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EXPLORING NATURAL CONVECTION AND ENTROPY GENERATION IN A CLOSED WATER TANK UTILIZING NANOFLUID: A COMPUTATIONAL STUDY

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ABSTRACT

Theoretical framework: This study presents a comprehensive investigation into three-dimensional natural convection within a confined cavity filled with an alumina-water nanofluid.

Objective: Utilizing numerical simulations, we explore the influence of nanoparticles' volume fraction and Rayleigh number (Ra) on entropy generation, heat transfer efficiency, and fluid behavior within the water tank.

Method: The study delves into the conservation equations governing mass, momentum, and energy within the context of three-dimensional laminar natural convection. It focuses on steady, incompressible flow, employing the Boussinesq approximation to account for variations in fluid density due to temperature gradients.

Results and conclusion: Our findings indicate that increasing Rayleigh numbers lead to heightened entropy generation, with values ranging from 10^7 to 3×10^8, primarily driven by intensified buoyant flow. However, the presence of nanoparticles significantly mitigates entropy generation, enhancing the overall thermal performance of the system. Moreover, nanofluids demonstrate superior heat transfer capabilities compared to pure fluids, with higher nanoparticle concentrations resulting in increased heat transfer rates, ranging from 1% to 10% alumina.

Research implications: As a result of such thorough research, qualitative examinations of velocity fields and entropy generation patterns further highlight the role of nanofluids in improving heat transfer efficiency while reducing irreversible processes within the cavity.

Keywords: Alumina, Nusselt Number, Rayleigh Number, Finite Volumes Method, CFD.

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EXPLORANDO CONVECÇÃO NATURAL E GERAÇÃO DE ENTROPIA EM UM TANQUE DE ÁGUA FECHADO UTILIZANDO NANOFLUIDO: UM ESTUDO COMPUTACIONAL

RESUMO

Estrutura teórica: Este estudo apresenta uma investigação abrangente sobre convecção natural tridimensional dentro de uma cavidade confinada preenchida com um nanofluido de água-alumina.

Objetivo: Utilizando simulações numéricas, exploramos a influência da fração de volume das nanopartículas e do número de Rayleigh (Ra) na geração de entropia, eficiência de transferência de calor e comportamento de fluidos dentro do tanque de água.

Método: O estudo aprofunda-se nas equações de conservação que regem a massa, o momento e a energia no contexto da convecção natural laminar tridimensional. Centra-se no fluxo constante e incompressível, empregando a aproximação de Boussinesq para explicar variações na densidade do fluido devido a gradientes de temperatura.

Resultados e conclusão: Nossos achados indicam que o aumento dos números de Rayleigh leva a uma maior geração de entropia, com valores variando de 〖10〗^7 a 3×〖 〗10^8, principalmente impulsionado por um fluxo dinâmico intensificado. No entanto, a presença de nanopartículas diminui significativamente a geração de entropia, melhorando o desempenho térmico geral do sistema. Além disso, os nanofluidos demonstram capacidades superiores de transferência de calor em comparação com os fluidos puros, com concentrações mais elevadas de nanopartículas resultando em taxas de transferência de calor maiores, variando de 1% a 10% de alumina.

Implicações da pesquisa: Como resultado de tal pesquisa minuciosa, exames qualitativos de campos de velocidade e padrões de geração de entropia destacam ainda mais o papel dos nanofluidos na melhoria da eficiência da transferência de calor, reduzindo processos irreversíveis dentro da cavidade.

Palavras-chave: Alumina, Número Nusselt, Número de Rayleigh, Método de Volumes Finitos, CFD.

EXPLORAR LA CONVECCIÓN NATURAL Y LA GENERACIÓN DE ENTROPÍA EN UN TANQUE DE AGUA CERRADO UTILIZANDO NANOFLUIDOS: UN ESTUDIO COMPUTACIONAL

RESUMEN

Marco teórico: Este estudio presenta una investigación exhaustiva sobre la convección natural tridimensional dentro de una cavidad confinada llena de un nanofluido de alúmina-agua.

Objetivo: Utilizando simulaciones numéricas, exploramos la influencia de la fracción de volumen de las nanopartículas y el número de Rayleigh (Ra) en la generación de entropía, la eficiencia de transferencia de calor y el comportamiento del fluido dentro del tanque de agua.

Método: El estudio profundiza en las ecuaciones de conservación que rigen la masa, el momento y la energía dentro del contexto de la convección natural laminar tridimensional. Se centra en el flujo constante e incompresible, empleando la aproximación de Boussinesq para tener en cuenta las variaciones en la densidad del fluido debido a los gradientes de temperatura.

Resultados y conclusión: Nuestros hallazgos indican que el aumento del número de Rayleigh conduce a una mayor generación de entropía, con valores que van desde 〖10〗^7 hasta 3×〖10〗^8, impulsados principalmente por un flujo flotante intensificado. Sin embargo, la presencia de nanopartículas mitiga significativamente la generación de entropía, mejorando el rendimiento térmico general del sistema. Además, los nanofluidos demuestran capacidades de transferencia de calor superiores en comparación con los fluidos puros, con concentraciones de nanopartículas más altas que resultan en mayores tasas de transferencia de calor, que van desde el 1% al 10% de alúmina.

Implicaciones de la investigación: Como resultado de esta investigación exhaustiva, los exámenes cualitativos de los campos de velocidad y los patrones de generación de entropía destacan aún más el papel de los nanofluidos en la mejora de la eficiencia de la transferencia de calor al tiempo que reducen los procesos irreversibles dentro de la cavidad.

Palabras clave: Alúmina, Número de Nusselt, Número de Rayleigh, Método de Volúmenes Finitos, CFD.

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1 INTRODUCTION

In recent years, there has been a surge in interest in studying natural convection and entropy generation in enclosures filled with nanofluids. These investigations are crucial for optimizing thermal management systems in various engineering applications. The interaction of nanofluids with complex flow and heat transfer phenomena offers valuable insights into convective heat transfer processes. Natural convection in enclosed spaces is pivotal across thermal engineering applications such as solar collectors, cooling systems for electronics, and insulation in buildings. Traditional fluids often exhibit limited heat transfer rates due to low conductivity. Hence, researchers are turning to nanofluids infused with solid particles of high thermal conductivity—to enhance heat transfer properties and overcome such limitations Benabderrahmane (2017a); Fouakeu-nanfack *et al*. (2023); Benabderrahmane *et al*. (2016), Benabderrahmane A (2017b); Bouhelal *et al*. (2023); Laaraba *et al*. (2018); Benhabib *et al*. (2021); Satari *et al*. (2021).

In the area of heat transfer enhancement, the utilization of nanofluids within enclosed cavities presents an exciting frontier for advancing thermal management technologies. Zemani *et al*. (2023) conducted a detailed investigation into the behavior of water-based Fe_3O_4 nanofluids within a square cavity, revealing a remarkable enhancement in heat transfer rates. At a Rayleigh number of 10^6, their study observed a notable increase of 75.92% in the average Nusselt number, showcasing the superior heat transfer efficiency of nanofluids over conventional base fluids.

Building upon this groundwork, Yuan *et al*. (2023) embarked on a computational exploration of natural convection and entropy generation in a semicircular cavity filled with $CuO - H_2O$ nanofluid under varying magnetic fields. Their research elucidated the delicate interplay between Rayleigh and Hartmann numbers in optimizing heat transfer and entropy generation. Notably, they identified a critical Hartmann number (Ha_{cr}) of 30 as pivotal for maximizing thermal performance. Diving deeper into the domain of nanomaterial-based thermal enhancement, Bilal *et al*. (2023) investigated the thermal behavior of water dispersed with single-wall carbon nanotubes (SWNTs) within an open cavity. Their findings underscored the remarkable heat transfer capabilities of SWNTs compared to conventional metallic nanoparticles, underscoring the versatility and efficacy of CNTs in augmenting heat transfer within confined spaces.

Moreover, Selimefendigil *et al*. (2016) explored the influence of magnetic fields on nanofluid-filled trapezoidal cavities, shedding light on the nuanced effects of magnetic forces on heat transfer and entropy generation. Their study highlighted the differential impact of magnetic fields on CuO-water and AlO-water nanofluids, providing valuable insights into the complex interplay between magnetic fields and nanofluid behavior. Nuanced understanding of how magnetic fields can be leveraged to fine-tune thermal management systems.

Marzougui *et al*. (2021) conducted an extensive numerical investigation into the magneto-convective flow of copper–water nanofluid within a cavity featuring chambers, with a particular focus on entropy generation dynamics. Their study provided valuable insights into the intricate interplay between magnetic field intensity, nanoparticle volume fraction, and flow behavior, elucidating the irreversible processes occurring within the system. Concurrently, Vedavathi *et al*. (2023) undertook a comprehensive examination of natural convection within a trapezoidal enclosure filled with porous medium-laden $Cu{-}H_2O$ nanofluid. Their research underscored the significant influence of governing parameters on fluid flow patterns and temperature gradients, shedding light on the complex thermal phenomena prevalent in such systems.

The study of Brito *et al.* (2024) is grounded in the concepts of heat transfer, thermally insulating coatings, and their impact on cutting tool performance. Key theories and models include thermal conductivity, thermal insulation, and heat dissipation mechanisms. Still, regarding numerical simulation, it is important to discuss how it was addressed by Silva *et al*. (2024), about dynamic mesh study. This study, although it has been studied in a combustion engine chamber, could be used cavities study. The work of Albuquerque *et al.* (2013) use the photoacoustic spectroscopy (PAS) as a useful photothermal technique to obtain thermal and optical parameters of materials based on heat transfer due to absorption of radiation by the matter. Hilario et al. (2024) presented a work on the physico-chemical properties of biodiesel that could contribute to the study of nanofluids.

In the work conducted by Solomon *et al.* (2017), the impact of the aspect ratio (AR) on natural convection heat transfer in a rectangular cavity filled with nanofluids was experimentally investigated. Three cavities with ARs of 1, 2, and 4 were fabricated and tested using deionized water and Al_2O_3/water nanofluids. The findings revealed that the AR significantly influences the heat transfer coefficient and Nusselt number. Notably, the optimal nanofluid concentration for maximum heat transfer varies with the AR. The study also found that the Rayleigh number strongly affects the Nusselt number and nanofluid buoyancy. Furthermore, the AR significantly impacts the optimal nanoparticle concentration, which increases with increasing AR. These results are crucial for designing cavities using nanofluids as working fluids in applications such as solar collectors and heat exchangers.

Alsabery *et al*. (2018) contributed to the field by exploring entropy generation and natural convection within a square cavity filled with nanofluid, featuring a concentric solid insert. Their study provided valuable insights into optimizing heat transfer through variations in thermal conductivity ratio and adjustments in solid size. Additionally, Tayebi and Chamkha (2020) delved into the entropy generation dynamics during MHD natural convection flow of hybrid nanofluid within a square cavity containing a corrugated conducting block. Their research highlighted the intricate influence of magnetic fields and fluid–solid thermal conductivity ratios on heat transfer dynamics, offering significant contributions to the understanding of thermal management in such systems.

Armaghani *et al*. (2020) delved into the entropy generation aspects of an I-shaped cavity saturated with porous media, offering detailed insights into the effects of magnetic field inclination and nanofluid volume fraction on heat transfer characteristics and overall thermal performance. Meanwhile, Gibanov *et al*. (2018) investigated the intricacies of mixed convection and entropy generation in a lid-driven cavity filled with alumina–water nanofluid. Their work highlighted the critical role played by solid wall thickness and nanoparticles volume fraction in enhancing heat transfer rates within the cavity.

In the study by Khan *et al*. (2023), the natural convection of Titanium Oxide-water nanofluid in a cavity with partially active walls is examined using the finite element method (FEM). The study investigates two cases of heat transfer within the enclosure. In the first case, heat sinks with a constant temperature are present on the left and right partially active cavity walls. In the second case, the left and right walls of the cavity are heated while a partially active bottom wall is cold. The study demonstrates the significance of the Rayleigh number and volume fractions of nanopowders against fluid flow and heat transfer. The results conclude that the velocity increases with the escalation of the Rayleigh number, and the heat transfer rises with the volume fraction of nanoparticles. The local Nusselt number is also enhanced with the Rayleigh number and nanoparticle volume fraction. The study is particularly relevant to nanotechnology, heat transfer devices, mechanical engineering, fuel cells, electronic cooling devices, nuclear and solar collectors, and many other sectors.

The novelty of this study lies in its comprehensive analysis of three-dimensional natural convection within a confined cavity filled with an alumina-water nanofluid. By exploring the impact of nanoparticles volume fraction and Rayleigh number on entropy generation, the study sheds light on the intricate dynamics of heat transfer phenomena within the cavity. Notably, the investigation includes a meticulous assessment of solution grid independence, revealing that while finer grids yield more accurate results, the choice of grid resolution does not significantly influence the outcome. Additionally, the study quantitatively compares the average Nusselt number at the cavity's hot wall across varying Rayleigh numbers, demonstrating the enhanced convective heat transfer efficiency facilitated by nanofluids. Moreover, the qualitative examination of velocity fields and entropy generation patterns provides valuable insights into the fluid behavior and irreversible processes within the cavity.

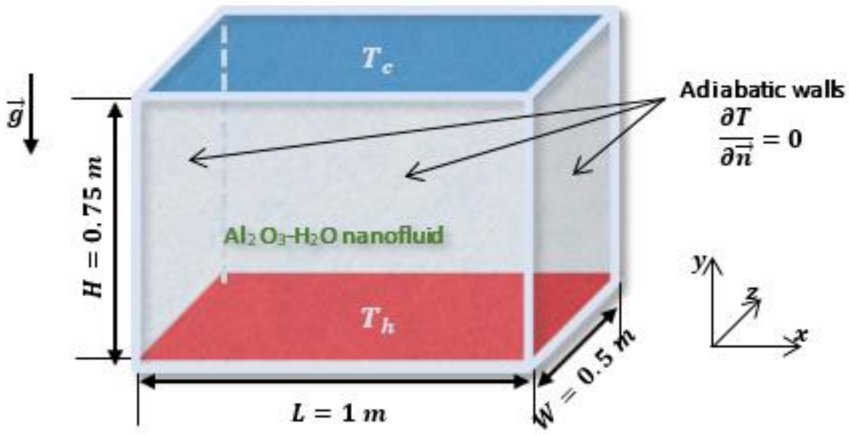
2 METHODOLOGY

2.1 MODEL SPECIFICATION

The study presents a comprehensive analysis of three-dimensional natural convection occurring within a confined water tank. This closed cavity, characterized by dimensions of length ($L = 1\ m$), height ($H = 0.75\ m$), and width ($W = 0.5\ m$), is filled with an alumina-water (Al_3O_2-H_2O) nanofluid. Within this enclosure, the horizontal walls are maintained at constant temperatures, with the bottom surface (T_h) serving as a heat source, while the top surface (T_c) acts as a heat sink. In contrast, the remaining walls are thermally insulated, enforcing adiabatic conditions ($\frac{\partial T}{\partial \vec{n}} = 0$). For a visual representation, the model description and boundary conditions are illustrated in Figure 1. This configuration sets the stage for a detailed investigation into the intricate dynamics of heat transfer phenomena within the water tank.

Figure 1

Water tank model description



The study delves into the conservation equations governing mass, momentum, and energy within the context of three-dimensional laminar natural convection. It focuses on steady, incompressible flow, employing the Boussinesq approximation to account for variations in fluid density due to temperature gradients. The resulting dimensionless governing equations are formulated as follows:

Continuity equation:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}+\frac{\partial W}{\partial Y}=0 \tag{1}$$

Momentum (Navier-Stokes) equations:

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}+W\frac{\partial U}{\partial Z}=-\frac{\partial P}{\partial X}+\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right) \tag{2}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}+W\frac{\partial V}{\partial Z}=-\frac{\partial P}{\partial Y}+\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}+\frac{\partial^2 V}{\partial Z^2}\right)+Ra\,T \tag{3}$$

$$U\frac{\partial W}{\partial X}+V\frac{\partial W}{\partial Y}+W\frac{\partial W}{\partial Z}=-\frac{\partial P}{\partial Z}+\frac{1}{Re}\left(\frac{\partial^2 W}{\partial X^2}+\frac{\partial^2 W}{\partial Y^2}+\frac{\partial^2 W}{\partial Z^2}\right) \tag{4}$$

Energy equation:

$$U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}+W\frac{\partial T}{\partial Z}=\frac{1}{Re\,Pr}\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}+\frac{\partial^2 T}{\partial Z^2}\right) \quad (5)$$

Re, Ra, and Pr are Reynolds, Rayleigh and Prandtl numbers respectively.

2.2 GRID CONVERGENCE ASSESSMENT IN COMPUTATIONAL MODELING

In order to ascertain the independence of the solution from grid resolution, the calculations were meticulously replicated across multiple grid sizes (Santos *et al.* 2023; Brito *et al.* 2009; Brito *et al.* 2024). Specifically, the average Nusselt number was computed for three distinct grid configurations: $75 \times 50 \times 25$, $100 \times 75 \times 50$, and $150 \times 120 \times 90$, encompassing a range of discretization levels. These computations were performed across a spectrum of Rayleigh numbers to comprehensively assess the solution's behavior under varying conditions. The resulting findings, tabulated in Table 1, reveal that the maximum deviation observed across the different grid sizes was less than 4%. This indicates that the choice of grid resolution does not significantly impact the results, underscoring the robustness of the numerical solution. However, it's worth noting that while grid size does not affect the outcome substantially, finer grids necessitate longer computational times for convergence. Therefore, for the sake of computational efficiency, the $75 \times 50 \times 25$ grid configuration was selected as the optimal choice for this study.

Table 1

Mesh size independency

Ra	Nu			ε_{max} %
	$70 \times 50 \times 25$	$100 \times 75 \times 50$	$150 \times 120 \times 90$	
10^7	71.820	74.120	73.317	3.103
$2x10^7$	98.129	99.112	100.407	2.27
10^8	112.201	113.107	111.822	1.13
$3x10^8$	139.962	141.005	140.125	0.73

2.3 NUMERICAL PROCEDURE

The numerical simulation in this study is conducted employing the finite volume method (FVM), a widely utilized technique for solving partial differential equations. Specifically, the pressure-based solver is employed to tackle the linked velocity-pressure equations; where the pressure equation was solved using the body force weighted scheme. For handling the convection-diffusion equations, a first-order upwind scheme (FOU) is adopted, ensuring accuracy in the numerical solution. To maintain consistency and efficiency in the pressure-velocity coupling process, the SIMPLER algorithm is utilized, effectively managing the interplay between pressure and velocity fields throughout the simulation. This comprehensive approach ensures robustness and reliability in the computational analysis of the studied phenomena. The thermo-physical properties of Al_2O_3 and H_2O are presented in Table.2

Table 2

Thermal properties of the base fluid and the used nanoparticles.

Properties	Base fluid (H_2O)	Nanoparticles (Al_2O_3)
Density (kg/m^3)	988.2	3880
Specific heat (J/kgK)	4182	773
Thermal conductivity (W/mK)	0.64	36
Dynamic viscosity ($Pa.s$)	10^{-4}	-
Thermal expansion coefficient (K^{-1})	2.1×10^{-4}	6.3×10^{-6}

2.4 ENTROPY GENERATION ANALYSIS

In the process of converting thermal energy into various other forms, such as mechanical work within a heat engine, and the inevitable dissipation of other energy forms into thermal energy through processes like heat generation, additional complexities often emerge, leading to confusion. Entropy generation, serving as an indicator of a system's imperfections, encompasses both entropy produced by the viscous effects of the fluid and that generated by thermal effects. This relationship is expressed by the following equation:

$$S = S_{heat} + S_{friction} \quad (6)$$

The entropy balance equation cast three-dimensionally in the absence of mass transfer and chemical reactions can be expressed in the Cartesian coordinates, by the following correlation:

$$S = \left[\left(\frac{\partial T}{\partial X}\right)^2 + \left(\frac{\partial T}{\partial Y}\right)^2 + \left(\frac{\partial T}{\partial Z}\right)^2\right] + \varphi\left\{2\left[\left(\frac{\partial U}{\partial X}\right)^2 + \left(\frac{\partial V}{\partial Y}\right)^2 + \left(\frac{\partial W}{\partial Z}\right)^2\right] + \left[\left(\frac{\partial V}{\partial X} + \frac{\partial U}{\partial Y}\right)^2 + \left(\frac{\partial W}{\partial Y} + \frac{\partial V}{\partial Z}\right)^2 + \left(\frac{\partial U}{\partial Z} + \frac{\partial W}{\partial X}\right)^2\right]\right\} \quad (7)$$

$$\varphi = \frac{\mu T}{\lambda}\left(\frac{\alpha}{L(T_h - T_c)}\right)^2 \quad (8)$$

T is the mean temperature $T = (T_h - T_c)/2$.

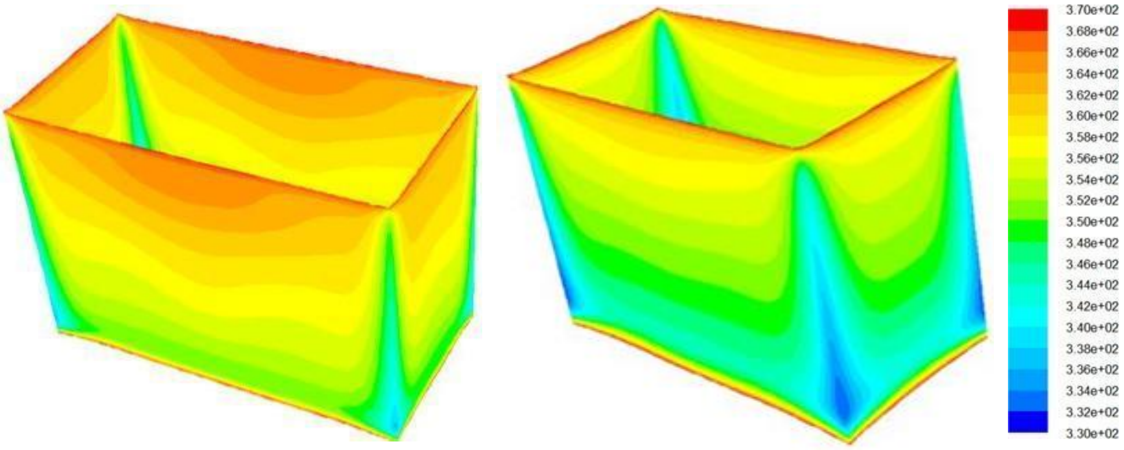
3 FOUND RESULTS

3.1 EFFECT OF NANOFLUID INSERTION ON TEMPERATURE DISTRIBUTION

The temperature distribution of the adiabatic water tank wall, both with and without nanofluid, is illustrated in Figure 2. It's evident that incorporating 1% of Al_2O_3 a nanoparticle in water as the base fluid leads to a notable reduction in the temperature of the water tank walls. Additionally, Figure 3 depicts the temperature distribution at the midpoint of the water tank ($Z = 0.25\ m$), revealing that the utilization of nanofluid results in an overall increase in temperature throughout the water tank. This indicates that dispersing nanoparticles in the base fluid facilitates higher fluid temperatures and lower wall temperatures, consequently enhancing convective heat transfer.

Figure 2

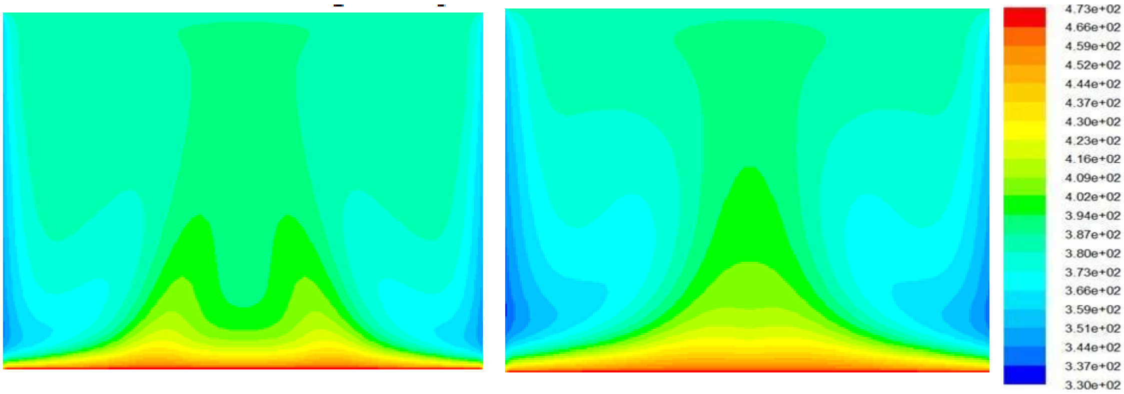
Temperature distribution of the adiabatic walls of the water tank



Without nanofluid With nanofluid ($\phi = 1\%$)

Figure 3

Temperature distribution on the middle of the water tank



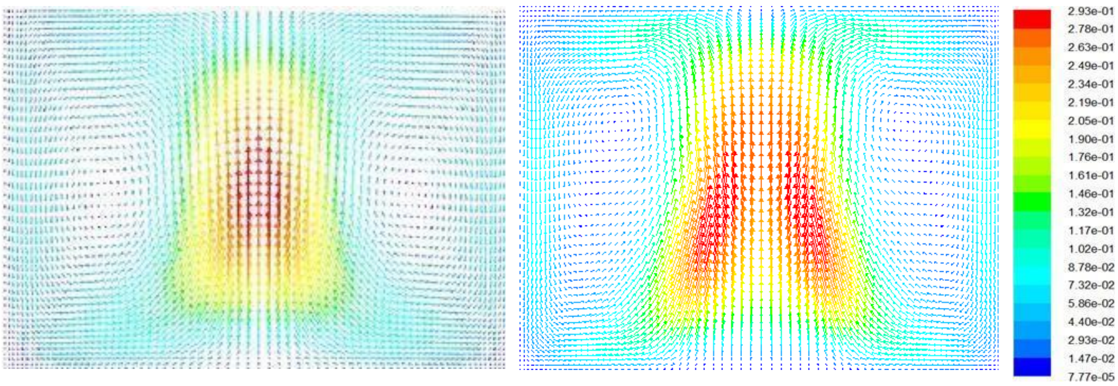
Without nanofluid With nanofluid ($\phi = 1\%$)

3.2 EFFECT OF NANOFLUID ADDITION ON VELOCITY FIELD

The impact of nanofluid on the velocity field is examined qualitatively in Figure 4. It is evident that the velocity increases in the fully developed region when nanofluid is utilized. The velocity contours converge towards the central area of the water tank and exhibit uniformity across the water tank. Additionally, there is a slight elevation in velocity near the hot wall, attributed to the phenomenon where the fluid adjacent to the hot surface absorbs heat, becomes less dense, and rises due to buoyancy. Conversely, near the cold wall, the fluid cools, becomes denser, and descends, adhering to the principle of natural convection.

Figure 4

Velocity field on the middle of the water tank



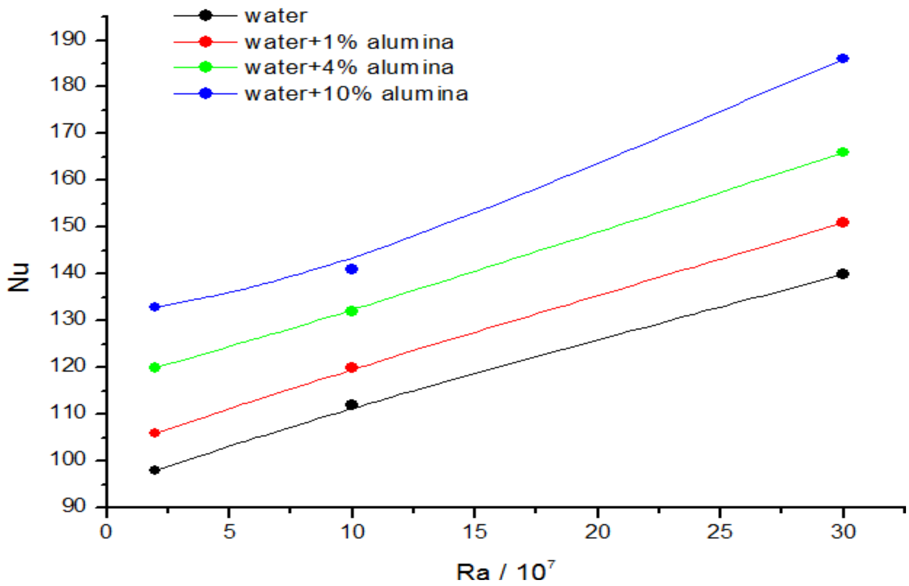
Without nanofluid With nanofluid ($\phi = 1\%$)

3.3 HEAT TRANSFER CHARACTERISTICS USING NANOFLUID

Figure 5 provides a quantitative comparison of the average Nusselt number at the hot wall of the water tank as the Rayleigh number varies from 10^7 to 3×10^8. It is observed that the Nusselt number increases with the rise in Rayleigh number, attributed to the intensified buoyant flow. Additionally, the use of nanofluid leads to an increase in the Nusselt number, with a slight increase observed with the higher volume fraction of nanoparticles. This phenomenon can be attributed to the alterations in the thermo-physical properties of the fluid induced by the presence of nanoparticles.

Figure 5

Average Nusselt number for the water tank hot wall



The graph also displays the average Nusselt number (Nu), a dimensionless parameter representing the convective heat transfer relative to conductive heat transfer, as a function of the Rayleigh number. The lines represent different concentrations of alumina nanoparticles in water: pure water (0%), water with 1% alumina, water with 4% alumina, and water with 10% alumina. The trend indicates that the average Nusselt number increases with the Rayleigh number for all fluids, suggesting that as the temperature difference driving the convection increases (which is what the Rayleigh number represents), so does the convective heat transfer efficiency. Additionally, the graph shows that the addition of alumina nanoparticles to water generally increases the Nusselt number, meaning that nanofluids have a higher rate of heat transfer compared to the base fluid (pure water). The more nanoparticles added, the higher the increase in heat transfer rate, as seen by the steeper slopes for higher concentrations of alumina.

3.4 ENTROPY ANALYSIS

Figure 6 illustrates the distribution of local entropy generation resulting from heat transfer and fluid friction irreversibility for both pure fluid and nanofluid. This analysis investigates the influence of nanoparticles' volume fraction and Rayleigh number on entropy generation. The findings indicate that an increase in Rayleigh number leads to a corresponding increase in heat entropy generation, attributed to the increased buoyancy effect. Notably, the presence of nanoparticles demonstrates a significant role in mitigating entropy generation. In a broader context, entropy can be understood as a measure of energy distribution; low entropy indicates concentrated energy, while high entropy signifies energy dispersion. Similarly, the graph representing entropy generation within the water tank as a function of the Rayleigh number shows an increase in entropy generation with increasing Rayleigh number for all cases, indicating a greater irreversibility in the system with higher driving temperature differences. The addition of nanoparticles also influences entropy generation, as higher concentrations enhance heat transfer but also lead to increased irreversibility, likely due to intensified fluid motion and higher rates of heat transfer.

Figure 6

Entropy generation variation inside the water tank

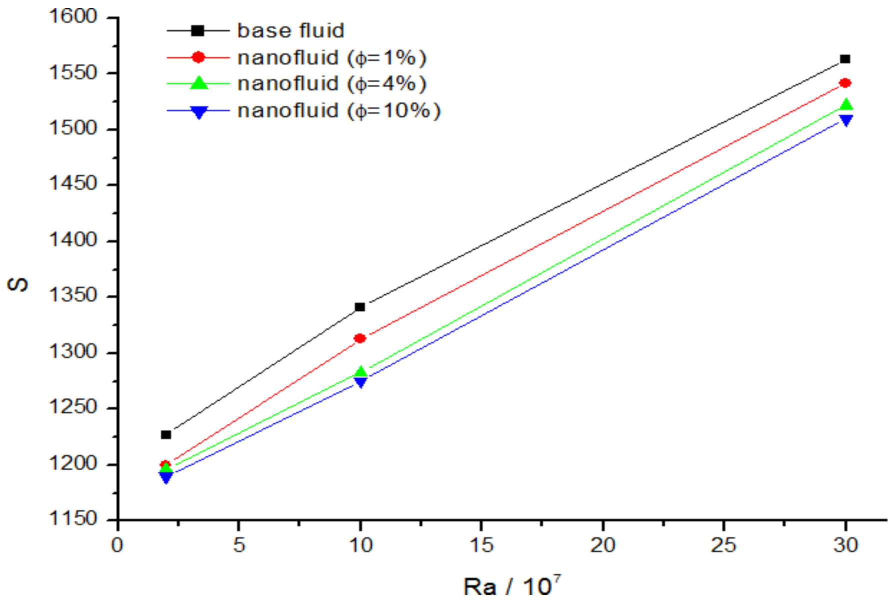
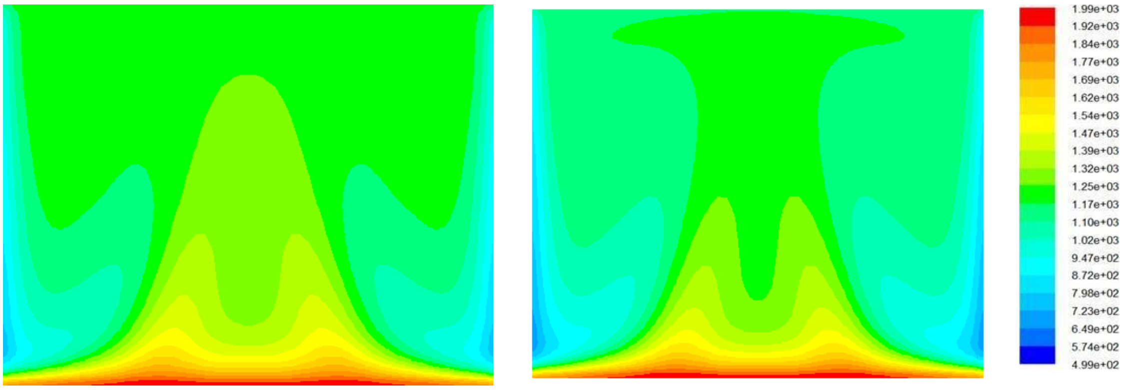


Figure 7 illustrates a qualitative comparison of entropy generation at the midpoint of the water tank. It is notable from this figure that the introduction of 1% alumina nanoparticles leads to a reduction in entropy within the fully developed region. This observation underscores the role of nanofluid in augmenting heat transfer while simultaneously reducing entropy generation.

Figure 7

Qualitative comparison of entropy generation at the center of the water tank



Without nanofluid With nanofluid ($\phi = 1\%$)

4 CONCLUSION

In this study, we conducted a comprehensive analysis of three-dimensional natural convection within a confined water tank filled with an alumina-water nanofluid. Our investigation focused on understanding the influence of nanoparticles' volume fraction and Rayleigh number on entropy generation, heat transfer efficiency, and fluid behavior within the water tank. Through meticulous numerical simulations and analysis, we observed that an increase in Rayleigh number led to heightened entropy generation, with values ranging from 10^7 to 3×10^8, primarily due to intensified buoyant flow. However, the presence of nanoparticles played a crucial role in mitigating entropy generation, thereby enhancing the overall thermal performance of the system. Additionally, our findings revealed that nanofluids exhibited superior heat transfer capabilities compared to pure fluids, with higher nanoparticle concentrations resulting in increased heat transfer rates, ranging from 1% to 10% alumina. Qualitative examinations of velocity fields and entropy generation patterns further underscored the significance of nanofluids in improving heat transfer efficiency while reducing irreversible processes within the water tank. Overall, our study provides valuable insights into the complex dynamics of natural convection in nanofluid-filled cavities, contributing to the advancement of thermal management technologies widely used in industrial applications.

REFERENCES

Albuquerque, J. E. de, Santiago, B. C. L., Campos, J. C. C., Reis, A. M., Silva, C. L. da ., Martins, J. P., & Coimbra, J. S. R.. (2013). Photoacoustic spectroscopy as an approach to assess chemical modifications in edible oils. *Journal of the Brazilian Chemical Society*, 24(3), 369–374. https://doi.org/10.5935/0103-5053.20130047

Alsabery, A. I., Ishak, M. S., Chamkha, A. J., & Hashim, I. (2018). Entropy generation analysis and natural convection in a nanofluid-filled square cavity with a concentric solid insert and different temperature Distributions. *Entropy*, 20(5), 336. https://doi.org/10.3390/e20050336

Armaghani, T., Chamkha, A., Rashad, A. M., *et al*. (2020). Inclined magneto: convection, internal heat, and entropy generation of nanofluid in an I-shaped cavity saturated with porous media. *Journal of Thermal Analysis and Calorimetry*, 142, 2273-2285. https://doi.org/10.1007/s10973-020-09449-6

Benabderrahmane, A. (2017a). Numerical investigation of heat transfer enhancement inside a parabolic trough solar collector using dimpled absorber. *International Journal of Energetica*, 2(2), 01-05. http://dx.doi.org/10.47238/ijeca.v2i2.41

Benabderrahmane, A., Benazza, A., & Samir, L. (2017b). Numerical analysis of compound heat transfer enhancement by single and two-phase models in parabolic through solar receiver. *Mechanika*, 23. https://doi.org/10.5755/j01.mech.23.1.14053

Benabderrahmane, A., Benazza, A., Aminallah, M., & Samir, L. (2016). Heat transfer behaviors in a parabolic trough solar collector tube with compound technique. *International Journal of Scientific Research Engineering & Technology*, 5(11).

Benhabib, L., Marif, Y., Hadjou Belaid, Z., Kaddour, A., Benyoucef, B., & Aillerie, M. (2021). Simulation of different modes of heat transfer on a parabolic trough solar collector. *International Journal of Energetica*, 6(2), 07-12. http://dx.doi.org/10.47238/ijeca.v6i1.151

Bilal, S., Shah, I. A., Ghachem, K., Aydi, A., & Kolsi, L. (2023). Heat transfer enhancement of MHD natural convection in a star-shaped enclosure, using heated baffle and MWCNT-water nanofluid. *Mathematics*, 11(8), 1849. https://doi.org/10.3390/math11081849

Bouhelal, M., Rouag, A., Bouhelal, A., & Belloufi, Y. (2023). Optimizing parabolic through collectors for solar stills: a 2D CFD parametric analysis. *International Journal of Energetica*, 8(2), 11-19. http://dx.doi.org/10.47238/ijeca.v8i2.224

Brito, R. F., Menon, G. J. & Pirani, M. J. (2009). Turbulent natural convection in enclosures using large-eddy simulation with localized heating from horizontal bottom surface and cooling from vertical surfaces. *Journal of the Brazilian Society of Mechanical Sciences and Engineering (Printed)*, 31, 199-209. https://doi.org/10.1590/S1678-58782009000300005

Brito, R. F., Teixeira, R. L. P., Siqueira, A. M. de O., Lacerda, J. C. de, Fetuga, I. A., Abderrahmane, K., & Campos, J. C. C. (2024). Analysis of contact thermal resistance and the use of coatings on heat transfer in cemented carbide metal cutting tools. *Revista De Gestão Social E Ambiental*, 18(7), e05929. https://doi.org/10.24857/rgsa.v18n7-085

Brito, R. F., Teixeira, R. L. P., Siqueira, A. M. de O., Lacerda, J. C. de, Fetuga , I. A., Abderrahmane, K., & Campos , J. C. C. (2024). Analysis of Contact Thermal Resistance and the Use of Coatings on Heat Transfer in Cemented Carbide Metal Cutting Tools. *Revista De Gestão Social E Ambiental*, *18*(7), e05929. https://doi.org/10.24857/rgsa.v18n7-085

Fouakeu-nanfack, G., Kewou, S., Ngouem, F., Tetang Fokone, A., Edoun, M., & Zeghmati, B. (2023). Numerical and experimental characterization of internal heat and mass transfer during convective drying of papaya (Carica papaya L.) in a drying air stream. *International Journal of Energetica*, 8(2), 1-10. https://www.ijeca.info/index.php/IJECA/article/view/221

Gibanov, N. S., Sheremet, M. A., Oztop, H. F., & Abu-Hamdeh, N. (2018). Mixed convection with entropy generation of nanofluid in a lid-driven cavity under the effects of a heat-conducting solid wall and vertical temperature gradient. *European Journal of Mechanics - B/Fluids*, 70, 148-159. https://doi.org/10.1016/j.euromechflu.2018.03.002

Hilário, C. V., Campos, J. C. C., Siqueira, A. M. de O., Leite, M. de O., Martins, M. A., Brito, R. F., Fetuga, I. A., & Abderrahmane, K. (2024). Physical-Chemical Properties of First-Generation Biofuel Aiming Application in Diesel Locomotive. *Revista De Gestão Social E Ambiental*, 18(5), e05080. https://doi.org/10.24857/rgsa.v18n5-042

Khan, S. A., Yasmin, S., Imran, M., Muhammad, T., Alhushaybari, A., Farooq, U., & Waqas, H. (2023). Computational analysis of natural convection with water based nanofluid in a square cavity with partially active side walls: Applications to thermal storage. *Journal of Molecular Liquids*, 382, 122003. https://doi.org/10.1016/j.molliq.2023.122003

Laaraba, A., & Khechekhouche, A. (2018). Numerical simulation of natural convection in the air gap of a vertical flat plate thermal solar collector with partitions attached to its glazing. *Indonesian Journal of Science and Technology*, 3(2), 95-104. https://doi.org/10.17509/ijost.v3i2.12753

Marzougui, S., Mebarek-Oudina, F., Assia, A., et al. (2021). Entropy generation on magneto-convective flow of copper–water nanofluid in a cavity with chambers. *J Journal of Thermal Analysis and Calorimetry*, 143, 2203-2214. https://doi.org/10.1007/s10973-020-09662-3

Satari, C., Sidqi, R., Putra, R., Putri, S., & Nandiyanto, A. (2021). Literature review: synthesis of CuO (Copper Oxide) nanoparticles for thermal energy storage. *International Journal of Energetica*, 6(2), 21-34. http://dx.doi.org/10.47238/ijeca.v6i2.176

Selimefendigil, F., Öztop, H. F., & Abu-Hamdeh, N. (2016). Natural convection and entropy generation in nanofluid filled entrapped trapezoidal cavities under the influence of magnetic field. *Entropy*, 18(2), 43. https://doi.org/10.3390/e18020043

Silva, J. A. D., Silva, L. P. D., Campos, J. C. C., Siqueira, A. M. D. O., Gurgel, A., & Gómez, L. C. (2023). Dynamic mesh analysis by numerical simulation of internal combustion engines. REM - *International Engineering Journal*, 77(1), 27-37. https://doi.org/10.1590/0370-44672023770003

Silva, J. A. da., Silva, L. P. da., Campos, J. C. C., Siqueira, A. M. de O., Gurgel, A., & Gómez, L. C.. (2024). Dynamic mesh analysis by numerical simulation of internal combustion engines. *REM - International Engineering Journal*, *77*(1), 27–37. https://doi.org/10.1590/0370-44672023770003

Solomon, B., van Rooyen, J., Rencken, M., Sharifpur, M., & Meyer, J. P. (2017). Experimental study on the influence of the aspect ratio of square cavity on natural convection heat transfer with Al2O3/Water nanofluids. *International Communications in Heat and Mass Transfer*, 88, 254-261. https://doi.org/10.1016/j.icheatmasstransfer.2017.09.007

Tayebi, T., & Chamkha, A. J. (2020). Entropy generation analysis during MHD natural convection flow of hybrid nanofluid in a square cavity containing a corrugated conducting block. *International Journal of Numerical Methods for Heat & Fluid Flow*, 30(3), 1115-1136. https://doi.org/10.1108/HFF-04-2019-0350

Vedavathi, N., Venkatadri, K., Mozhi, K. S., et al. (2023). Numerical analysis of Cu-H_2O nano-fluid natural convection in a trapezoidal enclosure filled with porous medium. *International Journal of Applied and Computational Mathematics*, 9, 121. https://doi.org/10.1007/s40819-023-01602-7

Yuan, Z., Dong, Y., & Jin, Z. (2023). Numerical Simulation of MHD Natural convection and entropy generation in semicircular cavity based on LBM. *Energies*, 16(10), 4055. https://doi.org/10.3390/en16104055

Zemani, F., Ladjedel, O., & Sabeur, A. (2023). Simulation of CuO-water nanofluid natural convection in a U-shaped enclosure with a T-shaped baffle. *Journal of Engineering and Applied Science*. 70, 99. https://doi.org/10.1186/s44147-023-00257-x

ANNEX

Nomenclature

C_p	Specific heat, J/kgK
H	Cavity height, m
L	Cavity length, m
W	Cavity width, m
Nu	Nusselt number
P	Pressure, Pa
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
S	Entropy, J/K
T	Temperature, K
U, V, W	Velocity, m/s
X, Y, Z	Cartesian coordinates

Greek symbols

ρ	Density, kg/m^3
μ	Viscosity, Pa s
α	Thermal diffusivity, m^2/s
λ	Thermal conductivity, W/mK
ϕ	Nanoparticles volume fraction

Subscripts

c	cold
h	hot