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Nanofluids in nuclear power plants: A comprehensive review

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Abstract

Nuclear power plants play a significant role in global electricity generation, offering a reliable and low-carbon energy source. Maximizing the efficiency of nuclear power plants is crucial for optimizing energy output and reducing operational costs while ensuring safety and environmental sustainability. This paper provides a comprehensive review of the potential applications of nanofluids in nuclear power plants, with a particular focus on their role in enhancing cooling and heat exchange processes. The increasing demand for electricity production and the need for improved efficiency and safety in nuclear reactors have prompted extensive research in this area. The review explores various types of nuclear reactors, including Light Water Reactors (LWRs) and Heavy Water Reactors (HWRs), and discusses the associated risks and challenges. The paper highlights the promise of incorporating nano-fluids into the cooling and heat exchange systems of nuclear reactors, showcasing their potential to enhance efficiency and safety. It specifically considers nanoparticles such as Al_2O_3, SiO_2, TiO_2, CeO_2, and CuO for their unique heat transfer properties. The use of nano-fluids in these systems offers the prospect of increasing electricity production while addressing safety concerns. In essence, this comprehensive review underscores the significant potential of nano-fluids for improving heat transfer in nuclear reactors and addresses the growing global demand for electricity production. It emphasizes the need for further scientific research and technological advancements in this field to fully harness the benefits of nanofluids in nuclear power plants.

Keywords: Nuclear Power Plant; Nanofluid; Heat Transfer; Efficiency; Enhancement; Performance; Safety

1. Introduction

In the ever-evolving landscape of energy production, nuclear power stands as a promising solution for meeting growing global demands while minimizing environmental impact. However, efficient heat transfer management is crucial for the optimal performance and safety of nuclear power plants. To address this, innovative technologies, such as nanofluids, are being explored to enhance heat transfer efficiency within these complex systems.

Nuclear power plants rely on the controlled fission of nuclear fuel to generate heat, which is then used to produce steam and drive turbines for electricity generation. The efficiency of this process depends significantly on the effective transfer of heat between various components, including the reactor core, coolant, and heat exchangers.

Nanofluids, engineered by suspending nanoscale particles in traditional heat transfer fluids, present a cutting-edge solution to improve the thermal properties of coolants in nuclear power plants. The addition of nanoparticles, such as metallic oxides or carbon-based materials, enhances the heat-carrying capacity and overall thermal conductivity of the fluid. This results in improved heat transfer rates, reduced operating temperatures, and enhanced system efficiency.

The unique characteristics of nanofluids, including their high surface area and thermal conductivity, make them promising candidates for optimizing heat transfer in nuclear power plants. Researchers and engineers are actively

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exploring the potential of nanofluids to mitigate challenges associated with overheating, reduce energy consumption, and enhance the overall safety and performance of nuclear power systems.

This introduction lays the foundation for delving into the intricate interplay between heat transfer mechanisms and nanofluid technologies within the context of nuclear power plants. As we explore the potential benefits and challenges, it becomes evident that these advancements hold promise for shaping the future of sustainable and efficient nuclear energy production.

2. Nuclear Power Plant

Nuclear energy is a form of energy released from the nucleus, the core of atoms, made up of protons and neutrons. This source of energy can be produced in two ways: fission – when nuclei of atoms split into several parts or fusion when nuclei fuse together. The nuclear energy harnessed around the world today to produce electricity is through nuclear fission, while technology to generate electricity from fusion is at the R&D phase [1]. A nuclear power plant is a thermal power plant, in which a nuclear reactor is used to generate large amounts of heat. This heat is used to generate steam (directly or via steam generator) which drives a steam turbine connected to a generator that produces electricity.

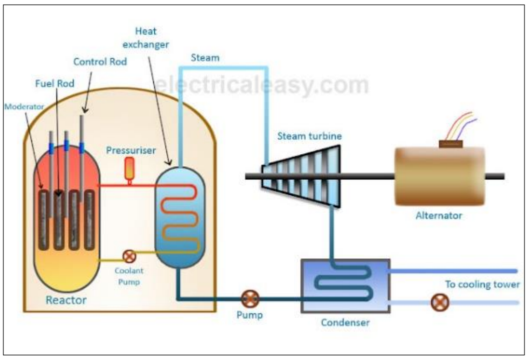

Figure 1 Basic Components and layout of a Nuclear Power Plant [2].

Heavy elements such as Uranium (U235) or Thorium (Th232) are subjected to nuclear fission reaction in a nuclear reactor. Due to fission, a large amount of heat energy is produced which is transferred to the reactor coolant. The coolant may be water, gas or a liquid metal. The heated coolant is made to flow through a heat exchanger where water is converted into high-temperature steam. The generated steam is then allowed to drive a steam turbine. The steam, after doing its work, is converted back into the water and recycled to the heat exchanger. The steam turbine is coupled to an alternator which generates electricity. The generated electrical voltage is then stepped up using a transformer for the purpose of long distance transmission [2].

Nuclear power plants are advanced facilities designed to harness the incredible energy released during nuclear reactions for the generation of electricity. These plants play a crucial role in meeting the growing global demand for energy while minimizing greenhouse gas emissions. Unlike conventional power plants that rely on burning fossil fuels, nuclear power plants generate electricity through controlled nuclear fission reactions.

3. Nanofluid

A nanofluid is a fluid containing nanometer-sized particles, called nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol and oil [3]. Nanofluids have novel properties that make them potentially useful in many applications in heat transfer [4], including microelectronics, fuel cells, pharmaceutical processes, and hybrid-powered engines [5], engine cooling/vehicle thermal management, domestic refrigerator, chiller, heat exchanger, in grinding, machining and in boiler flue gas temperature reduction. They exhibit enhanced thermal conductivity and the convective heat transfer coefficient compared to the base fluid [6]. Knowledge of the rheological behavior of nanofluids is found to be critical in deciding their suitability for convective heat transfer applications [7, 8]. Nanofluids also have special acoustical properties and in ultrasonic fields display additional shear-wave reconversion of an incident compressional wave; the effect becomes more pronounced as concentration increases [9].

Nanofluids are produced by several techniques:

- Direct Evaporation (1 step)
- Gas condensation/dispersion (2 step)
- Chemical vapor condensation (1 step)
- Chemical precipitation (1 step)
- Bio-based (2 step)

Several liquids including water, ethylene glycol, and oils have been used as base fluids. Although stabilization can be a challenge, on-going research indicates that it is possible. Nano-materials used so far in nanofluid synthesis include metallic particles, oxide particles, carbon nanotubes, graphene nano-flakes and ceramic particles [10, 11].

3.1. Thermophysical Properties of Nanofluids

Thermal conductivity, viscosity, density, specific heat, and surface tension are considered some main thermophysical properties of nanofluids. Various parameters like nanoparticle type, size, and shape, volume concentration, fluid temperature, and nanofluid preparation method have effect on thermophysical properties of nanofluids [12].

3.2. Application of Nanofluid

Nanofluids are primarily used for their enhanced thermal properties as coolants in heat transfer equipment such as heat exchangers, electronic cooling system (such as flat plate) and radiators. Heat transfer over flat plate has been analyzed by many researchers. However, they are also useful for their controlled optical properties [13]. Graphene based nanofluid has been found to enhance Polymerase chain reaction efficiency [14]. Nanofluids in solar collectors is another application where nanofluids are employed for their tunable optical properties [15].

Abu Raihan Ibna Ali and Bodius Salam provided a comprehensive overview of nanofluids, exploring their potential to enhance heat transfer in diverse applications. Nanofluids, suspensions of nanoparticles in base fluids, exhibit superior thermal conductivity and rheological properties. The review surveyed prior research and recent advancements in nanofluid development, covering preparation methods, stability enhancement, and thermophysical properties. Highlighted advantages of nanofluids include increased thermal conductivity, expanded specific surface area, enhanced turbulence, and reduced pumping power for equivalent heat transfer. The paper emphasized the wide-ranging applications of nanofluids, spanning from automotive engine coolants to nuclear systems and solar energy absorption [16].

Md. Saadbin Chowdhury performed thesis on enhancement of heat transfer through turbulent swirl flow in a circular pipe by numerically rotating a twisted tape insert with ribs on the inner surface. Using the realizable k-epsilon model, the study considered the impact of turbulence. The study evaluated the effect of nanofluid on heat transfer. The result demonstrated higher heat transfer rate using nanofluid [17].

Md. Saadbin Chowdhury and Bodius Salam performed study aimed to enhance the efficiency of a flat plate solar collector by using nanofluid, a fluid containing nanoparticles, instead of solely water as the circulating medium. Nanofluid, known for its improved thermal conductivity, was tested with varying concentrations of aluminum oxide nanoparticles. The results demonstrated a significant increase in efficiency: from 70% with water alone to 78% with 10gm of aluminum oxide in 1300gm of circulating water. Further, efficiency increased to 81% when the nanoparticle concentration was increased to 20gm in the same water volume. This study highlighted the positive impact of nanofluid utilization on the efficiency of flat plate solar collectors, showcasing its potential for improving solar energy conversion systems [18].

Nanofluids, engineered by dispersing nanoparticles in traditional heat transfer fluids, have found diverse applications across multiple industries. With enhanced thermal conductivity, nanofluids are employed in electronics for efficient cooling, preventing overheating in devices like computer chips and LEDs. In the energy sector, particularly in solar and nuclear power, nanofluids improve heat transfer, enhancing overall system efficiency and safety.

4. Inclusion of Nanofluid in Nuclear Power Plant

The utilization of nanofluids in nuclear power plants represents a cutting-edge approach to enhance heat transfer efficiency and optimize the performance of these critical energy systems. Nuclear power, with its low carbon footprint, has the potential to play a significant role in addressing global energy demands. However, efficient heat transfer management is crucial for the safety and efficiency of nuclear reactors. The inclusion of nanofluids, which are engineered suspensions of nanoparticles in traditional heat transfer fluids, introduces innovative possibilities for improving thermal characteristics within nuclear power plant systems. Nanofluids, known for their exceptional thermal conductivity and unique rheological properties, offer a promising avenue to address challenges associated with heat transfer in nuclear reactors. By introducing nanoparticles into the coolant, the heat-carrying capacity of the fluid is significantly enhanced, leading to improved heat transfer rates. This can have a profound impact on reactor cooling systems, reducing the risk of overheating and enhancing overall efficiency. The inclusion of nanofluids in nuclear power plants is a subject of active research and development. Scientists and engineers are exploring various nanomaterials, including metallic oxides and carbon-based nanoparticles, to optimize heat transfer properties. Additionally, studies focus on understanding the impact of nanofluids on reactor safety, stability, and long-term performance. This introduction sets the stage for a deeper exploration of the potential benefits, challenges, and implications of incorporating nanofluids into nuclear power plants. As advancements in nanotechnology continue to unfold, the inclusion of nanofluids stands as a promising avenue to usher in a new era of improved heat transfer efficiency and safety in nuclear energy production.

4.1. Heat Transfer

Seyed Mohammad Mousavizadeh et el. investigated the effects of using a nanofluid (TiO_2/water) on heat transfer characteristics in a VVER-1000 nuclear reactor. It focused on parameters such as thermal conductivity, heat transfer coefficient, fuel clad, and fuel center temperatures. The study found that adding nanoparticles to the coolant enhances heat transfer due to the increased thermal conductivity of the nanofluid. Moreover, smaller nanoparticle sizes further improve heat transfer. The nanofluid also leads to an increase in the coolant's outlet temperature, which can enhance the thermal efficiency of nuclear power plants. Additionally, the use of nanofluids reduced the Minimum Departure from Nucleate Boiling Ratio (MDNBR), which is important for reactor safety. The paper suggested that nanofluids, with their enhanced thermal properties, can be beneficial for cooling in VVER-1000 reactors [19].

Deepak Sharma and K. M. Pandey investigated the influence of CuO/water-based nanofluid on heat transfer in a VVER-440 type nuclear reactor, focusing on a portion of a hexagonal fuel rod assembly. Employing a two-phase model, the study examined the impact of nanoparticle concentration and flow rate in a triangular channel. The results revealed that the addition of CuO nanoparticles, particularly at low concentrations, enhanced the heat transfer coefficient. Higher Reynolds numbers and smaller nanoparticle sizes contribute to increased heat transfer coefficients. The study emphasized that the nanofluid's higher thermal conductivity leads to a decrease in clad wall temperature, demonstrating the potential of CuO/water-based nanofluids for improving heat transfer in nuclear reactors, especially within triangular fuel rod assemblies [20].

4.2. Heat Transfer Enhancement

In the realm of nuclear power plants, optimizing heat transfer is crucial for safe and efficient operations. Nanofluids, engineered fluids containing nanoparticles suspended in a base fluid, offer a groundbreaking approach to enhancing heat transfer within these plants. Their application in nuclear power plants holds promise for advancing safety, performance, and overall efficiency in the realm of nuclear energy generation.

Jacopo Buongiorno and Lin-wen Hu researched nanofluid use in light water reactors (LWRs) to improve heat transfer and power density, targeting financial viability. They highlighted nanofluids' potential to expedite quenching during submersion, aiding emergency cooling systems in nuclear reactors. Despite acknowledging challenges, the study remains optimistic about nanofluids' ability to enhance nuclear reactor performance and economics, stressing the importance of addressing associated concerns [21].

Kang Liu explored nanofluids efficacy in enhancing heat transfer within simulated nuclear fuel rod bundles, particularly focusing on 0.5% and 2% ZnO nanoparticles in deionized water compared to standard coolants. The study revealed a substantial 33% improvement in heat transfer with the 2% ZnO nanofluid under specific flow conditions, but encountered deposition issues on rod surfaces at higher temperatures, limiting experimentation to 80 degrees Celsius. The research emphasized the importance of addressing nanoparticle deposition challenges and refining predictions for nanofluid thermal conductivity to enable their practical application in improving nuclear fuel rod bundle heat transfer [22].

Kang Liu et al. investigated the augmentation of heat transfer in pressurized water nuclear reactors (PWR) using nanofluids and simulated surface roughness akin to nuclear fuel rods. They examined two roughness types (2D and 3D) and ZnO nanoparticles in varying concentrations (0.5% and 2.0%) mixed with deionized water as coolants. Results demonstrated a notable 33% increase in heat transfer coefficient with the 2% ZnO nanofluid, particularly on rods with 3D surface roughness at specific flow conditions, emphasizing the correlation between higher Reynolds numbers and enhanced heat transfer. The study underlined the significance of optimizing nanofluid concentrations and surface roughness geometries for practical implementation in nuclear reactors, illustrating potential improvements in heat transfer for enhanced reactor performance [23].

Mohammad Nazififard et al. conducted a numerical analysis on water-based nanofluids as coolants in small modular reactors (SMRs), specifically focusing on Al2O3 nanofluids. Their investigation explored the thermohydrodynamic and neutronic characteristics, revealing a 31.29% enhancement in heat transfer at 6% particle concentration and a Reynolds number of 65,000. While indicating the feasibility of nanofluid use in SMRs, the study recommends further research to optimize nanoparticle concentration and assess their impact on normal and abnormal reactor operations. It highlighted nanofluids' potential to enhance heat exchange while minimizing pressure drop in nuclear reactors, emphasizing the need for extensive exploration and optimization for practical implementation in SMRs [24].

Z. Rahnama and G.R. Ansarifar investigated the potential of Al2O3-Water nanofluids as coolants in NuScale's small modular nuclear reactor (SMR) to bolster safety, heat transfer, and natural circulation. The study employing computational fluid dynamics (CFD) modeling, assessed factors like bulk velocity, pressure drop, heat transfer coefficient, and safety ratios. Results suggested that nanofluids could augment heat transfer and safety margins in nuclear reactors without markedly affecting reactor performance, showcasing their potential for enhancing nuclear safety and efficiency [25].

Zeina Ali Abdul Redha and Farhan Lafta Rashid explored the use of Yttrium oxide nanofluid within pressurized water reactor (PWR) subchannel designs to boost heat transfer. Computational fluid dynamics (CFD) simulations under operational conditions revealed that while Yttrium oxide nanoparticles improve convective heat transfer, their integration increases pressure drop. The study highlighted a significant enhancement in heat transfer coefficients with higher nanoparticle volume fractions, indicating the trade-offs between improved heat transfer and heightened pressure drop when utilizing Yttrium oxide nanofluid in PWR sub channel geometries [26].

Sojibul Islam Shojib et al. investigated the use of nanofluids in Pressurized Water Reactors (PWRs) to boost heat transfer, focusing on improving critical heat flux (CHF) and overall reactor efficiency. By introducing 1-4% nanoparticles into the base fluid, the study observed substantial enhancements in heat transfer, lowering bulk and fuel rod temperatures. Computational Fluid Dynamics (CFD) simulations supported these findings, highlighting the potential of nanoparticle inclusion in Al_2O_3/water nanofluids to augment convective heat transfer and improve reactor performance, although reaching a saturation point in heat transfer enhancement at higher concentrations [27].

Jubair A. Shamim et al. explored water-alumina nanofluid's effectiveness as a coolant in a square array subchannel setup within Pressurized Water Reactors (PWRs). Their study focused on analyzing how flow rates, nanoparticle concentrations (ranging 0.5% to 3.0%), and pitch-to-diameter ratios impacted heat transfer and pressure drop. They discovered that while nanofluids improved convective heat transfer, they also increased pressure drop, prompting the proposal of a new correction factor to refine existing heat transfer correlations for square array subchannels. This adjustment aimed to better predict heat transfer in these geometries, highlighting the potential of nanofluids for enhanced PWR heat transfer alongside the trade-offs involving increased pumping power [28].

Deepak Sharma et al. studied SiO_2-water nanofluids in a light water nuclear reactor to boost heat transfer, using Ansys CFX 14 CFD software and varying nanoparticle concentrations (1%, 2%, and 3%). They found a 16% increase in heat transfer coefficient with 1% nanofluid concentration compared to pure water, but increasing to 2% showed a lesser enhancement. Notably, the clad wall temperature saw more significant reduction at 1% concentration, offering insights into optimizing nanofluid use for improved reactor performance [29].

4.3. Application of Nanofluid

Junhao Li et al. conducted a thorough review on nanofluids, focusing on their thermal properties and wide-ranging applications in industries like automotive, electronics, and solar energy. They delved into experimental studies exploring factors influencing nanofluids' thermal conductivity, such as nanoparticle characteristics, volume fraction, temperature, aggregation, pH, additives, and magnetic fields. The review highlighted nanofluids' role in improving heat transfer, especially in automotive cooling systems, emphasizing stability aided by additives like surfactants. Additionally, it briefly discussed magnetic field effects on nanofluids' thermal conductivity, offering valuable insights into their potential applications across various industries [30].

Malek Khalaf Albzeirat et al. explored the use of nano-fluids in nuclear reactors to improve cooling and heat exchange for enhanced efficiency and safety. Highlighting the global need for electricity, particularly in nuclear power plants contributing about 11% to global electricity production, the paper discussed the significance of addressing challenges in the energy landscape. It differentiated Light Water Reactors (LWRs) and Heavy Water Reactors (HWRs) based on their coolant usage. Addressing risks in nuclear plants, the study proposed strategies for risk reduction, emphasizing the potential of nano-fluids like Al_2O_3, SiO_2, TiO_2, CeO_2, and CuO in water-based coolants to improve heat transfer and overall efficiency. Ultimately, the research emphasized the promise of nano-fluids in advancing safety, efficiency, and meeting the increasing demand for electricity production in nuclear energy [31].

Tahir Iqbal et al. highlighted nuclear energy's vital role in electricity production and stressed the need for efficient processes to reduce risks. They emphasized the potential of nano-fluids to enhance heat transfer in various devices, owing to their remarkable thermo-physical properties. Nano-fluids, developed through nanotechnology, exhibit exceptional heat transfer abilities, particularly in nuclear reactor cores, requiring minimal nanoparticle concentrations for significant property enhancements. Ongoing research aims to understand and leverage these unique heat transfer capabilities, holding promise across multiple industries like nuclear, transportation, electronics, and biomedicine. These fluids, often termed "smart fluids," offer controllable heat transfer characteristics, showcasing potential for tailored heat management. Overall, the review paper highlighted nano-fluids' diverse potential applications and controllable traits, especially their enhanced and manageable heat transfer properties [32].

K. Hadad et al. explored the use of nanofluids—water with suspended nanoparticles—as a coolant in a VVER-1000 nuclear reactor core. Their focus was on assessing how these nanofluids influence neutronic parameters to improve core safety by optimizing nanoparticle selection and volume fraction. They analyzed five different nanoparticles—Alumina, Aluminum, Copper oxide, Copper, and Zirconia—for their heat transfer properties. The study highlighted Alumina as the optimal nanoparticle for normal reactor operation at low concentrations (0.001 volume fraction). Additionally, it investigated nanoparticle deposition on fuel clad, noting Alumina's minimal impact on reactor performance drop-off. By emphasizing nanofluid use in the primary cooling loop of a light water reactor, the research suggested potential improvements in critical heat flux and safety. Notably, it stressed the importance of understanding both thermal and nuclear effects of nanofluids in reactor core applications. Employing the MCNP4C Monte-Carlo Code for modeling and calculations, the study provided insights into how different nanoparticles affect reactivity, power distribution, and overall safety in nuclear reactor cores. In essence, it illuminated the potential benefits and nuclear implications of using nanofluids in nuclear reactor cooling systems [33].

Kamal Hadad et al. examined nanofluids as coolants in a VVER-1000 nuclear reactor to improve heat transfer efficiency in the core. Their aim was to enhance heat transfer by blending nanoparticles with water as a cooling agent. Using computational fluid dynamics (CFD), they simulated the VVER-1000 fuel assembly's coolant channel, evaluating parameters like heat transfer coefficient, pressure drop, and temperature changes, specifically focusing on water/Al_2O_3 nanofluid. The study compared two modeling approaches: a single-phase model treating the nanofluid as a uniform mixture and a two-phase model treating nanoparticles as a distinct phase. Results favored the two-phase model, considering particle movement, indicating improved heat transfer coefficients, especially at higher Reynolds numbers and nanoparticle concentrations. Additionally, incorporating spacer grids in the two-phase model enhanced turbulence, proving effective even at lower nanoparticle concentrations. Overall, the research highlighted how nanoparticle concentration and modeling methods significantly impact heat transfer efficiency in a VVER-1000 reactor core, endorsing the effectiveness of a two-phase model with spacer grids for optimizing nanofluid-based heat transfer [34].

Palash K. Bhowmik et al. studied thermal-hydraulic behaviors in a 3x3 square array rod bundle resembling a unit block of a Small Modular Reactor (SMR). They examined pure water and water-based nanofluids containing Alumina nanoparticles across different flow conditions (Reynolds numbers from 21,000 to 100,000). The focus was on heat transfer performance measured by the Nusselt number (Nu) and pressure drop, comparing findings with established models. Results showed that nanofluid inclusion improved heat transfer (higher Nu) with increasing nanoparticle concentration. However, this also led to increased pressure drop, raising concerns for SMRs. The study highlighted potential benefits and challenges of nanofluid use in SMRs, especially in enhancing safety while noting the need to control nanoparticle inclusion within specific limits to manage pressure drop. It emphasized the necessity of separate tests to isolate nanofluid effects and urged careful consideration when implementing nanofluids in SMRs. Overall, it discussed both the potential and limitations of nanofluid usage in SMRs, stressing a cautious and thorough approach to their implementation [35].

4.4. Nanofluid Safeguard in NPP

Nanofluids, a novel class of fluids infused with nanoparticles, have garnered significant attention for their potential applications within Nuclear Power Plants (NPPs), particularly concerning safety measures. These engineered suspensions, typically comprising nanoparticles dispersed in a base fluid like water, showcase unique thermal and hydraulic properties that hold promise for enhancing safety protocols within nuclear facilities. In the context of NPPs, nanofluids offer intriguing possibilities in several safety-related areas. They have shown remarkable advancements in critical heat flux (CHF), a crucial parameter determining heat transfer limits, thereby potentially improving reactor cooling efficiency. Furthermore, their use in Emergency Core Cooling Systems (ECCS) might aid in rapidly restoring core cooling during critical incidents. The exploration of nanofluids within NPPs for safety-related measures represents a burgeoning area of research and development, aiming to harness their unique properties to enhance safety margins, improve heat transfer efficiency, and address challenges in nuclear safety protocols.

Jacopo Buongiorno and Lin-wen Hu explored nanofluid applications in nuclear systems, particularly Pressurized Water Reactors (PWRs). Nanofluids, composed of nanoparticles in water, show promise in improving boiling critical heat flux (CHF), indicating potential for better heat transfer in nuclear settings.

The study highlighted three key areas for nanofluid application:

PWR Main Reactor Coolant: Nanofluids could increase power density in PWR cores, potentially enhancing energy extraction without major plant modifications. Success relies on nanofluid stability, reactivity impact, and thermal-hydraulic performance.

Emergency Core Cooling System (ECCS) Coolant: Nanofluids might improve safety during coolant accidents by enhancing heat transfer and nucleate boiling. Stability is less critical in this context.

In-Vessel Retention (IVR) of Molten Core: Nanofluids could enhance safety in high-power-density reactors during severe accidents, benefiting designs like the Westinghouse AP1000 and Korean APR1400.

While the study highlighted potential benefits, it acknowledged challenges, demonstrating nanofluid performance in real reactor conditions, ensuring stability within reactor chemistry, and assessing nanoparticle impact on fuel surface corrosion. Nanofluids show promise for safety and performance improvements in nuclear systems, but further research and testing are crucial before implementing these applications in nuclear power plants [36].

S.M.Mousavi Zadeh and G.R.Ansarifar employed computational fluid dynamics (CFD) modeling to assess the impact of TiO_2/water nanofluids on heat transfer within a VVER-1000 nuclear reactor. The investigation focused on critical parameters such as thermal conductivity, heat transfer coefficients, and temperature profiles across the fuel assembly. The study highlighted the favorable impact of nanofluids on safety parameters, particularly reducing the Minimum Departure from Nucleate Boiling Ratio (MDNBR), a crucial safety measure in nuclear reactors. Interestingly, while nanofluids enhanced convection heat transfer, they don't significantly alter outlet or mean temperatures. Overall, the research suggested that TiO_2/water nanofluids possess the potential to improve heat transfer efficiency within nuclear reactors. Their ability to enhance thermal conductivity and convection heat transfer could lead to increased safety and efficiency in these critical systems [37].

Z. Rahnama and G.R. Ansarifar explored the application of Al_2O_3-Water nanofluids in NuScale SMRs, showcasing their potential to improve reactor operation and safety while preserving neutronic performance. It offers valuable insights into the viability of using nanofluids as coolants in small modular nuclear reactors [25].

5. Results

Enhanced Heat Transfer: Nanofluids show consistent improvements in heat transfer coefficients and coolant outlet temperatures across various reactor types, indicating enhanced heat removal capabilities and overall reactor performance.

Challenges and Uncertainties: Issues like nanoparticle deposition, elevated pressure drops, and uncertainties concerning their impact on neutronic behavior and reactor compatibility present significant challenges.

Need for Further Research: Optimizing nanoparticle concentrations, understanding their behavior under diverse flow conditions, addressing stability concerns, and developing specific models for reactor geometries are crucial for practical implementation. Extensive testing under reactor-specific conditions is essential to ensure safe and effective application.

6. Discussion

Overview of Nanofluid Applications and Heat Transfer Enhancements in Different Nuclear Reactor Types discussed in the Table 1.

Table 1 Nanofluid Applications and Heat Transfer Enhancements in Different Nuclear Reactor Types

Field of Review	Observation	Reference
Enhanced Heat Transfer in VVER-1000 Reactors:	Seyed Mohammad Mousavizadeh and team delved into the impact of TiO_2/water nanofluids on heat transfer within VVER-1000 nuclear reactors. Their study underscored the positive effects of nanofluids on heat transfer coefficients and the reduction of the Minimum Departure from Nucleate Boiling Ratio (MDNBR), vital for reactor safety.	[19]
Heat Transfer Enhancement in VVER-440 Reactors	Deepak Sharma and K. M. Pandey examined CuO/water-based nanofluids in VVER-440 nuclear reactors, highlighting significant heat transfer coefficient improvements. Their findings stressed the potential of these nanofluids to enhance heat transfer within triangular fuel rod assemblies.	[20]
Nanofluids in Light Water Reactors (LWRs)	Jacopo Buongiorno and Lin-wen Hu investigated the application of nanofluids in light water reactors, aiming to increase power density for improved economic viability. Their study highlighted nanofluids' capability to accelerate quenching, aiding emergency cooling systems while emphasizing the need to address concerns about reactor behavior and radioactivity.	[21]
Nanofluid's Role in Fuel Rod Bundles	Kang Liu's research examined ZnO-based nanofluids in simulated nuclear fuel rod bundles, showcasing heat transfer enhancement potential. However, challenges with nanoparticle deposition at higher temperatures highlighted the need for addressing deposition issues for practical application.	[22]
Nanofluids in Pressurized Water Reactors (PWRs)	Multiple studies by different researchers, including Mohammad Nazififard, Z. Rahnama, and G.R. Ansarifar, explored nanofluids (Al_2O_3, SiO_2, Yttrium oxide) in PWRs, demonstrating heat transfer improvements but noting concerns about increased pressure drop. These studies emphasized the importance of optimizing nanoparticle concentrations for practical implementation.	[24] [25] [26]
SMRs and Nanofluid Application	Researchers like Z. Rahnama, G.R. Ansarifar, and Palash K. Bhowmik explored nanofluid use in Small Modular Reactors (SMRs). While acknowledging the potential benefits of nanofluids for enhancing safety and efficiency, they highlighted challenges regarding pressure drop control and the need for careful consideration before implementation.	[25] [26] [35]
Safety Measures and Nanofluids in Nuclear Power Plants	Studies conducted by Jacopo Buongiorno, Lin-wen Hu, S.M.Mousavi Zadeh, and G.R.Ansarifar delved into nanofluids' role in enhancing safety in nuclear power plants. They pointed out the potential benefits of nanofluids in areas like Critical Heat Flux (CHF), Emergency Core Cooling Systems (ECCS), and In-Vessel Retention (IVR) during severe accidents. However, they stressed the necessity of further research to ensure safe and effective implementation.	[25] [36] [37]
Nanofluids in Various Reactor Configurations	Numerous studies, including those by Kang Liu, Jubair A. Shamim, and Deepak Sharma, investigated nanofluid applications in different nuclear reactor geometries. They highlighted the potential for enhanced heat transfer coefficients but also underscored trade-offs, such as increased pressure drop, emphasizing the need for precise modelling and optimization.	[20] [22] [23] [28]

These studies collectively featured the potential of nanofluids to enhance heat transfer in various nuclear reactor types while highlighting challenges that need to be addressed before practical implementation.

7. Conclusion

The integration of nanofluids into nuclear power plants offers remarkable potential to transform heat transfer efficiency and safety in these critical energy systems. While their application shows promising benefits in enhancing heat transfer coefficients, improving thermal conductivity, and reducing safety parameters like Minimum Departure from Nucleate Boiling Ratio (MDNBR), challenges such as nanoparticle deposition, increased pressure drops, and uncertainties regarding their impact on reactor behavior and radioactivity persist. Addressing these hurdles through rigorous research, testing, and understanding their effects on safety and performance is essential before practical implementation.

Compliance with ethical standards

Disclosure of conflict of interest

Authors have declared that no conflict of interests exists.

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