Transient Thermal Analysis for M.2 SSD Thermal Throttling: Detailed CFD Model vs Network-Based Model

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ABSTRACT

Solid State Drive (SSD) technology continues to advance toward smaller footprints with higher bandwidth and adoption of new I/O interfaces in the PC market segment. Power performance requirements are tightening in the design process to address specific requirement along with the development of SSD technology. To meet this aggressive requirement of performance, one major issue is thermal throttling. As the NAND and ASIC junction temperatures approach their safe operating limits, performance throttling is triggered and thus power consumption would drop accordingly. Therefore, robust thermal understanding on system level as well as reliable and fast thermal prediction are becoming essential in the process of system thermal design to optimize performance in a quick turnaround manner.

In this paper, we present two different modeling approaches on the system level to model and simulate M.2 2280 SSD thermal throttling behavior in a typical laptop working environment. One approach is to establish a detailed three dimensional CFD (computational fluid dynamics) model using traditional CFD tools. In this model, the motherboard is enclosed in a case or chassis. Major heat sources of components and packages on the motherboard are considered including CPU, GPU, M.2 SSD, DRAM etc. Advanced cooling solutions like heat pipe and blowers are also modeled. In order to accurately capture thermal behavior of the SSD, detailed structure and geometry of NAND, PMIC and ASIC packages are included. Both natural and force convection as well as radiation are considered in this model. Both steady state and transient simulation results are presented in this paper. Further, the simulation results are validated with experimental data to predict thermal throttling behavior. The experiment is carried out with the SSD running in a laptop and temperatures of NAND and platform are logged during the test.

In this paper, a second approach to generate accurate thermal models is presented for electronic parts. The thermal model of an electronic part is extracted from its detailed geometry configuration and material properties, so multiple thermal models can form a thermal network for complex steady-state and transient analyses of a system design. The extracted thermal model has the following advantages,

1. It can accurately predict both static and dynamic thermal behaviors of the electronic parts;
2. It can accurately predict the temperature at any probing node pre-defined in the electronic part;
3. It is independent of boundary condition and can accurately predict the thermal behavior regardless of the environment and cooling conditions.

With the accurate dynamic thermal models, a large thermal system can be decoupled into multiple domains such as air flows, chassis, heat sinks, PCB boards, packages, etc. The whole system can be consequently reconstructed as an integrated model-based network, and thermal simulation can be performed using fast network simulators. In comparison to the traditional CFD or FEM tools, the network-based approach improves efficiency in both thermal system construction and simulation. This approach is demonstrated through thermal simulation of the SSD drive within a laptop environment under natural convection in its working condition. The simulated system includes packages, M.2 PCB, motherboard, heat sink, and chassis.

KEY WORDS: network model, laptop, NAND, ASIC

INTRODUCTION

A HDD on a host level typical notebook was studied by Ilker Tari and Fidan Seza Yalcin [1] using CFD approach. N. Hariharan et al. [2] carried out a similar CFD work effort for a laptop cooling system with loop heat pipe technology. Qi Wu et al. [3] used HotSpot thermal simulator to carry out fast reasonable accurate thermal simulation based on equivalent circuits of thermal resistances and capacitances on the SSD drive level. Miaowen Chen et al. [4] have made efforts on the system level simulation of a tablet with package-on-package (PoP) stacking assembly using CFD method. Murakami Katsuya et al. [5] showed results of temperature simulation on NAND flash memory and controller which are influenced by their placement. Ting-Yuan Wang and Charlie Chung-Ping Chen [6] studied transient thermal simulation of PowerPC with 3-D thermal-ADI which was a linear-time chip level transient thermal simulator.

Thermal network has a long history of being used for temperature analysis and is known for its low computational cost. K. Nishi et al. [6] investigated a tablet device using one-dimensional thermal network approach constructed from thermal conduction simulation results. V. d'Alessandro and N. Rinaldi [7] discussed some issues of the current 2D thermal models for electro-thermal simulation and investigated simulation accuracy.

Recently, a network-based approach was developed for thermal simulation of electronic systems [8-10]. This approach decouples the modeling of solid and fluid regions and integrates them later. The simulation flow consists of three steps as illustrated in Fig. 1. First, solid extraction is performed using an advanced FEM-based numerical algorithm [8-10] to generate the thermal network of different solid components. Note each component from the solid region such as PC boards or packages can be also extracted separately. Second, fluid extraction is performed based on traditional CFD approach to form the fluid network. Third, all sub-networks generated from solid and fluid extractions along with the power input are assembled together to form the complete thermal network of the system. In essence, the network-based thermal model employs a divide-and-conquer approach for thermal modeling and it features the following advantages: First, the model size in network-based approach significantly reduces due to the decoupling of solid and fluid modeling as well as the separate extraction of different solid components. This makes it possible to simulate all detailed 3D geometry (traces/vias/etc.) without any simplification. Traditional CFD approach typically ignores such details due to the tremendous complexity and computational cost involved in the coupling of entire solid and fluid regions. Instead, it treats complex solid components using effective thermal properties with a few exceptions such as ANSYS Icepak ECAD option enabling mapped spatially distributed material properties. Second, different solid components can be extracted separately and therefore each individual solid component is formalized as its inherent thermal network and therefore forms as standalone module. Consequently, the thermal network of each component is reusable and readily available for various thermal construction and analysis. Third, by taking advantage of the thermal network solver, both steady state and transient thermal simulations become very fast.

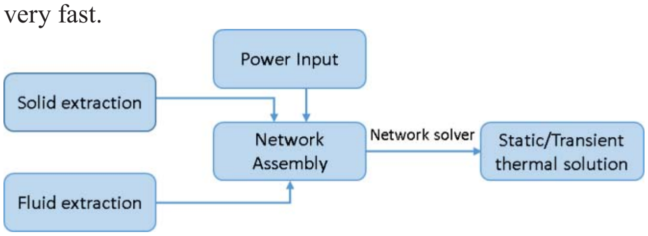

Fig1. Schematic of network thermal simulation flow

EXEPERIMENT AND SIMULATION SETUP

Experiment setup

As shown in Fig 2, Thermatron S1.2 thermal chamber is used to create a thermally quasi-steady state environment for the laptop. The laptop platform used in the test is 17" Lenovo Ideal Pad 700 model. In Fig 2, the M.2 SSD 2280 model tested is A400 from SanDisk. Power measurement of key components on the SSD PCB was monitored by connecting an extender with INA231 on 0.01Ohm measurement resistor. Three gauge 32 thermocouples together with Agilent 34972A data acquisition system have been used to monitor the temperature with time: one was attached to the top of one NAND package (closer to the socket), one was attached on the platform surface and another was attached on the device of copper foil. The SSD will enter the throttling mode using a combination rule of ASIC and NAND temperatures.


Fig 2. Testing platform in a thermal chamber

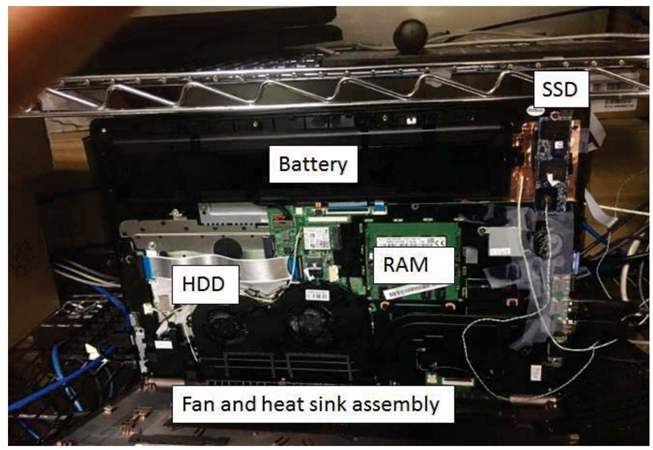

Fig 3. SSD test setup inside the chassis of laptop

CFD simulation

A detailed three-dimensional time-dependent CFD model was established in ANSYS Icepak base on the experimental setup described in the previous session. Two cases have been simulated in this study. A steady state case was simulated for idle state of SSD and a transient case was simulated under a typical SSW workload of SSD until throttling begins. Both natural and forced convection have been included in the simulation. Model layout has been shown in Fig 4. In the model, mother board was enclosed in the Chassis with heat convection coefficient assumed to be 10W/m2K. Due to the compactness of the notebook, there is not much air circulation in the chassis and heat is transferred to small side areas of the chassis and the bottom with the help of thermal dissipation plate and heat pipes [1]. Below the bottom surface heat is only dissipated by conduction through the thin air gap which acts more like an insulating layer [1]. Double fans have been placed against heat pipe with heat sink assembly. Custom fan curves have been used for both fans. Grills have been modeled for both inlet and outlet of the fan assembly. Boussinesq approximation have been used under operating pressure of 101325 Pascal. Ray tracing radiation model has been used. Discretization scheme was used for the governing equations: standard for pressure, first order for momentum and first order for temperature. Heat sources are shown in the Table 1. All power sources are assumed to be constant except for ASIC power which linearly increasing over time as shown in Fig 5. Material properties have been listed in Table 2. Chassis outside convection heat transfer coefficient was assumed to be 10 W/mK with ambient temperature set to 22°C. Radiation has also been considered on the chassis.

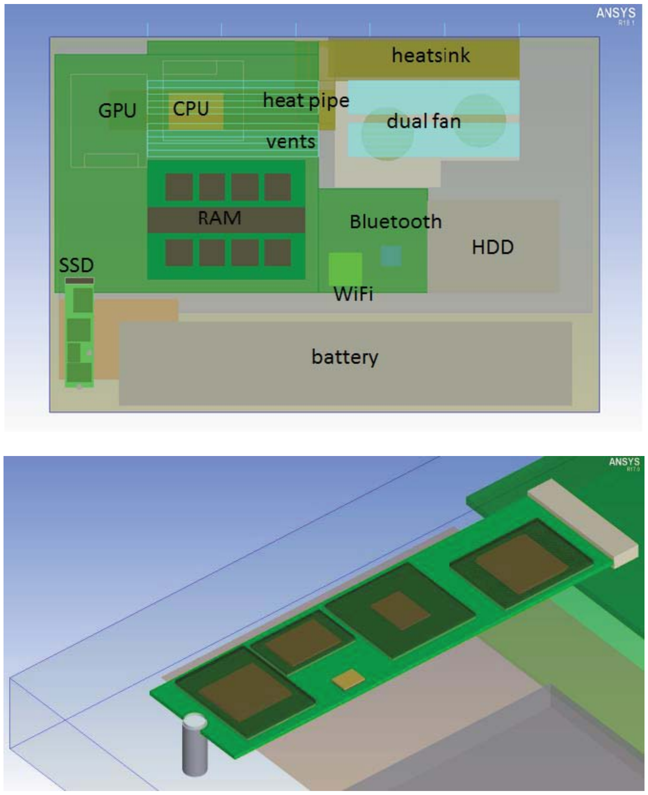

Fig 4 Detailed SSD model in a laptop environment

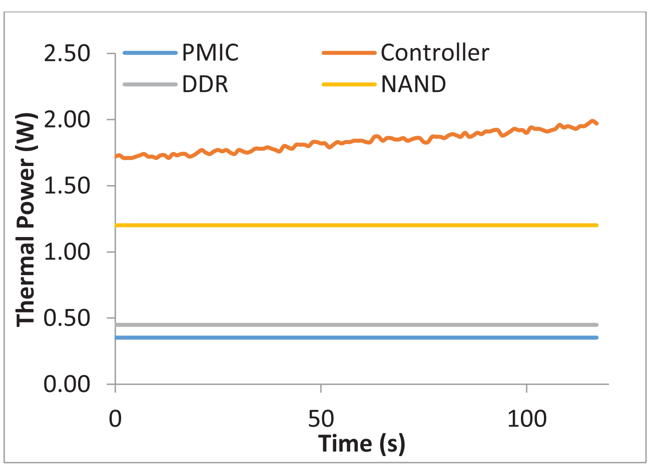

Fig 5 SSD major components averaged thermal power profiles

Table 1. Thermal power sources in the model (W)

Component	Thermal Power
CPU	45
GPU	33
SSD	3.7-4.1
RAM	3
WiFi/BT	2
Battery	2
HDD	2

Table 2. Thermal conductivity in the model (W/mK)

Material	Thermal Power
Silicon	148
Copper	387.6
Heat Pipe	40,000
Mother Board	(50, 50, 2.5)
Mold Compound	0.9
Substrate	(46, 46, 2.1)
Polycarbonate ABS	3.11

Network Thermal Model simulation

In solid extraction presented here, all solid components of laptop were divided into four groups including motherboard, SSD, CPU_GPU, and RAM. Note that solid components can be grouped in different ways that lead to different but equivalent network assembly. Fluid extraction was performed based on traditional CFD approach as presented in the CFD Simulation Section. Network models of solid components and associated fluid models are consequently assembled following their original design shown in Fig. 4. Fig. 6 shows the entire thermal model network assembly for the laptop after solid and fluid extractions. This network assembly is readily used to generate static and transient thermal solutions with power sources provided for components including CPU, GPU, dies in SSD and RAMs, etc.

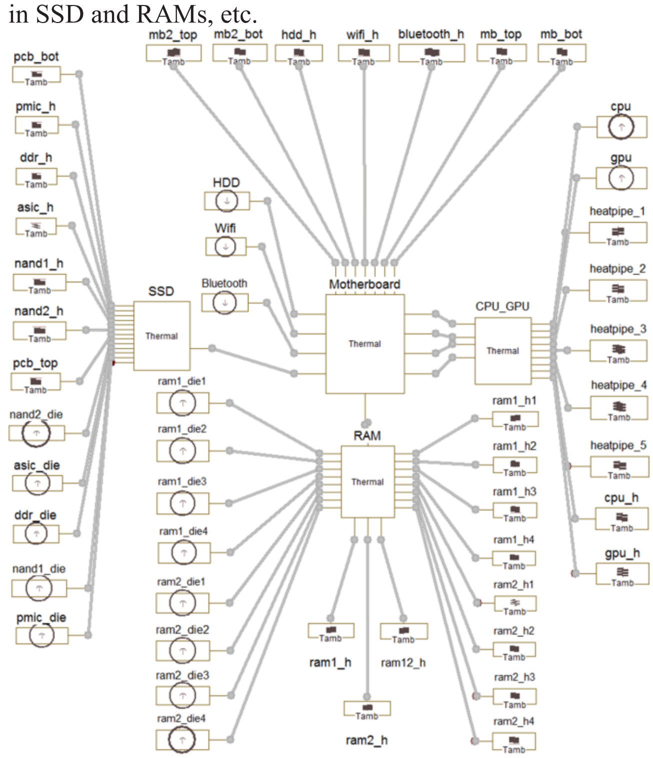

Fig. 6 Thermal model network assembly for laptop shown in Figs. 3 and 4

In order to validate the network thermal model approach, traditional FEM (Finite Element Method) simulation was also performed for the entire solid region. Heat transfer coefficients obtained from fluid extraction were applied at the outer surfaces of solids.

Results

Results show that the SSD was running at full performance for about two minutes before entering thermal throttling mode. And after that during the throttling period NAND package temperature cooling process on average takes about 35 seconds before entering full performance mode again. Once re-entering full performance mode, NAND package temperature ramping up process only takes about 15 seconds on average before entering throttling mode again.

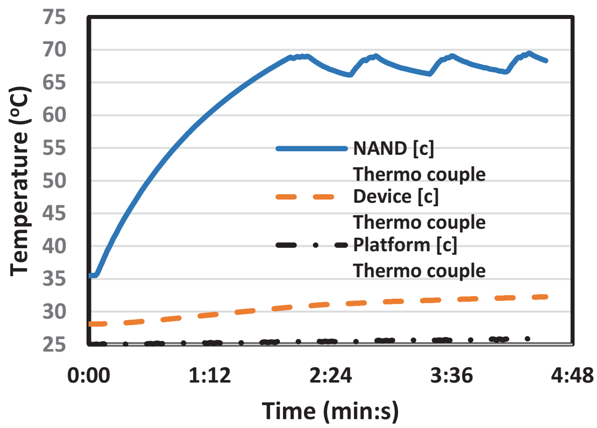

Fig. 7 Test data of transient temperature profiles

The CFD simulation results show that the NAND package temperature profile was well correlated with the experimental data in the full performance mode before entering the thermal throttling mode shown in Fig. 8. Comparing using the effective PCB properties versus importing detailed PCB model file from ECAD and using the PCB model within Icepak, NAND transient temperature results have improved after 20s when the heat majorly was spreading within the PCB. In this comparison, the case with effective PCB properties, the socket effective properties have tuned to match the experiment. However, changing the socket property seems to change the rate of temperature rising before entering the throttling mode which is not preferred. SSD temperature contour at time of 111 seconds was shown in Fig. 9 and it can be seen that ASIC is the hottest component on the PCB and the two NAND packages have relatively lower temperature compared to DDR or PMIC. The NAND package closer to the socket was cooler due to better cooling path to the motherboard.

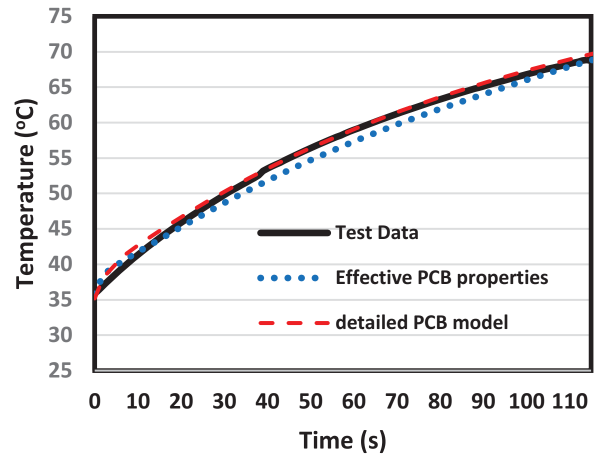

Fig. 8 Transient NAND temperature profiles comparison before thermal throttling: effective PCB properties vs detailed PCB model

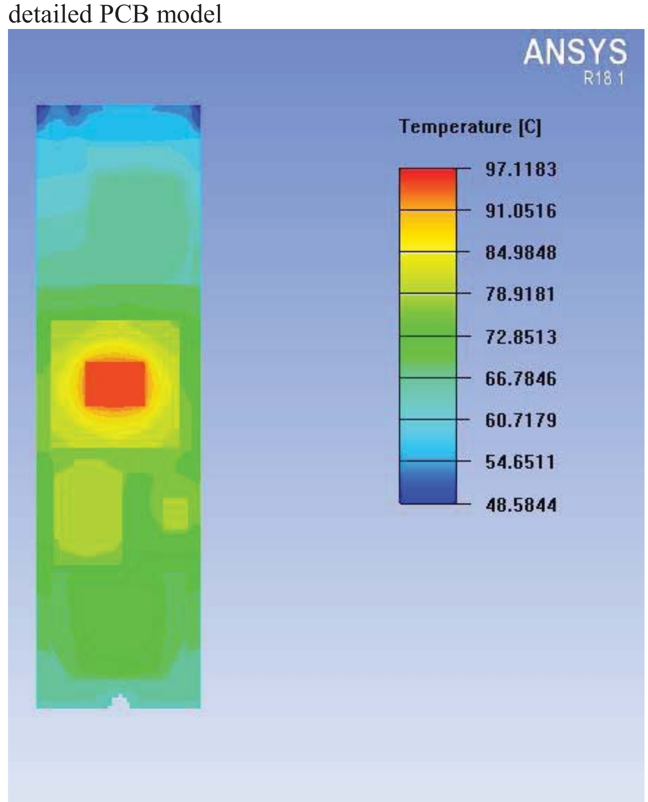

Fig. 9 Temperature contour of SSD at full performance mode at time = 111 seconds before entering throttling mode

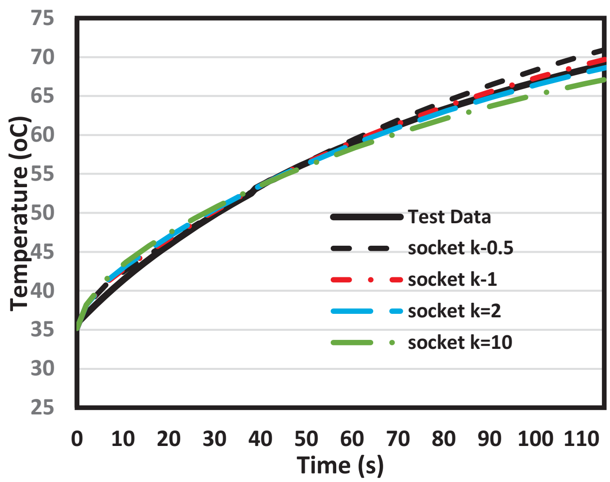

Fig. 10 Transient NAND temperature profiles comparison before thermal throttling with varying effective socket thermal conductivity (W/mK)

Sensitivity study shows that the transient behavior of NAND package may also rely on the effective socket thermal properties. From Fig. 10, varying the socket effective thermal conductivity from 0.5 W/mK to 10 W/mK would have impact on the NAND temperature trend after the SSD PCB temperature exceeded the motherboard temperature near the socket which is approximately between 40s and 50s. This would also matter to when NAND package would reach steady state if no throttling or if throttling it would affect the throttling behavior due to the difference in temperature rising rate. The effective socket thermal properties are affected by the limited contact area and contact pressure between the SSD PCB M.2 connector pins. Further study needs to be conducted regarding the impact of socket properties during throttling mode.

Fig. 11 shows the comparison of transient temperature curves obtained from network thermal model and FEM solutions for all dies in M.2 2280 SSD. It is evident from Fig. 11 that the network thermal model solution closely follows FEM solution for the entire time range studied. The maximum relative difference between the network thermal model and FEM solutions is only a few percentages. This supports the accuracy of the network thermal model approach. Moreover, the network thermal model runs a lot faster than FEM, namely, <10 s in network thermal model vs. ~30 min in FEM for the current laptop case studied.

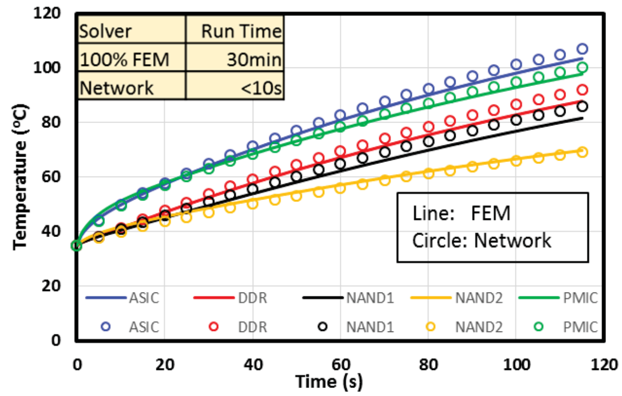

Fig. 11 Transient temperature trends of key SSD components: comparison of network thermal model vs FEM solutions

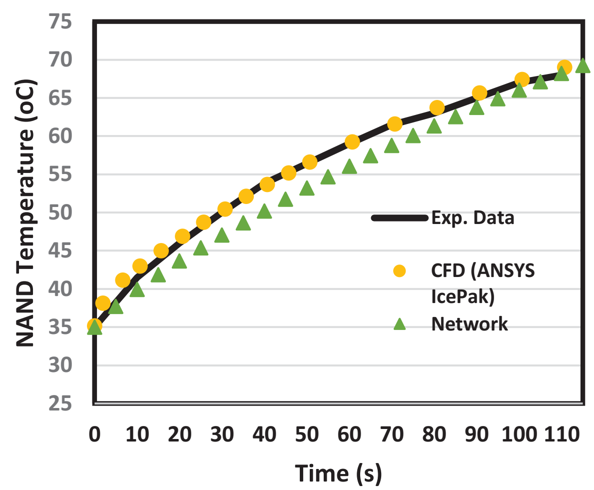

Fig. 12 Transient NAND package temperature: comparison of network thermal model vs CFD/Experimental results

Fig. 12 shows the comparison transient NAND2 temperature results obtained from the network thermal model approach and from traditional CFD approach along with experimental data presented in this paper. Fig. 12 demonstrates that the network thermal model solution agrees well with traditional CFD solution and experimental data. Due to its accuracy and fast simulation time, the network thermal model could be a very attractive and alternative approach for system level thermal simulations of electronic products and in various environments.

CONCLUSIONS

This paper investigated a typical laptop three-dimensional time-dependent CFD simulation model with a focus on the SSD detailed model within ANSYS Icepak. The CFD results are validated with experimental data presented in the paper. The detailed CFD model was able to accurately capture the transient temperature trend of NAND package accurately within full performance mode before entering the throttling mode. In the simulation results, sensitivity study has shown that the PCB and socket connection thermal properties play a role in the thermal performance of SSD. In ANSYS Icepak, importing a detailed PCB model of the SSD would correlate better with experiment compared to simply using an effective PCB thermal properties across the whole board.

The network thermal model approach has been demonstrated in the paper which decouples the solid and fluid modeling and is also capable of modeling different solid components separately. Solid and fluid network are thereafter reconstructed into a complete thermal network assembly. Such divide-and-conquer approach significantly reduces the model size in the network thermal model. This not only reduces the simulation cost but also enables the modelling of all detailed complex 3D geometry in electronic products unlike traditional CFD approach. This network-based approach has become attractive for its efficiency in thermal system construction and simulation.

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