Advances in CFD Assessment of Thermal-Hydraulic Performance of Transformer Cooling Oils: A Review

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Abstract: The thermal-hydraulic performance of transformer cooling oils is critical for ensuring the reliability, efficiency, and longevity of power transformers. This review explores recent advances (2020–2025) in the application of Computational Fluid Dynamics (CFD) to analyze and optimize transformer cooling systems using traditional mineral oils and alternative fluids such as natural esters, synthetic esters, and nanofluids. Mineral oils, while widely used, pose environmental and fire safety risks, prompting a shift toward biodegradable, fire-resistant esters and nanofluid-enhanced oils. CFD has emerged as a vital tool for simulating complex fluid flow and heat transfer phenomena within transformer systems, reducing the need for costly and time-consuming experiments. Recent studies employed advanced modeling techniques, including conjugate heat transfer, turbulence models, and multiphase flows, validated through experimental data and thermal benchmarking. CFD has not only facilitated the comparative analysis of cooling fluids but also guided the design of more efficient cooling structures and innovative cooling techniques. Optimization strategies, such as genetic algorithms and response surface methodology, further enhanced performance by minimizing hotspot temperatures and improving flow distribution. This review underscores CFD's crucial role in the development of safer, environmentally friendly, and high-performance transformer cooling solutions.

Keywords: CFD, transformer cooling, mineral oil, natural ester, synthetic ester, nanofluids, thermal-hydraulic performance, optimization.

I INTRODUCTION

Transformers are critical components of electrical power systems, facilitating electricity generation, transmission, and distribution. They are used at every transition point between voltage levels, making them one of the most strategic assets in power grids. Power systems consist of multiple generation locations, distribution points, and interconnections, and transformers must step up or down the voltage at each point. Transformers are classified based on various criteria, such as power capacity (distribution transformers: 50–2500 kVA; power transformers: above 2500 kVA), insulation type (dry-type or liquid-insulated), and their use in primary or secondary substations. In typical transformer stations, transformers account for nearly 60% of the total investment, underscoring their importance [1]. Transformer efficiency is a key concern for both transformer operators and regulators, particularly with regards to new transformers. Cooling is a critical factor in preventing overheating and controlling the ageing of transformer insulation [2]. Transformers generate significant heat during operation due to electrical losses. Effective cooling is essential to maintain performance, prevent insulation degradation, and extend service life. Traditional cooling methods use mineral oils for both insulation and heat dissipation [3]. However, concerns over environmental impact and fire safety have led to the development of alternative coolants, such as natural esters and synthetic fluids. Modern cooling approaches also explore advanced techniques like forced air, forced oil circulation, and even nanofluid-enhanced oils to improve thermal management and efficiency.

The life of machine depends upon the insulation level and in transformers, mineral oil performs two functions i.e., cooling, insulation, and these both functions are interrelated to the life of the transformer, if the mineral oil has high breakdown strength and best cooling, it will lead to increase in life of the transformers. To cope with the increasing demand for power in the future and the need of the hour will be transformers of small size [4]. The cooling oil is important for two reasons-aesthetic consideration and thermal management. Transformers generate heat with appreciable quantities, which surpasses border energy losses in the core and windings. These oils take the heat away from the active parts to avoid warming up [5]. Thru good heat dissipation, thermal stability of the transformer is preserved, which in turn is necessary for the maintenance of mechanical strength and dielectric properties of the insulation system. Temperature rise can speed up the aging of the insulation without adequate cooling; thus, operational efficiency is hampered and becomes susceptible to failure by electrical faults. Beyond thermal regulation, cooling oils act as an insulating medium. They prevent electrical discharges, arcing, and dielectric breakdown inm between transformer windings and the core parts. The reliability, efficiency, and service life of transformers are hence directly affected by the performance of cooling oils [6]. Special mineral oils available hitherto have been used extensively because of their good dielectric properties and thermal performance. However, considerations of environmental harm and fire safety led to other fluids being available such as natural esters and synthetic oils. T1he newer fluids are biodegradable and also present higher fire points and moisture tolerance, increasing the safety and sustainability of modern transformer systems [7].

Computational Fluid Dynamics (CFD) in thermal-hydraulic studies provides a wealth of information concerning fluid flow processes and heat transfer in transformer cooling systems. Regular experimental methods for testing cooling performance in transformers tend to be expensive, time-consuming, and incapable of capturing complex flow behaviors and temperature distributions [8]. CFD allows researchers and engineers to input a wealth of defining information into the simulation for precision in understanding the phenomena under consideration, enhancing the evaluation of cooling designs, oil types, and operational conditions without heavy physical prototypes [9]. The application of CFD leads to the optimization of the design of transformer cooling systems regarding thermal performance, hot-spot alleviation, and overall efficiency improvements. It also provides some unique opportunities to evaluate prospective new cooling fluids such as alternate oils and nanofluids under realistic operating conditions [10]. This predictive capability becomes crucial to developing cooling solutions that are, in fact, safer, more reliable, and environmentally friendly, especially as power systems gear toward meeting greater demands on the grid and incorporating more renewable energy sources [11]. Additionally, CFD supports the development and assessment of innovative cooling techniques, including forced oil circulation, directed airflow, and the use of nanofluids or hybrid cooling fluids. By predicting how these advanced methods will perform in real-world scenarios, CFD aids in reducing design risks, improving reliability, and accelerating the development cycle of transformer systems. In the context of modern power grids—which are becoming increasingly complex due to the integration of renewable energy and variable loads—CFD provides the flexibility and accuracy needed to design resilient and efficient cooling solutions that meet evolving demands [12].

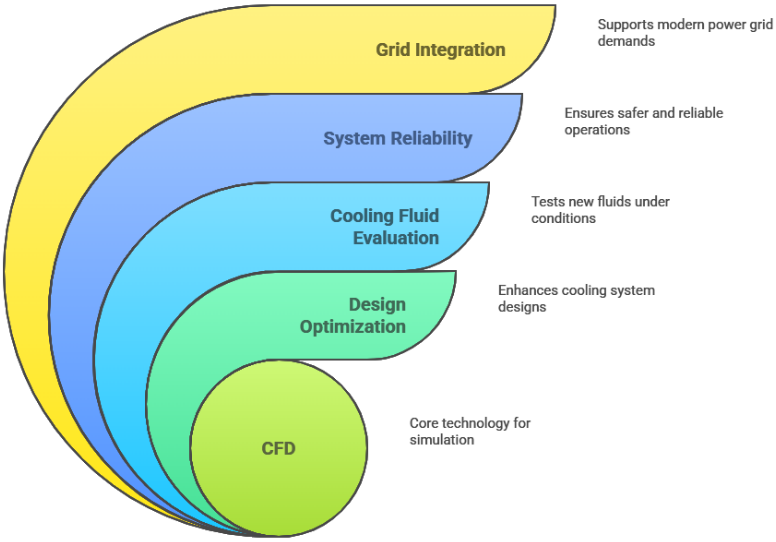

Figure 1: CFD in Transformer Cooling Systems

As illustrated by figure 1, CFD has many stages in enhancing transformer cooling systems. First-of-its-kind CFD serves as simulation technology through which fluid flow and heat transfer can be investigated in detail. This foundation enables engineering design optimization, wherein CFD can improve cooling system configurations. Taking this one step further, CFD also enables cooling fluid evaluation by running tests and performance assessments on newer more alternative fluids at different temperatures and pressures. The next layer of reliability in systems is added when CFD predicts and provides insight on risk failure events to ensure better safety and availability. At the highest level, CFD supports the design of transformers to ease their incorporation into the new power grid bearing in mind modern demands for efficiency, flexibility, and sustainability. Overall, the diagram illustrates how CFD underpins advancements both in terms of technology and strategy development for transformer cooling and power system reliability.

II TRANSFORMER COOLING OILS

Conventional mineral oils have been used for many decades as the cooling and insulating fluids for transformers. These oils, which come from refined petroleum, are well known for their very good dielectric properties that prevent electrical discharges and provide insulation between transformer components. They also have fair thermal conductivity and specific heat capacity to enable heat absorption and transfer away from the core and windings so that overheating is minimized [13]. Concerning performance, mineral oils ensure long-term reliable operation through a range of temperatures under which transformers are worked. They remain chemically stable and have good insulation and cooling properties for a long period of time with good maintenance practices. Mineral oils have low viscosity, allowing quick and effective circulation of fluids in natural and forced convection cooling processes [14]. However, they are not without drawbacks such as being flammable, environmentally hazardous due to low biodegradability, and potentially toxic. With the expectation of more grueling operational conditions, the search for alternative fluids with better safety, environmental, and performance index is now a necessity [15]. In regards to the limitations posed by the traditional mineral oils--especially their flammability, polluting behavior, and aging--a few other alternate insulating and cooling fluids were studied and developed; amongst them are natural esters and synthetic esters, which are currently two of the most promising choices. The oil derived from the vegetable source is called natural ester; synthetic ester is the one obtained from chemico-synthesis compounds. Therefore, oil-based cooling using esters appears to be a promising solution in the sustainable and environmentally friendly context [16]. Ester oil is becoming a substitute to replace mineral oil for transformers due to higher fire safe, environmentally friendly, higher thermal stability and or longer insulation life (transformer life). The chemical composition and molecular structure of ester oil groups of natural ester oil and synthetic ester oil are entirely different from commonly used petroleum based mineral oil. The higher viscous nature of ester oil will increase the oil temperature rise, winding temperature rise, winding gradient and hot-spot temperature due to less convective heat transfer [17].

Natural esters are biodegradable fluids obtained from vegetable oils, such as soybean oil, rape seed oil, or sunflower oil. The advantages are excellent biodegradability, low environmental toxicity, increased fire safety due to a much higher fire point as compared to mineral oils, and much better moisture tolerance; in other words, natural esters can absorb considerable amounts of water without substantial reduction of their dielectric strength, thus preventing electrical breakdown in humid conditions. Furthermore, good results have still been recorded with oxidation stability when natural esters are inhibited, but they can oxidize faster than synthetic esters themselves if not looked after properly [18]. Synthetic esters are designed with greater performance than mineral oils and natural esters. They maintain the high fire point of natural esters but offer greater thermal and oxidative stability, which makes their usage feasible in more demanding applications or environments where higher operating temperatures are expected [19]. Synthetic esters have similar excellent dielectric properties as those of natural esters while providing better characteristics of viscosity-temperature and cooling efficiencies through a wide temperature range.

Both types of ester-based oils favor an improvement towards a greener world through the reduction of environmental threats and an improvement in transformer fire safety. They also improve the life of the equipment by reducing insulation aging and decrease hot spot temperatures. However, the price usually shoots higher than that of mineral oils and may require special design, like compatibility with gaskets and other materials being used in existing transformer designs [20].

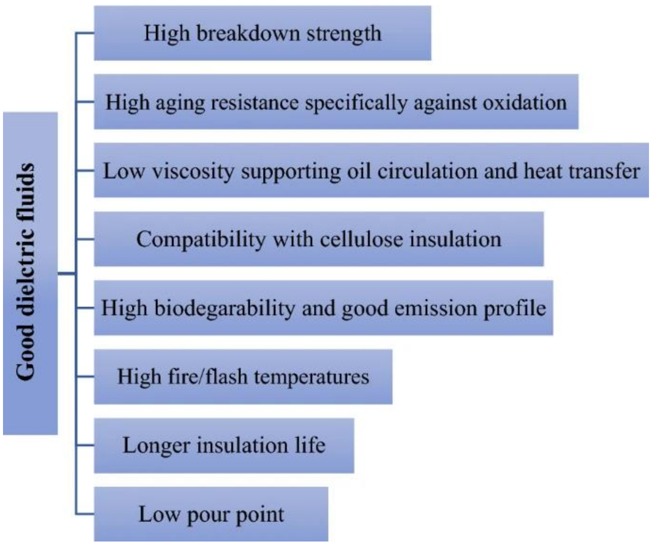

Figure 2. Desired characteristics of good dielectric fluids for transformers [21]

Figure 2 emphasizes the most essential requirements for transformer high-performance dielectric fluids. These fluids should possess high breakdown strength to withstand electrical stresses and provide insulation integrity. Good aging resistance, especially towards oxidation, prolongs fluid life and minimizes maintenance. Low viscosity will help the circulation of oil and therefore helps in heat transfer, which contributes to cooling. Compatibility with cellulose insulation is paramount for the performance of solid insulation systems. Environmental issues are addressed through high biodegradability and good emission profiles, thus reducing adverse ecological impacts. High fire point and flash point increase safety by reducing the risk of fire. It is also desirable for such fluids to extend insulation life and have a low pour point to remain fluid at low temperatures for reliable operation in very diverse conditions.

The environmental aspects involved in choosing the fluid cooling for transformers are becoming an increasingly important consideration. The obvious drawback associated with traditional mineral oils is their poor biodegradation and potential toxicity, resulting in adverse effects upon the environment [22]. They can potentially contaminate soil and water and involve expensive remediation driven by regulatory demands in the event of a leak or spillage. The fire points of these oils are relatively low, contributing to the risk of fire in case of an accident, especially in densely populated or sensitive areas [23]. On the other hand, natural esters and synthetic esters biodegrade easily and are non-toxic; their comparatively higher flash and fire point reduce the environmental hazard and improve safety considerably. These fluids are capable of maintaining dielectric performance even in conditions of moisture, promoting the reliability of the system and thereby minimizing environmental hazards associated with the failure of transformers [24]. Lower initial costs make mineral oils favorable for budget-oriented projects from the economic stand. However, long-term costs can be higher due to more frequent maintenance, environmental liability, and shorter fluid and insulation life. With ester-based fluids, front-end costs are offset by longer service life, reduced maintenance, and lower fire hazards, all of which add up to reduce total ownership costs over the transformer's lifecycle [25]. Where environmental regulations are tightening and the demand for sustainable energy solutions becomes stronger, ester fluids can become economic assets to utilities and industries seeking to avert penalties while achieving sustainability goals [26].

III CFD TECHNIQUES AND MODELING APPROACHES

CFD is a basic tool used to analyze thermal and fluid flow behaviors in transformer cooling systems. Such modeling typically encompasses the development of fine geometries, the generation of computational meshes, and the solving of quasi-governing equations (Navier-Stokes for fluid flows and energy equations for heat transfer) using either FVM or FEM. Turbulence models like k-ε and k-ω SST simulate the desired flow regimes, while CHT deals with the interaction between fluids and solids [27]. Other sophisticated studies involve transient simulations, multiphase flows, and optimization algorithms such as Response Surface Methodology (RSM) for design parameter tuning. The CFD methodology can vary from simplified 2D or axisymmetric models to more complex 3D simulations that entail full modeling of the transformer geometries, such as windings, cores, and cooling channels [28]. Usually, the CFD model findings are validated through experimental data and available benchmarks. For example, a detailed 3D CFD model against experimental measurements of hotspot temperatures in a 200 kVA transformer, finding a good correlation between the two and asserting that CFD is reliable for real performance predictions. Commonly, benchmarking is centered around major quantities, including hotspot temperature, heat flux distribution, and fluid velocity profiles. Finally, the validated models have endorsed various cooling design aspects (e.g., fin dimensions) but have also shown that CFD can predict the impacts of operating conditions and design variations with high fidelity [29]. Despite its strengths, CFD modeling in transformer cooling faces notable challenges. Accurately capturing complex flow behaviors, especially turbulence and natural convection within intricate geometries, requires fine meshing and high computational resources. Simplifications in geometry or boundary conditions, often necessary to reduce computational load, can lead to discrepancies between simulations and real-world performance.Additionally, obtaining precise thermo-physical properties of cooling fluids (especially alternative oils) under varying operating conditions remains difficult. Dynamic scenarios like fluctuating loads and fault conditions add further complexity to the simulations, often requiring transient analysis that increases computational cost and time [30].

IV CFD STUDIES ON TRANSFORMER COOLING OILS

CFD studies during 2020 to 2025 made great strides in the understanding of transformer cooling oils, concerning mineral oils practically and alternative fluids such as natural esters, synthetic esters, and nanofluids. Detailed conjugate heat transfer models were created by researchers to compare the thermal performance of these fluids in disc-type winding configurations that were found to deliver a more uniform flow distribution and less hotspot temperatures of natural esters than that of mineral oils [31]. Another study studied insulating oils concerning low ambient temperatures, and it was found that esters maintained good cooling performance while highly viscous and thus made them suitable for application under extreme environmental conditions [32]. The reviews also included coverage of thermal and dielectric improvements up to which nanofluids were associated with the use of these in achieving the better thermal conductivities and breakdown voltages while addressing environmental and safety concerns [33]. Further work involved the development of advanced CFD modelling methods, which should be verified against either experimental or benchmark data. Some of the studies compared CFD models and thermal hydraulic networks specifically for transformer windings, thereby enhancing one's understanding of the various thermally refractive oils [34]. Coupled CFD and electromagnetic analyses have been used to assess the ONAN transformer performance with mineral oils and biodegradable esters and verify for commercial quality measurements the ability of CFD to predict the real cooling behavior [35]. Closed loop CFD models for very large transformers predicted correctly the hotspot temperatures and also provided major flow features such as reverse flow and stagnation zones, leading to design improvements [36,37,38]. In this regard, these studies validate CFD as a robust tool in the analysis of complicated thermal-fluid interactions in transformer cooling. Along with CFD, optimization strategies were enhancing cooling designs. For example, in renewable energy applications, hotspot temperatures were markedly decreased by optimizing transformer cooling systems using genetic algorithms and CFD combinations [39]. Parametric studies using response surface methodology determined geometrical factors governing cooling efficiency, namely fin height and spacing [40]. Altogether these studies showcase the adaptableness of CFD for modeling, validating, and optimizing transformer cooling systems using different fluids toward the advancement of safer, highly efficient, and environmentally benevolent transformers.

TABLE 1 Comparative Summary of Key CFD Studies on Transformer Cooling Oils

Authors (Ref. No.)	**CFD Focus/Technique**	**Cooling Fluids Studied**	**Key Findings**	**Validation Approach**
[1] Salerno et al., 2024	Conjugate heat transfer model	Mineral oil, natural/synthetic esters	Natural esters lowered hotspot temperatures	Simulation vs. experimental comparison
[2] Lopez-Rodriguez et al., 2022	Low-temperature CFD performance analysis	Mineral oil, esters	Esters effective despite high viscosity at low temps	Field data comparison
[3,8] Sorte et al., 2025	Comprehensive reviews of CFD and cooling techniques	Mineral oils, esters, nanofluids	Nanofluids improved thermal and dielectric properties	Literature review and synthesis
[4] Santisteban et al., 2019	CFD vs. thermal-hydraulic network models	Mineral and ester-based oils	Highlighted thermal performance differences	Comparison with network model results
[5] Renedo et al., 2020	Coupled CFD and electromagnetic analysis	Mineral oil, biodegradable esters	Validated CFD accuracy in ONAN transformers	Experimental validation
[6] Zhang et al., 2023	Closed-loop CFD modeling	Mineral oil	Accurate hotspot temperature prediction	Experimental validation
[7] Yuan et al., 2023	Reverse oil flow characterization	Mineral oil	Identified flow stagnation zones and proposed design changes	CFD simulation validated by flow studies
[9] Yükselen & Iskender, 2023	CFD + Genetic Algorithm optimization	Mineral oil	Reduced hotspot temperatures in solar transformer	Simulation results compared with benchmarks
[10] Xu et al., 2023	CFD-based IEC thermal model improvement	Mineral oil	Improved hotspot prediction accuracy	IEC model comparison

[11] Bingshan Ma et al., 2024	CFD + Response Surface Methodology optimization	Mineral oil	Improved cooling by introducing V-shaped structures to disrupt boundary layer	CFD simulation validated by thermal performance testing

V CONCLUSION

Effective cooling is critical for ensuring the reliability, efficiency, and longevity of power transformers. Transformer cooling oils not only manage heat dissipation but also provide essential insulation, directly influencing performance and lifespan. Traditional mineral oils have long been used for their good dielectric and thermal properties, but their environmental impact, flammability, and aging limitations have prompted the development of alternative fluids such as natural esters, synthetic esters, and nanofluids. These alternatives offer advantages like biodegradability, higher fire points, and improved thermal stability, contributing to safer and more sustainable transformer operation. Computational Fluid Dynamics (CFD) has emerged as a powerful tool for analyzing and optimizing thermal-hydraulic performance, enabling precise simulation of heat transfer and fluid flow without reliance on expensive physical testing. Advanced CFD techniques—including turbulence modeling, conjugate heat transfer, and multiphase flow analysis—allow for detailed evaluation of cooling system designs and fluid behaviors under a variety of operational conditions. Validation methods confirm the accuracy of simulations, while optimization strategies help reduce hotspot formation and enhance overall cooling efficiency. As power systems evolve to meet increasing energy demands and environmental standards, the integration of CFD and innovative cooling fluids supports the development of high-performance, reliable, and eco-friendly transformer technologies.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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