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A Numerical Study to Verify the Importance of Using Several Nanomaterials in Improving Heat Transfer in Pipes

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ABSTRACT

A numerical investigation was conducted to investigate the importance of using nanomaterials to improve heating and cooling in tubes. This study examined the incorporation of nanoparticles such as iron oxides, aluminium oxides, titanium dioxides, silicon oxides, and carbon nanotubes into the chosen metal at concentrations of 1%, 5%, and 10%. Copper was selected as the pipe material, with iron oxides, aluminium oxide, titanium dioxide, silicon oxide, and carbon nanotubes incorporated as nanomaterials. The study was conducted using Ansys/Fluent 16 software. The findings demonstrate that, among the nanomaterials tested, only carbon nanotubes enhance heat transfer, with a nanoparticle concentration of 10% yielding a significant improvement in heat transmission. By contrast, iron oxides, aluminium oxide, titanium dioxide, and silicon oxide have no effect on heat transfer when used, and some of these nanomaterials reduce heat transfer. When copper is heated and a larger amount of these low-thermal-conductivity materials is added, the heat flux decreases.

1. Introduction

Across the globe, there is a noticeable trend in adopting cutting-edge technologies and innovations. The transfer of heat is an essential component in a wide range of scientific applications and has a substantial impact on a variety of aspects of life, including electronic devices, X-rays, optical devices, and cooling equipment. These technologies and devices have proliferated quickly due to shrinking components, enhanced data storage, and optimised operating speeds, leading to considerable difficulties in managing their thermal conditions [1]. The low thermal conductivity of these materials is the key factor underlying the need for improved thermal conductivity. To address this issue, one must either concentrate on the utilisation of materials that have a high thermal conductivity or on the enhancement of the thermal conductivity of materials that are already in existence. Given the significance of this topic, researchers have devoted considerable attention and effort to identifying the most effective techniques for enhancing thermal energy transfer properties [2–5]. When it comes to the design of a variety of applications in the commercial, industrial, and

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domestic appliance sectors, having a solid understanding of heat transfer mechanisms and being aware of their existence is necessary, which comprises Solar energy, air conditioning, the oil and gas industries, energy generation, and electronic refrigeration [6–8]. Heat transmission is a vital component in a variety of applications that are essential to human existence. To improve heat transfer, scientists have employed diverse strategies, including equipping materials with fins for greater heat transmission or increasing their surface area to maximise the region of heat exchange. A key strategy is the integration of fins to boost heat transmission [9–15]. This additional method involves improving how heat moves from carrier fluids, making heat dissipation and absorption faster and more effective [16–21].

Incorporating nanoparticles into heat transfer chemicals and the enhancement of their capacity for rapid heat exchange are two key modern approaches that have been developed to improve heat transfer. The advent of nanomaterials has spurred a significant revolution in various sectors, and heat transfer stands out as paramount because of its wide-reaching influence [22–29]. Adding nanomaterials to metals improves their thermal conductivity [30–38].

The current work employs Ansys Fluent software to simulate the phase transition of paraffin wax utilising a combination of CuO and Al_2O_3 hybrid nano-additives. The thermo-physical properties of paraffin were quantified, and a 10% to 19% reduction in charging time was achieved through incorporating hybrid nanoparticles. Theoretical efficiency experienced a significant improvement, rising from 61.7% to 84.8%, as a result of an elevated heat transfer fluid inlet temperature [39]. The investigation also aims to enhance the thermal efficiency of paraffin-based triplex tube heat storage systems by integrating conductive mono nanoparticles and hybrid nano additives. The experimental effort entails the measurement and preparation of nano phase change material (PCM) as well as the simulation of the melting process. The results indicate that including 1.6% hybrid nanoparticles can increase the stored energy by 5.97%, resulting in a 76.8% improvement in storage efficiency [40]. The study further examines the improvement of convective heat transfer in smooth tubes by incorporating TiO_2-SiO_2 nanoparticles into a base fluid comprising water and ethylene glycol (W/EG). Last but not least, the study investigates the impact of nanofluid volume concentrations and Reynolds number on heat transfer coefficients and friction factors. The hybrid nanofluid at a concentration of 3.0% exhibits the highest Nusselt number [41].

The present investigation provides an insight into how to enhance the heat transfer rate using multiple types of nanoparticles: iron oxides (Fe_3O_4), aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), silicon oxide (SiO_2), and carbon nanotubes. A layer of copper will be applied to improve thermal conductivity and augment heat transmission. A numerical analysis was also conducted to facilitate the process of determining the best nanomaterials for experimental study and application in a variety of thermal applications.

This study presents several original points. First, it emphasises the significance of numerical research in enhancing heat transfer in pipes, showcasing a modern and innovative approach. Second, the utilisation of various nanomaterials, including iron oxides, aluminum oxide, titanium dioxide, silicon oxide, and carbon nanotubes, demonstrates a focus on innovative advancements in material science and nanotechnology. Subsequently, the utilisation of Ansys/Fluent software exemplifies the employment of sophisticated numerical simulation methods, reinforcing the scientific credibility of the investigation. The empirical evidence shows a marked enhancement in heat transfer capabilities attributable to incorporating nanomaterials, notably carbon nanotubes, and the findings underscore that elevated concentrations, precisely at 10%, yield substantial improvements. Collectively, these points reflect the originality of the research, showcasing technological advancements and innovation in improving heat transfer efficiency using nanomaterials in pipes.

2. Methodology

2.1 Governing Equations

Establishing appropriate operating conditions and formulating the governing equations (continuity, momentum, and energy) is essential for the CFD analysis of the pipeline. The flow is assumed to be incompressible and is represented in time-averaged, two-dimensional form. The governing equations comprise the Navier–Stokes equations together with the energy equation, which, for certain systems, may be expressed:

Continuity equation

$$\frac{\partial \rho_{nf}}{\partial t} + \nabla \cdot \left(\rho_{nf} V \right) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial \left(\rho_{nf} V \right)}{\partial t} + \nabla \cdot \left(\rho_{nf} V \right) = -\nabla P + \mu \nabla^2 V + \rho_{nf} g \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial t}\left(\rho_{nf} H \right) + \nabla \cdot \left(\rho_{nf} V H \right) = \nabla \cdot \left(K_{nf} \nabla T \right) \tag{3}$$

2.2 Thermophysical Properties of Nanofluid

The nanoparticles featured in nanofluids possess a dimensional range of one to one hundred nanometres and can adopt multiple morphologies, including nanospheres (spherical), nanoreefs, nanoboxes, nanocubes, and more. For this experiment, carbon nanotubes are being utilised. The present study investigates the impact of diverse carbon nanotube concentrations on thermal conductivity and heat transfer, with their significance in various applications. The mass in grams of nanoparticles required for preparing nanofluids with different volume concentrations can be calculated using Equation (5) [35].

$$\%\varnothing = \frac{V_{np}}{V_{np} + V_{bf}} \tag{4}$$

$$m = \rho_{np} V_{np} \tag{5}$$

The thermal conductivity can be introduced via the Maxwell model [42].

$$K_{nf} = \frac{K_p + 2K_{bf} + 2\varphi\left(K_p - K_{bf} \right)}{K_p + 2K_{bf} - \varphi\left(K_p - K_{bf} \right)} K_{bf} \tag{6}$$

According to the equation proposed by Pak and Cho, the density of nanofluids can be determined as follows.

$$\rho_{nf} = \varnothing \rho_p + \left(1 - \varnothing \right) \rho_{bf} \tag{7}$$

The equation developed by Xuan and Roetzel introduces the specific heat of nanofluids [42].

$$\left(C_p \right)_{nf} = \frac{\left(1 - \varphi \right)\left(\rho C_p \right)_{bf} + \varphi \left(\rho C_p \right)_p}{\varphi \rho_p + \left(1 - \varphi \right) \rho_{bf}} \tag{8}$$

Transient conduction refers to the mode of heat transfer occurring during any period in which the temperature at a location within a body varies with time. Such conditions may arise from the sudden introduction of a new heat source or sink within the object, resulting in localised, time-dependent temperature variations in its vicinity.

$$Q_{\text{conduction}} = -\frac{KA}{\Delta x}\left(T_{out} - T_{in}\right) \tag{9}$$

Thermal properties influencing conduction and convection include thermal conductivity, specific heat capacity, and density, and accurate thermal property data are essential for the reliability of any heat transfer model. Accordingly, the thermal properties of the copper tube incorporating nanomaterials were calculated, as presented in Table (1).

Table 1
Thermal properties of the material and nanoparticles [42- 50]

Copper	ρ = 8978 kg/m^3
	K = 387.6 W/(m.K)
	C_P = 381 J/(kg.K)
Tio$_2$	ρ = 4240 kg/m^3
	K = 12.6 W/(m.K)
	C_P = 683 J/(kg.K)
Fe$_3$O$_4$	ρ = 5180 kg/m^3
	K = 17.65 W/(m.K)
	C_P = 104 J/(kg.K)
Al$_2$O$_3$	ρ = 3950 kg/m^3
	K = 20 W/(m.K)
	C_P = 750 J/(kg.K)
SiO$_3$	ρ = 2650 kg/m^3
	K = 1.5 W/(m.K)
	C_P = 680 J/(kg.K)
CNTs	ρ = 1.3 kg/m^3
	K = 4000 W/(m.K)
	C_P = 686 J/(kg.K)

Table 2
The properties of nanofluids with different volume fractions [51- 54]

Nanofluids		**Different volume fractions**		
		1%	**5%**	**10%**
Tio$_2$	ρ (kg/m^3)	8930	8550	8504
	K (W/(m·K))	382	360	326
	C_P (J/kg.K))	382	397	396
Fe$_3$O$_4$	ρ (kg/m^3)	8940	8788	8598
	K (W/(m·K))	382	361	327
	C_P (J/kg.K))	397	372	364
Al$_2$O$_3$	ρ (kg/m^3)	8927	8726	8475
	K (W/(m·K))	382	362	328
	C_P (J/kg.K))	382	389	398
SiO$_3$	ρ (kg/m^3)	8914	8661	8345
	K (W/(m·K))	385	365	331
	C_P (J/kg.K))	381	395	390
CNTs	ρ (kg/m^3)	8888	8529	8080
	K (W/(m·K))	396	433	482
	C_P (J/kg.K))	381	381	381

3. Physically Form

A two-dimensional pipe with an inner diameter of 0.7 metres and an outer diameter of 1 metre is illustrated in the visual representation of the physics model shown in Figure 1. Copper is used in the construction of this pipe, and carbon nanotubes are incorporated into the pipe in certain proportions to improve the flow of heat within the tube. A larger tube diameter was selected to more effectively show the influence of nanoparticle addition on the heat transfer process [55-56].

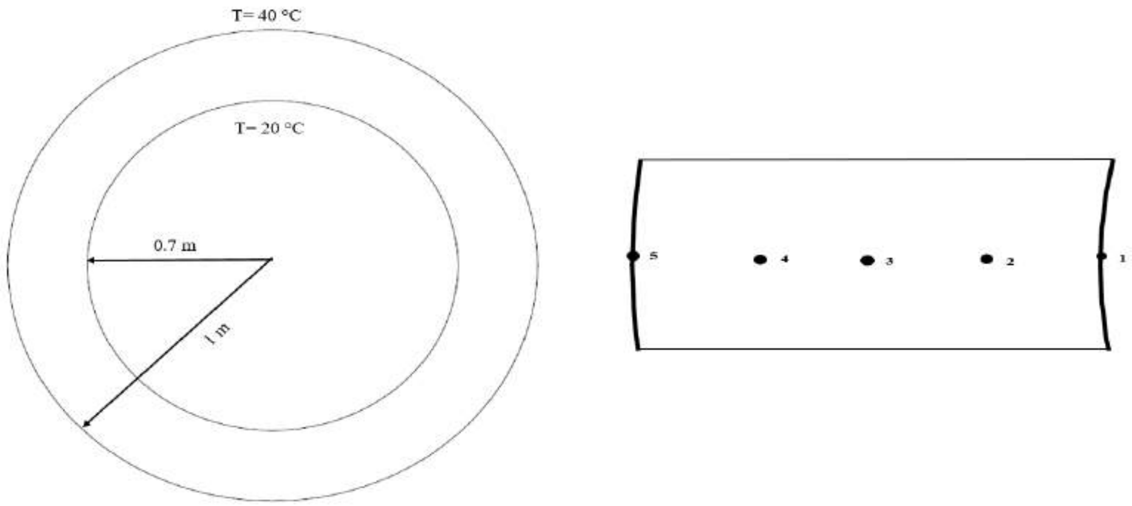


Fig. 1. Physically modelling layout

4. Boundary Conditions

The system is represented using a two-dimensional, transient, laminar, and incompressible model. The pipe has an initial internal temperature of 20°C, while the surface temperature is maintained at 40°C. The disparity in temperature acts as the key factor that drives the heat to move through the pipe's material.

5. Grid Independence Test

The grid independence study, a crucial initial step in computational fluid dynamics (CFD) research, was meticulously conducted to assess the effects of varying mesh densities on the phase change behaviour inside a specific geometric arrangement. We examined four mesh densities (21,332, 23,644, 25,876, and 26,879), which were selected to cover a spectrum of computational precisions. A grid independence study was conducted, and the results exhibited that the temperature distribution trends remained consistent across all mesh densities, confirming that the solution was grid independent. For the subsequent simulations, the lowest element number (21,332) was carefully selected to improve computing efficiency without sacrificing accuracy due to its short computational period.

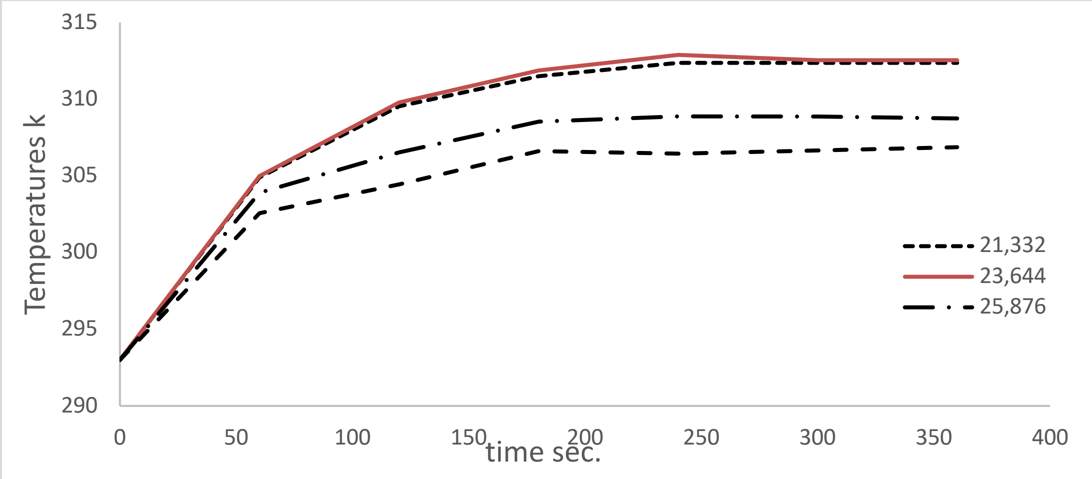


Fig. 2. Grid independence test in the cell without nanomaterials

6. Assumptions

In the process of developing a mathematical equation that will represent the melting processes that occur within a rectangular cell, we take into consideration the following assumptions:

- A model that is only two-dimensional is used to simulate the melting process itself.
- The flow is characterised as incompressible, laminar, and transient. Viscous dissipation is assumed to be negligible. Additionally, volumetric changes resulting from the solid-to-liquid phase transition are neglected.
- There is no exchange of heat with the surrounding environment. The current work assumes that the thermal characteristics of the PCM remain the same in both the solid and liquid forms. A representation of the spatial organisation of the mesh for the model being investigated can be found in Figure 3.

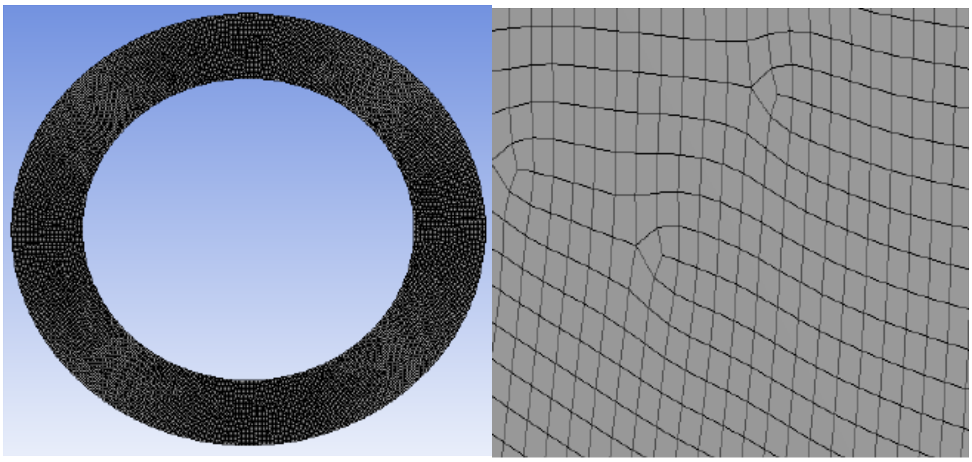


Fig. 3. Configuration of the mesh model

7. Results and Discussion

This investigation highlights the importance of using nanoparticles to enhance heat transfer processes. For the purpose of this investigation, numerical methods were employed to analyse the process of heat transmission, initially in the absence of nanomaterials. After that, nanomaterials were introduced, notably carbon nanotubes, titanium dioxide (TiO_2), silicon oxide (SiO_2), iron oxides

(Fe_3O_4), and aluminium oxide (Al_3O_3) in certain ratios. This endeavour sheds light on the effects of incorporating nanomaterials and to emphasise the significance of these materials in a variety of sectors.

7.1 The Cell Bare of Nanoparticles

The thermal conductivity of copper, being notably high, plays a crucial role in the heat transfer between associated materials. The process of heat transfer that occurs inside the cell is illustrated in Figure 4, which makes use of a larger cell size to more accurately depict this process. By taking into consideration the points that are mentioned in the accompanying image, Image 5 provides an illustration of the heat transmission that occurs within the cell. This facilitates a comparative analysis of heat transfer, both with and without the inclusion of nanoparticles.

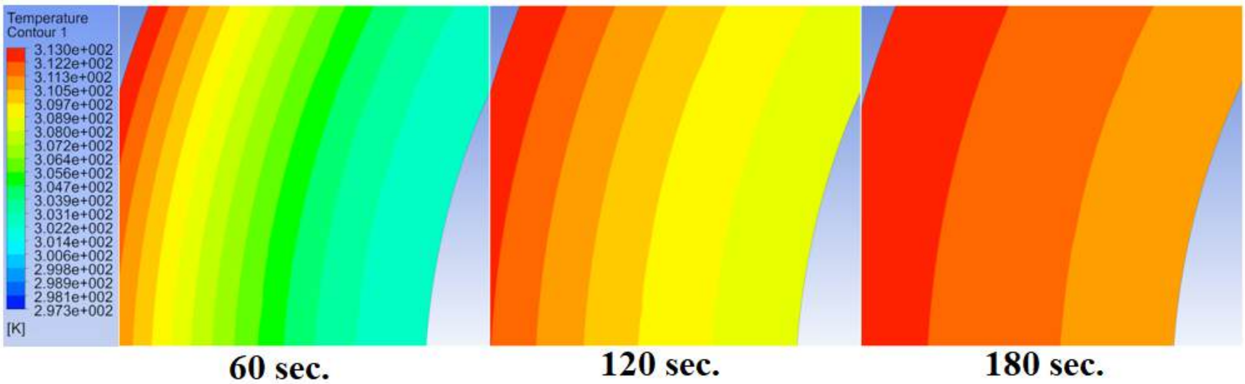


Fig. 4. The transport of heat within the cell in the absence of nanoparticles

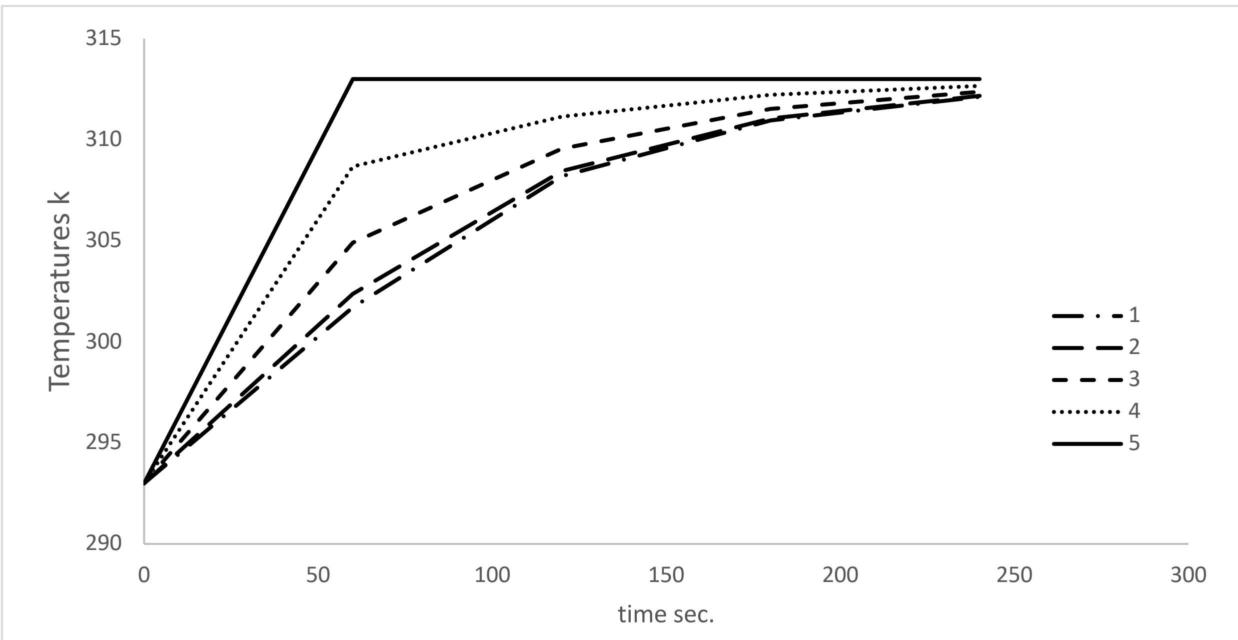


Fig. 5. The temperatures at the indicated points within the cell are measured in the presence of nanoparticles

7.2 The Cell with Nanomaterials (Iron Oxides Fe_3O_4)

Incorporating nanomaterials does not inherently guarantee enhanced heat transfer. The study demonstrated that including iron oxides at varying concentrations (1%, 5%, and 10%) failed to improve thermal conductivity. Instead, the heat transfer performance diminished as the proportion of nanomaterials increased, attributed to their lower thermal conductivity relative to the base metal, copper. Fig. 6 shows the heat transfer when adding nanomaterials at 1%, 5%, and 10%, respectively, and it shows that heat transfer decreases when the percentage of nanomaterials is increased. Fig. 7 displays temperature variations within the metal, highlighting a drop in temperature as the concentration of nucleic materials increases. This observation suggests that the use of iron oxides does not enhance heat transmission efficiency.

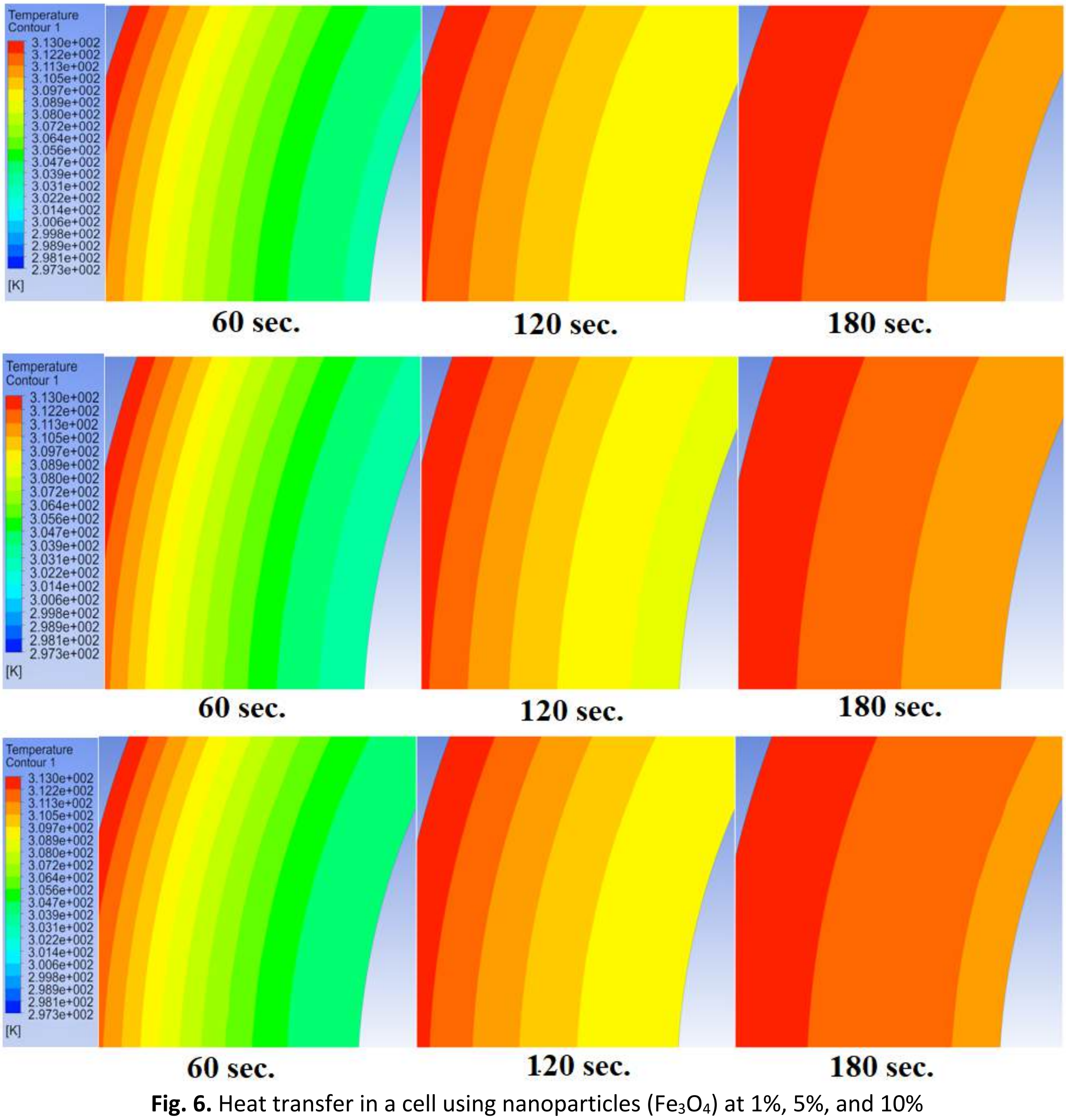


Fig. 6. Heat transfer in a cell using nanoparticles (Fe_3O_4) at 1%, 5%, and 10%

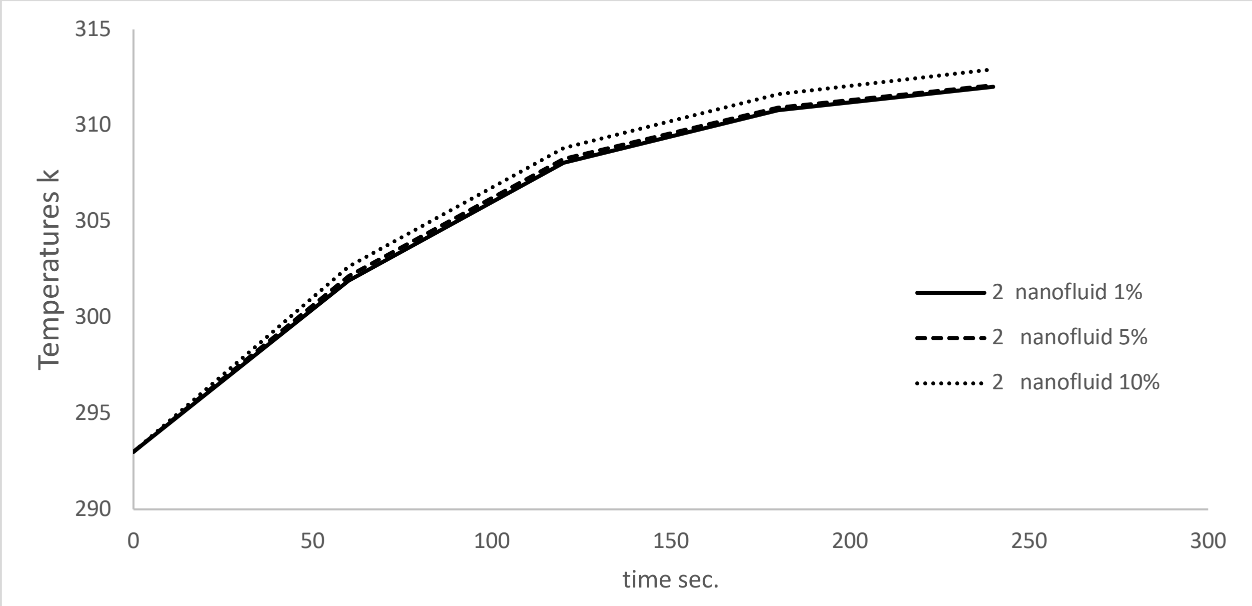
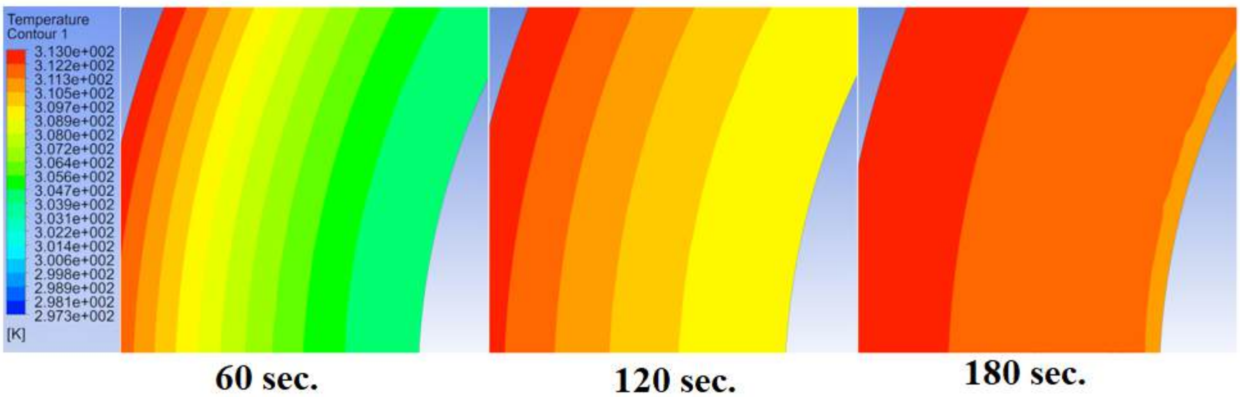


Fig. 7. Temperatures at the locations (2) shown inside the cell with nanomaterials (Fe_3O_4) at 1%, 5%, and 10%

7.3 The Cell with Nanomaterials (aluminium oxide Al_2O_3)

Incorporating nanomaterials does not invariably enhance heat transfer efficiency. For example, the study shows that adding aluminium oxide in different amounts (1%, 5%, and 10%) does not improve heat transfer. In fact, it makes heat transfer worse when the percentage of nanomaterials is increased because aluminium oxide is not as good at conducting heat as copper. Fig. 8 shows the heat transfer when adding nanomaterials at 1%, 5%, and 10%, respectively. A higher percentage of nanomaterials leads to reduced heat transfer. Temperature fluctuations within the metal are shown in Fig. 9, with a notable drop correlating to an increase in nucleic material. This observation suggests that the use of aluminium oxide does not enhance heat transfer.



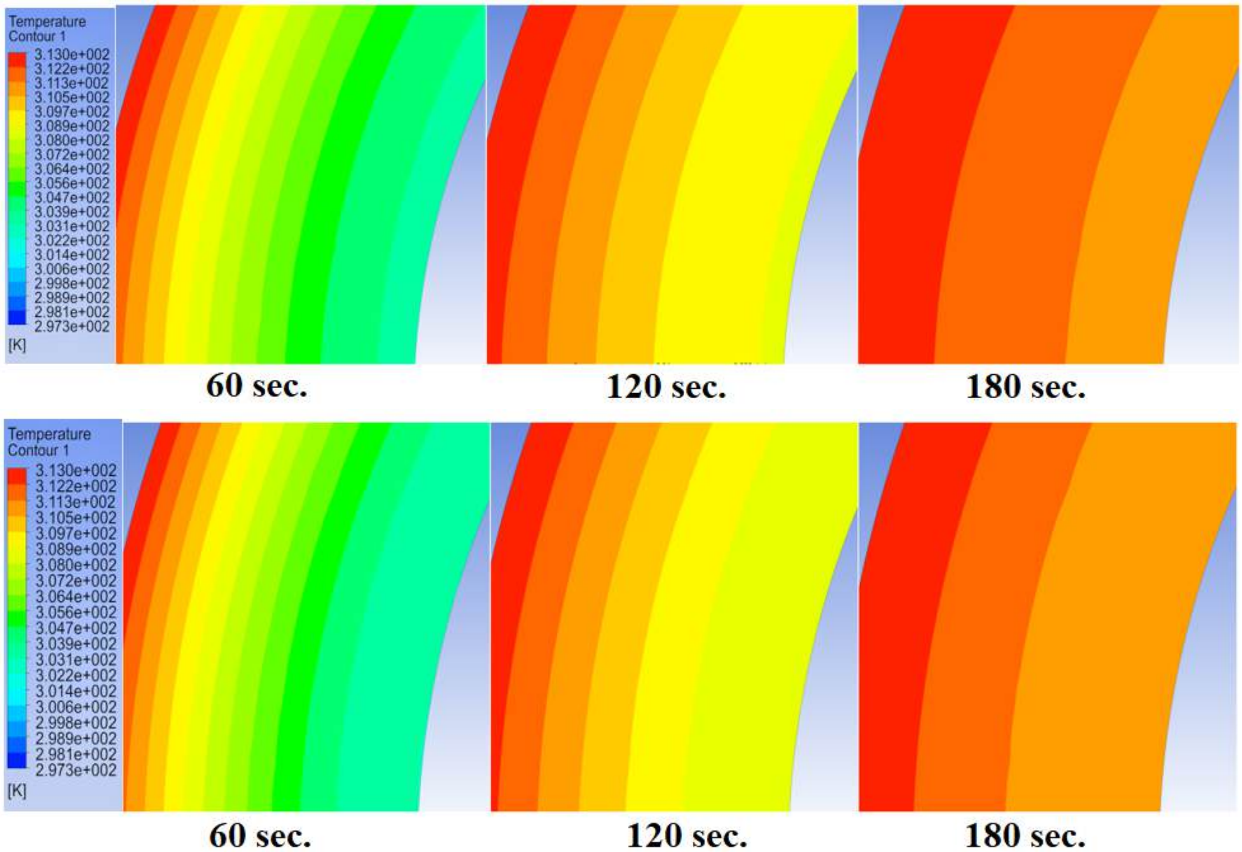


Fig. 8. Heat transfer in A cell with nanoparticles (Al_2O3) at 1%, 5%, and 10%

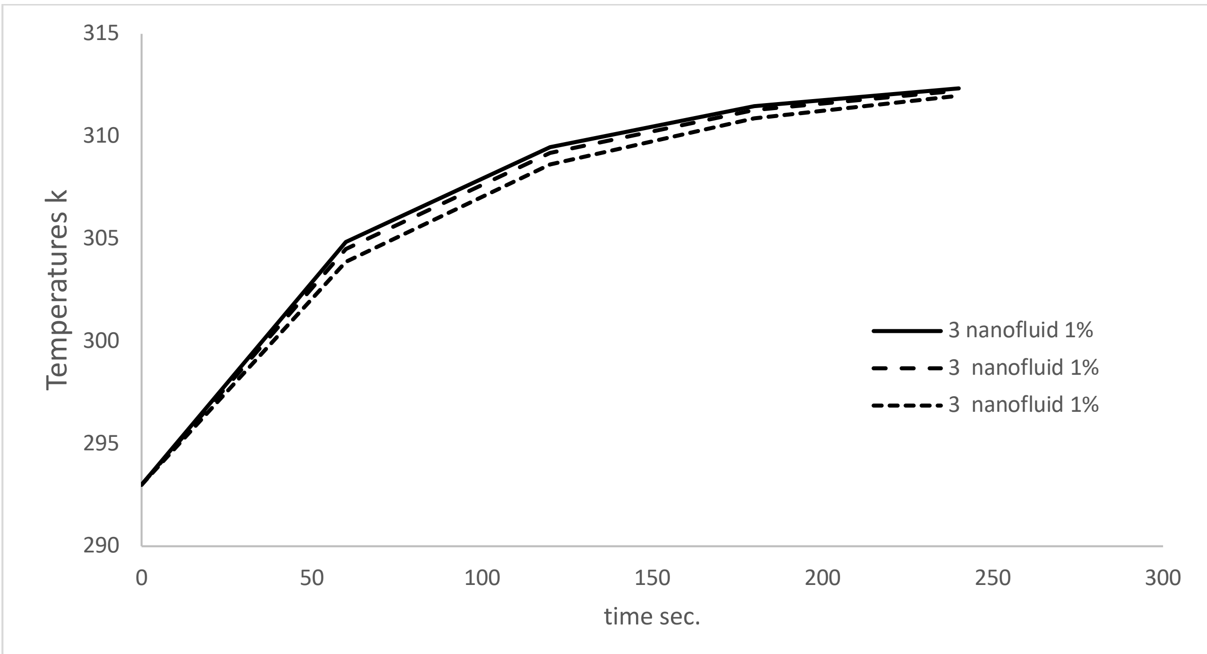


Fig. 9. Temperatures at the locations (3) shown inside the cell with nanomaterials (Al_2O3) at 1%, 5%, and 10%

7.4 The Cell with Nanomaterials (Titanium Dioxide TiO_2)

The enhancement of heat transfer by nanomaterials is not a guaranteed outcome. For example, the study shows that adding titanium dioxide in different amounts (1%, 5%, and 10%) does not improve heat transfer. When the proportion of nanomaterials rises, heat transfer deteriorates because titanium dioxide is a less effective heat conductor than copper. Fig. 10 shows the heat transfer when adding nanomaterials at 1%, 5%, and 10%, respectively. As the percentage of nanomaterials increases, heat transfer diminishes. Fig. 11 shows how the metal's temperature changes, indicating that temperatures decrease as more nucleic material is present, which suggests that the use of titanium dioxide does not enhance heat transmission efficiency.

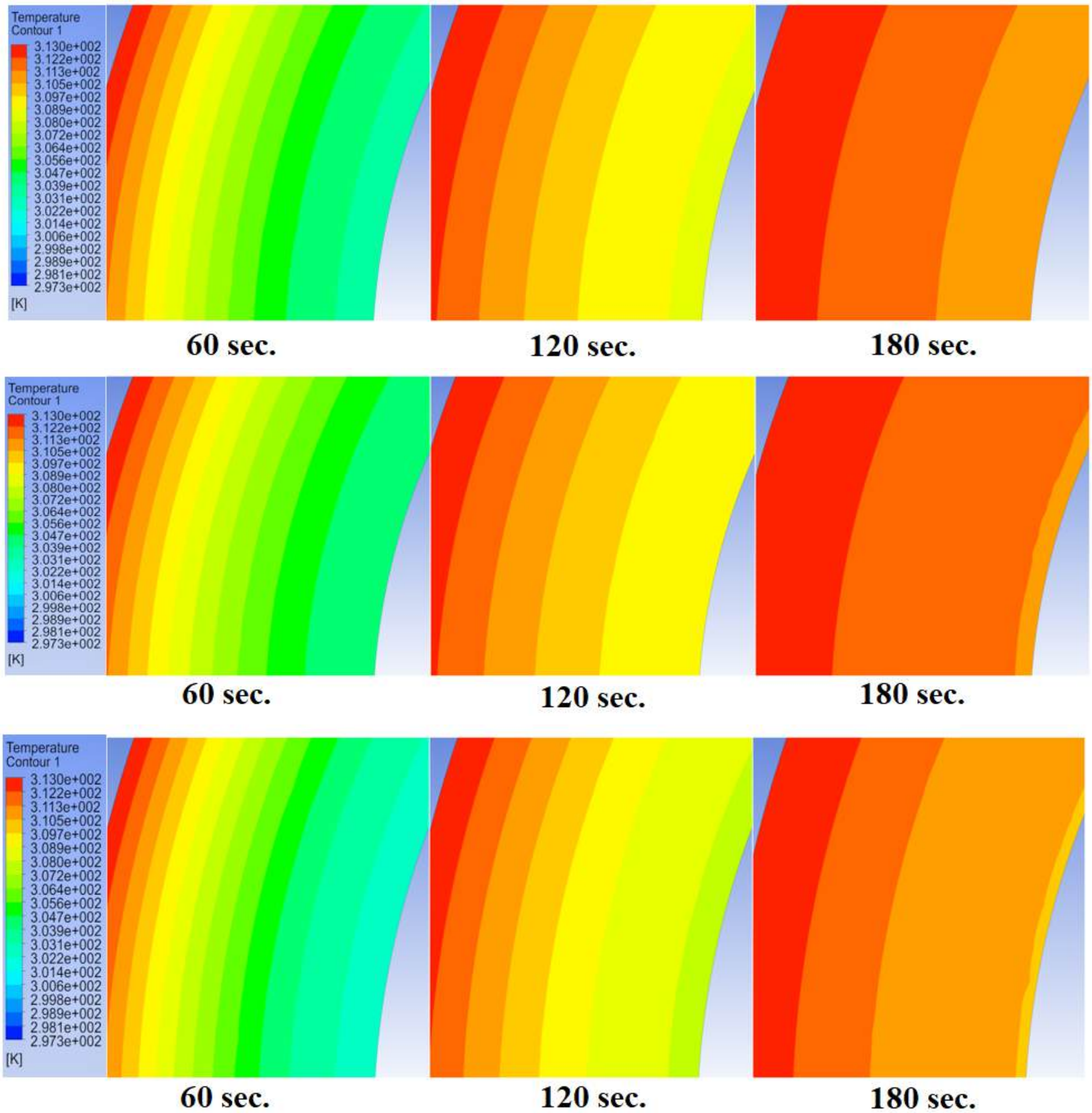


Fig. 10. Heat transfer in a cell with nanoparticles (TiO_2) at 1%, 5%, and 10%

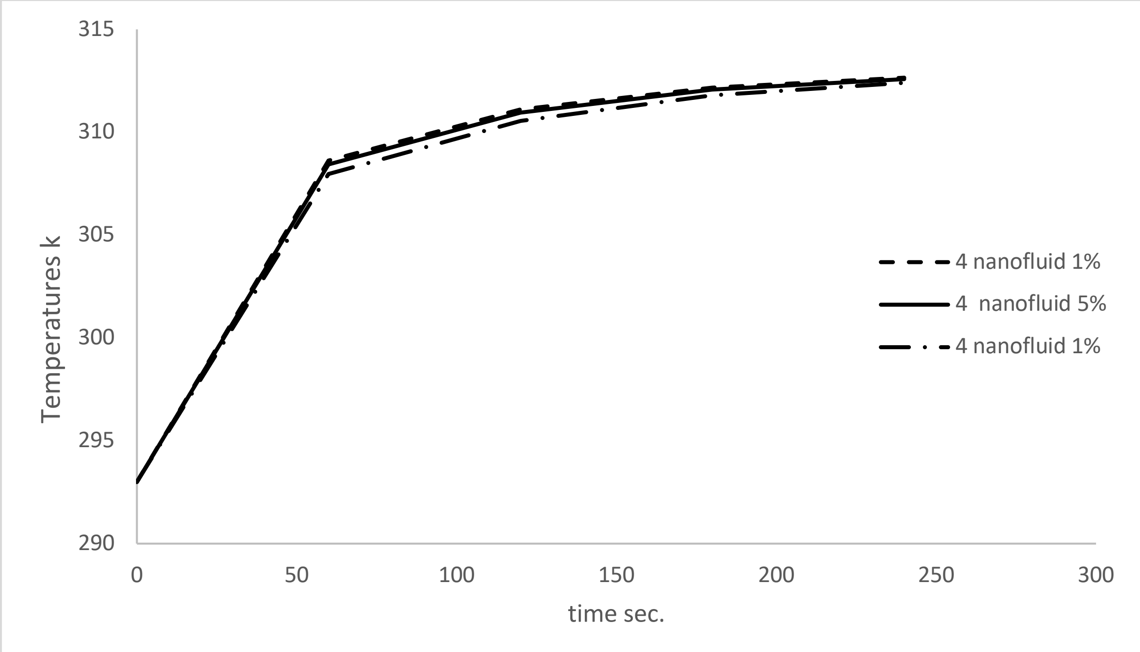
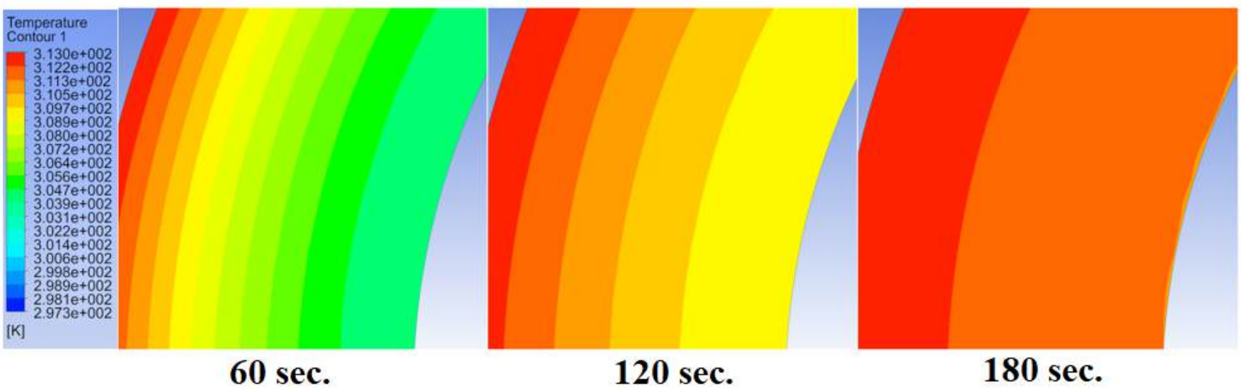


Fig. 11. Temperatures at the locations (4) shown inside the cell with nanomaterials (TiO2) by 1%, 5%, and 10%

7.5 The Cell with Nanomaterials (Silicon Oxide SiO_2)

The study confirms that adding silicon oxide in different proportions (1%, 5%, and 10%) does not necessarily improve heat transfer but rather reduces it due to its low thermal conductivity compared to the used metal (copper). Fig. 12 shows the heat transfer when adding nanomaterials at 1%, 5%, and 10%, respectively. As the percentage of nanomaterials increases, heat transfer is observed to decrease. In Fig. 13, upon examining the temperature readings at certain locations within the metal depicted in the attached file, it becomes clear that there is a decrease in temperature as the amount of nucleic material increases. This finding indicates that employing silicon oxide does not confer benefits in improving heat transfer.



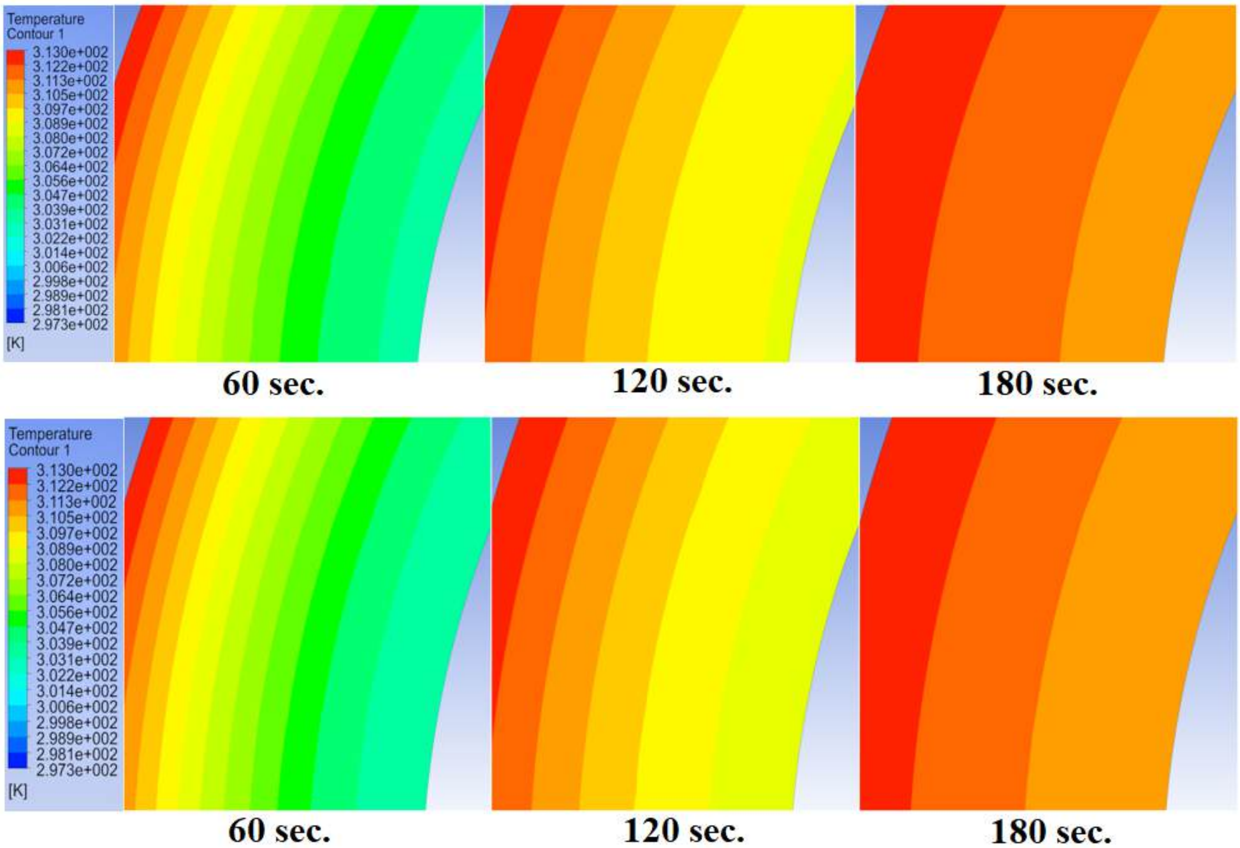


Fig. 12. Heat transfer in a cell with nanoparticles (SiO_2) at 1%, 5%, and 10%

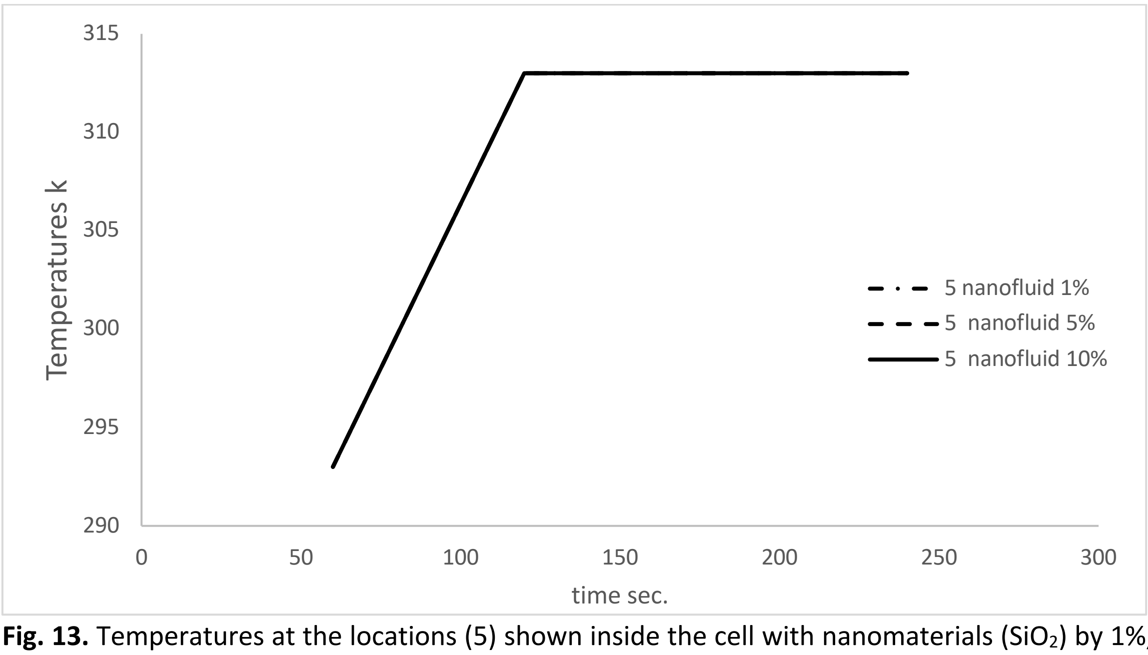


Fig. 13. Temperatures at the locations (5) shown inside the cell with nanomaterials (SiO_2) by 1%, 5%, and 10%.

7.6 The Cell with Nanomaterials (Carbon Nanotubes)

This investigation observes that nanotube utilisation significantly enhances thermal conductivity, thereby improving upon copper's heat transfer capabilities. Carbon nanotubes have been identified as one of the most effective nanomaterials for enhancing heat transfer. Figure 14 presents the heat flux through the copper pipe with carbon nanotube additions of 1%, 5%, and 10%, demonstrating a progressive increase in heat transfer with rising nanomaterial concentration. Fig. 15 presents the temperature distribution at the designated monitoring locations, illustrating a notable rise in temperature with increasing nanomaterial concentration.

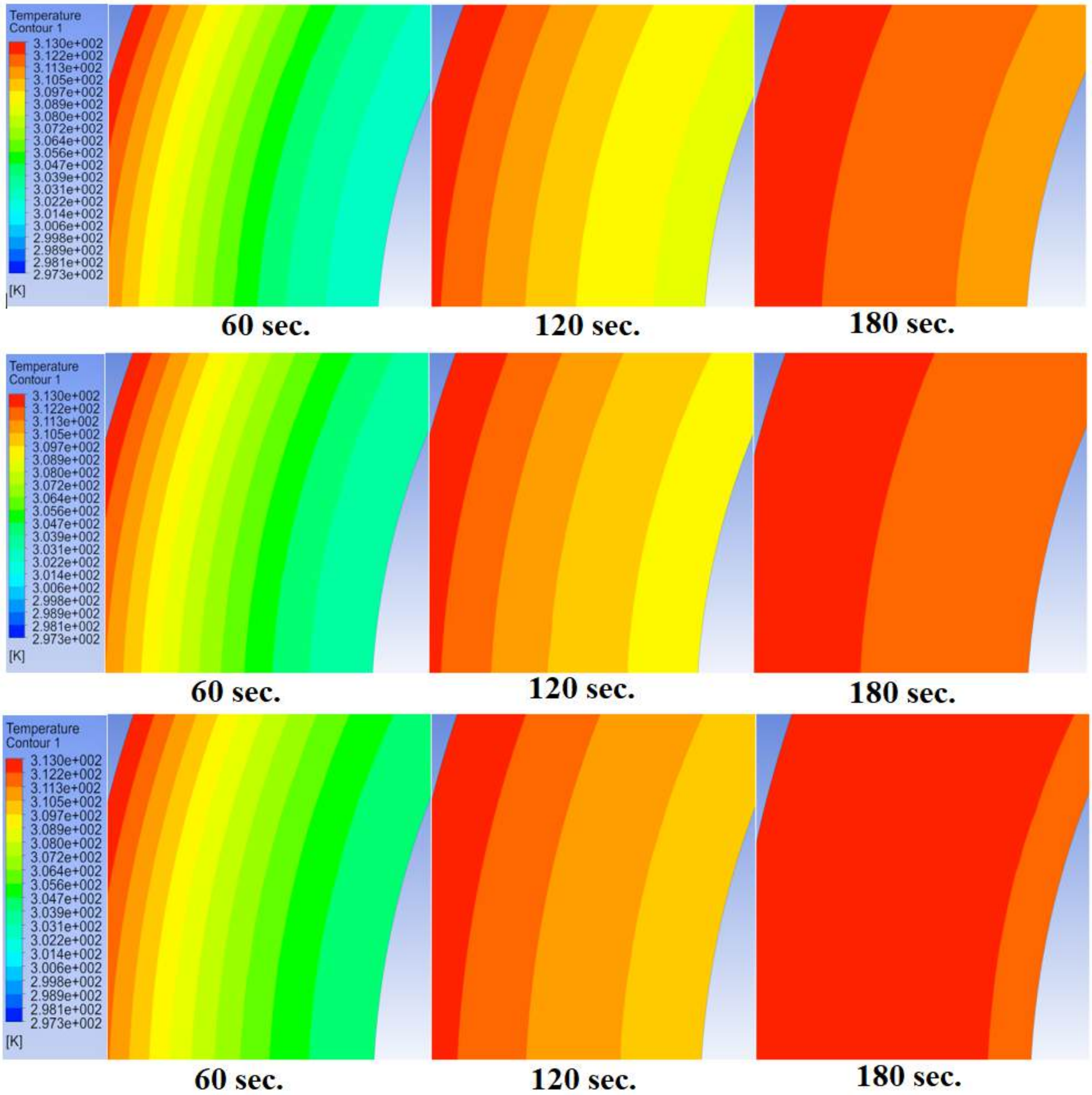


Fig. 14. Heat transfer in a cell with nanoparticles (carbon nanotubes) at 1%, 5%, and 10%

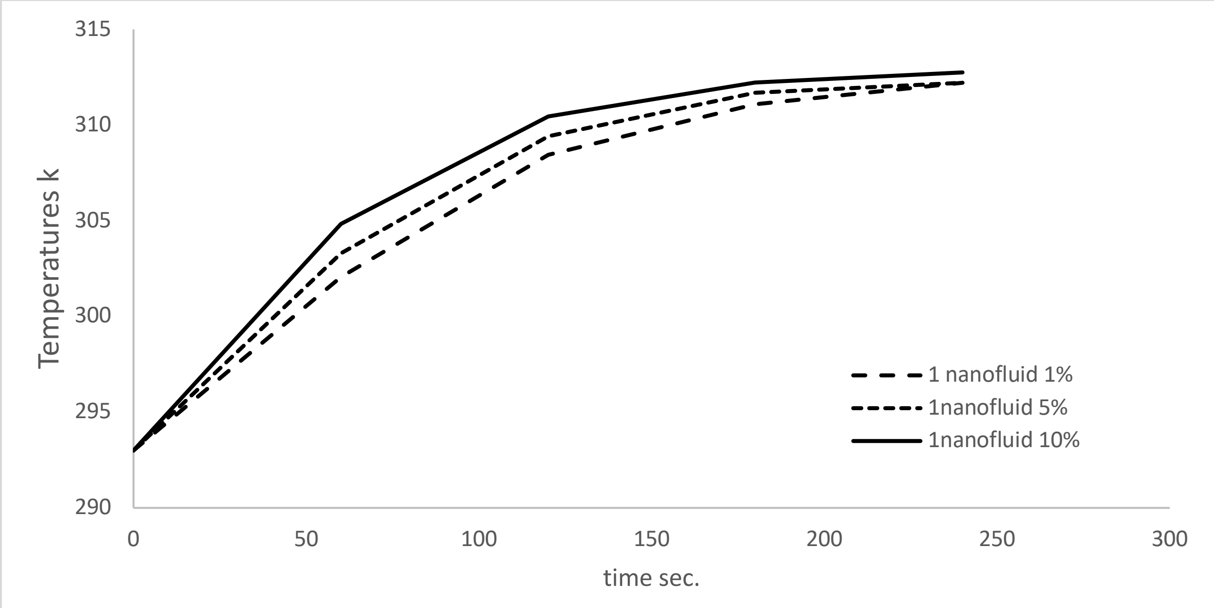
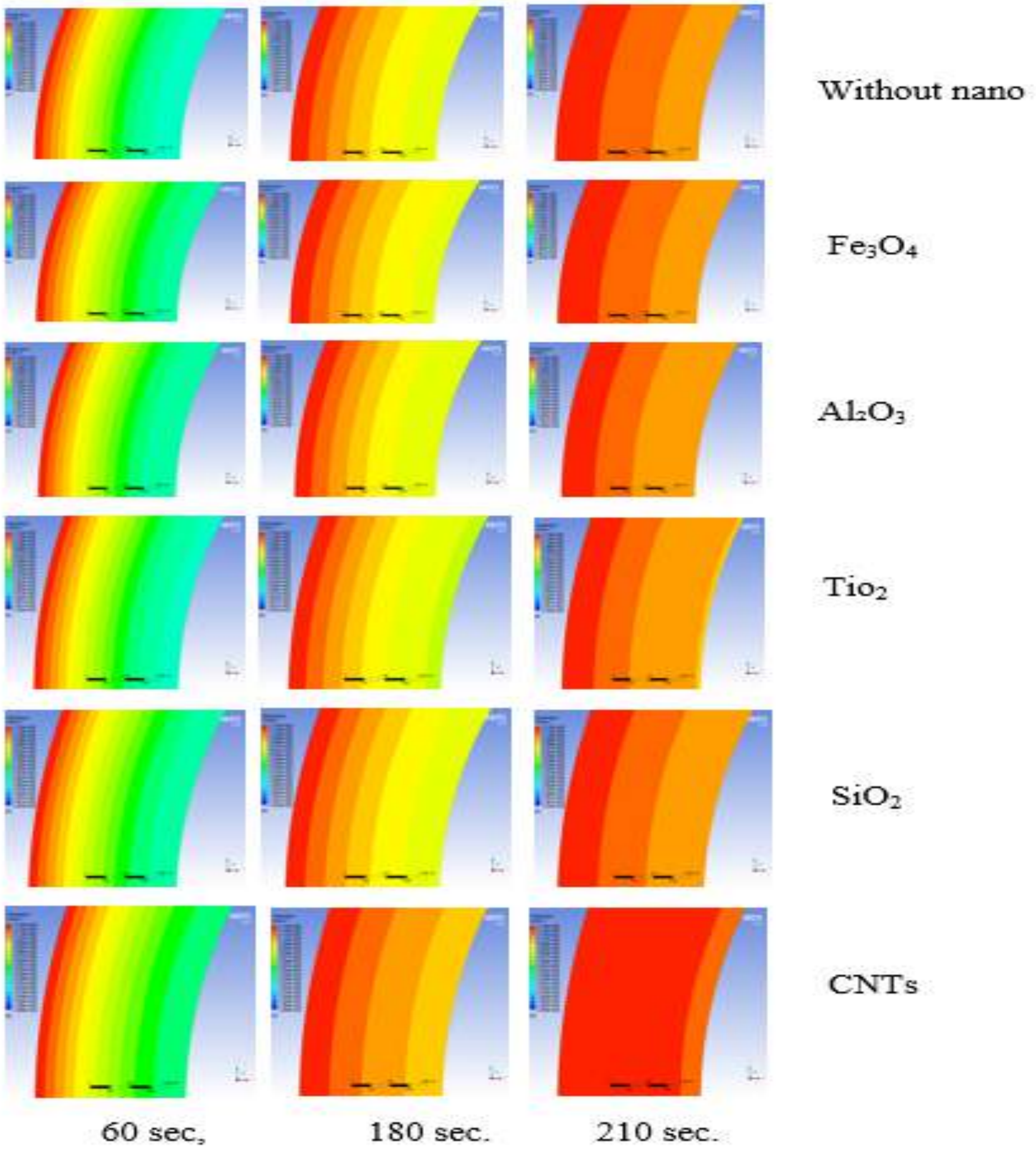


Fig. 15. Temperatures at the locations (4) shown inside the cell with nanomaterials (Carbon Nanotubes) by 1%, 5%, and 10%

7.7 Case Comparative

The numerical examination of the significance of utilising nanomaterials to improve heat transfer is the primary topic of this investigation. Our research concentrated on evaluating various nanomaterials, including carbon nanotubes, to identify the most effective for heat transfer. It has been observed that a greater quantity of nanomaterials, such as carbon nanotubes, leads to a substantial increase in heat transfer. In addition to not affecting heat transmission, several of the remaining nanoparticles weaken the heat transferred. Figure 16 presents a comparison of the investigated scenarios, highlighting the effectiveness of carbon nanotube incorporation and its influence on heat transfer performance. A comparison of temperatures in the middle of the picture is shown in Figure 17, which reveals that the utilisation of carbon nanotubes results in an increase in temperatures. Additionally, it has been demonstrated that a greater proportion of carbon nanotubes leads to an increase in the amount of heat transfer. It has been observed that nanomaterials such as iron oxides, aluminum oxide, titanium dioxide, and silicon oxide do not influence heat transfer.


Without nano
Fe3O4
Al2O3
Tio2
SiO2
CNTs
60 sec,
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210 sec.

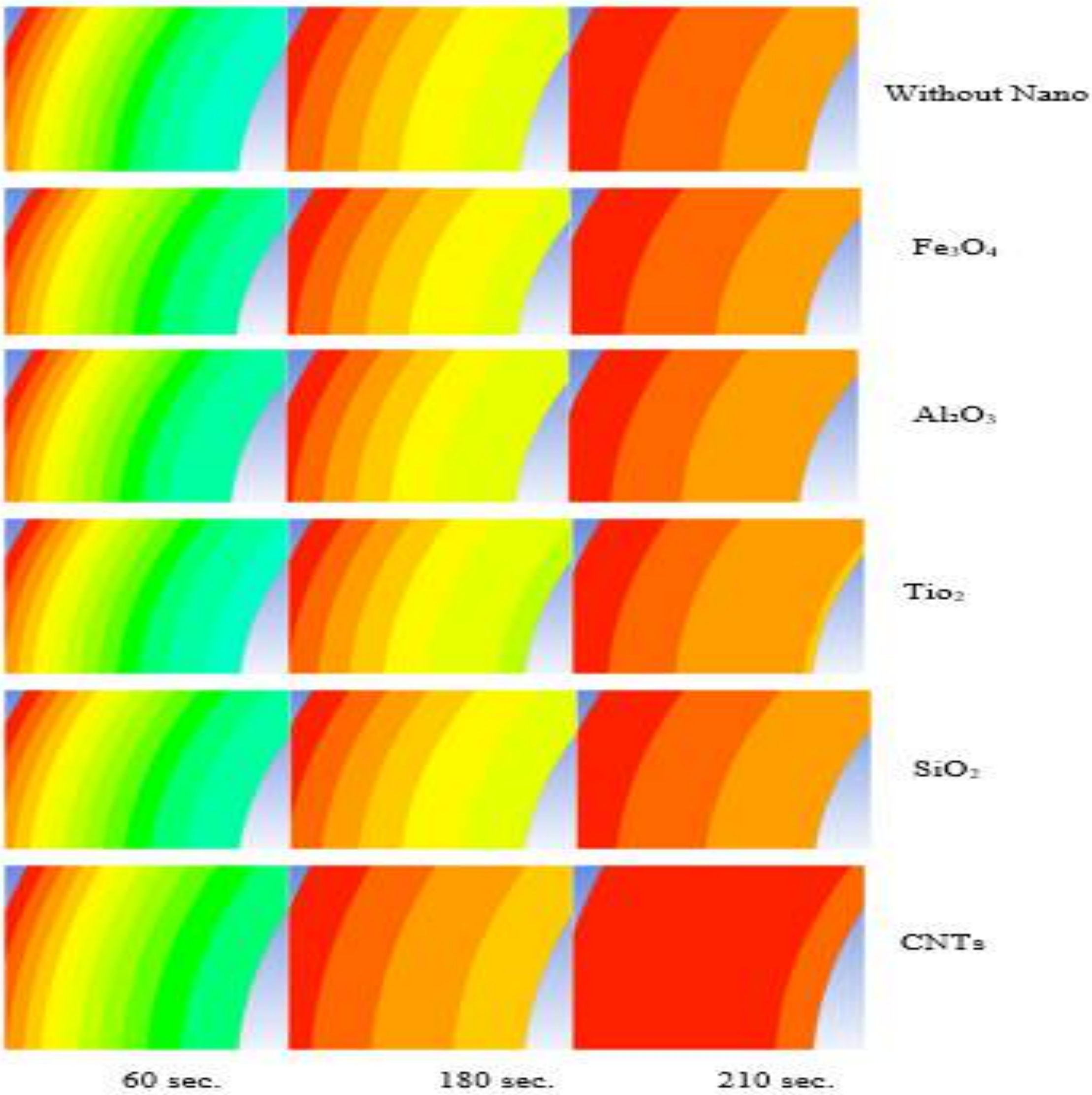

Fig. 17. Heat transfer in a cell with nanoparticles at 1% and 10%

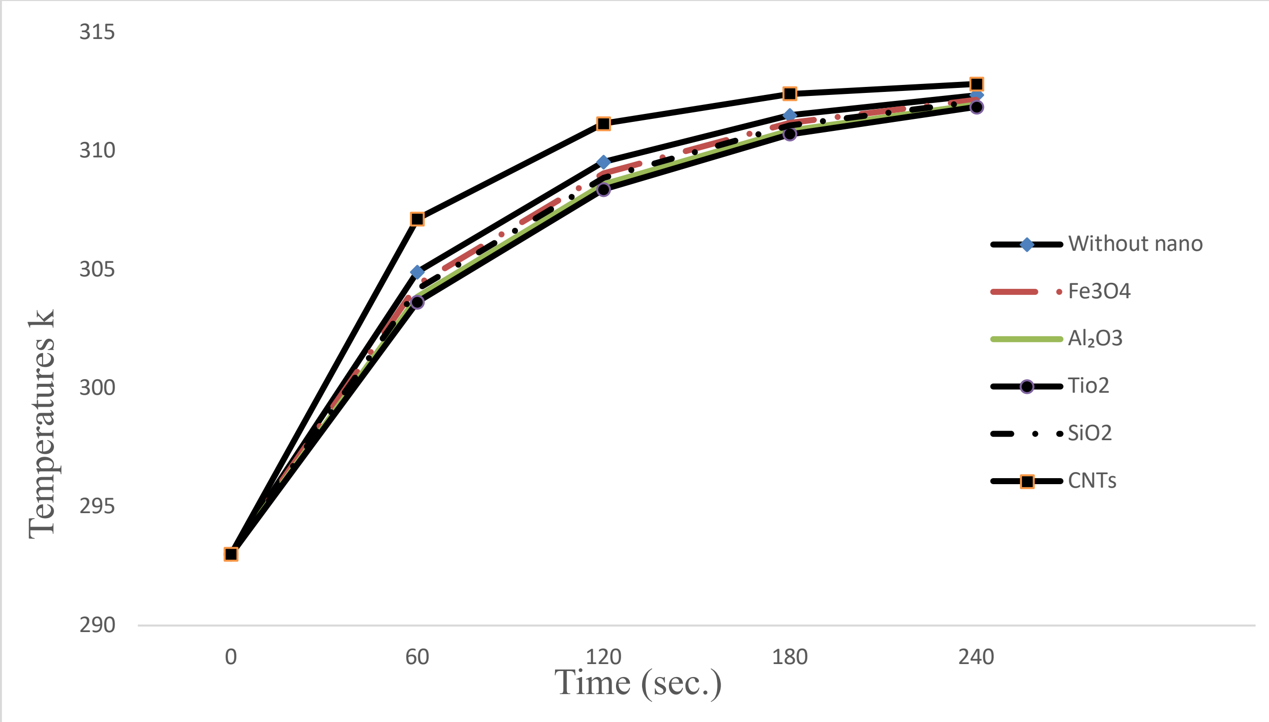

Fig. 18. Comparison of cases with nanomaterials at 1%, 5%, and 10%

8. Conclusions

This study focuses on the significance of employing nanoparticles to enhance heat transfer. We have conducted a study to examine the impact of specific ratios of nanomaterials (including iron oxides, aluminium oxide, titanium dioxide, silicon oxide, and carbon nanotubes) on the process of heat transmission. The investigation was conducted with the Ansys/Fluent 16 software. This study employed copper as a medium to illustrate the process of heat transmission. Various nanomaterials, including iron oxides, aluminium oxide, titanium dioxide, silicon oxide, and carbon nanotubes, were incorporated at concentrations of 1%, 5%, and 10% to emphasise the notable impact of these substances on improving heat transfer. The study yielded five significant findings:

1. Carbon Nanotubes (CNTs) demonstrate a positive impact on heat transfer, leading to improved thermal performance.
2. Heat transmission is greatly improved when the amount of nanotechnology, notably CNTs, is increased to 10%.
3. Using iron oxides, aluminium oxide, titanium dioxide, and silicon oxide nanoparticles does not improve heat transfer and, in some cases, can even reduce heat transfer.
4. The addition of certain nanomaterials, such as iron oxides, aluminium oxide, titanium dioxide, and silicon oxide, results in decreased heat flux in copper due to their low thermal conductivity.
5. The study highlights the importance of carefully selecting and utilising nanomaterials for heat transfer enhancement, as not all nanoparticles yield positive results.

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