Pertanika J. Sci. & Technol. 30 (2): 1073 - 1086 (2022)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

# Experimental Study and CFD Modelling for Thermal Cooling Improvement of Electronic Components Using Graphene Nanosheets Coated

**Maher Al-Baghdadi[1]*, Amel Ahmed Ridha[1], Salam Al-Abassi[1,2] and Haider Hadi Jabber[3]**

[1] *Department of Electronics and Communications Engineering, Faculty of Engineering, University of Kufa, Najaf, Iraq*
[2] *Electron Devices Department, Budapest University of Technology and Economics, Budapest, Műegyetem rkp. 3, 1111, Hungary*
[3] *Iraqi Ministry of Electricity, General Company of Electricity Al-Furat middle region, Najaf, Iraq*

## ABSTRACT

Electronic circuit boards' heat dissipation capability directly impacts their service life since the heat dissipation efficiency of components directly impacts the board's life. This work focused on the problem of the high surface temperature of the electronic components at the control unit stage of a cement production line. Three dimensional CFD model has been developed to simulate all components in this circuit board. A thermographic camera has been used to measure the surface temperatures of the components on the circuit board. Consistency was very good in the results. Two cooling mechanisms were examined, one of which is a traditional technique by forced air cooling technology. The other is using graphene nanosheets coating technology to increase the dissipation of the generated heat to the surrounding atmosphere. Although an electronic fan was very effective in cooling the electronic circuit components, which reduced the temperature by 22.6%, it has two undesirable features: the need to install it in a safe place and the need for power to run it. Graphene nanosheets coatings provide efficient and economical heat dissipation. The thin graphene layer enhances the radiation effect for the heat significantly. The results showed that the smooth aluminium plate coated with graphene and mounted directly to the back part of the transistor behind the plastic chip carrier piece for heat dissipation provided an efficient, sustainable

ARTICLE INFO

*Article history:*
Received: 08 October 2021
Accepted: 07 January 2022
Published: 03 March 2022

DOI: https://doi.org/10.47836/pjst.30.2.12

*E-mail addresses*:
mahirar.albaghdadi@uokufa.edu.iq (Maher Al-Baghdadi)
amala.alsudani@uokufa.edu.iq (Amel Ahmed Ridha)
sal-abassi@edu.bme.hu; salam.waheed@uokufa.edu.iq (Salam Al-Abassi)
haider-81@live.com (Haider Hadi Jabber)
* Corresponding author

ISSN: 0128-7680
e-ISSN: 2231-8526

and economical solution in thermal management. In comparison with the fan, the graphene nanosheets coating technology reduces the temperature by an average of 16.4% without consuming any energy.

*Keywords:* CFD, efficient heat dissipation, electronic cooling, graphene nanosheets, thermal analysis

---

## INTRODUCTION

In recent years there has been an increase in the failure of electronic circuit boards, particularly those used in industries, due to the fact that they have reached temperatures they had not previously reached. It is a result of global climate change and global warming. The increase in the ambient temperature has reduced the efficiency of the cooling previously designed for these boards due to a decrease in the amount of heat transferred from the electronic components to the atmosphere by convection and radiation, which requires either re-designing the electronic circuit boards and their components, which is very expensive or properly enhancing the cooling them without changing them.

Increasing temperatures in electronic components due to electronic cooling problems cause more errors and failures in electronic systems. In fact, the high temperature of electronic components does not only cause their failure, but the effect of high temperature increases the error in the work of these components. As electronics' operating temperatures increase, their failure rates increase almost exponentially. Generally, if the junction temperature of electronic components is reduced by ten degrees centigrade, the failure rate will be halved (Çengel, 2007).

Various cooling techniques are studied and used in the thermal design of electronic equipment, including passive cooling systems, forced-air cooling systems, and liquid cooling systems (Galins et al., 2019). Passive cooling systems or natural cooling systems use natural conduction, convection, and radiation to cool components (Alhattab et al., 2016). Thermal sinks generally use passive cooling methods, relying on the principle of heat transfer. It also has no power requirement, compact, noiseless, and reliable. Passive cooling systems are therefore very popular in many applications. The primary means of heat transfer under these conditions are natural convection and radiation. In traditional forced-air cooling systems, a small electronic fan provides a substantial amount of airflow for quick and effective cooling (Ghyadh et al., 2021; Rohachev et al., 2020). However, since the fan requires power and place for installation, the use of this method will be minimal. A liquid cooling system is a complete unit that circulates a coolant to a predetermined temperature (Al-Baghdadi et al., 2020; He et al., 2021; Zhuang et al., 2020). In this system, coolant is circulated by a pump, a heat exchanger dissipates heat, and coolant is transferred from the heat source to the liquid cooling system by a liquid circuit. In this case, components are cooled to a greater extent than those in traditional air coolers that use cooling fans. In addition to being expensive and complex to install, liquid cooling systems require much maintenance. It can cause metal parts to corrode faster and damage electronic components (He et al., 2021; Zhuang et al., 2020).

Graphene is the hexagonal structure of carbon atoms arranged in one atom of thickness. This one atom thick compound is strong, stable and conducts electricity and heat well at room temperature (Ali et al., 2021). As graphene has a much higher thermal conductivity and emissivity than copper, it can significantly improve the efficiency of passive cooling (Jaafar et al., 2020). Nano-carbon technology, which uses graphene as a thermal transfer bridge, is the current leading heat transfer technology (Galins et al., 2019; Ali et al., 2021). There is no comparison between the thermal conductivity of graphene (over 2000 W $(m K)^{-1}$) and that of copper (401 W $(m K)^{-1}$). A wide range of applications is expected soon for this technology (Galins et al., 2019). By using these materials with high emissivity and unmatched conductivity coefficient, these advantages can be used to improve heat sinks through coating processes without the need for space and cooling equipment that consumes power. Heat transfer of passive heat sinks was enhanced by graphene coating (Jaafar et al., 2020; Zu et al., 2021), making it a promising option as a material for thermal management. Recently, several high-emissivity and high-conductivity materials have been used as a composite with graphene in the coating processes. Copper (Wong et al., 2021; Hsieh et al., 2017), silver (Fan et al., 2020), and graphite have all been used to enhance heat transfer for electronics applications. In high-heat flow density devices, nanocomposites can provide an effective thermal design for efficient cooling (Gan et al., 2020; Yang et al., 2021).

As electronics have grown more complex and power-dense in recent years, the traditional approach of testing and prototyping has been challenged. Computational Fluid Dynamics (CFD) software has opened new avenues for developing efficient devices that can operate in demanding environments and have high power dissipation (Chu et al., 2020; Brahim & Jemni, 2021). CFD models can often be built and analysed at a fraction of the cost and time of physical models. Seeing more options and exploring what might happen lets us speculate more confidently than ever. Furthermore, flow and heat transfer models provide insight into fluid flow phenomena that could not be obtained by experiments alone. Flow and heat transfer modelling adds insight and understanding to our design proposals, reducing risk and avoiding cost oversizing and over stipulations. Many research studies have used CFD simulations for the electronics cooling applications, such as improving and design of air-cooled heat sinks (Alhattab et al., 2016; Chu et al., 2020) improving forced-air cooling heat sinks (Ghyadh et al., 2021; Brahim & Jemni, 2021), and designing liquid cooling heat sinks (Al-Baghdadi et al., 2020; Cheng et al., 2020; Xie et al., 2021).

This study uses very efficient thermal material (graphene nanosheets) to provide an effective cooling solution without changing the original structure layout considering the high surface temperatures of components in the control unit of a cement production line. An advanced CFD model for all components on this circuit board has been developed, as well as a thermographic camera has been used for measuring surface temperatures of the components.

## PROBLEM FORMULATION

### CFD Modelling of the Thermal Analysis of the Electronic Equipment

In this study, a CFD model of a three-dimensional board for industrial electronic applications has been analysed. In the model, heat transfer takes place through conduction through the circuit board components and natural convection to the ambient air temperature and radiation to the surroundings.

**Computational Domain and Material Properties.** An industrial electronic card (LF01) at the control unit stage of a cement production line from Kufa Cement Company has been used in this study. This study considered all the components of electronic parts such as printed circuit boards, transistors, resistances, capacitance, miscellaneous, and is modelled according to measured dimensions and manufacturers' specifications, as shown in the computational domain in Figure 1. Components and circuit boards are made from different materials. Each component's material properties are listed in Table 1.

The components on this board are close together, leaving little place for air to flow. It reduces the air present inside the chassis so much that convection cannot be the predominant mode of heat transfer. The result is that conduction plates, and heat sinks are the most common methods available to transfer heat from sources to surfaces. Heat is dissipated passively through heat conduction plates, and heat sinks on the chassis' outer surfaces.

**Modelling Equations.** Conduction, convection, and radiation are the three ways heat is transferred on a printed circuit board. Using the energy equation (Alhattab et al., 2016; Al-Baghdadi et al., 2020; Brahim & Jemni, 2021), one can calculate the temperature field. Conduction is the transfer of heat within or between two materials. The energy transfer phenomenon is thought to occur through kinetic energy exchange between atoms and

Table 1
*Properties of the materials in the circuit board (Alhattab et al., 2016)*

| Material | Density $\rho$ [kg/m$^3$] | Heat capacity $C_p$ [J/kg.K] | Thermal conductivity $k$ [W/m.K] | Emissivity $\varepsilon$ |
|---|---|---|---|---|
| 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 |
| Aluminium Alloy 6063 | 2700 | 900 | 200 | 0.6 |
| Copper | 8700 | 385 | 400 | 0.6 |

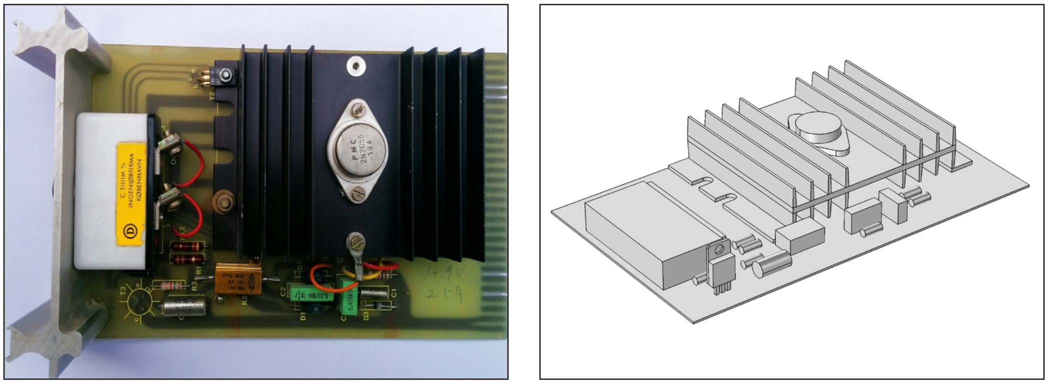

(a) (b)

*Figure 1.* The control unit (LM7815) that used in the production line from Kufa Cement Company (a) and the three-dimensional computational domain (b)

electron drift due to elastic and inelastic collisions between atoms. The transfer of heat energy from an area of higher energy to an area of lower energy is constant. The vibration level of molecules within a substance determines the energy level or temperature of the material. Heat cannot be transferred between regions with equal temperatures.

In solids, heat conduction is determined by using Equation 1 (Al-Baghdadi, 2009);

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

where $\rho$ 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].

Molecular motion and fluid motion transfer energy during convection. Heat conduction and energy storage are two important factors in convection. It involves the transport of macroscopic parts of hot and cold fluid elements, mixing the fluid elements inside the coolant medium, and mixing the fluids themselves. Coolant media in contact with the device can expand, resulting in convection. Convection of this sort is called natural convection, or free convection. Other forces can also cause convection, such as the use of a pump or fan to move the coolant media. Heat can only be transferred through radiation in a vacuum and depends on the radiating surface's temperature.  An object's surface modulates heat transfer by emittance, absorption, reflection, and transmission. In the presence of ambient, all external surfaces convect and radiate heat towards the ambient according to Equation 2 (Al-Baghdadi, 2010);

$$-\mathbf{n}.(-k\nabla T) = h(T_{amb} - T) + \varepsilon\sigma\left({T_{amb}}^4 - T^4\right) \tag{2}$$

where **n** is the unit vector normal to the surface, $h$ is convection coefficient [W/m$^2$.K], $T_{amb}$ is ambient temperature [K], where ε is emissivity, and $\sigma$ is Stefan-Boltzmann constant = 1.38E$^{-23}$ [J/K].

**Computational procedure, Grid, and Boundary Conditions.** In order to solve the governing equations, a COMSOL Multi-physics computational fluid dynamic (CFD) package was used. It uses a discretisation method and a finite-volume solution method. Simulating this process involves defining a heat transfer coefficient corresponding to a natural convection state, the heat source of each component in the circuit board, and the ambient temperature of the surrounding air.

The boundary and initial conditions are outlined as follows. Each component in the circuit board has been subjected to uniform heat flux as a heat source calculated from the Muillitusm program explained in the next section. A constant heat transfer coefficient of 5 W/m$^2$.K, representing natural convection, has been applied with the ambient external air temperature of 25 C (Alhattab et al., 2016; Zu et al., 2021).

The solutions were subjected to rigorous numerical tests to ensure their independence from grid size. Five meshes of different sizes were generated to calculate the relative error, $[(T_{max\ mesh_{(n+1)}} - T_{max\ mesh_{(n)}})/T_{max\ mesh_{(n+1)}}]$. There are a total of 89037 domain elements, 50531 boundary elements, and 4539 edges in the computational quadratic mesh have been selected, as shown in Figure 2, which meets the requirement of having an error of less than 0.1% (Table 2). In two consecutive iterations of solving the coupled set of equations, the relative error within each field was considered the same or less than $1.0 \times 10^{-6}$. After this criterion has been met, the final solution can be reached, whereby the numerical data are analysed and then the cooling methods proposed are explored.

## Computer Simulation of the Printed Circuit Board

The circuit board with all its components was simulated with the Muillitusm-12 program. Three cases of operation in the production line were taken into consideration. In order to determine the power of each component in the circuit board, the current and voltage

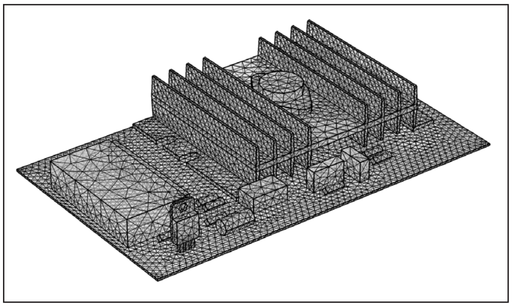
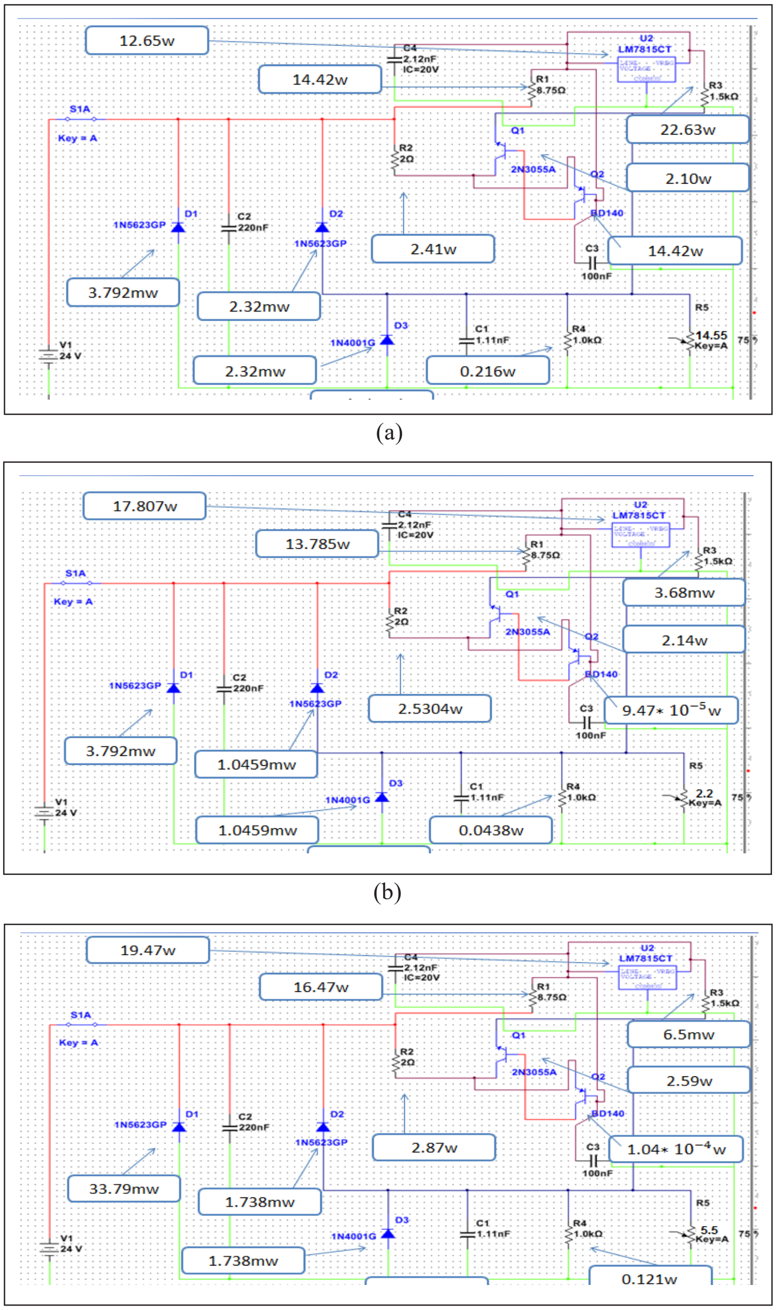


*Figure 2.* The computational mesh for the computation domain (quadratic)

Table 2
*Grid independence test*

| n | COMSOL label | The complete mesh consists of elements | | | Relative error $T_{err}$ |
|---|---|---|---|---|---|
| | | Domain | Boundary | Edge | |
| 1 | Coarser | 9209 | 6318 | 1716 | - |
| 2 | Coarse | 17128 | 11113 | 2281 | 0.001627 |
| 3 | Normal | 34951 | 21402 | 3067 | 0.000816 |
| 4 | Fine | 89037 | 50531 | 4539 | 0.000746 |
| 5 | Finer | 165887 | 85611 | 5776 | 0.000702 |

across each component were measured. Figure 3 shows the power of each component for the three currents 1.011, 2, and 3.1 Ampere.



(a)

(b)

(c)

*Figure 3.* The power of each component for three cases of circuit board current: (a) Current 1.011 Amp; (b) Current 2.000 Amp; and (c) Current 3.100 Amp

## Thermal Imaging of the Electronic Components

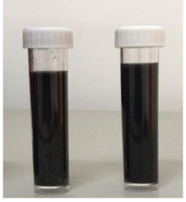
A thermal imaging camera was used to measure the local temperatures of the electronic equipment components. It is very important for the thermal analysis of the printed circuit board and all its attached electronic components. Thermal imaging cameras can analyse electronic components and circuits to identify heat patterns. Thermal imaging is advantageous over contact temperature measurement devices because the object is not affected by contact, thus ensuring that the temperature is not affected while measuring. Moreover, measuring the entire circuit or component is more accurate than measuring a single point.

The temperature fields can be precisely measured with thermal, temporal and spatial resolution through a thermal imaging camera. A thermal camera, type (FLIR ONE Pro), was used to visualise the temperature distribution in the electronic components at the control unit stage of a cement production line, with a sensitivity that detects temperature differences down to 70 mK. Its 19,200-pixel resolution provides a clear and accurate image, which proffers seeing more detail. Thermal imaging techniques ware indicated how much heat is produced by electronic components.

The maximum temperature uncertainty has been calculated using the method described in Moffat (1985). Approximately 0.142653% uncertainty is associated with the temperature values measured.

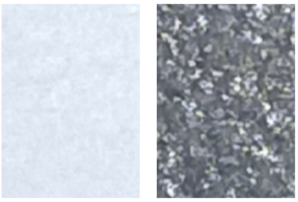
## Graphene Nanosheets Coated

In consequence of its unique structure, graphene has exceptional thermal conductivity. A thin layer of graphene can slash the temperature of electronic components, resulting in longer component life. The graphene nanosheets coating technique was used for the component of higher temperature in the circuit board, which is the 2N3055A transistor in this work. A smooth aluminium plate, with dimensions of 15 lengths, 10 mm width and 1 mm thickness, has been coated with graphene and mounted directly to the back part of the transistor behind the plastic chip carrier piece for heat dissipation, providing a good convenient path for heat conduction out. The graphene was weighed using a high-sensitivity balance, and an amount of 60 µg was used to prepare a homogeneous mixture of ethanol and graphene. A hotplate and stirrer were used to mix graphene and ethanol for 20 minutes. An Ultrasonic mixer was used to homogenise the mix with a 2-second power-on time and a 2-second power-off time for 20 minutes. The chemical spray system was used to form a graphene layer on an aluminium plate and then mounted on the back metal part of the transistor. Before the coating process, the aluminium plate was cleaned by MTI ultrasonic cleaner device for 20 minutes. A heater controls the aluminium plate temperature is to 200 C to give the coating process of the graphene nanosheets a homogenous surface. The coating thickness of the graphene layer was 120µm, measured by using an optical thin film measurement device, Lambda scientific Pty ltd. (LIMF-10). A metallurgical microscope, Device Corporation, X 1600, was used to measure the surface morphology. The prepared graphene solution, the chemical spray system, the coated aluminium plate and the surface morphology used are shown in Figure 4.



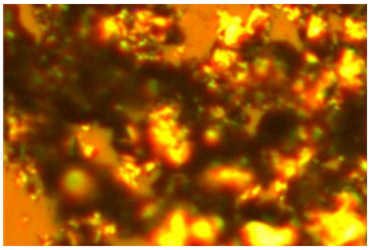
Prepared graphene solution

Chemical spray system



Before After

Upper surface of the aluminium plate



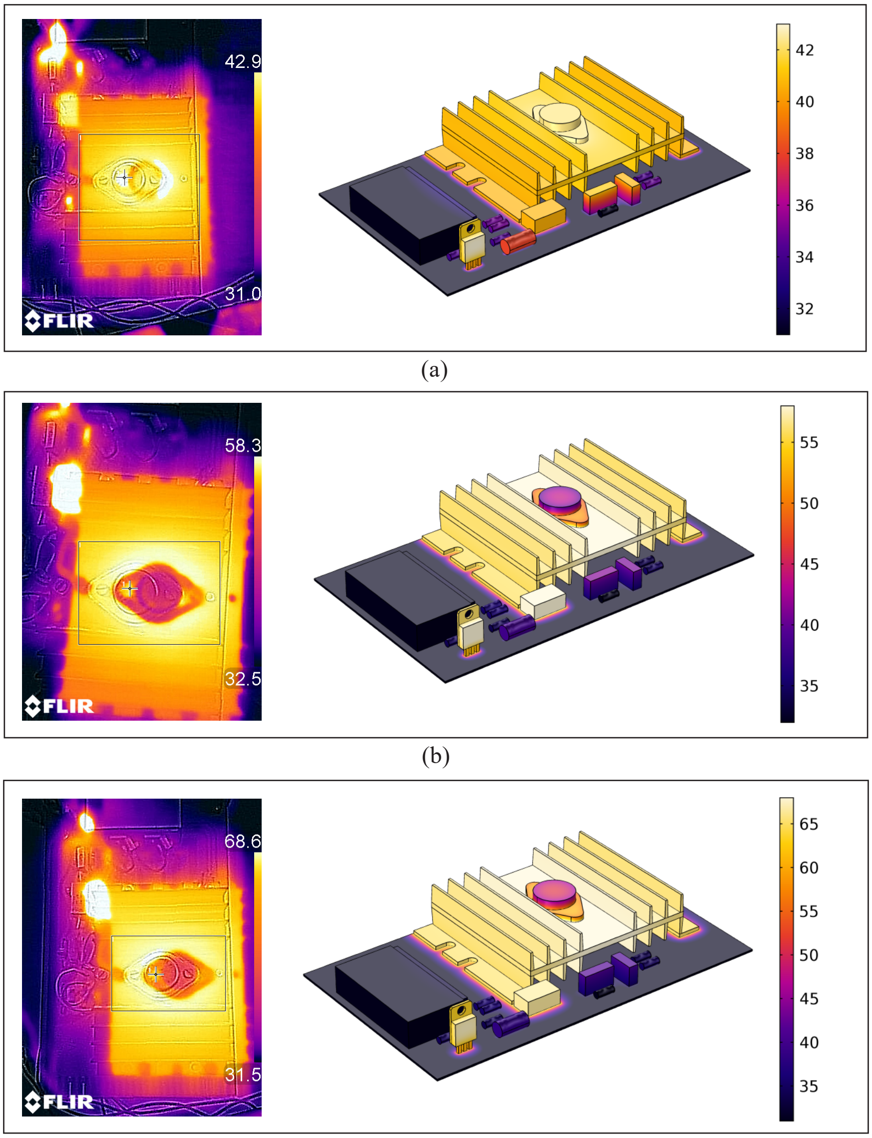
Surface morphology

*Figure 4.* The prepared graphene solution, the chemical spray system, the coated aluminium plate and the surface morphology

## RESULTS AND DISCUSSIONS

CFD models allow for detailed assessment of complex heat transfer processes within electronic components on a circuit board and their transfer to ambient air by convection and radiation. Experimental results from three operating cases were used to validate the results of the CFD model (Figure 5). The thermographic camera type (FLIR ONE Pro) was used to measure the surface temperatures of the components on the circuit board. As can be seen from the heat spots on the CFD simulation results and the thermal image taken with the thermal imaging camera, the results are extraordinarily similar. The difference between the two degrees does not exceed one degree Celsius (±1$^{o}$C). Consistency is very good in the results. These results confirm that it is possible to predict the temperature field accurately for electronics components based on the simulation analysis. Simulating the cooling of electronic components is still one of the most efficient cooling methods.

The above analysis revealed significant improvements needed for the circuit board to prevent excessive overheating and the eventual failure of the electronic components. The results show that the highest temperature in all cases was on the transistor piece. Within a few periods, this part is usually damaged by this high temperature. Therefore, on the basis of the results obtained, a mechanism must be developed to cool the electronic part with the highest temperature, which is the transistor. Two cooling mechanisms were proposed: a traditional technique by installing a small electronic fan. The other is using graphene nanosheets coating technology to increase the dissipation of the generated heat to the surrounding atmosphere.



(a)

(b)

(c)

*Figure 5.* Temperature distribution [°C] for the three cases of the operating, (left) thermal image and (right) CFD simulation results: (a) Current 1.011 Amp; (b) Current 2.000 Amp; and (c) Current 3.100 Amp

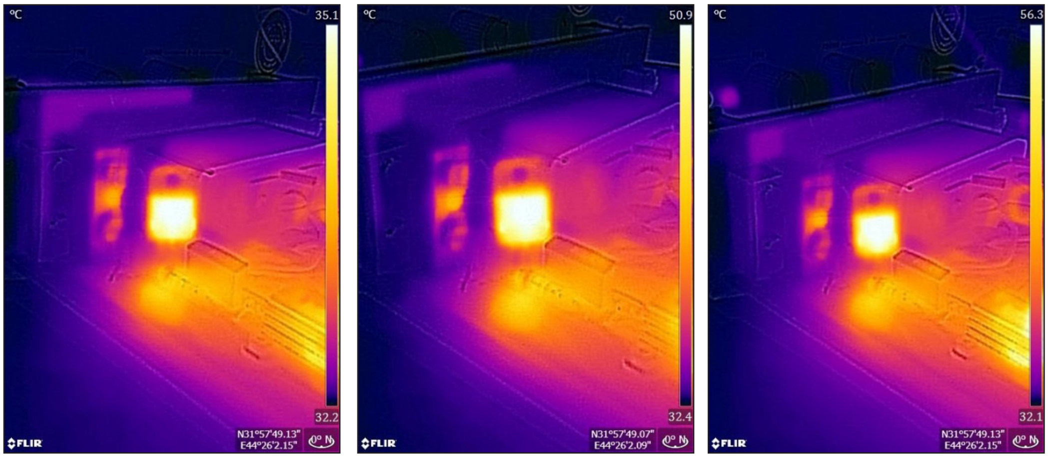
Electronic fans are widely used to cool electronics (forced air cooling technology). By installing a small electronic fan on the circuit board near the transistor, the temperatures of all components were significantly decreased. Figure 6 shows the results of the temperatures distribution when installing an electronics cooling fan for the three operating cases. Despite the effectiveness of an electronic fan in cooling electronic circuit components, as seen in results, it had two shortcomings, since it required a place to be installed, as well as electricity.

Heat dissipation by graphene nanosheets coating is a new efficient and economical technique. The technique is characterised by the fact that it does not require a place and does not consume power (natural cooling), so it is suitable for tight spaces. Figure 7 shows the surface temperatures distribution of the components on the circuit board when using a graphene-coated aluminium plate mounted directly to the back part of the transistor for the three operating cases. The results show a significant decrease in temperatures across the board. The thin graphene layer works for the radiation effect enhanced significantly. Although the higher temperatures did not drop as much as when using the electronic fan, this amount of descent was adequate in keeping the transistor from damage economically. The thermal cooling was achieved without modifying the internal structure of the circuit board.

Figure 8 compares the cooling methods used in this work for a maximum temperature reached on the circuit board during operation. For all the studied cases, forced air cooling reduced the temperature by 22.6%, but this technology consumes energy. In comparison,

(a) (b) (c)

*Figure 6.* Temperature distribution [°C] for the three operating cases using an electronic cooling fan: (a) Current 1.011 Amp; (b) Current 2.000 Amp; and (c) Current 3.100 Amp



(a) (b) (c)

*Figure 7.* Temperature distribution [°C] for the three operating cases using a graphene-coated plate mounted directly to the back part of the transistor: (a) Current 1.011 Amp; (b) Current 2.000 Amp; and (c) Current 3.100 Amp

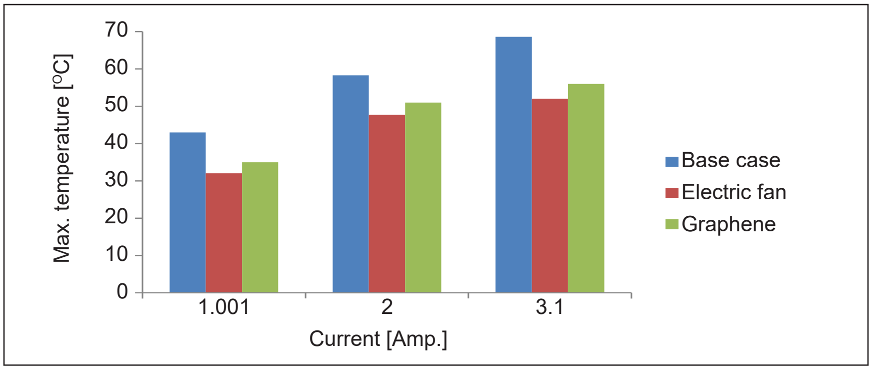


*Figure 8.* Comparison of the cooling methods used in this work for the surface temperature of the back part of the transistor reached on the circuit board during operation

the graphene nanosheets coating technology reduces the temperature by an average of 16.4% without consuming any energy. With the demand for smaller devices, cooling electronic circuits have become more challenging. Compared to conventional electronics cooling methods, i.e. forced-air cooling by using the electronic fan, graphene nanosheets coating shows exceptional cooling performance. This technique involves controlling the heat generated by electronic devices effectively and sustainably. It is demonstrated that the passive cooling methods remain a good choice for the thermal management in the circuit boards if only the outer surfaces of the electronic components are coated with the graphene nanosheets coating.

## CONCLUSION

With the three-dimensional CFD model, information is available about how to transport heat is generated inside the electronic components and transferred to an ambient environment through convections and radiations. With the model, electronic circuit boards can be designed with efficient and economical cooling solutions that can be optimised with the aid of computers. Using this model, the designer can understand interacting processes and heat transfer that are difficult or impossible to study experimentally. At the control unit stage of the cement production line, high surface temperatures were very affecting electronic components. Although forced air cooling technology was effective, it has two shortcomings: it requires a place to be installed and power. The graphene nanosheets coating technique used for electronics cooling has the advantage of requiring no place and using no power, so it is suitable for tight areas in a sustainable manner. The heat was removed from the transistor effectively and economically by using an aluminium plate coated with graphene nanosheets and mounted directly to the back part of the transistor. This work also showed that simulation analysis remains one of the most valuable ways to cool electronics components efficiently since, through conformity modelling of the object, it is possible to recognise the temperature fields effectively for the circuit board.

## ACKNOWLEDGEMENTS

This work was funded by the Kufa Cement Company and the Department of Electronics and Communications Engineering, Faculty of Engineering, University of Kufa. Additionally, Kufa Centre for Advanced Simulation in Engineering (KCASE) is well appreciated.

## REFERENCES

Al-Baghdadi, M. (2009). A CFD study of hygro–thermal stresses distribution in PEM fuel cell during regular cell operation. *Renewable Energy, 34*(3), 674-682. https://doi.org/10.1016/j.renene.2008.05.023

Al-Baghdadi, M. (2010). A CFD analysis of transport phenomena and electrochemical reactions in a tubular-shaped ambient air-breathing PEM micro fuel cell. *HKIE Transactions, 17*(2), 1-8. https://doi.org/10.1080/1023697X.2010.10668189

Al-Baghdadi, M., Noor, Z., Zeiny, A., Burns, A., & Wen, D. (2020). CFD analysis of a nanofluid-based microchannel heat sink. *Thermal Science and Engineering Progress, 20*, Article 100685. https://doi.org/10.1016/j.tsep.2020.100685

Alhattab, H. A., Al-Baghdadi, M., Hashim, R., & Ali, A. (2016). Design of micro heat sink for power transistor by using CFD. In *Al-Sadiq International Conference on Multidisciplinary in IT and Communication Science and Applications (AIC-MITCSA)* (pp. 268-272). IEEE Publishing. https://doi.org/10.1109/AIC-MITCSA.2016.7759948

Ali, S., Ahmad, F., Yusoff, P., Muhamad, N., Oñate, E., Raza, M., & Malik, K. (2021). A review of graphene reinforced Cu matrix composites for thermal management of smart electronics. *Composites Part A: Applied Science and Manufacturing, 144*, Article 106357. https://doi.org/10.1016/j.compositesa.2021.106357

Brahim, T., & Jemni, A. (2021). CFD analysis of hotspots copper metal foam flat heat pipe for electronic cooling applications. *International Journal of Thermal Sciences, 159*, Article 106583. https://doi.org/10.1016/j.ijthermalsci.2020.106583

Çengel, Y. A. (2007). *Heat and mass transfer: A practical approach*. McGraw-Hill Higher Education.

Cheng, C., Chang, P., Li, H., & Hsu, F. (2020). Design of a single-phase immersion cooling system through experimental and numerical analysis. *International Journal of Heat and Mass Transfer, 160*, Article 120203. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120203

Chu, W., Tsai, M., Jan, S., Huang, H., & Wang, C. (2020). CFD analysis and experimental verification on a new type of air-cooled heat sink for reducing maximum junction temperature. *International Journal of Heat and Mass Transfer, 148*, Article 119094. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119094

Fan, D., Jin, M., Wang, J., Liu, J., & Li, Q. (2020). Enhanced heat dissipation in graphite-silver-polyimide structure for electronic cooling. *Applied Thermal Engineering, 168*, Article 114676. https://doi.org/10.1016/j.applthermaleng.2019.114676

Galins, J., Laizans, A., & Galins, A. (2019). Review of cooling solutions for compact electronic devices. *Research for Rural Development, 1*, 201-208. https://doi.org/10.22616/rrd.25.2019.030

Gan, J., Yu, H., Tan, M., Soh, A., Wu, H., & Hung, Y. (2020). Performance enhancement of graphene-coated micro heat pipes for light-emitting diode cooling. *International Journal of Heat and Mass Transfer, 154*, Article 119687. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119687

Ghyadh, N., Ahmed, S., & Al-Baghdadi, M. (2021). Enhancement of forced convection heat transfer from cylindrical perforated fins heat sink - CFD Study. *Journal of Mechanical Engineering Research and Developments, 44*(3), 407-419.

He, Z., Yan, Y., & Zhang, Z. (2021). Thermal management and temperature uniformity enhancement of electronic devices by micro heat sinks: A review. *Energy, 216*, Article 119223. https://doi.org/10.1016/j.energy.2020.119223

Hsieh, C., Chen, Y., Lee, C., Chiang, Y., Hsieh, K., & Wu, H. (2017). Heat transport enhancement of heat sinks using Cu-coated graphene composites. *Materials Chemistry and Physics, 197*, 105-112. https://doi.org/10.1016/j.matchemphys.2017.05.012

Jaafar, A. A., Al-Abassi, S. A. W., Alhattab, H. A., Albaghdad, M. A., Mosa, A. A., Al-Musawi, H. K., & Gneem, L. M. (2020). Improvement of heat sink performance by using graphene nanosheets coated by chemical spray method. In *IOP Conference Series: Materials Science and Engineering* (Vol. 811, No. 1, p. 012027). IOP Publishing. https://doi.org/10.1088/1757-899X/811/1/012027

Moffat, R. J. (1985). Using uncertainty analysis in the planning of an experiment. *Journal of Fluids Engineering, 107*, 173-178. https://doi.org/10.1115/1.3242452

Rohachev, V. A., Terekh, O. M., Baranyuk, A. V., Nikolaenko, Y. E., Zhukova, Y. V., & Rudenko, A. I. (2020). Heataerodynamic efficiency of small size heat transfer surfaces for cooling thermally loaded electronic components. *Thermal Science and Engineering Progress, 20*, Article 100726, https://doi.org/10.1016/j.tsep.2020.100726.

Wong, R., Antoniou, A., & Smet, V. (2021). Copper-graphene foams: A new high-performance material system for advanced package-integrated cooling technologies. In *2021 IEEE 71st Electronic Components and Technology Conference (ECTC)* (pp. 1945-1951). IEEE Publishing. https://doi.org/10.1109/ectc32696.2021.00307

Xie, L., Yuan, X., & Wang, W. (2021). Thermal-flow network modeling for virtual prototyping of power electronics. *IEEE Transactions on Components, Packaging and Manufacturing Technology, 11*(8), 1282-1291. https://doi.org/10.1109/TCPMT.2020.3009156

Yang, D., Yao, Q., Jia, M., Wang, J., Zhang, L., Xu, Y., & Qu, X. (2021). Application analysis of efficient heat dissipation of electronic equipment based on flexible nanocomposites. *Energy and Built Environment, 2*(2), 157-166. https://doi.org/10.1016/j.enbenv.2020.07.008

Zhuang, D., Yang, Y., Ding, G., Du, X., & Hu, Z. (2020). Optimization of microchannel heat sink with rhombus fractal-like units for electronic chip cooling. *International Journal of Refrigeration, 116*, 108-118. https://doi.org/10.1016/j.ijrefrig.2020.03.026

Zu, H., Dai, W., Li, Y., Li, K., & Li, J. (2021). Analysis of enhanced heat transfer on a passive heat sink with high-emissivity coating. *International Journal of Thermal Sciences*, *166*, Article 106971. https://doi.org/10.1016/j.ijthermalsci.2021.106971