Fire Behavior and Safety Assessment of Transformer Oils and Alternative Insulating Fluids: A Review of Cone Calorimeter and Pool Fire Studies

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Abstract - With modern experimental techniques, fire safety research is becoming increasingly interested in determining the flammability and combustion characteristics of vital industrial materials. One such technique is the cone calorimeter, which is one of the most commonly used devices when it comes to quantitative evaluation of fire behaviour by providing accurate measurements of the radiant heat exposure conditions it applies. This review compiles results from several studies on combustion characteristics of transformer mineral oil, an important dielectric fluid used in electrical equipment, since it may pose a fire hazard in case of faults or overheating. Important fire parameters such as heat release rate, mass loss rate, peak heat release rate, and total heat release have been analysed, as these are important for interpreting fire development, spreading probability, and energy output. By comparing results from different studies, this paper indicates the common trends and the variations in experimental outcomes regarding the effect of oil composition and testing conditions on fire behaviour. The discussion will also draw attention to the importance of these combustion properties in risk assessment, material safety evaluation, and designing safer alternatives or prevention measures within industrial applications.

Key Words: *Cone calorimeter, mineral transformer oil, radiant heat, dielectric, thermal characteristics*

1. INTRODUCTION

Transformer oils and insulating fluids play a critical role in the safe and reliable operation of power transformers by providing both dielectric strength and thermal management. However, their high flammability poses a significant fire hazard during fault conditions, thermal degradation, or accidental ignition. Transformer fires, once initiated, can propagate rapidly due to pool fire dynamics, release large amounts of heat and smoke, and compromise both equipment safety and personnel security. For this reason, the fire behaviors, combustion characteristics, and suppression strategies of transformer oils and alternative insulating fluids have attracted extensive research attention.

The cone calorimeter, widely regarded as the "gold standard" for bench-scale fire testing, provides fundamental parameters such as heat release rate (HRR), ignition time, mass loss, critical heat flux, and combustion efficiency. These parameters are essential for developing predictive fire models and for comparing the relative fire risk of different dielectric fluids. However, accurately defining the flame heat flux—the net energy transferred from flames to the fuel surface—remains a challenge, particularly for condensed-phase fuels and liquids. This has led to investigations into methods such as the effective heat of gasification approach and direct flux gauge measurements, each with distinct limitations.

Beyond laboratory-scale cone calorimeter studies, large-scale transformer oil pool fire experiments provide critical insights into burning rate, flame height, radiative heat flux, and flame temperature structure, helping to establish empirical correlations for fire hazard assessment. Complementary studies on fire suppression with water mist highlight operational challenges and design dependencies, while material modifications such as the addition of flame retardants or the substitution of bio-based insulating oils (e.g., coconut oil and natural esters) demonstrate promising pathways for reducing fire risk and improving thermal stability.

Furthermore, the long-term ageing behaviors of insulating oils under thermal and electrical stress impacts their breakdown voltage, viscosity, and chemical stability, thereby influencing both operational reliability and fire hazard potential. Comparative analyses reveal that alternative natural and synthetic insulating fluids often outperform conventional mineral oils in terms of fire resistance and ageing properties, making them viable candidates for safer transformer operation.

Despite these advancements, several research challenges remain. Cone calorimeter techniques for liquids are not yet standardized, flame heat flux estimation methods vary in accuracy, and difficulties persist in scaling bench-scale data to real-world transformer accidents. Novel apparatus such as the Controlled Atmosphere Cone Calorimeter (CACC) offer new opportunities for toxicity and combustion characterization but require further development.

The purpose of this review is to consolidate current experimental and analytical knowledge on the ignition, combustion, suppression, and ageing behaviour of transformer oils and alternative insulating fluids. By examining cone calorimeter methodologies, pool fire investigations, liquid modification strategies, and suppression effectiveness, this work aims to provide a holistic understanding of transformer oil fire hazards and mitigation strategies, while identifying research gaps to advance future fire safety and transformer reliability.[1], [2]

2. FIRE BEHAVIOR ASSESSMENT METHODS

2.1. Fundamentals of Cone Calorimetry and Measurement Techniques

To accurately model the flaming combustion of condensed-phase fuels, the heat flux from flame to fuel surface (flame heat flux) must be defined in the bench-scale test used to obtain mass loss and heat release rate data. In practice, however, flame heat flux data for such tests is usually unavailable. This study assessed two methods for estimating flame heat flux for fire models. The first method calculated effective heats of gasification from tests at multiple external heat fluxes. For methanol, averaged results across three burning domains were consistent, between 16.6 and 17.5 kW/m². For PMMA, values varied widely, from 3.5 to 18.2 kW/m², with only Burning Domain 3 yielding results comparable to the second method. The second method measured total surface heat flux using a heat flux gauge, with flame heat flux taken as the difference between measured total heat flux and baseline cone irradiance. For methanol, this method gave 16.4 kW/m² at 10 kW/m² external flux, but values decreased sharply with higher flux, becoming negative above 40 kW/m² due to attenuation of cone radiation by flame and fuel vapors. For PMMA, average flame heat flux was 15.6 ± 1.9 kW/m² over five tested fluxes. The effect of participating media on surface heat flux under external radiation requires further study, especially for defining flame heat flux in cone calorimeter models. Because of uncertainties in total surface heat flux measurements, a gauge-based technique is not recommended without deeper investigation of factors influencing results. At present, the effective heat of gasification method is preferred for estimating flame heat flux of condensed fuels with the cone calorimeter. For PMMA, however, only Domain 3 results appeared reasonable, which may be coincidental and needs further study. While this method shows promise, results are sensitive to the burning domain chosen, and further research is needed to confirm whether this approach can provide consistent estimates across different fuels.[3]

The Cone Calorimeter can assess the fire behavior of liquids from their ignition, boiling, and burning characteristics and combustion properties. Results should be calculated according to standard test methods (e.g., ISO 5660-1), with a few exceptions noted here. The best ignition tendency assessment for liquid fuels in Cone Calorimeter is Critical Heat Flux (CHF); however, such application is valid only for those fuels with high fire point. Ignition time is an adequate measure of ignition tendency for other fuels, but is less reliable for fuels which ignite within a few seconds upon exposure. And here, for fuels such as alcohols, the Cone Calorimeter may not prove a useful measure of ignition tendency.
Average Heat Release Rate (HRR) and Mass Loss Rate (MLR) provide the best assessment of burning tendency of liquid materials in Cone Calorimeter. These results should be averaged from ignition until flame extinction. Peak Heat Release Rate (PHRR) is another good measure, being highly variable, mainly due to its considerable dependence on experimental setup. The Boiling Transition Time is another measure that would be considered reliable for boiling tendency in the Cone Calorimeter. Because the observation of boiling as opposed to evaporation could become somewhat subjective, BTT shall be calculated from the mass data measured. Bulk Boiling Temperature might also be considered good, but it requires a sophisticated modification of the apparatus which could interfere with other main measurement results. Hence, if BBT is desired, it would be best conducted as a separate test. In terms of combustion properties for liquid fuels in the Cone Calorimeter, EHC is the favorite. Note that EHC should only be calculated in the burning phase, that is, the mass loss before ignition is solely due to evaporation. The remaining combustion parameters, Specific Extinction Area (SEA), yield of carbon monoxide (CO), and yield of carbon dioxide (CO_2), are, although not as much reported as EHC, also relevant. The remaining ones being Effective Heat of Gasification and B-number could gain from thorough testing to be applicable.
This review identifies some questions that remain unanswered with respect to Cone Calorimeter liquid testing in need of further research. Some guidance exists for the selection of vessels; however, developing a standard sample holder for liquid testing remains to be completed. Present tests have been carried out on variable depth samples (i.e., fixed initial fuel), while constant depth (i.e., continuous fuel supply) tests may provide more meaningful results in some instances. Future studies would focus on either designing a different way to mitigate this concern. Another application of Cone Calorimeter data is on the prediction for large-scale fire performance; thus, future works should also test the feasibility of predicting large-scale pool fire behavior from Cone Calorimeter measurements.[4]

This study was mostly concerned with the Controlled Atmosphere Cone Calorimeter (CACC), more especially in discussing the reasons for its development and standardization, the main design features, and future opportunities and limitations. Some knowledge gaps that could potentially be addressed in follow-up studies to increase the scalability of this apparatus and allow more accurate comparison with large-scale tests have been identified. Moreover, the CACC promises some standardization of equipment for the assessment of toxic effluents. This is mainly because its similarity with the Cone Calorimeter, which has received wide acceptance as a method for determining Heat Release Rate (HRR), is a major advantage for this approach. But, as per the review done in this study, further work is needed in improving the control of conditions during the test and the sampling of the toxic gases released.[5]

The cone calorimeter is a widely accepted apparatus used to characterize the fire behavior of materials in controlled heat flux situations. Infrared radiation measurements are fundamental for calculating the following parameters: heat release rate, ignition time, and mass loss during combustion. Nevertheless, the recent popularization of intumescent fire-retardant systems has depicted some shortcomings in the application of traditional methods, due to their dynamic character, particularly during testing where shape changes take place. Processes such as swelling and char formation make the irradiance distribution nonuniform and the thermal boundaries unsteady, thus quite inaccurate with respect to heat flux estimation. For a cone calorimeter, the view factor describes how much of the radiation from the cone heater hits the flat specimen surface. Earlier experimentation has tackled irradiance variations under the application of view factor equations from standard references.
Although these experiments have confirmed the presence of non-uniform irradiance across specimen surfaces, they did not perform accurate modeling concerning complex geometrical relationships such as those between the truncated cone heater and the extended perimeter of the test samples. This inability to calculate view factors accurately in such configurations resulted in underestimation of thermal loads, with special regard to

expanding or deforming materials. More recent progress has been committed to contour integration techniques of view factor calculation for plane versus truncated cone surfaces set either parallel or perpendicular. This method permits double-area integration, providing accurate predictions of irradiance in different localities on a surface. The comparative studies have shown that these predictions are in very close agreement with both experimental work and literature values, with agreements to four numbers after the decimal. View factor maps carried on Cartesian coordinate systems have illustrated the variation in irradiance in a graphical manner, thus giving an insight into the spatial distribution of the heat under the cone. Such advancements are quite useful for specimens that undergo geometrical changes, as they would yield a better estimate of heat absorption. Finally, the innovative view factor developed in this study for cone calorimetry would further enhance the understanding of fire behavior for modern fire-retardant material. [6], [7], [8]

To quantitatively evaluate the behavior of materials subjected to fire testing, thermal boundaries must be accurately characterized; cone calorimetry is perhaps the best place to start. Until recently, more conventional approaches relied on 1D models of heat transfer and Kirchhoff's approximation of emissivity equal to absorptivity. Several authors have pointed out the restrictive nature of these assumptions, especially in the situations of transient heat transfer when the discrepancies in heat storage predictions arise (Tewarson, 2008; Quintiere, 2006); the invalidity of these assumptions will most likely yield skewed evaluations of both flammability and thermal resistance of the material.

Specifically, recent research seeks to enhance the understanding of heat transfer mechanisms by investigating the individual contributions of radiation, forced convection, and conduction. Heat et al. (2019) and Zhang et al. (2021) drew attention to the importance of view factor and surface absorptivity in radiation-dominated environments, particularly under cone heaters. Some advanced computational techniques have enabled more accurate calculation of view factors through contour integration techniques or modeling of convection coefficients through correlations from empirical fluid dynamics (Incorporeal & DeWitt, 2011).

In this respect, the currently reviewed study builds upon the existing literature and proposes a framework to derive all four important thermal boundary parameters—view factor, convection coefficient, emissivity, and absorptivity—from a rigorously established experimental validation using steel blocks. In analyzing emissivity and absorptivity separately and their distinct roles during transient conditions, the authors attain a more correct representation of transient heat transfer processes. By virtue of this improved methodology, thermal analyses conducted as part of fire safety engineering with strong dependency on boundary conditions will gain in reliability. [9]

2.2 Ignitability analysis using the cone calorimeter and lift apparatus

The apparatus for calorimetry and LIFT (Lateral Ignition and Flame Spread Test) is often used to assess matter ignitability. Studies have shown that the two methods yield similar results with respect to significant thermal properties, such as ignition temperature, thermal diffusivity, and thermal conductivity, which indicates that it is reasonable to use either method for judging the ignition behavior of materials under controlled heat flux conditions. On the other hand, the critical irradiance-attributed to signify the minimum heat flux required for ignition-has been reported to be conflicting between these methods. This inconsistency in judgments is primarily ascribed to the mechanisms of convective cooling within the two setups, rendering critical irradiance an unreliable distinct parameter for ignition analysis.

In order to improve the reliability of ignitability testing and thermal conduction measurements, surface emissivity, density, moisture content, and thickness of a material should be measured before testing. Such characteristics influence the absorption and transportation of heat through the material when exposed to an external heat source.

Moreover, careful calibration of the irradiance profile and convective heat transfer coefficient must be performed for each testing apparatus to obtain accurate and comparable results. This study further recommends that testing be conducted over a wide range of irradiance levels to gain insight into piloted ignition processes. The empirical relations developed by the authors of this study may be used to determine ignition temperature and thermal properties of finitely thick materials reliably, thereby enhancing the validity of the ignitability tests. In the future, this work will extend to other wood-based materials to validate the findings over a wide spectrum of material types. [10]

2.3 Combustion and Fire Behaviour of Transformer Oils & Liquids

This study looked at how transformer oil burns in pool fires. Experiments were done with different pool sizes, and measurements were taken for burning rate, flame height, oil layer and flame temperatures, and radiation. The main results are as follows:

New key values ($m_\infty'' = 28.65$ g/m^2 and $\kappa' = 1.78$ m^{-1}) for transformer oil pool fires were found from the tests and checked with earlier studies. Different models for flame height were tested, and those made for heavy fuels matched transformer oil fires better, similar to results in Muñoz et al.'s diesel fire study. In the oil layer, a boiling layer and a gradient layer were seen in temperature tests, with the boiling layer about 2.6 mm thick during steady burning. A new piecewise formula was given to calculate flame temperature, close to results for aviation kerosene pool fires. Formulas were also made for radiation fraction and flame surface power. Radiation fraction was linked with pool diameter, and the solid flame model with flame temperature worked well to predict the heat given off to nearby objects in transformer oil fire accidents. These results add to the small amount of data available for transformer oil fires and help build a strong base for studying the thermal hazards of real accidents.[11]

Evaluating the fire safety of cooling-insulation fluids requires the high performance both on ignitability and on post-ignition combustion characteristics.

•For ignitability, the ignition response to radiant heat flux, or in other words the critical radiant heat flux, is a valid indicator. The higher critical radiant heat flux gives higher fire safety performance which give the resistance to fire flashing. Naturally, the fluids must have a flash point that has to be higher than the upper boundary for the dangerous substance category under the Fire Service Law (must have flash point of 250°C or higher). Thermal inertia ($\lambda\rho c$) is the item for judging the dependence of ignitability on radiant heat flux. The thermal inertia of the cooling-insulation fluid has to have the almost

equal value to those of solid materials for electrical devices, i.e., epoxy resin.
•Indicators of appropriate combustion characteristics are: that the cooling-insulation fluids have to have a low peak heat release rate and small total heat release. It is expected that self-extinguishing, and less emits of smoke (and corrosive gases). [12]

An experimental study on the ignition and combustion behavior of three common oils (diesel, lubricating oil, and aviation kerosene) was carried out under radiant heat flux. Ignition time and several combustion factors were measured using a cone calorimeter. Ignition time varied during tests with different radiant heat flux levels. The relation between radiant heat flux and ignition time of diesel, lubricating oil, and aviation kerosene matched well with a 0.55 power rule using Janssens' method. The effect of liquid depth on ignition was also considered, showing a maximum 25% change in ignition time in this study. In addition, several combustion factors were recorded. The maximum and average HRR, average MLR, and CO/CO2 ratio showed a linear trend with radiant heat flux. However, the average specific extinction area shifted within a certain range and differed with oil density. [13]

In this paper, a cone calorimeter was used to study the combustion characteristics of typical plant insulating oils (camellia seed oil, soybean oil) and mineral oil (25# mineral oil) under different radiant heat flux and initial oil thickness.
Major results are as follows:
- The TTI of the three insulating oils decreased with the rise of ERHF and oil thickness. Under the same conditions, soybean oil showed a longer TTI and better safety.
- The HRR and CO production rate of the three insulating oils increased with higher ERHF and oil thickness, and the fire risk of mineral oil was greater.
- The Petrella fire risk assessment method was used to evaluate the fire risk of the three insulating oils. Results showed the fire risk order from high to low was mineral oil, camellia seed oil, and soybean oil. In terms of fire safety, natural ester insulating oils had higher safety, with soybean oil being the safest and most suitable for transformer insulating oil. [14]

Cone calorimeter studies are well known through studies on the fire and combustion behaviour of flammable liquids like Chinese liquor. In recent research, combustion features were examined for ethanol-water mixtures and for Chinese liquor by a cone calorimeter (ISO 5660-1) and an automatic flash point tester. The study aspired to obtain an understanding of the fire hazards that accompany something known to be highly flammable, explosive, and fire-promoting in nature.
The results show that with increasing ethanol concentration, burning time, mass loss rate, heat release rate, CO, and CO_2 production are also proportionally increasing. Similar-determined combustion behaviour was shown for Chinese liquor in comparison to ethanol-water mixtures; therefore, sometimes the ethanol-water data is able to predict the fire properties of Chinese liquor. However, some differences are notable. Chinese liquor was found to have a lower closed-cup flash point than ethanol–water mixtures; therefore, ignition becomes easy and a flame hazard is enhanced. The mass loss rate per unit area is slightly lower, whereas the yield of CO_2/CO ratio is higher, indicating more efficient combustion.
Most importantly, a critical ethanol volume fraction is redefined with respect to fire risk classification. For Chinese liquor, the cut-off for Class I fire risk should be 34.8 vol%, which is lower than current recommendations. With most Chinese liquors containing 30-65 vol% ethanol, many fall under the highest risk category. The study also points to fire hazards from the nearly-invisible light blue flame of the liquor, necessitating new fire detection and suppression means. Subsequent works will focus on understanding and improving fire extinguishing strategies for Chinese liquor. [15], [16], [17]

3. Fire Suppression and Safety Strategies

The studies into the suppression of transformer oil fires by means of water mist have been completed. The following inferences can be drawn:
•Longer times are required to put out fires in increasing size oil pools and poorer injection pressure levels of the water mist system.
•The dimensions and behavior of the flame generated in transformer fires once the water mist system has been activated will depend on the size of the oil pool and injection pressure of the system. Lower injection pressure increases flame size considerably.
•Strong intensification of flame was seen with larger oil pools coupled with lower injection pressure; as this happens, there is increased flame height, higher CO concentration, and increased radiative heat flux.
•Designing the properties of water mist for optimum effectiveness as suppressants of liquid pool fires such as those of the above-mentioned transformer oils must be done. [18], [19], [20]

2.4 Modification of Oils and Alternative Insulating Fluids

Adding a high flash point flame retardant to mineral oil can raise the flash point within a certain range. However, adding even a small amount of flame retardant with a lower flash point than mineral oil will sharply reduce its flash point. In practical use, mixing low flash point liquids with insulating oil should be avoided. The addition of 12.5% IPPP reduced the maximum heat release rate of insulating oil by 32%, nearly one third of pure mineral oil. At the same time, compared with the same volume of mineral oil, the ignition time was delayed by 5 s. The modified oil improved the thermal stability of mineral oil and resulted in a complete weightless temperature rise. [21]

The study was meant to search for a new insulating material for transformers to replace petroleum-based mineral oil. The electrical and chemical properties were studied experimentally by standard procedures. Results show that pure coconut oil has good potential to be an alternative to petroleum-based mineral oil. With respect to electrical properties, pure coconut oil qualifies as transformer insulation due to its excellent properties. Experimental results have shown that the breakdown voltage (BDV) of pure coconut oil is high and comparable to that of mineral oil. In terms of resistivity, pure coconut oil opposes the electric current flow in the transformer very well. In chemical properties, the Flash Point (FP) of pure coconut oil is higher than that of mineral oil, thereby lowering the fire risk when compared to mineral oil. [22]

Vegetable esters are rapid alternatives to mineral oil for use as transformer insulating fluids. This development comes at a time when nullifying the criteria of cleanliness, biodegradability, and thermal proficiency has received a lot of hype. Among such esters that are catching attention as a renewable source, palm oil methyl ester (POME) can blend well with mineral oil augmenting thermal properties. It is said that the higher the mixing ratio of POME and mineral oil, the higher is the increase of thermal conductivity and lower the reduction of viscosity and density at higher temperatures, thereby enhancing cooling and heat dissipation in transformers. For instance, blends such as 80:20 and 70:30 mineral oil;POME express greater thermal conductivity than pure POME, thus implying greater heat transferability. Cut down viscosity and density at higher temperatures improve convection flow and cooling. However, POME has low oxidation resistance, while the thermal resistance of the blend has helped reduce oxidative breakdown. Nevertheless, the oxidation induction time was higher in mineral oil, which decreased with the addition of POME, raising concerns about long-term stability. These POME-mineral oil blends, on the other hand, provide a combination of performance and sustainability in view of better thermal performance and lower greenhouse gas emissions. Nonetheless, further tests must evaluate dielectric strength, long-term aging, and component compatibility. It is only upon passing these tests that POME-ester blends will be declared safe for practical use in electrical insulation systems. [23]

2.5. Aging, Electrical & Thermal Properties of Oils

To actually age the transformer insulating oil under thermal conditions, an experimental apparatus was designed and constructed, and thermal aging was done over a period of 42 days. Based on this, tolerance assessments of power frequency, DC, lightning shock, and gas chromatographic analysis of the insulating oil were made, leading to the following conclusions. During all electrical parameter tolerance tests for transformer insulating oil, the power frequency breakdown voltage and DC breakdown voltage would decrease initially and then increase with time, while the breakdown voltage due to lightning shocks would gradually lower with increased aging. The maximum power frequency breakdown voltage was noted at 41.4 kV, while the maximum DC breakdown voltage observed was 33.5 kV. The maximum observed lightning breakdown voltage was 66.7 kV. In gas chromatography, on transformer insulating oil, the concentration of C_2H_6 increased with aging, reaching its peak. Hydrogen content first increased and then decreased reaching a maximum of 432 µl/l. The amount of methane produced with aging increased, with a maximum of 478 µl/l. The amounts of CO and CO_2 released increased with the aging period, with maximums of 4410 µl/l and 141,000 µl/l respectively. The major insulation aging index A and the operating index of insulation oil B were used to evaluate transformer oil. The ageing assessment reference was Unit 1. When T approaches 0.6, the insulation oil ageing is still in a safe range, indicating no impairment has taken place. T equal to 1 denotes that oil has reached an alarm level. Parameter T is a holistic determinant of transformer insulation oil ageing; it may help detect ageing issues early on, bring down its T value, and thus help enhance the working life of the transformer. [24], [25], [26]

Tests conducted on Natural esters and mineral oil confirm the feasibility of Natural esters in power transformers. Natural esters at 0% kerosene showed initial performance without copper plate and kraft paper components after the accelerated heating test, yet suffered a greater material property loss in the presence of these components, while the 5% kerosene Natural esters showed slow ageing in oil, with SIFs ageing slower for 30 days than Natural esters without kerosene. On the contrary, SIFs with 10% kerosene exhibit a more accelerated ageing mechanism, although it is still slower than mineral oil. Compared against mineral oil, the oil-initiated ageing of superior insulating fluid with and without CP and KP was established, with the highest oil-induced ageing (in terms of dielectric properties) observed at three to four times compared to SIFs (B2 and B5). Within 70 days, the reduction in auto-ignition points MO by 66.6%, doubling of kinematic viscosity, and acid number walking towards lead suggest that MO is the most degraded with an extrapolated rate of up to 50% of strength in 90 days. The breakdown voltage appears to have better consideration for NEs with 5% KER over 10% in reduced life with 10% increase from the maximum rated level, while MO hardly lasts over 90. Those results indicate that, being a miscible dielectric, KER works not only as a thinner medium but also acts as a better insulator than Copper Plate, with a superior dissipation of heat. In addition, the effect of kerosene in lower percentages, like 5%, on cellulose insulation ageing is not significant, thus allowing NEs to maintain reasonable acid numbers for some months. The ultrasonic waves work to reduce molecular distances among carbon atoms within NEs but when kerosene is added, its effect in relaxing viscosity has shown promise by filling up the Carbon-Carbon chain *(C-C)* gaps effectively. Thus, the addition of kerosene does not lead to viscosity reduction with time. Under accelerated heating, SIFs showed a superior performance compared to that represented by the MO in extending the life of solid insulation and internal components of power transformers. In conclusion, this shows that SIFs are useful as liquid insulation for power transformers. [27], [28], [29]

In this study, an experimental evaluation of new and used oils for transformer life assessment in India was carried out. The authors tested several properties of pure and aged oils; results showed that pure oil had better qualities, while filtered and unfiltered used oils displayed changes linked to degradation. The main reason for degradation is the release of gases caused by the decomposition of hydrocarbons, cellulose, and transformer materials under temperature, acidity, and moisture. Properties like breakdown strength and dissipation factor were strongly affected, while interfacial tension also showed major variation. Filtered oils performed better than unfiltered oils. Functional groups were analyzed in both filtered and unfiltered oils using Fourier transform infrared spectroscopy. In filtered oil, the effect of these groups was overshadowed due to minimal light absorption as revealed by UV spectroscopy. For other properties, filtered oil showed clear advantages. Although the two oils are alike and normally free from miscibility issues, the results from separation and mixing tests differed due to varying ageing levels and water content. Changes in parameters did not correlate linearly with water content, suggesting multiple factors influenced mixture behaviour. Further research is needed to separate the base oil and water effects. Water content, resistivity, dissipation factor, and discharge voltage were highly variable in oil mixtures. A strong correlation was seen between water content and discharge voltage, making these parameters important in transformer insulation studies. Adding Borak 22 improved Nynas oil properties to standard levels except discharge voltage, which was unaffected in all mixture ratios. The discharge voltage of Borak 22 was almost double that of Nynas oil, possibly due to mixture non-homogeneity, though water content improved to acceptable levels after the 50/50 ratio. Acidity, color, permittivity, viscosity, and flash point were mostly unchanged even in the worst oil mixtures.[30]

3.CONCLUSION

The reviewed studies collectively highlight that cone calorimetry and pool fire experiments are essential tools for evaluating the fire behaviour, heat transfer, and suppression characteristics of transformer oils and alternative insulating fluids. Flame heat flux quantification remains a major challenge, with the effective heat of gasification method presenting more consistent results than direct surface heat flux measurements, though both require refinement to reduce uncertainties. Experimental investigations into transformer oil pool fires establish characteristic parameters such as burning rate, flame height, temperature profile, and radiative heat fraction, supporting the development of empirical models for predicting fire hazards in transformer accidents.

Flame retardant additives and natural oils such as coconut oil demonstrate potential to improve fire safety by delaying ignition, reducing heat release rate, and enhancing thermal stability, while new-generation insulating fluids exhibit slower aging and better dielectric properties compared to conventional mineral oils. Suppression studies reveal that water mist is effective under optimized injection conditions but can intensify flames when poorly applied, underlining the need for proper system design. The controlled atmosphere cone calorimeter and liquid fuel cone calorimeter techniques show promise for more accurate toxicity and combustion measurements, while ignitability studies confirm that critical heat flux, ignition delay, and effective heat of combustion are robust metrics for fire risk assessment of fluids.

In conclusion, while significant progress has been made in establishing key fire safety parameters for transformer oils and alternative insulating fluids, gaps remain in standardization, flame heat flux estimation, and scaling results from bench-scale cone calorimeter tests to large-scale fire scenarios. Advanced correlations and modified apparatus such as the CACC may bridge these limitations in the future. Overall, integrating flame retardancy, alternative bio-based insulating oils, refined calorimetric methods, and optimized suppression strategies will be vital for enhancing transformer fire safety and reducing associated thermal hazards.

REFERENCES

[1] D. Drysdale, An introduction to fire dynamics, Chichester, West Sussex : Wiley, 2011.

[2] A. Atreya, SFPE Handbook of Fire Protection Engineering, Springer.

[3] Ibrahimli, Vusal, Matthew J. DiDomizio, Ayaan A. Lakhani, and Elizabeth J. Weckman. "Measurement of Flame Heat Flux Using the Cone Calorimeter." *Obtaining Data for Fire Growth Models* (2023): 108-131.

[4] DiDomizio, Matthew J., Vusal Ibrahimli, and Elizabeth J. Weckman. "Testing of liquids with the cone calorimeter." *Fire Safety Journal* 126 (2021): 103449.

[5] Bray, Robert John, Svetlana Tretsiakova-McNally, and Jianping Zhang. "The controlled atmosphere cone calorimeter: a literature review." *Fire Technology* 59, no. 5 (2023): 2203-2245.

[6] Kang, Sungwook, Sengkwan Choi, and J. Yoon Choi. "View factor in cone calorimeter testing." *International Journal of Heat and Mass Transfer* 93 (2016): 217-227.

[7] Mandelbaum DG. Alcohol and culture. Curr Anthropol.1965;6(3):281–93.

[8] Center for Chemical Process Safety. Guidelines for engineering design for process safety. 2nd ed. New York: American Institute of Chemical Engineers; 1993.

[9] Kang, Sungwook, Minjae Kwon, Joung Yoon Choi, and Sengkwan Choi. "Thermal boundaries in cone calorimetry testing." *Coatings* 9, no. 10 (2019): 629.

[10] Dietenberger, Mark A. "Ignitability analysis using the cone calorimeter and LIFT apparatus." In *Proceedings of the International Conference on Fire Safety: July 22-26, 1996, Columbus, OH. Volume 22.[Sl: Product Safety Corporation, 1996?]: Pages 189-197*. 1996.

[11] Zhao, Jinlong, Shansheng Wang, Jianping Zhang, Rui Zhou, and Rui Yang. "Experimental study on the burning characteristics of transformer oil pool fires." *Energy & Fuels* 34, no. 4 (2020): 4967-4976.

[12] Suzuki, Kuniko, Osami Sugawa, Akira Yamagishi, Katsunori Miyagi, and Kyoko Kamiya. "Experimental study on ignition and combustion behaviors of insulation fluids for transformer using cone calorimeter." *IEEJ Transactions on Power and Energy* 127, no. 7 (2007): 797-802.

[13] Chen, Xiao, Shouxiang Lu, Changhai Li, Jiaqing Zhang, and Kim Meow Liew. "Experimental study on ignition and combustion characteristics of typical oils." *Fire and materials* 38, no. 3 (2014): 409-417.

[14] Huang, Qingdan, Huihong Huang, Jing Liu, Yuqing Chen, and Haoyong Song. "Scaled experimental study on the initial oil thickness effect on the combustion characteristic of the typical transformer insulating oil." In *Journal of Physics: Conference Series*, vol. 2614, no. 1, p. 012014. IOP Publishing, 2023.

[15] Chen, Qinpei, Xuehui Wang, Tiannian Zhou, Chao Ding, and Jian Wang. "Investigation on the fire hazard characteristics of ethanol–water mixture and Chinese liquor by a cone calorimeter." *Journal of Thermal Analysis and Calorimetry* 135, no. 4 (2019): 2297-2308.

[16] Bartholmai, Matthias, Robert Schriever, and Bernhard Schartel. "Influence of external heat flux and coating thickness on the thermal insulation properties of two different intumescent coatings using cone calorimeter and numerical analysis." *Fire and materials* 27, no. 4 (2003): 151-162.

[17] BS 476-15 (ISO 5660-1), Fire tests on building materials and structures — Part 15: Method for measuring the rate of heat release of products, British Standard (1993).

[18] Zhu, Pei, Xishi Wang, Zhigang Wang, Haiyong Cong, and Xiaomin Ni. "Experimental study on transformer oil pool fire suppression by water mist." In *Fire Science and Technology 2015: The Proceedings of 10th Asia-Oceania Symposium on Fire Science and Technology*, pp. 895-901. Singapore: Springer Singapore, 2016.

[19] Duarte, Dayse. "Aspects of transformer fires in Brazil." (2012).

[20] Petersen A, Blanc R, Carrander K et al (2012) Guide for transformer fire safety practices, Working Group A2.33

[21] Huang, Ying, Jiaqiang Wei, and Jianxing Yi. "Combustion behavior of mineral insulating oil with addition of flame retardants." In *IOP Conference Series: Earth and Environmental Science*, vol. 508, no. 1, p. 012155. IOP Publishing, 2020.

[22] Muhamad, N. A., and S. H. M. Razali. "Electrical and chemical properties of new insulating oil for transformer using pure coconut oil." *Journal of Advanced Research in Materials Science* 25, no. 1 (2016): 1-9.

[23] Walvekar, Rashmi, Danial Aminin Zairin, Mohammad Khalid, Nabisab Mujawar Mubarak, and Gupta Tcsm. "Thermo-physical properties of naphthenic-palm oil methyl ester (POME) blended transformer oil." *Journal of Thermal Analysis and Calorimetry* 147, no. 13 (2022): 7193-7201.

[24] Luo, Yan, Xiu Zhou, Lin Zhu, Jin Bai, Tian Tian, Bo Liu, and Heng Zhang. "Transformer oil electrical–thermal

characteristics analysis and evaluation." *Aip Advances* 14, no. 7 (2024).
[25] Senoussaoui, Mohammed El Amine, Mostefa Brahami, and Issouf Fofana. "Transformer oil quality assessment using random forest with feature engineering." *Energies* 14, no. 7 (2021): 1809.
[26] Gu, Zhaoliang, Wenbing Zhu, Zhen Li, Mu Qiao, Chao Gu, Mengzhao Zhu, and Ran Xu. "Research on influence factors of micro-bubbles generation mechanism in oil paper insulation of 1000 kV transformers." *Energy Reports* 8 (2022): 352-360.
[27] Raj, Raymon Antony, Ravi Samikannu, Abid Yahya, and Modisa Mosalaosi. "Comparison of ageing characteristics of superior insulating fluids with mineral oil for power transformer application." *IEEe Access* 8 (2020): 141111-141122.
[28] IBERRAKEN, FAIROUZ, RAFIK MEDJOUDJ, RABAH MEDJOUDJ, DJAMIL AISSANI, and KLAUS DIETER HAIM. "Reliability-based preventive maintenance of oil circuit breaker subject to competing failure processes." *International Journal of Performability Engineering* 9, no. 5 (2013): 495.
[29] Reynolds, I. H., and B. Fallou. "Dielectric liquids for capacitors–Review of the supply position in September 1978." *Electra* 67 (1979): 93-99.
[30] Moulai, H., I. Khelfane, A. Yahiat, T. Toudja, A. Nacer, M. M. Zemirli, and F. Doussas. "Physico-chemical properties of power transformer oil mixtures." In *Melecon 2010-2010 15th IEEE Mediterranean Electrotechnical Conference*, pp. 1105-1110. IEEE, 2010.