAM and register can be predicted by following equations:

$$T_{j\_DRAM} = T_{la} + P_D R_D + P_R R_{RD} + P_{adj\_DIMM} R_{adj\_D} \quad (1)$$

$$T_{j\_Reg} = T_{la} + P_D R_{DR} + P_R R_R + P_{adj\_DIMM} R_{adj\_Reg} \quad (2)$$

By using engineering simplification, all DRAMs are lumped as one term. Therefore, DRAM power in the above equation is the total DRAM power and the junction temperature of DRAM represents the hottest DRAM junction temperature on the module. In equation (1) and (2), parameter $T_{j\_DRAM}$ is the junction temperature of the hottest DRAM; $T_{j\_Reg}$ is the junction temperature of the register; $T_{la}$ is the memory local ambient temperature; $P_D$ is the total DRAM power; $P_R$ is the register power; $P_{adj\_DIMM}$ is the total adjacent DIMM power; $R_D$ is the DRAM self-heating resistance; $R_R$ is the register self-heating resistance; $R_{RD}$ is the register to DRAM heating resistance; $R_{DR}$ is the DRAM to register heating resistance; $R_{adj\_D}$ is the adjacent DIMM to DRAM heating resistance and $R_{adj\_R}$ is the adjacent DIMM to register heating resistance.

In the third step, memory cooling capability can be estimated when the maximum device operating temperature (Tj,max) specification is known. Meanwhile, memory power under targeted memory operating bandwidth can be extracted for particular memory configurations and supplier characteristics. There will be no gap between the memory power and memory cooling capability if both DRAM and register (or buffer) are below the devices junction temperature specifications. If any device on the DIMM has the junction temperature over the Tj,max, a thermal solution has to be considered to close the gap to ensure a satisfactory memory operation.

**Case study and results**

With the approach described above, a case study is conducted on the DDR3 dual rank by 4 (DRx4) RDIMM. DRx4 card consists of 9 dual die stacking DRAM packages on both sides of DIMM and a DDR3 register package on the middle of front side. DRx4 is typically considered as the most thermally critical card for DDR3 RDIMM configurations currently considered.

Figure 3 shows a typical temperature profile along the DIMM when 15W total power is dissipated at 3m/s and 45°C local thermal environment. In the figure, each point represents a device junction temperature. The inlet is close to the F1 and B1 (the first devices next to inlet on front and back sides). Register is the hottest device on module because of the high power density. The downstream DRAMs behind the register experience higher junction temperatures due to worsened air temperature from upstream heating.

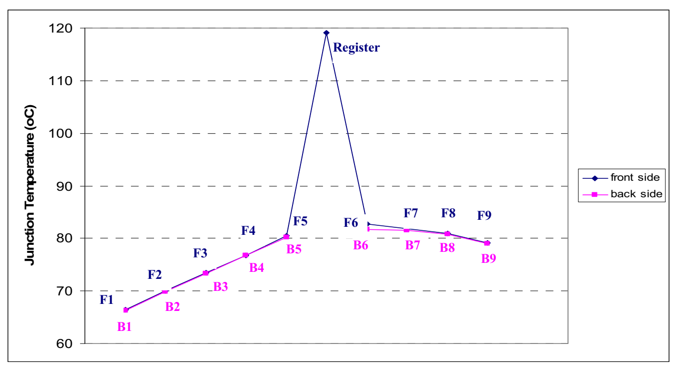



Figure 3: Typical temperature profile along the RDIMM

CFD simulation is used to assess memory cooling capability of different systems that represents typical reference configurations. Figure 4 shows the results for four system platforms with different DIMM locations, duct layouts, and CPU powers. System 1 has the best memory thermal environment because of its low CPU preheating and high DIMM inlet air speed. As expected, system 1 has the highest memory cooling capability. It can meet the system cooling capability without any thermal solution on DIMM. System 2, 3, and 4 reveal cooling gaps of 2~4W. In order to meet the requirements for all the platforms, a low-cost thermal solution such as full DIMM heat spreader (FDHS) is recommended for the high power DIMMs.

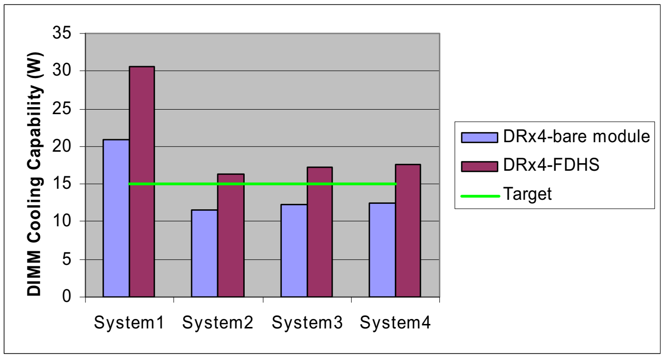



Figure 4: Memory cooling capability comparison among four different systems

To further help system layout design and fan selection, parametric study has been done to capture the memory thermal resistance sensitivity curves with the variation of two parameters, DIMM inlet flow and DIMM pitch. The inlet air velocity is varied from 1m/s to 4 m/s. The DIMM pitch varies from 0.35 inch to 0.4 inch. Figure 5 and Figure 6 illustrate the six thermal resistances sensitivity curves with air speed and DIMM pitch. The nonlinear curves in Figure 5 reveal that resistances have the tendency of rapid decreasing at low speed range. The decrease slows down and eventually becomes stable. It is noted that $R_{RD}$ is higher than $R_{DRAM}$ because of the lumped DRAM power used in Equation (1) and (2). As shown in Figure 6, with a constant DIMM inlet flow rate, the resistance linearly increases with the increase of DIMM pitch.

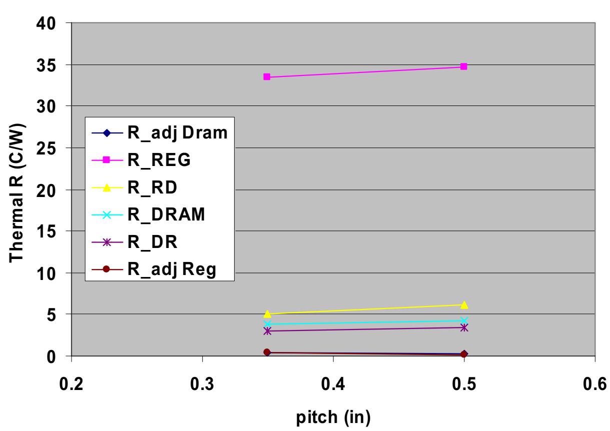



Figure 5: Thermal resistance vs. air flow

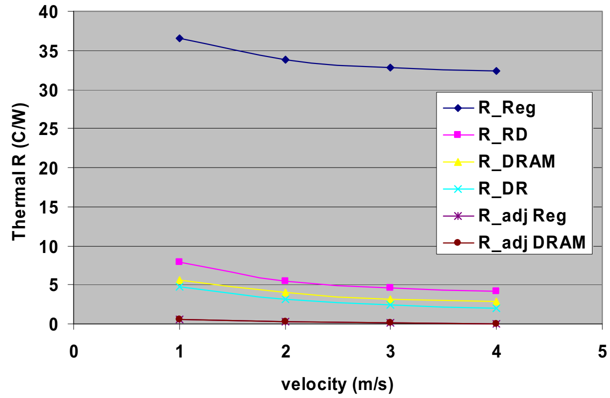
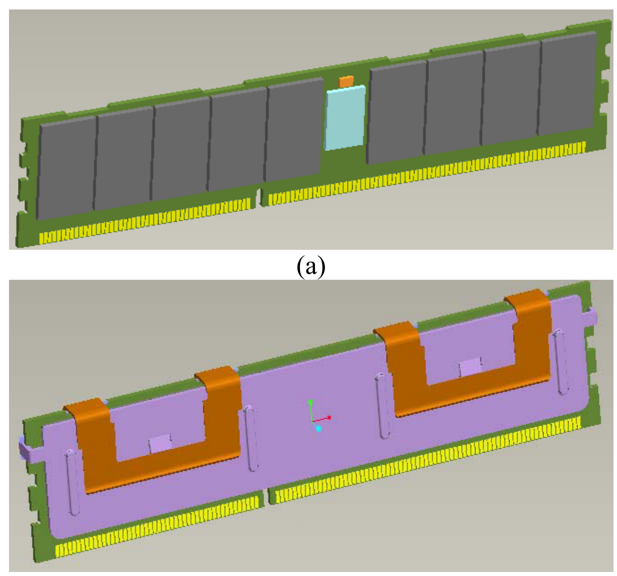



Figure 6: Thermal resistance vs. DIMM pitch

## THERMAL SOLUTION DEVELOPMENT

### FDHS design concept

Based on the thermal gap analysis, a reference FDHS is developed to meet the cooling needs of high power module. The FDHS consists of 3 major parts: two flat aluminum plates that fully cover the both front and back sides of DIMM, two stainless steel retention clips and thermal interface material (TIM) between FDHS and DIMM packages.



(a)

(b)

Figure 7: Full DIMM heat spreader (FDHS) (a) Bare module without thermal solution; (b) FDHS assembly

### FDHS thermal design

Thicker metal plates can improve the heat spreading along the DIMM and lower the thermal impedance. However, thicker plates could block more flow and increase the flow impedance. A parametric analysis (see Table 1) has been conducted to find an optimum FDHS thickness by considering the trade offs between the flow and thermal impedances.

Table 1: Design matrix of FDHS thickness

| Case # | Front plate thickness (mm) | Back plate thickness (mm) |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 0.5 | 0.5 |
| 3 | 1 | 0.5 |
| 4 | 1 | 1 |
| 5 | 1.5 | 0.5 |
| 6 | 2 | 0.5 |
| 7 | 1.5 | 1.5 |
| 8 | 2 | 2 |

With CFD simulations, the impedance curves are predicted for various FDHS thickness, as shown in Figure 8. The intersection of the impedance curve and system operating curve is the actual DIMM entrance flow in a server system. The system operating curve is dependent on the particular fan characteristic and system layout. The memory local inlet air velocity is determined according to Figure 8. With the same inlet temperature and same power on, the junction temperatures for DIMMs with different FDHS design can be predicted and compared. In Figure 9, it is found that with the minimum device junction temperature, the thermally optimum FDHS thickness is 1.5mm on both front and back sides of DIMM.

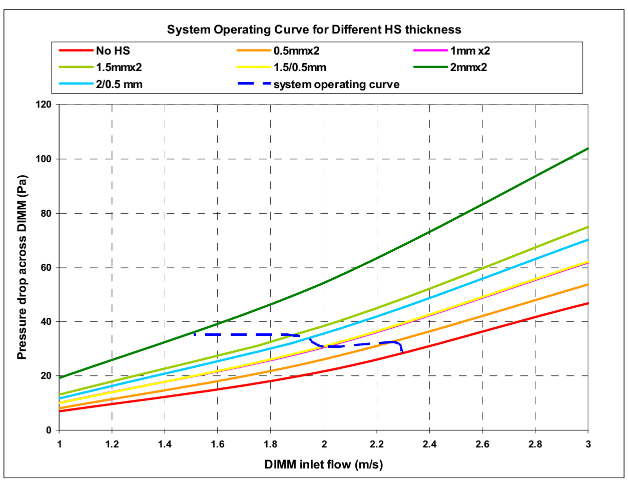



Figure 8: Impedance curves of different FDHS thicknesses

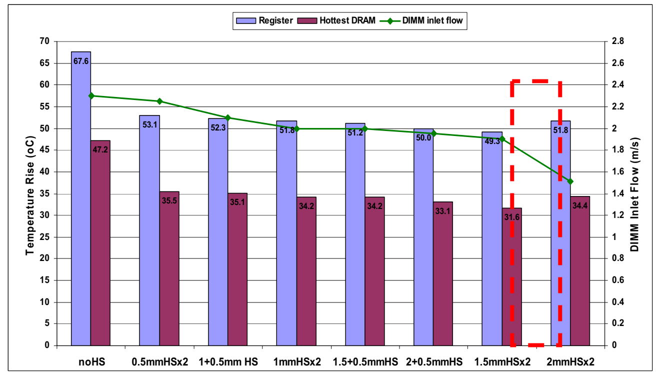



Figure 9: Junction temperature comparison among different FDHS thickness design

However, this conclusion is based on thermal performance only. In reality, more factors have to be considered such as system volumetric constrain, structure stiffness, mechanical reliability and manufacturing cost. For example, for a particular platform, 1.0mm on both front and back sides of DIMM is chosen as the optimum FDHS thickness by considering all the factors that mentioned above.

**FDHS structure analysis**

DRAM packages on DIMM exhibit height variations due to package molding compound thickness tolerances and due to after-assembling solder height differences from solder ball size tolerances and solder reflow variations. Moreover, register height is often different from DRAM packages, and this difference is very difficult to control due to possible combinations of register and DRAMs from different suppliers. The height difference on the DIMM, which is essentially a multi-components module (MCM), can cause air gaps between devices and heatspreader, as shown in Figure 10 (a). Air gap voids the effectiveness of an FDHS and exacerbates cooling condition of a device. In addition to certain specification control on DRAM and register height variations, FDHS needs to be designed with proper level and distribution of retention force to overcome certain air gaps, as shown in Figure 10 (b).

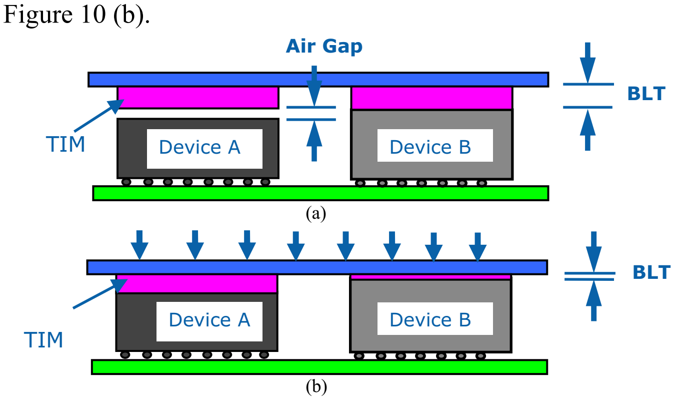



Figure 10: Air Gap in the FDHS Assembly, (a) without clip; (b) with clip

<u>**Modeling assumptions**</u>. To better understand the TIM contact between heatspreader and devices, structure analysis is

performed using ABAQUS to investigate the TIM bond line thickness (BLT) on each device. As shown in Figure 11, the non-linear compression-only spring elements have been used to model the TIMs. The heatspreader and DIMM module are simplified as 2D structure and simulated with beam elements.

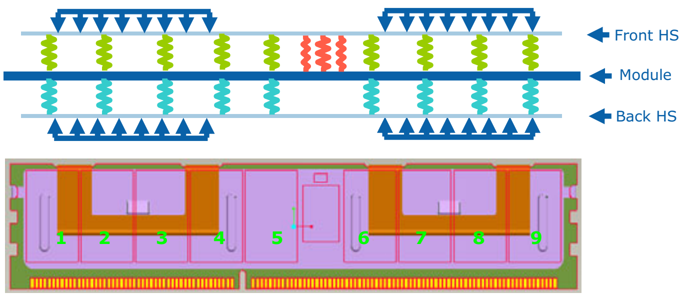



Figure 11: FDHS structure modeling

**Mechanical properties of TIM.** Several TIMs have been investigated in this work. TIM A property is illustrated here as an example. Figure 12 shows the test data of BLT vs. pressure of TIM A. The original thickness of TIM A is 0.25mm (10mil) without any pressure.

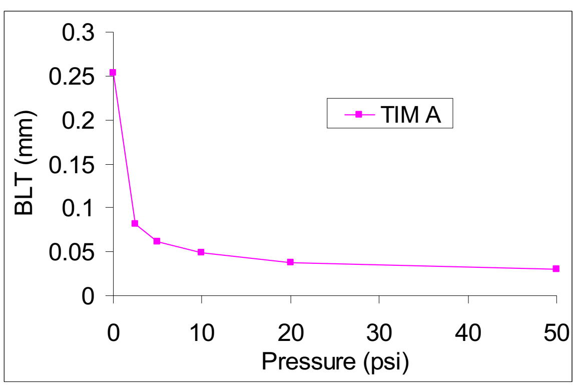
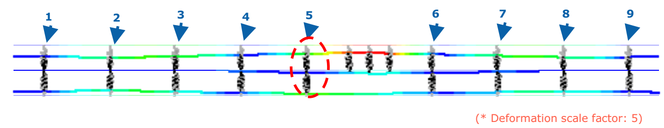



Figure 12: Compressibility of a thermal interface material

**A case study.** Figure 13 shows the results of a 1.0mm FDHS with 0.6mm retention clips at 4lb distributed loading on the clipping area. Scenarios with different height between register and DRAM packages have been investigated. Figure 13(a) shows that when DRAM is lower than register, DRAM #5 and #6 have more risks of air gap than the others packages on DIMM. When the height difference is more than 0.27mm, there will be an air gap on DRAM #5. Figure 13(b) shows that when DRAM is higher than register, the register has more risks of air gap than the DRAMs. When the height difference is more than 0.14mm, the air gap will be identified above the register. The structure analysis result therefore defines a safe zone of this FDHS with TIM A: register package should not be >0.27mm higher or >0.14mm lower than the DRAM package.

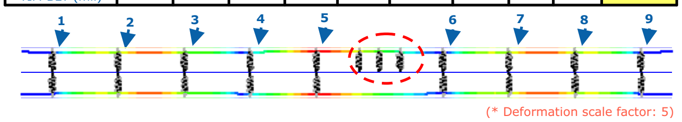
This example only demonstrates an approach to address the air gap issue with a flat FDHS. In general, if the height differences between register and DRAMs can not be overcome with proper retention pressure level and distribution, additional features on FDHS, such as a punch-in or punch-out area on register can be considered to accommodate the height differences.

| | DRAM (0.27mm lower than Register) | | | | | | | | | Register |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| TIM BLT (mil) | 2.926 | 2.358 | 3.222 | 6.025 | 9.892 | 9.247 | 5.149 | 3.000 | 2.651 | 1.113 |




(a)

| | DRAM (0.14mm higher than Register) | | | | | | | | | Register |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | |
| TIM BLT (mil) | 3.499 | 2.590 | 2.693 | 3.711 | 4.553 | 3.236 | 2.303 | 2.393 | 3.516 | 9.747 |




(b)

Figure13: Structure analysis results (a) DRAM is lower than register; (b) DRAM is higher than register

## SUMMARY AND CONCLUSIONS

High power memory module thermal analysis approach has been introduced first in the paper. Six thermal resistances that represent the thermal interactions between different components on DIMM and from adjacent DIMMs have been applied to predict the device junction temperature. DIMM cooling capability therefore can be estimated when junction specifications are defined. Case study shows that for a DRx4 dual die stacking RDIMM, thermal solution is needed to meet the system cooling target. A reference FDHS design has been proposed here as an efficient and low-cost thermal solution. An optimal heatspreader thickness has been chosen by considering the trade offs among flow impedance, thermal impedance and many other factors. Structure analysis explains that there is a safe zone on the components height difference to ensure no air gap in the FDHS assembly. Otherwise, punched FDHS may be needed.


### Acknowledgments
Thanks to Christian Le for providing the system operating curve.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