INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 11, Issue 2, 2020 pp.97-106
Journal homepage: www.IJEE.IEEFoundation.org

Experimental and CFD study on the dynamic thermal management in smartphone and using graphene nanosheets coating as an effective cooling technique

Maher A.R. Sadiq Al-Baghdadi [1,2]

[1] Kufa Centre for Advanced Simulation in Engineering (KCASE), Department of Mechanical Engineering, Faculty of Engineering, University of Kufa, Iraq.

[2] Computational Fluid Dynamics Center, International Energy and Environment Foundation (IEEF), Iraq.

Received 1 June 2020; Received in revised form 7 July 2020; Accepted 13 July 2020; Available online 1 Nov. 2020

Abstract
Thermal management is essential in electronics, as it improves reliability and enhances performance by removing heat generated by the devices. Maintaining safe chip and device skin temperatures in small form-factor mobile devices (such as smartphones) while continuing to add new functionalities and provide higher performance has emerged as a key challenge. A significant increase in reliability and smartphones life can be achieved by a small reduction in operating temperature. With the limitations of space and power, radiation and natural convection plays an important role in heat removal mechanisms in smartphones engineering designs. A case study on an iPhon5 using CFD is provided to relate the device performance to the skin temperature and investigate the thermal path design. Three dimensional CFD model of an iPhone5 has been presented. The model accounts for heat transfer for conduction through the phone components materials and for both natural convection and radiation to the ambient air temperature. The comparison between the CFD simulation and the thermal image obtained by the thermal camera shows some similarities like, for example, hot-spots located in the same places. The present CFD study allow accurate, rapid, physical modelling to make decisions on materials, components and layout beside power control feedback to achieve performance and target lifetime with reduced testing requirements. Parametric study considered operating time, ambient temperatures, and materials to investigate the impact of each on the temperature distribution in smartphones has been presented.

Keywords: Electronic cooling; Thermal management; Mobile phone; CFD; Thermal imaging; Graphene.

1. Introduction
Smartphone has become necessities for everyday life and attracted much attention due to its great market value. Manufacturers are integrating mobile phone with more and more functionalities while making it smaller and smaller. High consuming power and compact structure combine together and a great challenge comes for thermal management engineers. Smartphone is unique in thermal characteristics because it has not only high power density but also limited freedom for thermal enhancement. This

means it is rather difficult to add heat sink and fan because both need space. Therefore, much emphasis is put on system analysis and design, including system numerical simulation and system experiment [1, 2].
Designing a premium smartphone has been a delicate balance between performance and battery life for generations. However, continued increases in performance cause growing concerns around heat.
The thermal management is a crucial design problem for smartphones devices because it greatly affects not only the device reliability, but also the leakage energy consumption. Conventional dynamic thermal management techniques work well for the computer systems. However, due to the limitation of the physical space in smartphones devices, the thermal coupling effect between the major heat generation components, such as the application processor and the battery, plays an important role in determining the temperature inside the smartphone package. Due to this effect, the thermal behaviour of one part is no longer independent of the other, but is affected by the temperature of other parts [3, 4].
Thermal management studies ideally allow accurate, rapid, physical modelling to make decisions on materials, components and layout beside power control feedback to achieve performance and target lifetime with reduced testing requirements.
A smartphone that is not running is in thermal equilibrium with its surroundings, and thus is at the temperature of the surrounding medium. When the smartphone is turned on, the temperature of the components and thus the smartphone starts rising as a result of absorbing the heat generated. The temperature of the smartphone stabilizes at some point when the heat generated equals the heat removed by the cooling mechanism. At this point, the smartphone is said to have reached steady operating conditions [2, 5]. The warming-up period during which the component temperature rises is called the transient operation stage (Figure 1). Transient operation can also be caused by large swings in the environmental conditions [1, 2].

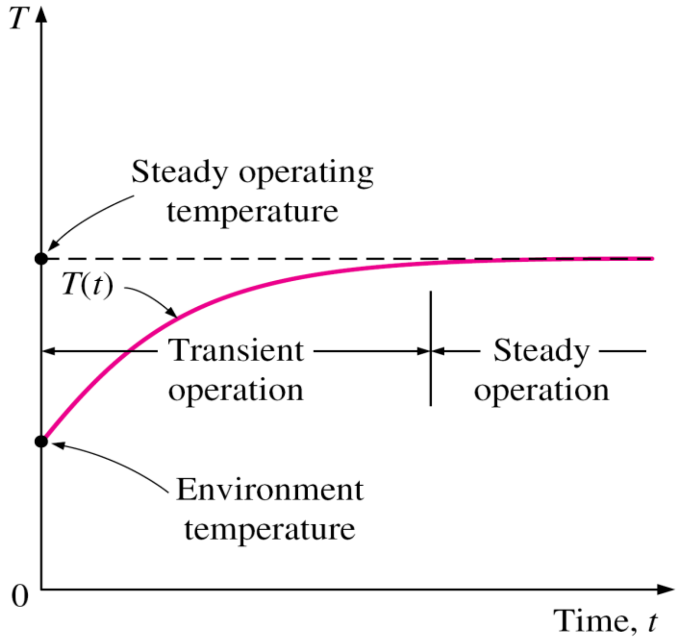


Figure 1. The temperature change of a smartphone component with time as it reaches steady operating temperature after it is turned on.

2. Experimental setup

In order to quantify the rise in temperature of the stand-alone smartphones during the standardized operation (video test), we performed the experiment for about 45 minutes for three different types of commercial smartphones. The results showed that the temperature of the smartphones starts rising until 15 minutes of operating. After 15 minutes of the operating, the increases in temperature will be minimal (less than 1 ºC). Figure 2 shows thermal images of the three different types of the smartphones during operating using the thermal camera FLIR E50. The increases of the local temperatures were approximately from 6 ºC to 11 ºC. The results of the thermal imaging of the stand-alone phones during the standardized operating confirmed that all phones temperatures considerable rise above ambient temperature.

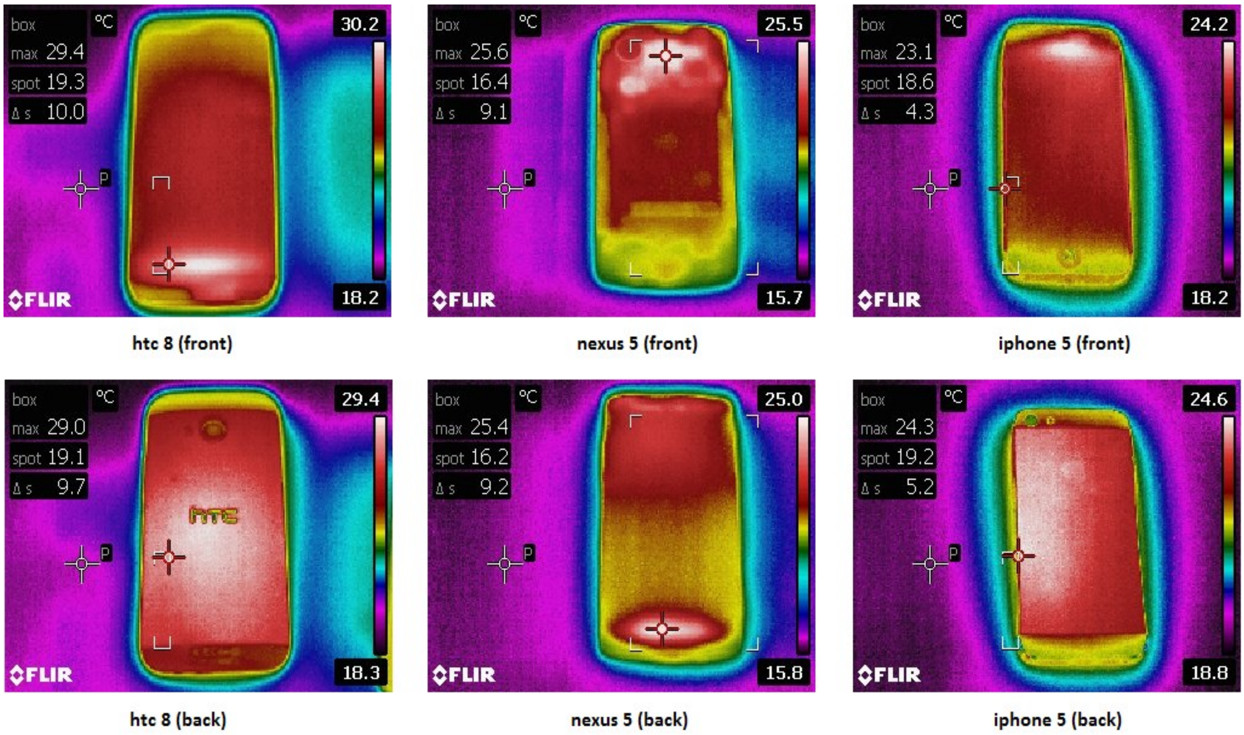


Figure 2. Thermal camera images from video test for 15 minutes of three different types of smartphones.

Graphene is a modern nanomaterial has a two-dimensional structure. In this structure, each carbon atom is connected to three other carbon atoms, forming a two-dimensional sheet. Graphene-based composites are emerging as new class of materials that hold promise for several applications. Graphene, a single sheet of graphite, possesses extraordinary electrical, thermal, and mechanical properties arising from its unique structure. Graphene is often thought to hold advantages over other materials in electronics cooling systems because of its higher thermal conductivity. Thus, high thermal conductivity could suggest very good heat sinking and low temperature rise during device operation [6-8].

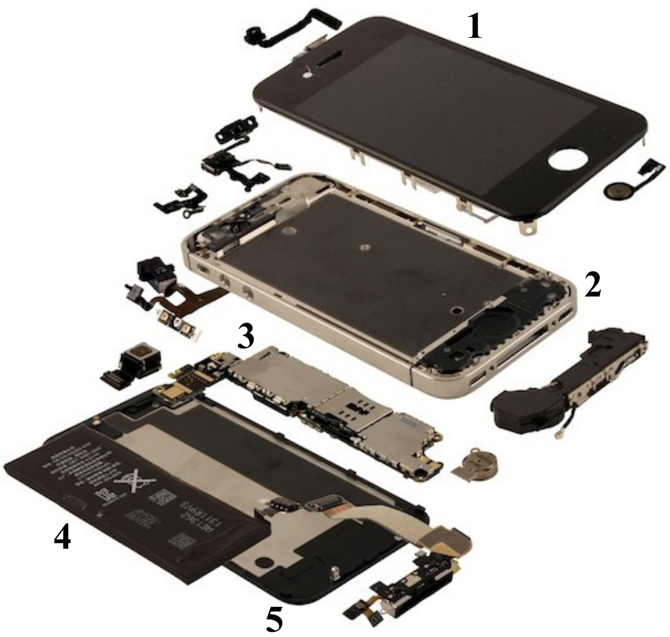
The increasing complexity and power density of modern electronics has challenged the traditional approach of using prototypes and testing. The modern Computational Fluid Dynamics (CFD) simulation software developed for challenging environments and high power dissipation devices has led to a reduction in the product development cycle [9-11]. CFD is the science of predicting fluid flow, heat transfer, mass transfer, phase change, chemical reaction, and related phenomena by solving the mathematical equations that govern these processes using a numerical algorithm on a computer [12]. The results of CFD analyses are relevant in: conceptual studies of new designs, detailed product development, troubleshooting, and redesign. CFD analysis complements testing and experimentation, by reduces the total effort required in the experiment design and data acquisition. CFD complements physical modelling and other experimental techniques by providing a detailed look into our fluid flow problems, including complex physical processes such as turbulence, chemical reactions, heat and mass transfer, and multiphase flows. In many cases, we can build and analyze virtual models at a fraction of the time and cost of physical modelling. This allows us to investigate more design options and "what if" scenarios than ever before. Moreover, flow and heat transfer modelling provides insights into our fluid flow problems that would be too costly or simply prohibitive by experimental techniques alone. The added insight and understanding gained from flow and heat transfer modelling gives us confidence in our design proposals, avoiding the added costs of over-sizing and over-specification, while reducing risk [12].

In this work, three dimensional CFD model of an iPhone5 has been presented. The model accounts for heat transfer for conduction through the phone materials and for both natural convection and radiation to the ambient air temperature. Some guiding principles will be provided for efficient thermal design of these systems.

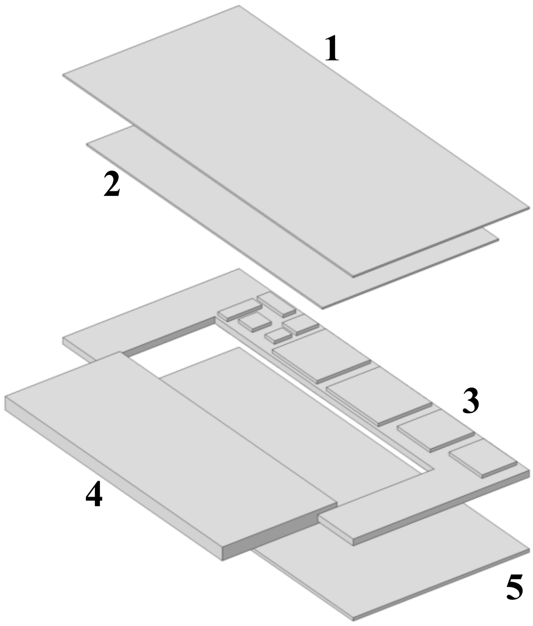
3. CFD modelling

3.1. Computational domain and material properties

iPhone5 has been used as a case study in this work. The major components considered in this study included the battery, back-plate, middle-plate (also known as stiffener plate), display, and PCB (Printed Circuit Board) as shown in Figure 3. The mobile phones components consist of different materials. Material properties of each component are shown in Table 1.



(a) iPhone5 components.



(b) three-dimensional computational domain.

(c) logic board.

Figure 3. iPhone5® components from Apple co.

Key: 1. External display screen, 2. LCD, 3. Printed circuit board (logic board), 4. Battery, 5. Back cover.

Table 1. Material properties.

Material	Density ρ [kg/m3]	Heat capacity C_p [J/kg.K]	Thermal conductivity k [W/m.K]	Emissivity ε
FR4 (Circuit Board)	1900	1369	0.3	0.6
Silicon	2329	700	130	0.6
Nylon	1150	1700	0.26	0.6
Glass	2200	480	1.1	0.6
Aluminum Alloy 6063	2700	900	200	0.6
Copper	8700	385	400	0.6
Copper coated with Graphene	8700	385	460	0.6

3.2. Modelling equations

The heat transfer in a mobile phone is take place in three ways, conduction, convection, and radiation. The temperature field is obtained by solving the energy equation [12]. Heat transfer by the conduction mode occurs when heat is transferred within a material or from one material to another. The energy transfer is postulated to occur because of kinetic energy exchange by elastic and inelastic collisions of atoms, and by electron drift. Heat energy is always transferred from a region of higher energy to an area of lower energy. The energy level, or temperature, of a material is related to the vibration level of the molecules within the substance. If the regions are at an equal temperature, no heat transfer occurs.
The heat conduction in solid is governed by;

$$\rho C_p \frac{\partial T}{\partial t} - \nabla.(k\nabla T) = Q \tag{1}$$

where ρ is density [kg/m^3], C_p is heat capacity [J/kg.K], k is thermal conductivity [W/m.K], T is temperature, Q is heat source [W], and t is time [s].

Convection is the result of two energy transfer mechanisms: fluid motion and molecular motion. Convection is a combination of the bulk transportation and mixing of macroscopic parts of hot and cold fluid elements, heat conduction within the coolant media, and energy storage. Convection can be due to the expansion of the coolant media in contact with the device. This is called free convection, or natural convection. Convection can also be due to other forces, such as a fan or pump forcing the coolant media into motion. The heat convective from all external surfaces to ambient is governed by;

$$-\mathbf{n}.(-k\nabla T) = h(T_{amb} - T) \tag{2}$$

where $\mathbf{n}$ is unit vector normal to the surface, h is convection coefficient [W/m^2.K], and T_{amb} is ambient temperature [K].

Radiation is the only mode of heat transfer that can occur through a vacuum and is dependent on the temperature of the radiating surface. Radiation heat transfer involves emittance, absorptance, reflectance, and transmittance at the surface of an object. The heat radiation from all external surfaces to ambient is governed by;

$$-\mathbf{n}.(-k\nabla T) = \varepsilon\sigma\left({T_{amb}}^4 - T^4\right) \tag{3}$$

where ε is emissivity, and σ is Stefan-Boltzmann constant = 1.38E^{-23} [J/K].

3.3. Computational grid

The governing equations were discretized using a finite-volume method and solved using an academic edition of multi-physics computational fluid dynamic (CFD) package. Stringent numerical tests were performed to ensure that the solutions were independent of the grid size. A computational quadratic mesh consisting of a total of 23776 domain elements, 12006 boundary elements, and 1711 edge elements was found to provide sufficient spatial resolution (Figure 4). The coupled set of equations was solved iteratively, and the solution was considered to be convergent when the relative error was less than 1.0×10^{-6} in each field between two consecutive iterations.

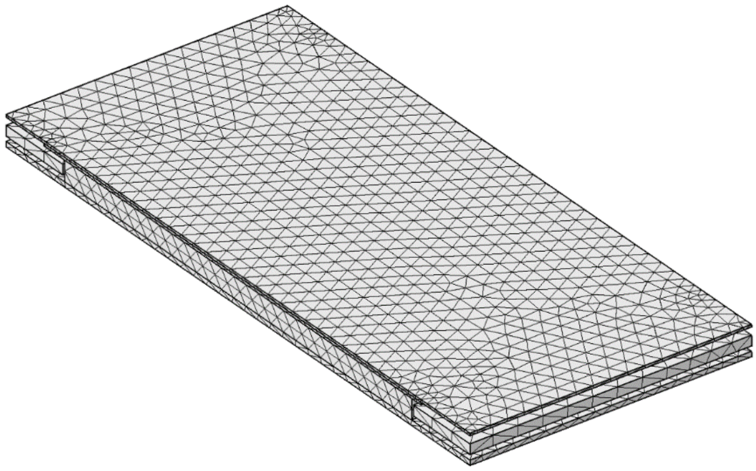


Figure 4. Computational mesh of the computational domain (quadratic).

4. Results

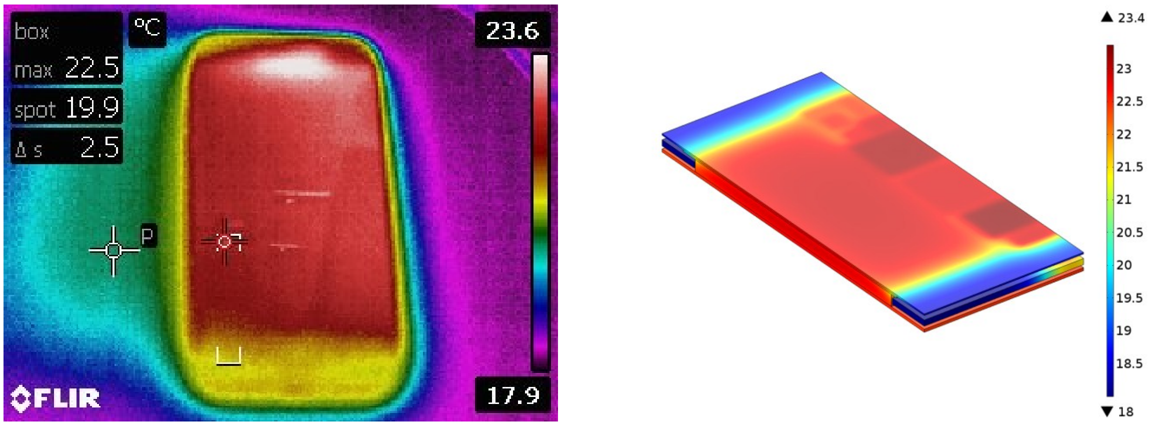
The results of the CFD model were verified with experimental results. The temperature distribution on the iPhone was captured using the thermal camera FLIR E50, Figure 5. The ambient temperature condition was 18 °C. The temperatures increase rapidly in the first 10 min after the power is turned on. Twenty minutes later, the temperatures change very little. Half hour later, the system becomes almost completely steady. The comparison between the CFD simulation and the thermal image obtained by the thermal camera shows some similarities like, for example, hot-spots located in the same places. In the model presented here, all the parameters are within physical limits and since no parameters needed to be adjusted, this will help to conduct a systematic study on the importance of each single parameter on the iPhone performance.

The validated model is now ready for studying the effects of different conditions on the temperature distribution in the iphone. Figure 6 shows the temperature distribution in the iPhone during operating for 30 minutes. The ambient temperature condition is set to room reference temperature 25 °C. The result shows that the maximum increasing in temperature is occurred during the first 5 minutes of operating. After 15 minutes of operating, the increment becomes minimal.

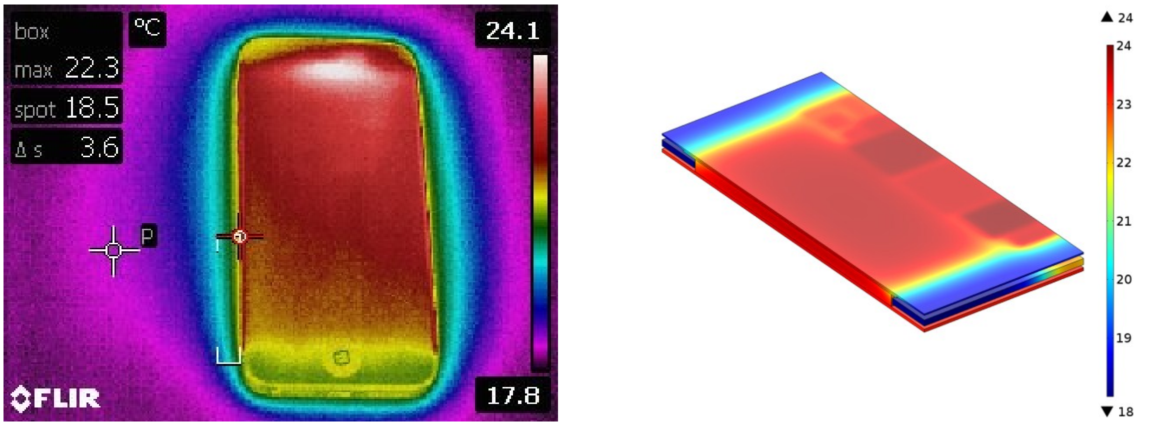
The effect of different ambient temperatures on the iPhone temperature distributions during operating for 15 minutes has been shown in Figure 7. The figure shows that the ambient conditions are an important factor in increasing of the temperature field in the mobile phones. This is due to the reduction in the heat transfer rate from the mobile phone to the environment when increases of ambient temperature.

The effect of using external plastic or leather cover to iPhones on the temperature distributions has been presented in Figure 8. The ambient temperature condition is set to room reference temperature 25 °C. The results show that the maximum temperature of iPhone with plastic cover is about 3 °C above the case of iPhone without any cover. The iPhone cover prevents the heat to transfer to surrounding and this increase the electronic components temperatures.

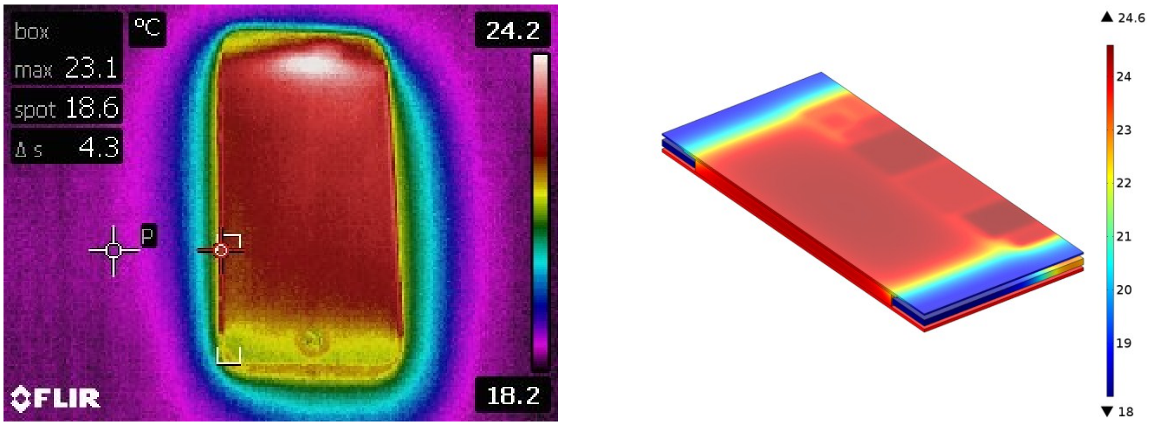
Figure 9 shows the temperature distribution in the iPhone during operating for 15 minutes with new suggested thermal management system. The new suggested design consist of a flat plate of copper material coated with graphene attached to the microprocessor of iPhone on the front side behind the LCD screen and turned to the back side to create a heat dissipation path from the front side of the iPhone to the back side with only passive cooling technique. Considerable drop in microprocessor temperature is obtained through the heat dissipation path suggested in the new design. The temperature drop in the new design is due to increasing of both surface area of heat transfer and thermal conductivity of the graphene.



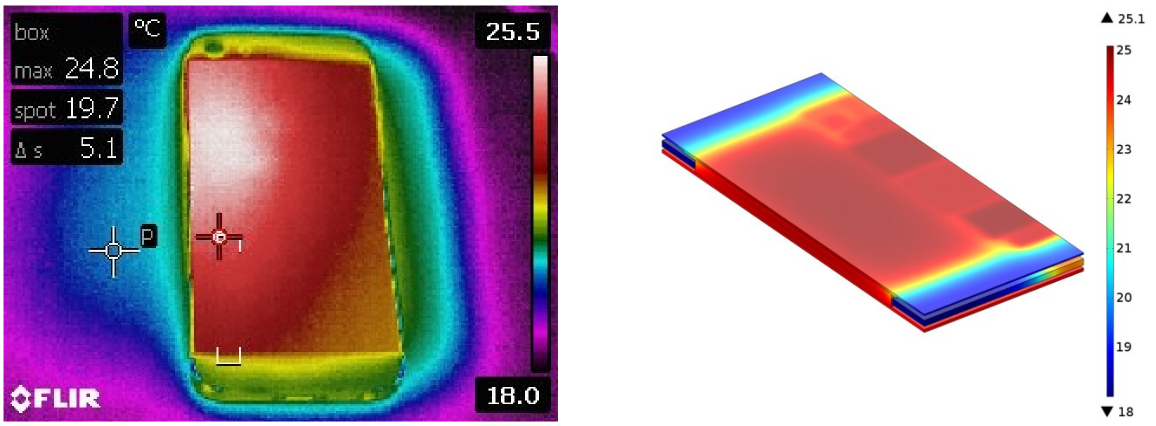
time = 5 minutes



time = 10 minutes



time = 15 minutes



time = 30 minutes

Figure 5. Temperature distribution in iPhone5 [ºC] during operating: (left) thermal camera image and (right) CFD simulation.

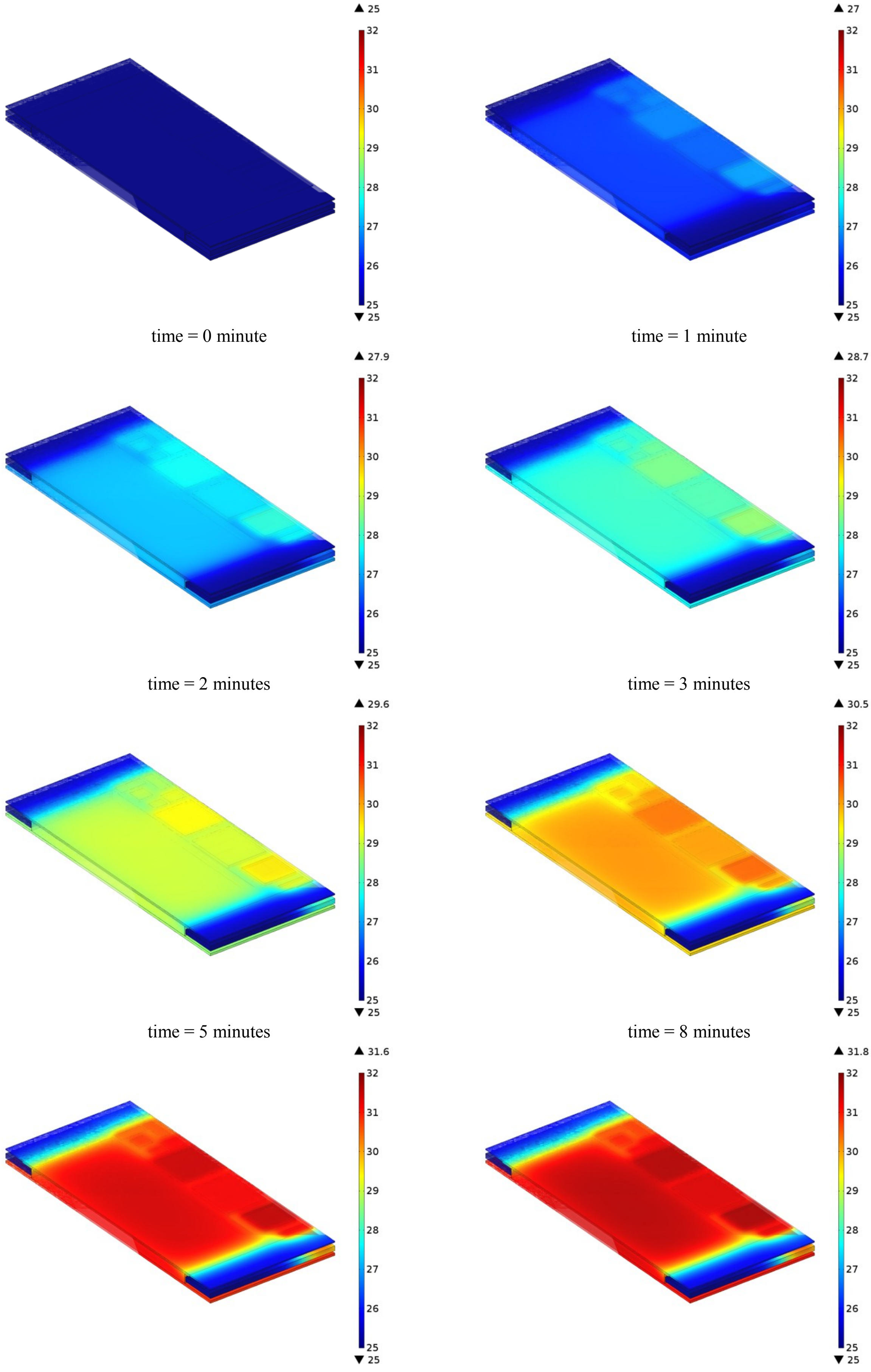
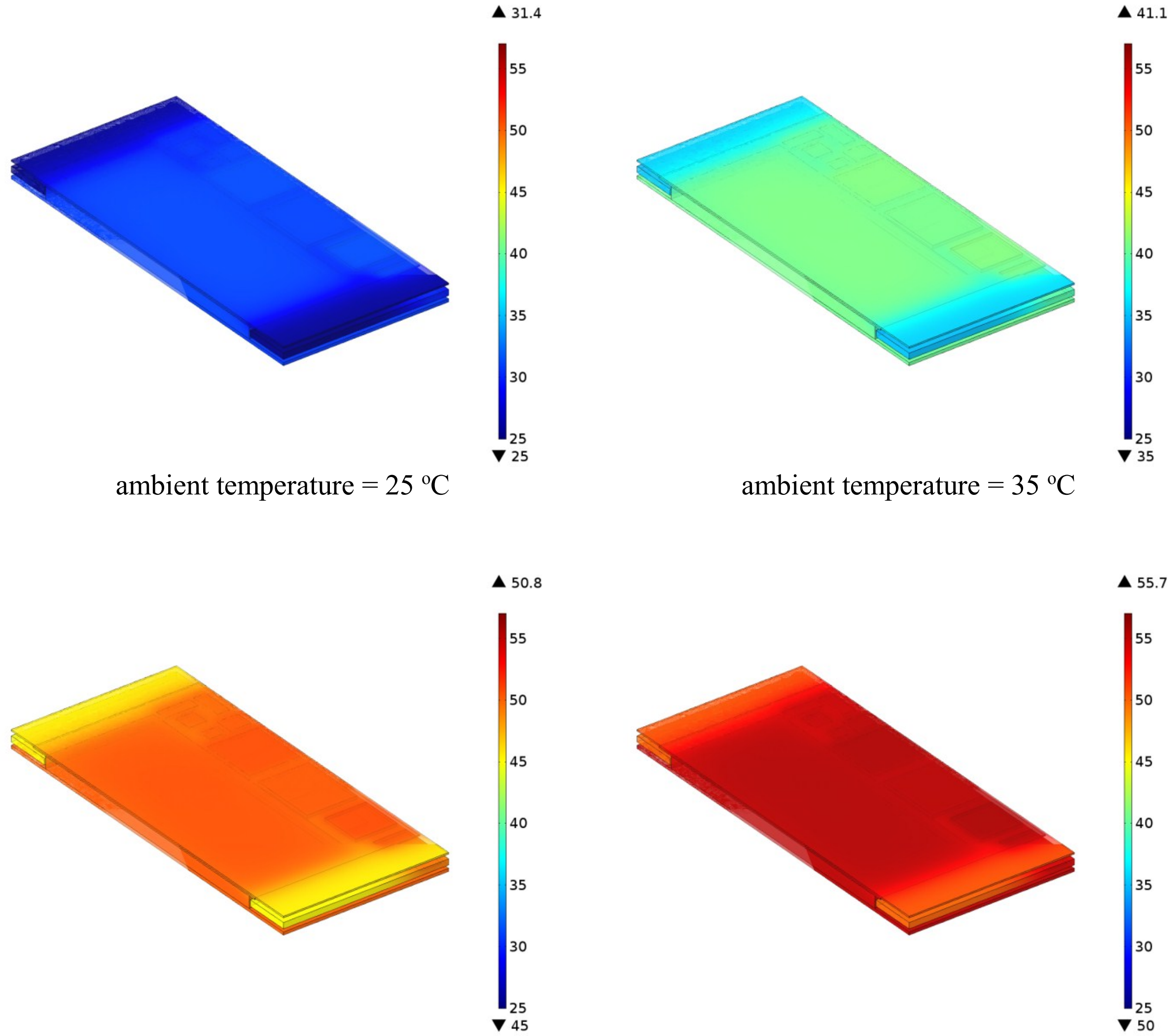


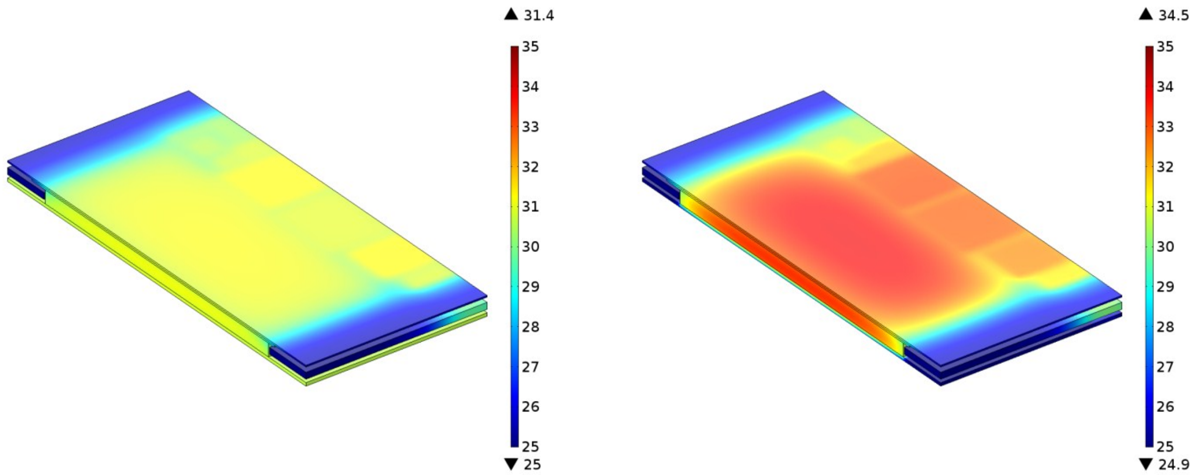
Figure 6. Temperature distribution in iPhone5 [ºC] during operating from 0 ~ 30 minutes.



ambient temperature = 25 °C ambient temperature = 35 °C

ambient temperature = 45 °C ambient temperature = 50 °C

Figure 7. Temperature distribution in iPhone5 [°C] during operating for 15 minutes at ambient temperatures of 25, 35, 45 and 50 °C.



without plastic cover with plastic cover

Figure 8. Temperature distribution in iPhone5 [°C] during operating for 15 minutes with and without plastic external cover (attached to the back of iPhone).

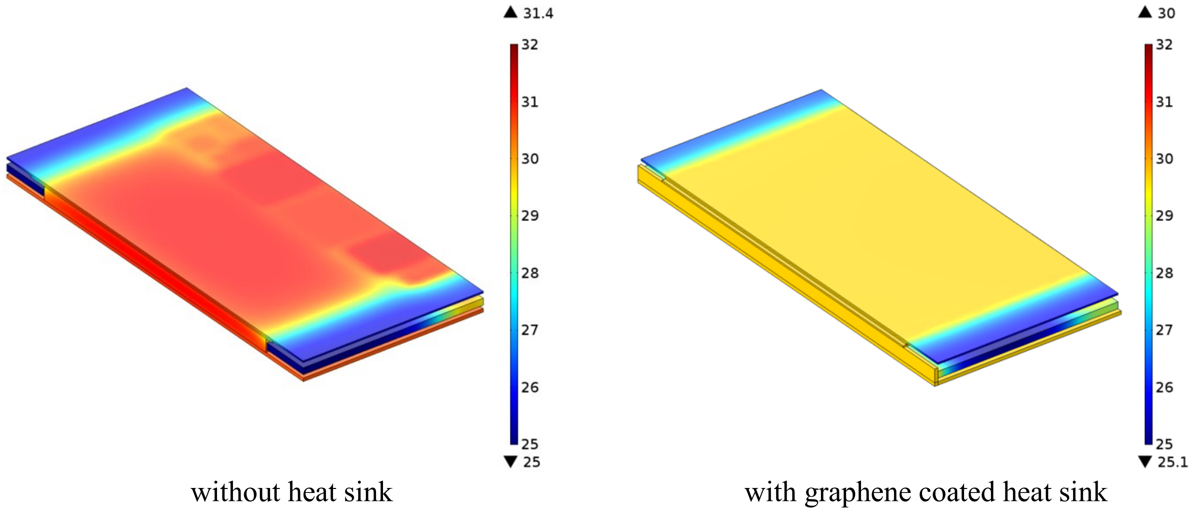


Figure 9. Temperature distribution in iPhone5 [ºC] during operating for 15 minutes without and with graphene coated copper flat plate heat sink.

5. Conclusion

Three dimensional CFD model of an iPhone5 has been presented. The model accounts for heat transfer for both natural convection and radiation to the ambient air temperature. The comparison between the CFD simulation and the thermal image obtained by the thermal camera shows some similarities like, for example, hot-spots located in the same places. The present CFD study allow accurate, rapid, physical modelling to make decisions on materials, components and layout beside power control feedback to achieve performance and target lifetime with reduced testing requirements. The model is shown to be able to: (1) understand the many interacting and heat transfer phenomena, which, very difficult or cannot be studied experimentally; (2) identify limiting steps and components; and (3) provide a computer-aided tool for design and optimization of future electronic cooling with efficient and economical solutions.

References

[1] Yunus A. Çengel. Heat and Mass Transfer: A Practical Approach, chapter 15: Cooling of Electronic Equipment, 3rd edition, 2007, ISBN: 0073129305, McGraw-Hill Higher Education.
[2] Remsburg Ralph. Thermal design of electronic equipment. 2001, ISBN 849300827, CRC Press, USA.
[3] Jagadish Thammanna, Ambuj Srivastav. Thermal management in electronic equipment. HCL Technologies, February 2010.
[4] Peter Rodgers. The Need for Electronics Thermal Design Practices to Embrace Sustainability. Electronics COOLING, September 2014, pp. 2.
[5] Lienard, J.H., IV and V, A Heat Transfer Textbook, 3rd edition, 2004, MIT Press.
[6] Eric Pop, Vikas Varshney, Ajit K. Roy. Thermal properties of graphene: Fundamentals and applications. MRS BULLETIN, volume 37, December 2012, pp.1273-1281.
[7] Goki Eda, Manish Chhowalla. Graphene-based composite thin films for electronics. Nano Letter 2009, 9(2), pp.814-818.
[8] Vivek Goya, Alexander A. Balandin. Thermal properties of the hybrid graphene-metal nano-micro-composites: Applications in thermal interface materials. Appl.Phys.Lett. 100, 073113, 2012.
[9] Siva P. Gurrum, Darvin R. Edwards, Thomas Marchand-Golder, Jotaro Akiyama, Satoshi Yokoya, Jean-Francois Drouard, Franck Dahan. Generic thermal analysis for Phone and tablet systems. IEEE 2012, pp.1488-1492.
[10] Zhaoxia Luo, Hyejung Cho, Xiaobing Luo, Kyung-il Cho. System thermal analysis for mobile phone. Applied Thermal Engineering 2008, 28, 1889-1895.
[11] Christian Kargel. Infrared thermal imaging to measure local temperature rises caused by handheld mobile phones. IEEE Transactions on instrumentation & measurement 2005, 54(4), pp.1513-1519.
[12] Maher A.R. Sasiq Al-Baghdadi. Applications of Computational Fluid Dynamics and Finite Element Methods in Engineering Education. Vol.1, IEEFound, ISBN-9781512122428, 2015.