Proceedings of CONF-MCEE 2026 Symposium: Advances in Sustainable Aviation and Aerospace Vehicle Automation
DOI: 10.54254/2755-2721/2026.KA26738

The Clogging Mechanism of Nanofluids in the Cooling System of Nuclear Reactors

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Abstract. Nanofluids have the potential to enhance heat transfer efficiency and increase safety margins in nuclear reactor cooling systems due to their superior thermophysical properties, such as significantly improving the thermal conductivity of the base liquid and enhancing convective heat transfer and critical heat flux. However, the deposition of nanoparticles within the system causes complex clogging problems, resulting in reduced flow channel cross-sectional area, increased pressure drop, deteriorated heat transfer and equipment wear. The blockage is caused by the combined effects of nanoparticle characteristics, fluid dynamics conditions and environmental or material factors (e.g., temperature, pressure, wall roughness). The clogging behavior of nanofluids in special conditions (such as strong corrosiveness and radiation fields) for advanced reactors (lead-cooled fast reactors, sodium-cooled fast reactors, molten salt reactors, and supercritical water-cooled reactors) has not been fully elucidated. Future work should focus on surface-modified particles, multi-scale simulations/machine learning for deposition prediction, and long-term behavior in extreme conditions. Controlling blockages is critical for scaling nanofluids in nuclear energy.

Keywords: Nanofluids, Nuclear reactor cooling systems, Blocking mechanism, Nanoparticle deposition

1. Introduction

Nanofluids, new types of fluids that disperse nanoscale (typically 1-100 nm) particles in traditional base fluids such as water, ethylene glycol, oil, etc., have shown great application potential in many engineering fields, especially in nuclear reactor cooling systems, due to their excellent thermophysical properties. By significantly improving the thermal conductivity and heat transfer coefficient of the base liquid, nanofluids are expected to enhance the cooling efficiency of nuclear reactors, increase safety margins, and support more compact reactor designs. For example, in pressurized water reactors (PWRS), nanofluids are seen as key to improving heat transfer performance and safety. However, the clogging problem caused by the deposition of nanoparticles in the cooling system is a major challenge for the practical application of nanofluids in nuclear reactors. This deposition can lead to channel blockage, increased pressure drop and deteriorating heat transfer, and even cause equipment wear and corrosion. This paper will delve into the heat conduction mechanism of nanofluids in nuclear reactor cooling systems, the clogging mechanism

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caused by nanoparticle deposition and its influencing factors, and look forward to future research directions, particularly those specific application areas that have not been fully reviewed.

2. The heat conduction mechanism of nanofluids in nuclear reactors

2.1. Enhanced thermal conductivity and convective heat transfer

The addition of nanoparticles significantly increases the effective thermal conductivity of the base liquid [1-3]. For example, Al_2O_3/H_2O nanofluids show better heat transfer performance with increasing concentration, especially when the volume fraction is less than 2.0%, but too high a concentration may backfire [1,4]. The application of silver water (Ag-H_2O) nanofluids in the HPR-1000 nuclear reactor shows that the average heat transfer coefficient is 67.15% higher than that of pure water, the minimum deviation from nuclear boiling ratio (MDNBR) is 45.23% higher, and the fuel rod wall temperature is 28.5K lower. This shows its great potential in enhancing thermal performance and safety [1,5]. Ternary mixed nanofluids (such as those containing gold, silver, and diamond nanoparticles) show superior thermal conductivity compared to single or double mixed nanofluids [6].

The Brownian motion of nanoparticles in the fluid increases the microscopic mixing of the fluid and breaks the boundary layer near the wall, thereby enhancing convective heat transfer [1,3,4]. The presence of nanoparticles also increases the intensity of fluid turbulence, further facilitating heat transfer [4].

2.2. Enhanced Critical Heat Flux (CHF) and Minimum Off-Nuclear Boiling Ratio (MDNBR)

CHF and MDNBR are key parameters for the safe operation of nuclear reactors. Nanofluids have been shown to significantly increase CHF, thereby maintaining stable nuclear-state boiling at higher thermal loads and preventing boiling crises [1,2,7]. The nanolayer formed by nanoparticles on the heated wall is considered the main reason for the increase in CHF, as it can increase nucleation sites and improve the wettability of the wall [7]. Research on the NuScale small modular reactor shows that Al_2O_3 nanofluids can increase MDNBR and heat transfer coefficients without a significant effect on neutron properties [1,4].

2.3. Factors affecting heat transfer performance

The heat transfer performance of nanofluids is influenced by a variety of factors, including the type of nanoparticles (Al_2O_3, CuO, TiO_2, Ag, etc.), volume fraction, particle size, shape, temperature, and base liquid type [1-5]. For example, Al_2O_3-Cu/ water mixed nanofluids have a higher heat transfer rate than Cu/ water nanofluids [8]. Magnetic fields, Prandti number, Brownian motion parameters, thermal swimming parameters, and thermal radiation also affect the velocity and temperature distribution of the nanofluid, thereby influencing heat transfer [3,6,8].

3. Clogging mechanisms caused by nanoparticle deposition

Despite the significant advantages of nanofluids in heat transfer, the deposition of nanoparticles on the walls of cooling systems is one of the major challenges for their application in nuclear reactors. This deposition can lead to many problems:

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3.1. Particle deposition phenomenon

Nanoparticles tend to form deposition layers on heated walls at high temperatures or high heat flux density regions [2,7]. During the boiling process, nanoparticles deposit onto the heated wall, while the growth and detachment behavior of bubbles also change [2,7]. This deposition not only alters the heat transfer properties but may also affect the two-phase flow structure of the fluid [2]. The deposited nanoparticles will gradually reduce the cross-sectional area of fluid flow, increase fluid flow resistance, resulting in an increase in pressure drop [2,3,7]. In lead-based fast reactor (LFR) fuel assemblies, corrosion products, thermal expansion of the material, and the accumulation of foreign matter can all lead to a reduction in the flow passage area, causing clogging accidents [2]. More seriously, solid particles released from damaged fuel casings may carry nuclear fuel, generating additional heat in the clogging area. Moreover, a reduction in the flow channel area and an increase in surface roughness can significantly increase the pressure drop in coolant flow, resulting in increased pumping power and higher system operating costs [3,7]. Studies have shown that when the nanoparticle volume concentration exceeds 3%, the core pressure drop can increase by more than 20%, which is unacceptable in engineering [7]. Deposition layers typically have a lower thermal conductivity, which creates additional thermal resistance that hinders heat transfer from the fuel rods to the coolant, causing local overheating and even leading to cladding failure and fuel melting. The deposition and interaction of nanoparticles may exacerbate the corrosion of materials in the cooling system, while high-speed flow of particle-containing fluids may also cause wear on pipes and equipment [2,3,7].

3.2. Complexity of clogging mechanisms and influencing factors

Nanoparticle characteristics include several key factors. The concentration of nanoparticles plays a crucial role, as high concentrations typically come with a higher risk of deposition and a more significant increase in pressure drop [1,7]. Their size and shape are also important, since smaller particle sizes lead to more intense Brownian motion, which may result in more uniform dispersion but also increase the likelihood of wall deposition [2,7], while non-spherical particles are more prone to cause clogging compared with spherical ones [4]. In addition, surface properties such as surface charge, hydrophilicity and hydrophobicity, the presence of functional groups, and whether nanoparticles have undergone surface modification can significantly influence their dispersion stability in the base liquid and their interaction forces with the wall (e.g., van der Waals forces), thereby affecting deposition [2,3,7]. Finally, the coefficient of static friction between particles also plays a role in clogging formation [2].

3.3. Hydrodynamic factors

Flow velocity has a significant influence on particle behavior, as deposition is more likely to occur in areas with low flow velocities [3,7], and changes in flow velocity also affect the shear force of particles on the wall, thereby influencing deposition [7]. Brownian motion, while enhancing heat transfer, may also cause nanoparticles to collide randomly and attach to the wall [3,7]. Thermal mobility further contributes to deposition, since in areas with temperature gradients nanoparticles tend to move from the high-temperature zone to the low-temperature zone, leading to accumulation on the cooled surface [2,3,7]. The shear force of the fluid on the wall affects the resuspension of deposited particles, while drag forces are closely related to particle movement in the fluid and the deposition process [3]. In addition, the resuspension behavior of aerosol particles in nuclear reactors is influenced by various factors such as airflow, Brownian force, and thermal swimming force, which may cause radioactive leakage [3].

3.4. System and environmental factors

Temperature and pressure have important effects, as high-temperature and high-pressure environments may alter the stability and agglomeration behavior of nanoparticles, thereby affecting deposition [1,3,7]. Wall properties, including roughness, material type, surface energy, and wettability, can also influence particle adhesion, and corrosion products may act as additional deposition sites [2,3,7]. Nanoparticles may undergo agglomeration in the fluid to form larger particle clusters that are more likely to settle and clog the flow channels [3,7]. Moreover, the chemical environment, such as the pH value of the coolant, the dissolved oxygen content, and the presence or absence of other ions or impurities, also affects the stability and deposition behavior of nanoparticles [7].

4. Numerical simulation and experimental research methods

Computational Fluid Dynamics (CFD) is widely used to simulate the flow and heat transfer behavior of nanofluids in complex geometries [1,2,5]. For example, CFD simulations can be used to analyze the heat transfer performance of Al_2O_3/H_2O nanofluids in pressurized water reactors (PWR). In the HPR-1000 nuclear reactor, the thermal-hydraulic properties of silver water nanofluids in the fuel rod flow channel were simulated using Euler computational fluid dynamics [5]. In nuclear reactors, by combining Monte Carlo particle transport code (MCNP) and COBRA IV PC code, the effects of mixed nanofluids on the heat transfer characteristics of VVER-1000 nuclear reactors, including axial coolant temperature distribution and MDNBR value [1], can be investigated. Direct observation of nanoparticle deposition and clogging by simulating the operating conditions of the nuclear reactor cooling system in an experimental setup [2,3]. For example, in a lead-based fast reactor, the flow resistance characteristics and clogging formation mechanism caused by solid particles in the fluid flow path were experimentally studied [2]. Experimental studies of flow blockages in fast reactors have shown that the ratio of particle diameter to outlet size is a key determinant of the probability and location of blockages [2]. Hybrid methods that combine traditional numerical simulations with machine learning algorithms such as DNN and LSTM can predict and control nanoparticle deposition in heat exchangers more accurately [2,9]. For example, studies have combined Eulerian-Lagrangian methods with neural network algorithms to predict the deposition behavior of alumina nanoparticles in hexagonal tube heat exchangers with a prediction accuracy of up to 97% [9].

5. Nanofluidic applications and clogging challenges

Although nanofluid applications in pressurized water reactors (PWRs) have been extensively studied, such as in the VVER-1000 reactor [1,4], there remains a significant gap in comprehensive reviews regarding their potential applications and associated clogging mechanisms in other advanced nuclear reactor types. The following are several directions worthy of further exploration.

In addition to studies on specific reactor types, other directions that deserve attention but have been less reviewed .

Nanoparticle surface modification on deposition inhibition is one of these directions. A systematic review of how different modification methods (such as polymer coating and charge

DOI: 10.54254/2755-2721/2026.KA26738

stabilization) affect their long-term stability and deposition inhibition effects in the specific environment of the nuclear reactor cooling system remains a worthy direction to delve into [7].

There are intense radiation fields within nuclear reactors, which may affect the physicochemical properties of nanoparticles, accelerate agglomeration or alter their deposition behavior [8]. There is relatively little research on this at present [8]. In addition, nanoparticles can also be used for radiation shielding. Dispersing high-Z-value nanoparticles in coolants can enhance the coolant's ability to absorb neutrons and gamma rays, but their long-term stability and clogging issues need attention [7].

Future research could focus on developing composite nanofluids with multiple functions (such as heat transfer enhancement, radiation shielding, and corrosion inhibition) and exploring their complex clogging mechanisms [7]. For example, mixed nanofluids may outperform single or dual mixed nanofluids in terms of thermal conductivity [6], but their long-term stability and clogging properties in nuclear reactor environments still require further study [8].

6. Prevention and mitigation strategies for nanofluid clogging

One way is to optimize nanoparticle properties. Firstly, surface modification of nanoparticles can change their surface charge as well as hydrophilicity or hydrophobicity, which in turn enhances the repulsive force between particles, inhibits agglomeration, and improves dispersion stability. Secondly, there is particle size and shape control, where one should select particle sizes and shapes that are less likely to deposit. Additionally, developing novel nanofluids is also important, and this involves exploring novel nanofluids with self-healing or anti-deposition properties [7].

Another approach is the improvement of the preparation and circulation system of nanofluids. For dispersion technology, more efficient dispersion methods and long-term stability technologies should be adopted to ensure the uniform and stable suspension of nanoparticles in the base liquid [7]. Moreover, online monitoring and filtration are crucial; advanced online monitoring techniques need to be developed to detect nanoparticle agglomeration and deposition in real time and intervene at the initial stage of clogging [2,7]. Furthermore, system design optimization plays a role as well. The flow channel design of the cooling system should be optimized to reduce dead zones, bends and abrupt changes, and lower local shear stress, thus reducing particle deposition in these areas [7].

An in-depth understanding of deposition mechanisms is also essential. To achieve this, multi-scale simulations can be utilized. By combining molecular dynamics, CFD, and system-level simulations, a comprehensive understanding of nanoparticle agglomeration, transport, and deposition processes from micro to macro levels can be gained, and the likelihood and location of blockages can be predicted [7]. Also, environmental compatibility studies are necessary. In-depth research should be conducted on the long-term stability of nanoparticles in specific high temperatures, high pressures, strong radiation, and corrosive media of nuclear reactors, along with their interactions with reactor structural materials [6,7].

7. Conclusions

Nanofluids have great potential to enhance the performance of nuclear reactor cooling systems, particularly in terms of improving heat transfer efficiency and increasing safety margins. However, the deposition of nanoparticles and the resulting clogging problem are key challenges that must be addressed before their widespread application. A deep understanding of the thermophysical properties of nanoparticles, their hydrodynamic behavior, and their interaction with the material of the cooling system is the foundation for solving the clogging problem.

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However, this paper fails to fully clarify the clogging behavior of nanofluids under the special operating conditions of advanced reactors (such as lead-cooled fast reactors and sodium-cooled fast reactors). There is insufficient research on the long-term stability and deposition characteristics of nanofluids in radiation environments and extreme accident conditions (strong radiation, high temperature, corrosive media). Moreover, it does not deeply explore the complex clogging mechanisms of multifunctional composite nanofluids, and there is still room for improvement in the accuracy and applicability of nanoparticle deposition prediction.

Subsequent research should focus on developing more stable and less depositable nanofluid formulations, optimizing the size, shape, and surface modification of nanoparticles; combining advanced experimental techniques, computational fluid dynamics (CFD), and machine learning methods to improve the simulation and prediction accuracy of nanoparticle deposition and clogging behavior in complex nuclear reactor cooling systems; conducting customized research on nanofluid applications and clogging mechanisms for specific advanced reactor types such as lead-cooled fast reactors, sodium-cooled fast reactors, molten salt reactors, and supercritical water-cooled reactors; and deeply studying the stability, deposition characteristics, and safety impacts of nanofluids under long-term operation and extreme accident conditions.

Through the continuous in-depth study of these challenges, it is expected to develop nanofluid coolants that can both efficiently transfer heat and effectively avoid clogging, thereby promoting the development of nuclear energy technology towards a safer and more efficient direction.

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