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Transformer Research Consortium – Phase 4

Thermal and Electrical Designs of Transformers by Considering Different Insulating Liquids

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Outline

- Introduction
- Thermal Design

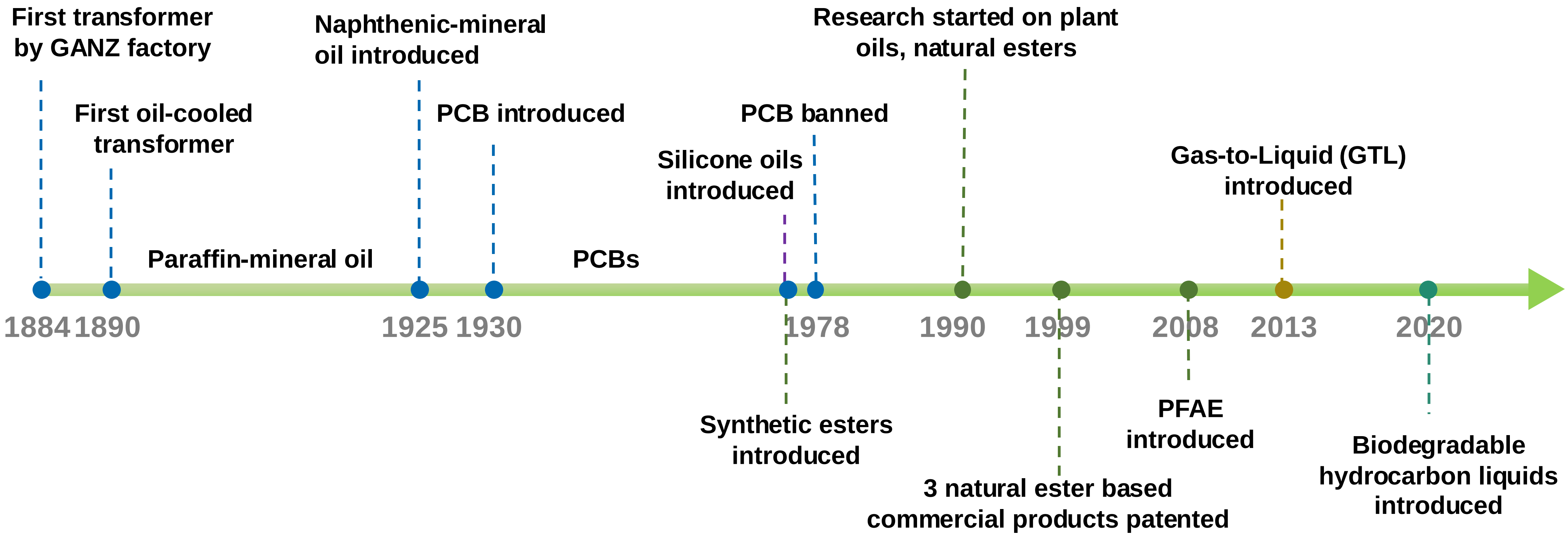
  - Complete-cooling-loop based CFD modelling

- Insulation Design

  - Large-scale lightning impulse breakdown tests

- Summary

History of Transformer Liquids



First transformer by GANZ factory

First oil-cooled transformer

Naphthenic-mineral oil introduced

PCB introduced

Silicone oils introduced

PCB banned

Research started on plant oils, natural esters

Gas-to-Liquid (GTL) introduced

Paraffin-mineral oil

PCBs

1884 1890 1925 1930 1978 1990 1999 2008 2013 2020

Synthetic esters introduced

3 natural ester based commercial products patented

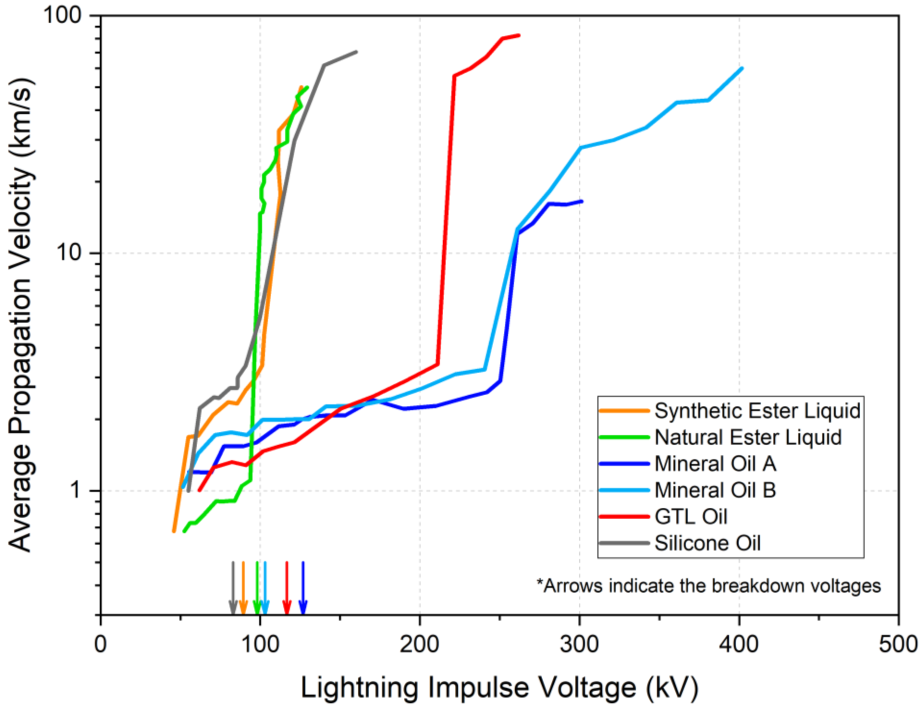
PFAE introduced

Biodegradable hydrocarbon liquids introduced

[1] U. M. Rao *et al.*, “Alternative dielectric fluids for transformer insulation system: Progress, challenges, and future prospects,” IEEE Access, vol. 7, pp. 184552-184571, 2019.
[2] Z. Shen, F. Wang, Z. Wang, and J. Li, “A critical review of plant-based insulating fluids for transformer: 30-year development,” Renew. Sust. Energ. Rev., vol. 141, p. 110783, 2021.
[3] CIGRE WG A2.35, "Experiences in service with new insulating liquids,” Technical Brochure 436, 2010.

Impacts on Insulation Design

- Knowledge of transformer insulation designs, has been accumulated mainly based on the experience of using mineral oils, which may not be readily applicable for these new liquids.
- Liquid chemistry has a large impact on breakdown phenomena under lightning impulse stress.



Streamer propagation velocity against positive lightning impulse voltage

Acceleration voltage: above which average streamer propagation velocity increases quickly with applied voltage.

Impacts on Thermal Design

- Understanding the thermal profile including the hotspot temperature within a power transformer is essential for optimising thermal design during the transformer manufacturing process and for managing thermal loading during the transformer operation.

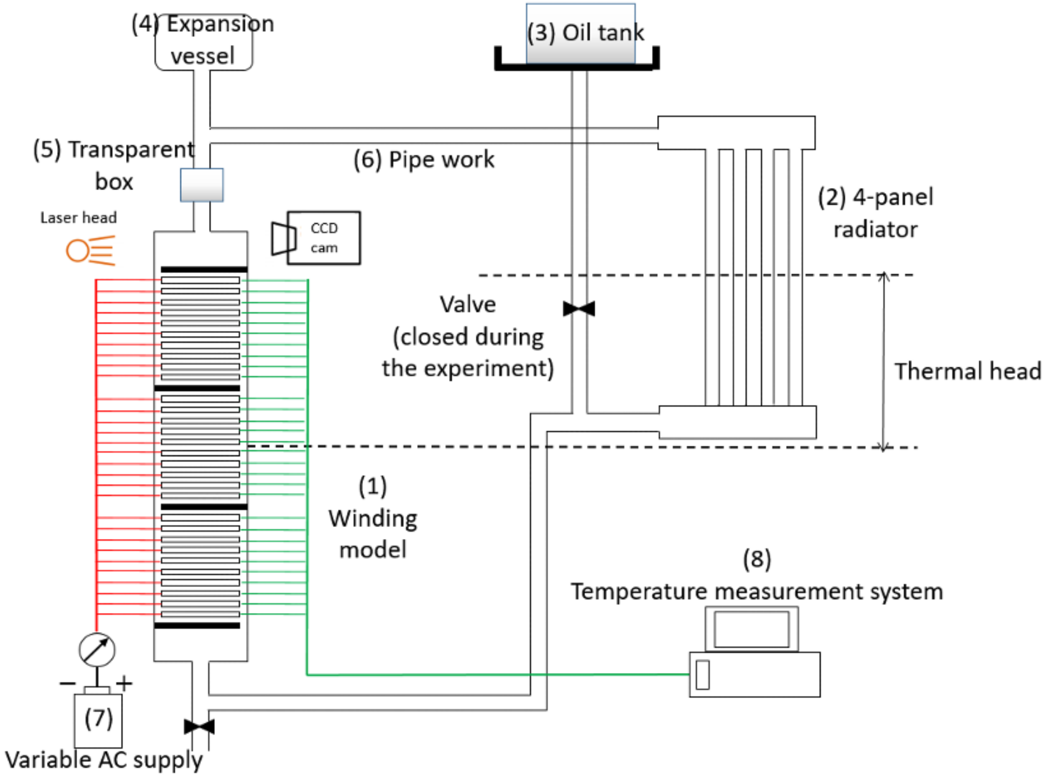
- There are at least three main drivers for further developing more accurate and capable transformer thermal models.

Energy Transition to Net Zero

Digital Twin of Transformers

Retro-filling with New Liquids

Complete-Cooling-Loop Experimental Setup



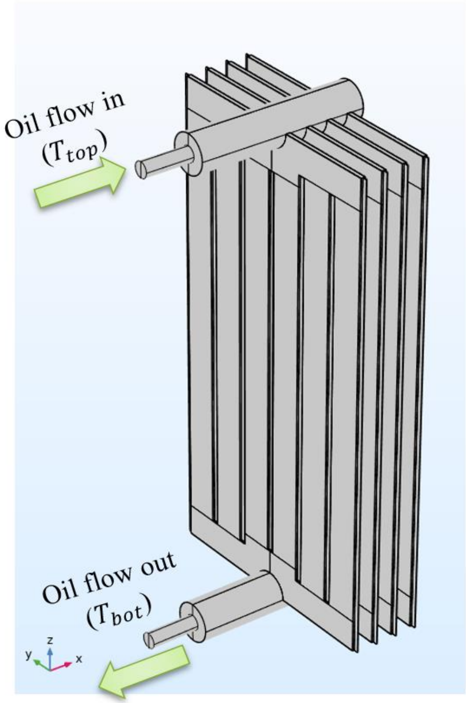
Schematic diagram of CCL experimental setup (ON/KN)

Photo of CCL experimental setup (ON/KN)

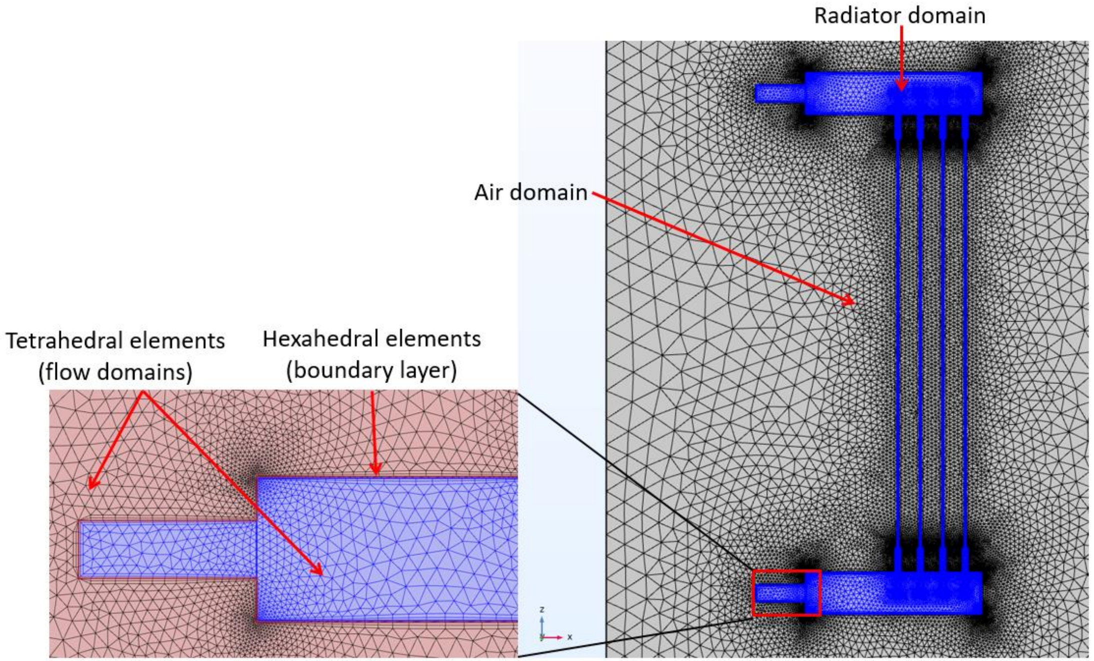
- Main components: winding model, 4 panel 1-meter radiator, oil expansion tank and connecting pipework
- Measurements: winding temperature profile, liquid temperatures, radiator surface temperatures and ambient temperatures

Development of Reduced Radiator CFD Model

- A reduced radiator CFD model is needed to enable the CCL CFD simulation.
- It is proposed to use an air heat transfer coefficient equation optimised for the transformer radiator to replace the air domain CFD simulation.



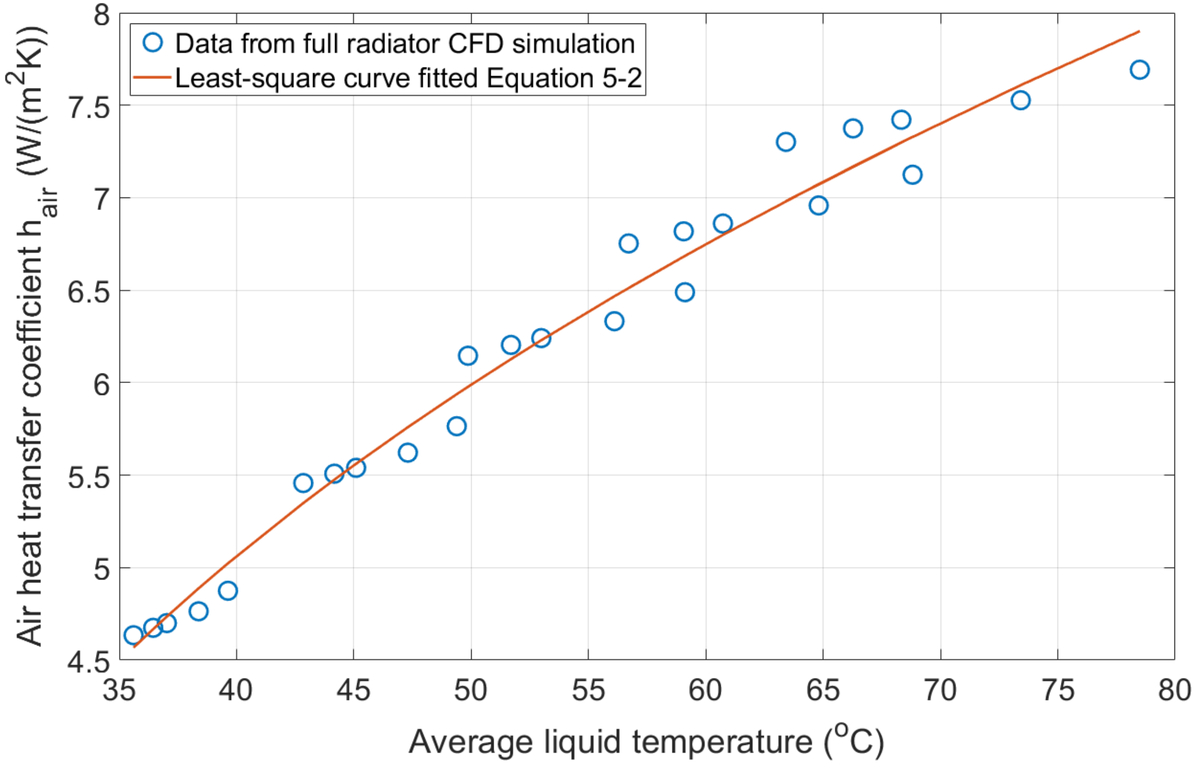
Radiator geometry



Mesh pattern of full radiator CFD models (radiator domain in purple, air domain in grey)

Derivation of h_{air} Equation

Parametric sweep using full radiator CFD simulations, mineral oil		
T_{amb} (℃)	T_{top} (℃)	$Q_{oil-top}$ $(10^{-5}\,m^3/s)$
20	40	3, 4, 5, 10, 50
20	50	3, 4, 5, 10, 50
20	60	3, 4, 5, 10, 50
20	70	3, 4, 5, 10, 50
20	80	3, 4, 5, 10, 50



$$\boxed{h_{air} = 1.461 \times (T_{avo} - T_{amb})^{0.4148}}$$

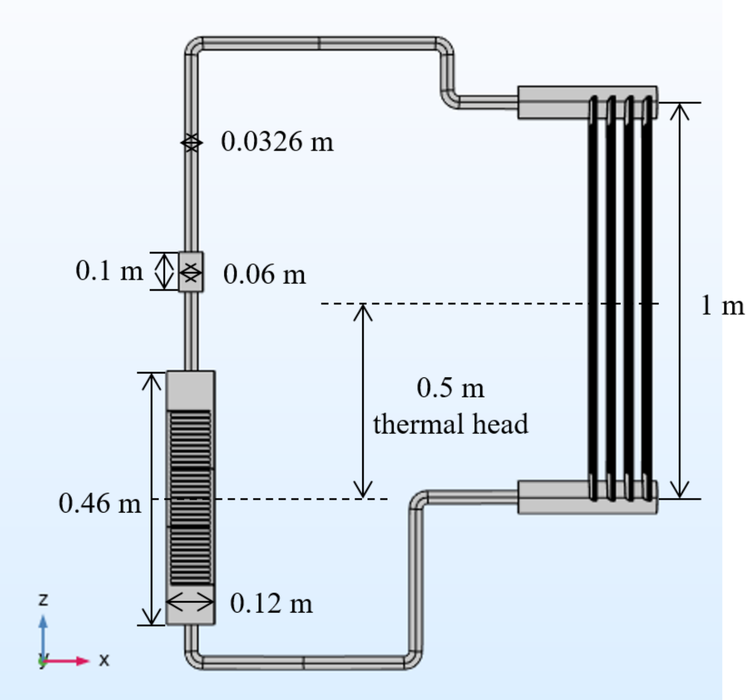
- h_{air} equation is derived by the least-square curve fit using the full radiator CFD simulation results.

Reduced Radiator CFD - Verification

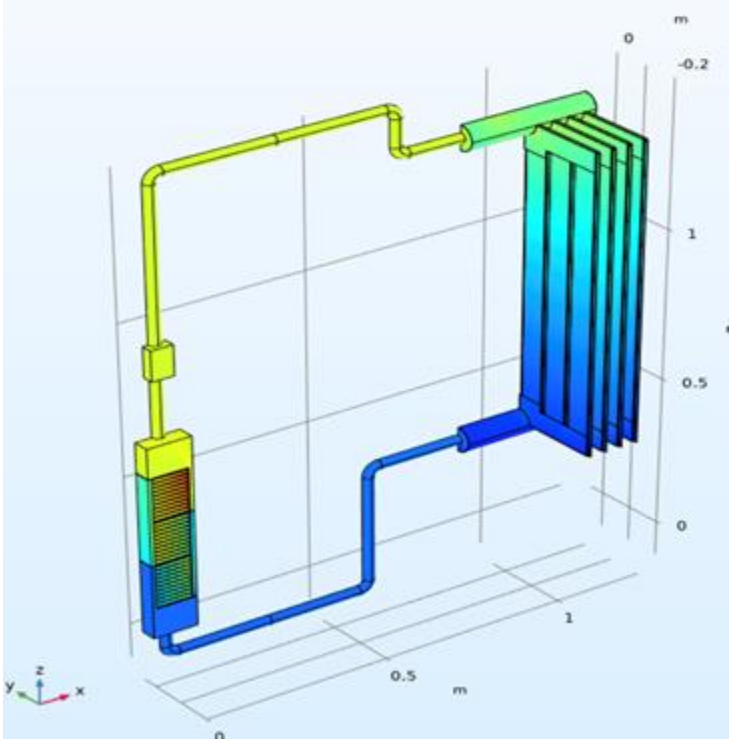
Case No.	Reduced radiator CFD simulation results		Full radiator CFD simulation results		Experimental measurements	
	$P\ (W)$	T_{bot} (°C)	$P\ (W)$	T_{bot} (°C)	$P\ (W)$	T_{bot} (°C)
1	181	25.2	185	25.0	190	24.3
2	367	29.5	378	29.4	392	28.7
3	577	38.9	580	38.8	600	38.1
4	808	38.9	820	38.6	800	38.7
5	1058	44.3	1066	43.7	1022	44.5
6	1231	47.7	1248	47.4	1212	47.8
7	1475	55.7	1485	55.4	1437	56.3

- Full radiator CFD simulations validated by the experiments ($\Delta T_{bot} < 0.9\ K$, $\Delta P < 1.3\%$)
- Reduced radiator CFD simulations matched with full CFD results ($\Delta T_{bot} < 0.3\ K$, $\Delta P < 2.2\%$)

Development of CCL CFD Model



Dimensions of the CCL CFD model (thermal head 0.5 m)



CCL CFD simulation (thermal head 0.5 m)

- Model inputs: Power injection, h_{air} equation and ambient temperature
- T_{top} and T_{bot} coupled with the h_{air} equation

CCL CFD Model Verification – Liquid Temperature

Experimental measurements, mineral oil		CCL CFD simulation results	
T_{top} (°C)	T_{bot} (°C)	T_{top} (°C)	T_{bot} (°C)
32.8 [31.9-33.5]	24.3 [23.4-24.8]	34.5	24.8
40.2 [39.1-41.2]	28.7 [27.6-29.5]	42.4	29.4
51.8 [51.0-52.5]	38.1 [37.9-38.4]	53.5	39.2
55.0 [54.2-55.2]	38.5 [37.9-38.8]	55.3	38.6
62.0 [61.4-62.5]	44.5 [44.0-45.0]	61.4	42.7
66.6 [65.8-68.1]	47.8 [47.5-48.5]	67.2	47.3
76.2 [75.4-77.4]	56.3 [55.9-56.8]	76.3	55.7

- The differences between experiments and CCL CFD simulations: T_{top} as 2.2 K, T_{bot} as 1.1 K

  - Uncertainties from the h_{air} curve fit process (<$\pm 1\ K$)

  - Uncertainties from temperature measurement method (<$\pm 1.2\ K$)

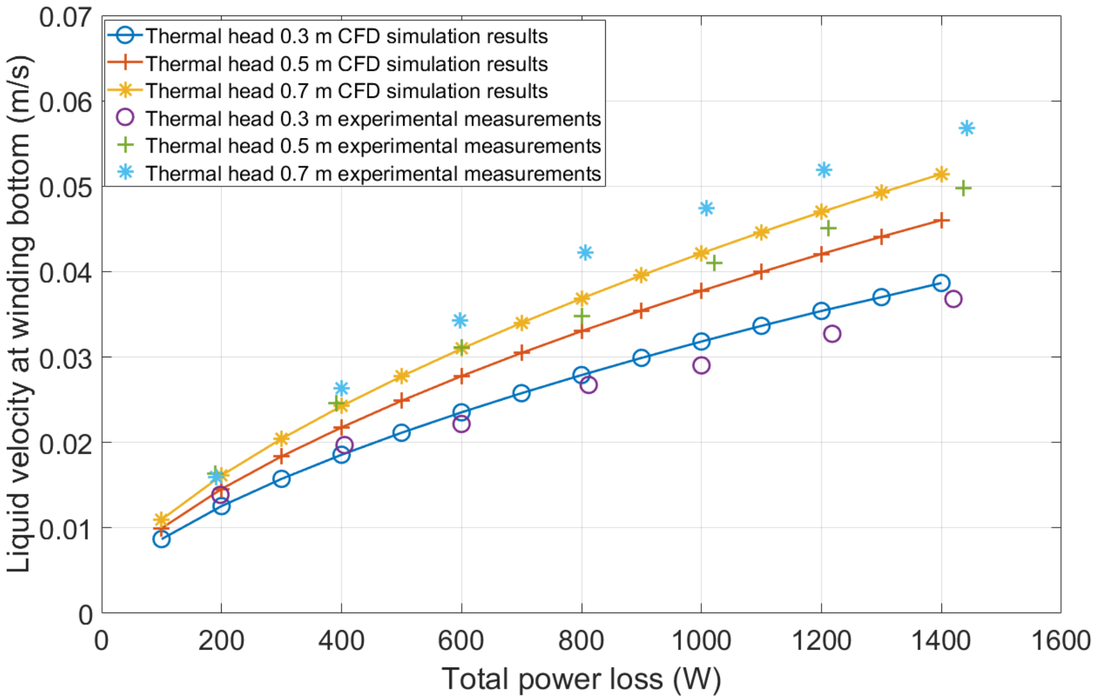
CCL CFD Model Verification – Liquid Velocity

$$v_{oil} = \frac{P}{(T_{top} - T_{bot}) C_p \rho_{bot} A_{bot}}$$

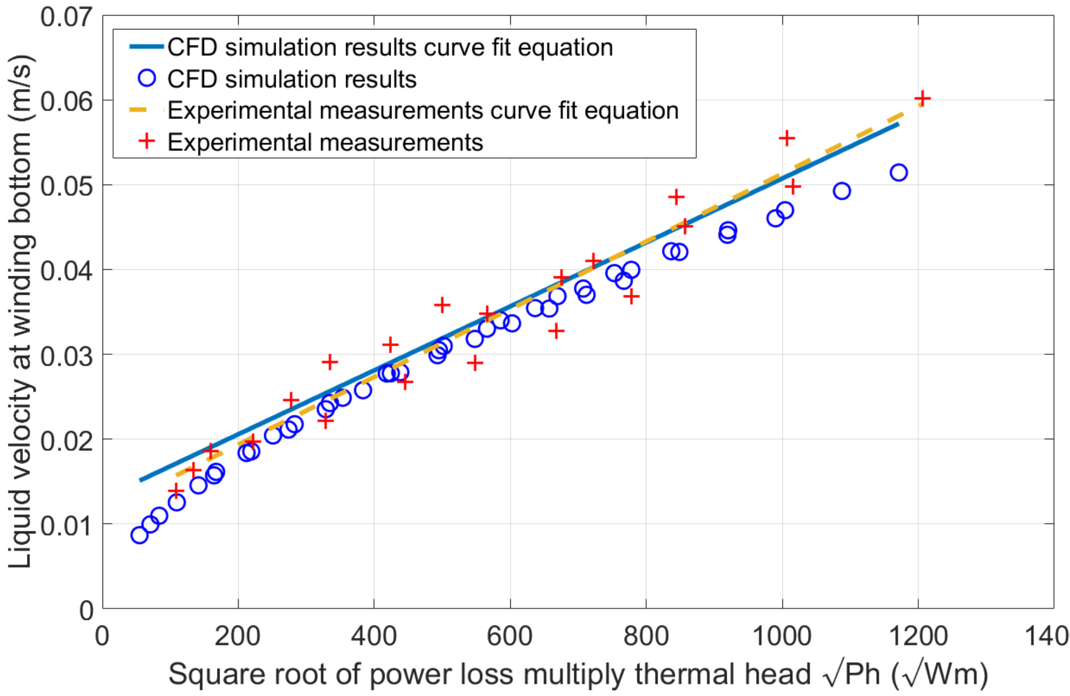
Liquid velocity calculated from the measurements, mineral oil	CCL CFD simulations
$v_{oil}\ (m/s)$	$v_{oil}\ (m/s)$
0.0163 [0.0137-0.0196]	0.0143
0.0240 [0.0208-0.0296]	0.0218
0.0311 [0.0292-0.0339]	0.0300
0.0348 [0.0328-0.0369]	0.0342
0.0410 [0.0388-0.0438]	0.0391
0.0450 [0.0410-0.0490]	0.0437
0.0498 [0.0461-0.0533]	0.0494

- The relative differences of the liquid velocity between experiments and CCL CFD simulations are less than 12.3 % (as 0.0022 m/s at the the 392 W power injection.).
- v_{oil} from the CCL CFD simulations are all in the ranges of the calculated liquid velocities.

Effects of Power Loss and Thermal Head



Comparison of v_{oil} under different power loss between experimental measurements and CCL CFD, mineral oil



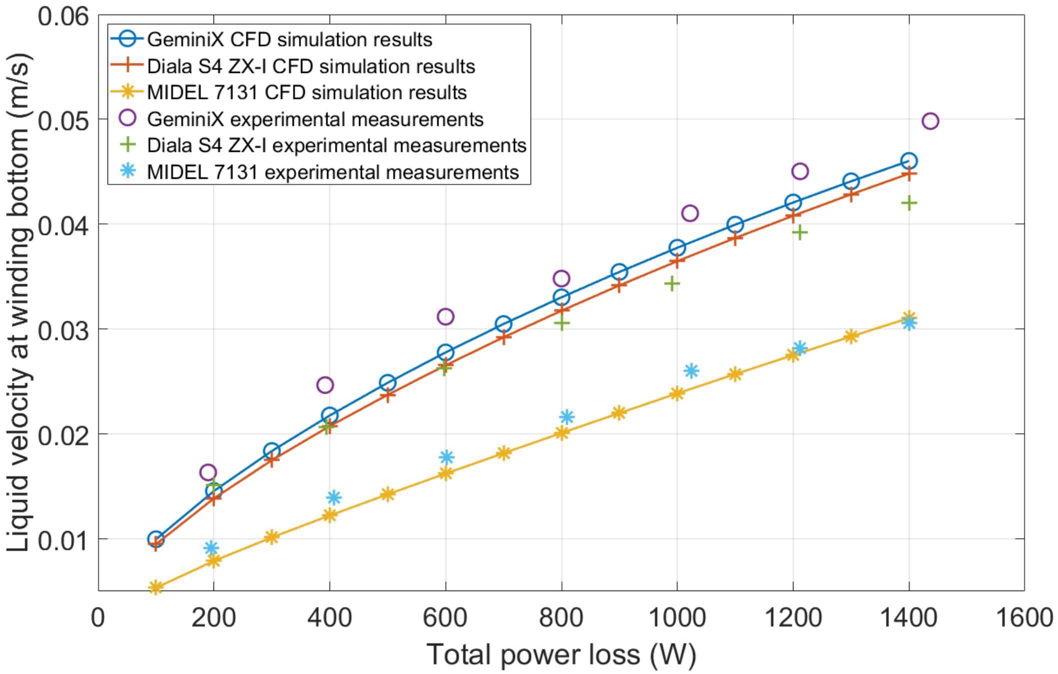
Comparison of v_{oil} under square root of power loss between experimental measurements and CCL CFD, mineral oil

- The differences of total liquid velocity between CFD simulations and experiments are within 12.7%.
- Liquid velocity shows a linear relationship with the square roof of power loss and thermal head

Experimental measurements: $v_{oil} = 0.0018\sqrt{Ph} - 0.002;\quad R^2 = 0.95$

CFD simulation results: $v_{oil} = 0.0019\sqrt{Ph} - 0.003;\quad R^2 = 0.98$

Comparison of Different Liquids



Comparison of v_{oil} of different insulating liquids between experimental measurements and CCL CFD, 0.5 m thermal head

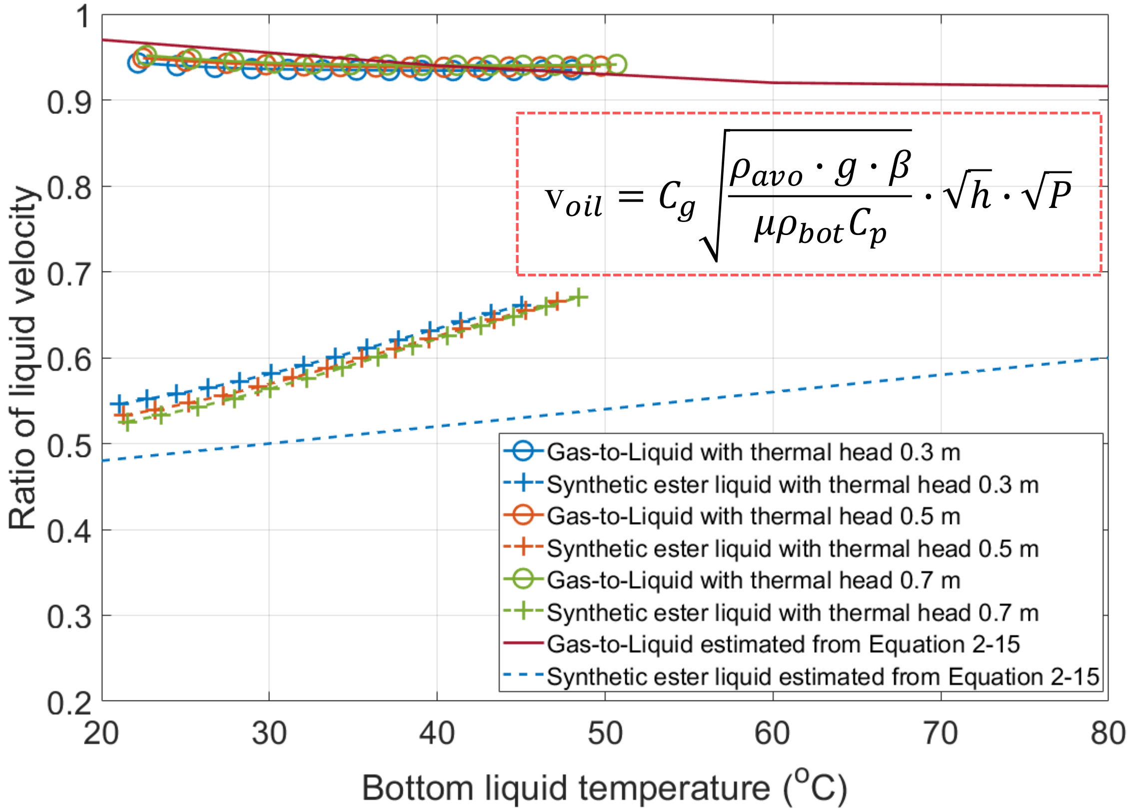
Compared to the mineral oil, GTL oil shows:

- 95% to 97% of total liquid flow rate based on CFD simulation results;
- 83% to 93% of total liquid flow rate based on experimental results.

Compared to the mineral oil, synthetic ester liquid shows:

- 56% to 69% of total liquid flow rate based on CFD simulation results;
- 55% to 63% of total liquid flow rate based on experimental results.

Comparison with Analytical Method



$$\mathrm{v}_{oil} = C_g \sqrt{\frac{\rho_{avo} \cdot g \cdot \beta}{\mu \rho_{bot} C_p}} \cdot \sqrt{h} \cdot \sqrt{P}$$

Comparison of ratio of liquid velocity between CCL CFD simulations and analytical estimations from [1]

- Analytical calculation underestimates the ratio of the liquid velocity of the synthetic ester liquid by 6.6% to 13.0% compared with CCL CFD simulations.
- The thermal studies of alternative insulating liquids need the CCL CFD model.

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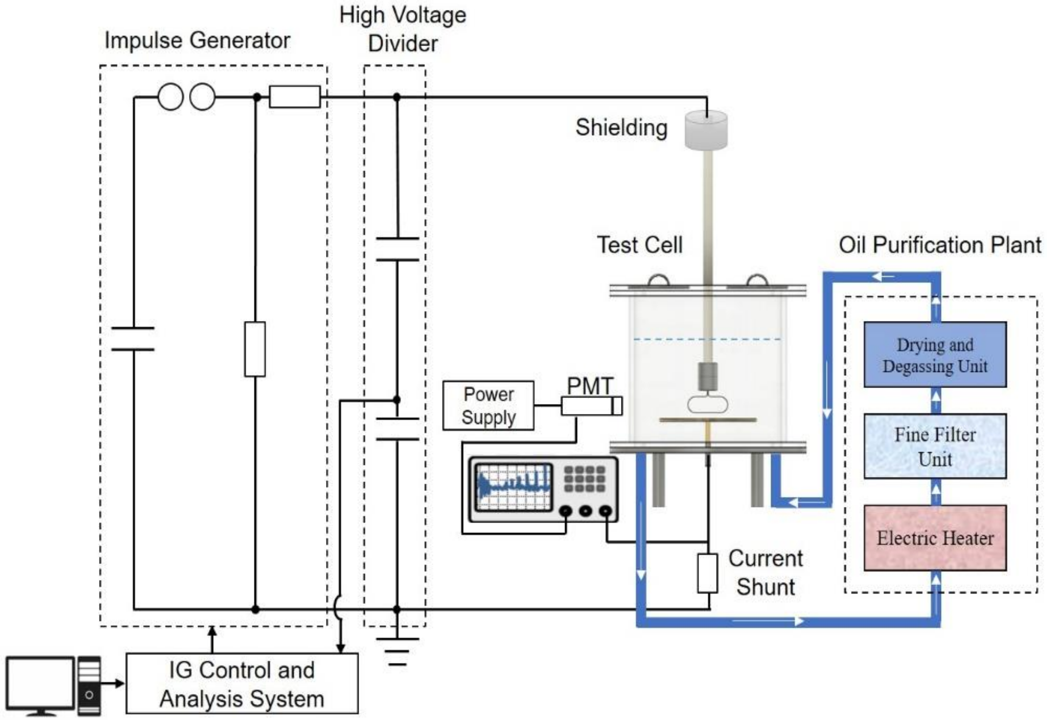
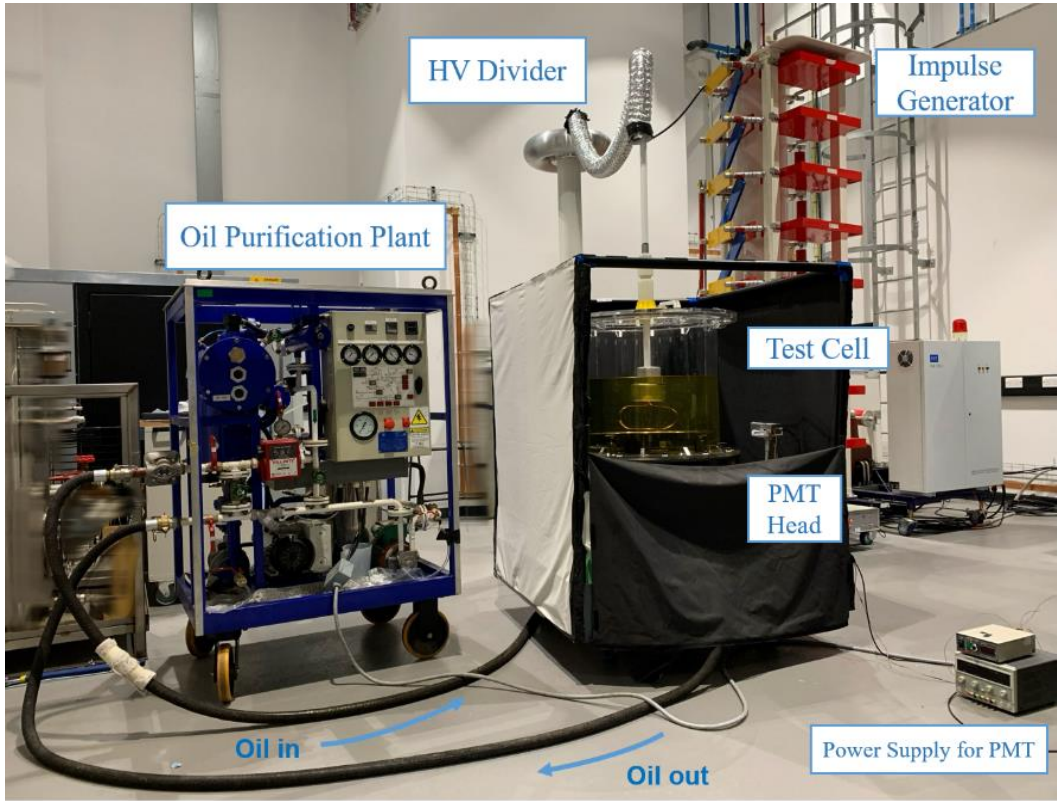
[1] X. Zhang, Z.D. Wang, Q. Liu, A. Gyore, and K. Rapp, "Investigation of the Total Flow Rates in Oil Natural Transformer Retrofilling Scenarios," in *20th International Conference on Dielectric Liquids (ICDL)*, pp. 1-4, Rome, Italy, 2019.

Impulse Breakdown Experimental Setup

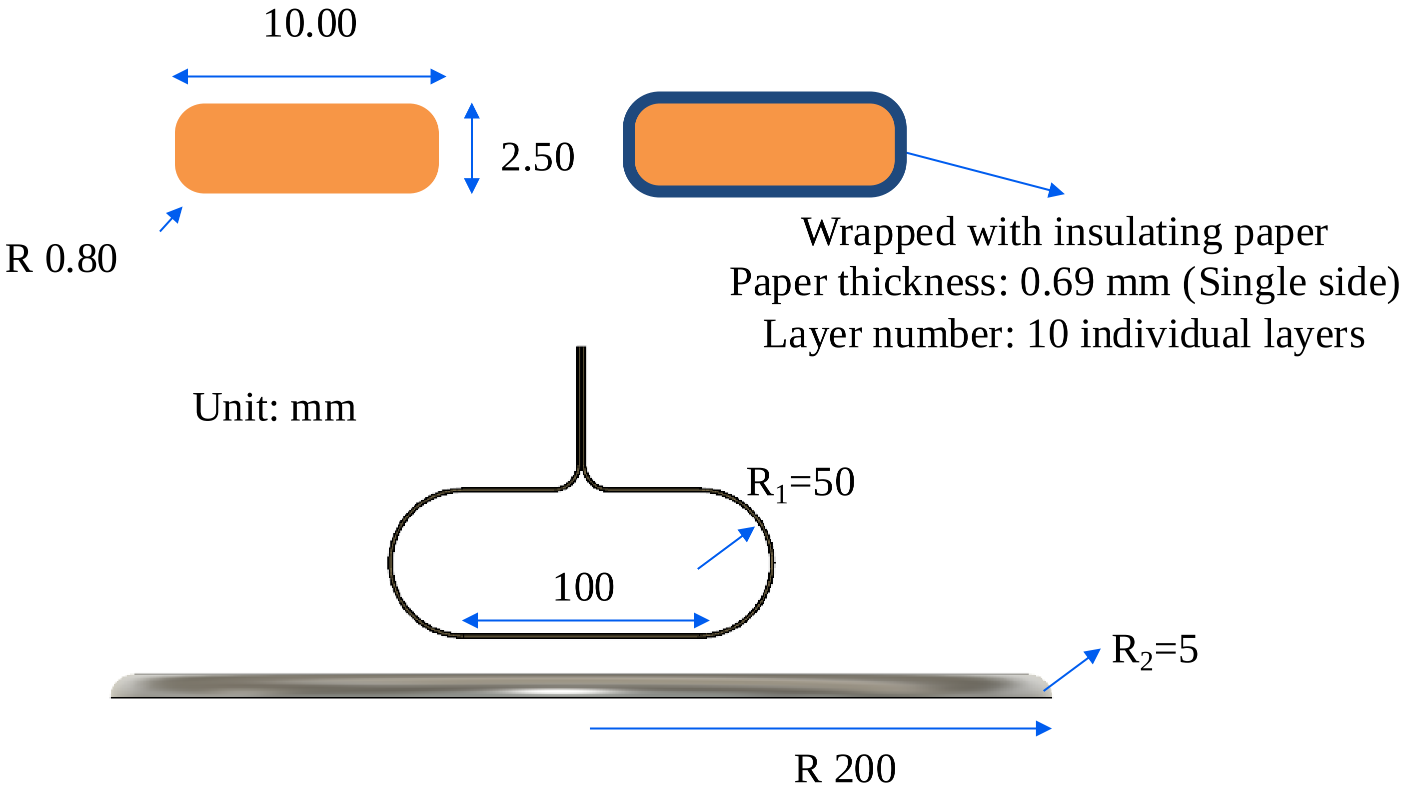
- To investigate the breakdown characteristics of transformer liquids using the large-scale winding conductor model, the experimental setup composed with a 170 L test cell was developed.





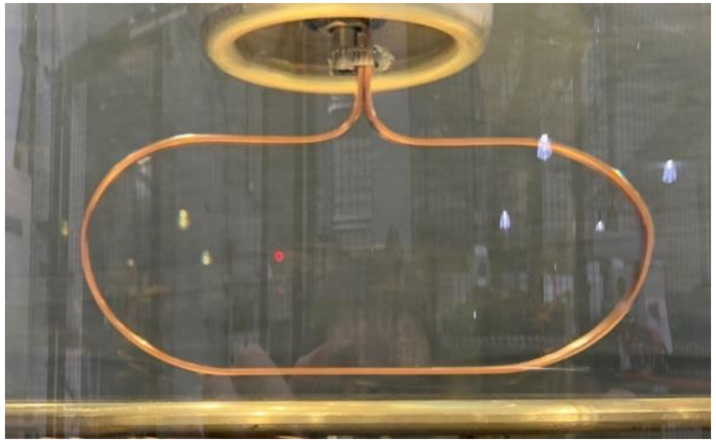
Electrode Configuration

- Paper wrapped copper conductor from transformer winding was used to make the energized electrode.
- Field factor of the electrode configuration is from 2.12 to 4.06.



Wrapped with insulating paper
Paper thickness: 0.69 mm (Single side)
Layer number: 10 individual layers

Electrode configuration

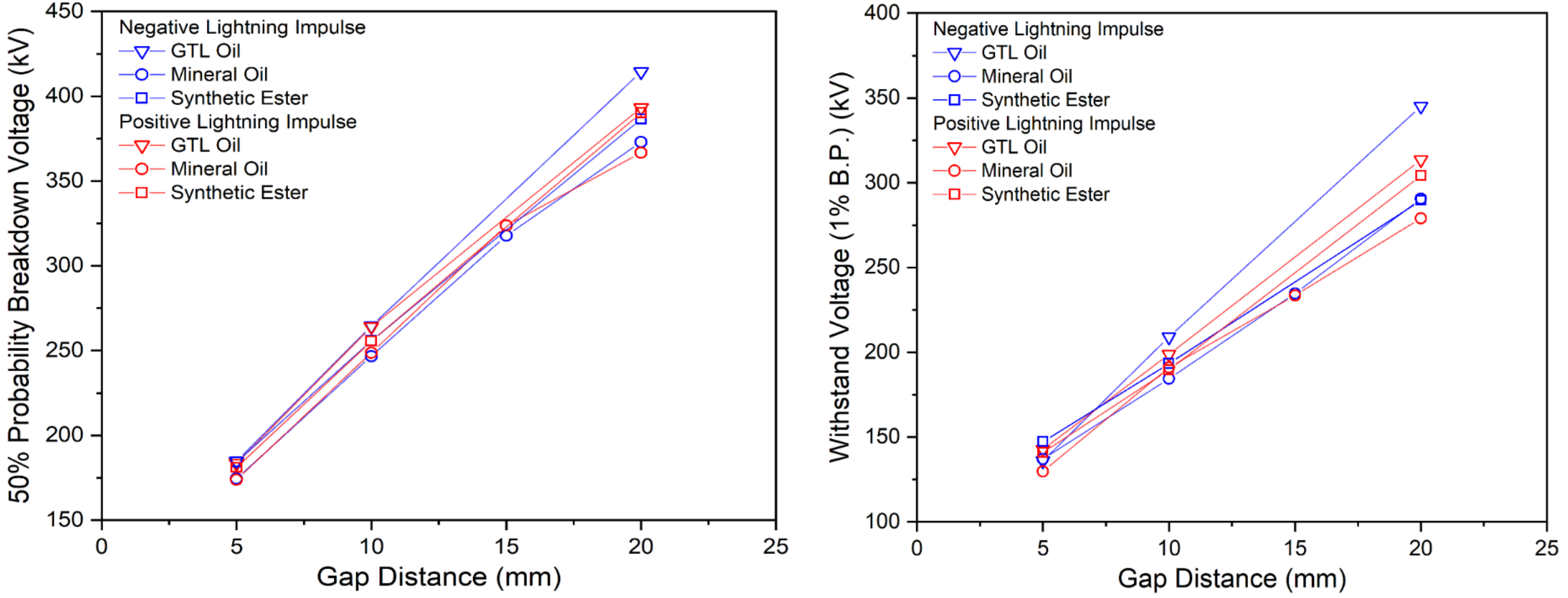


Installed bare electrode

Insulated electrode

Breakdown Voltage with Bare Electrode

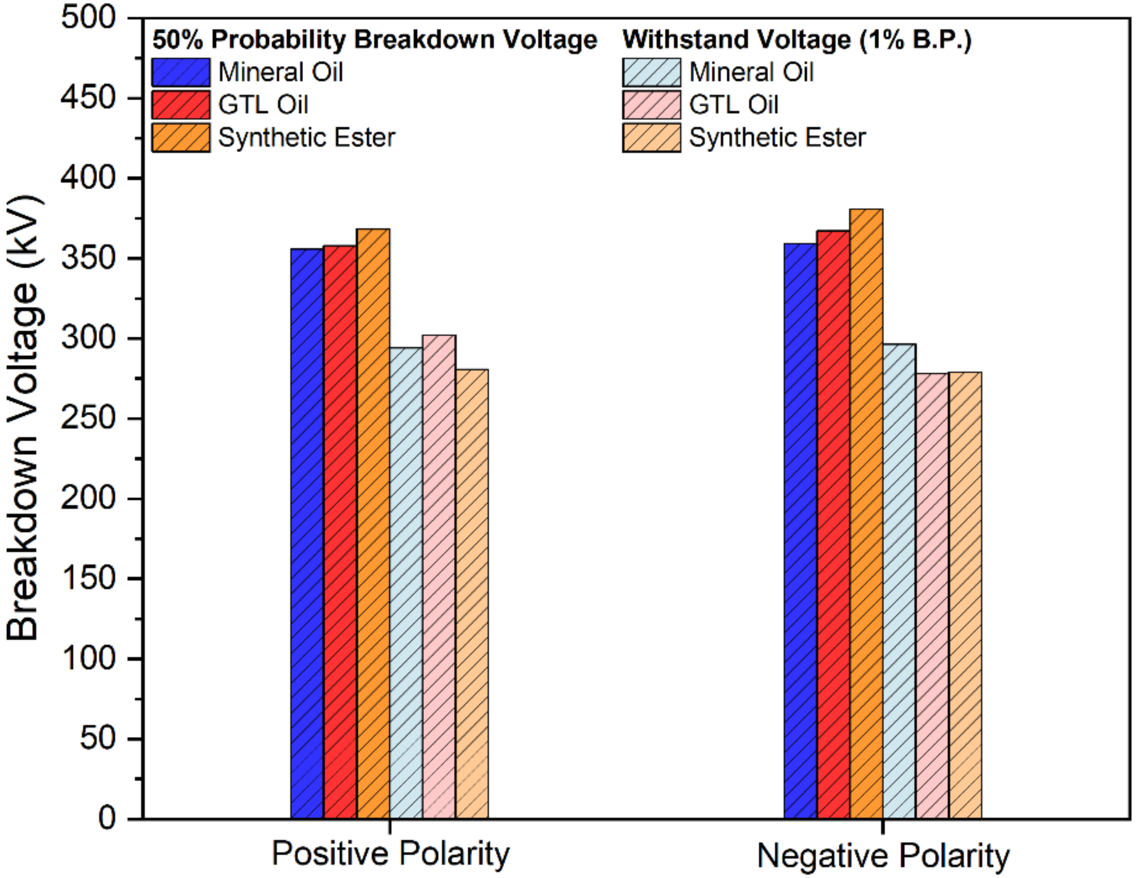
- Overall, the breakdown voltages are comparable among the three transformer liquids at the investigated electrode geometries.



Breakdown voltages comparison among transformer liquids with bare electrodes at different gap distances under lightning impulse

Breakdown Voltage with Insulated Electrode

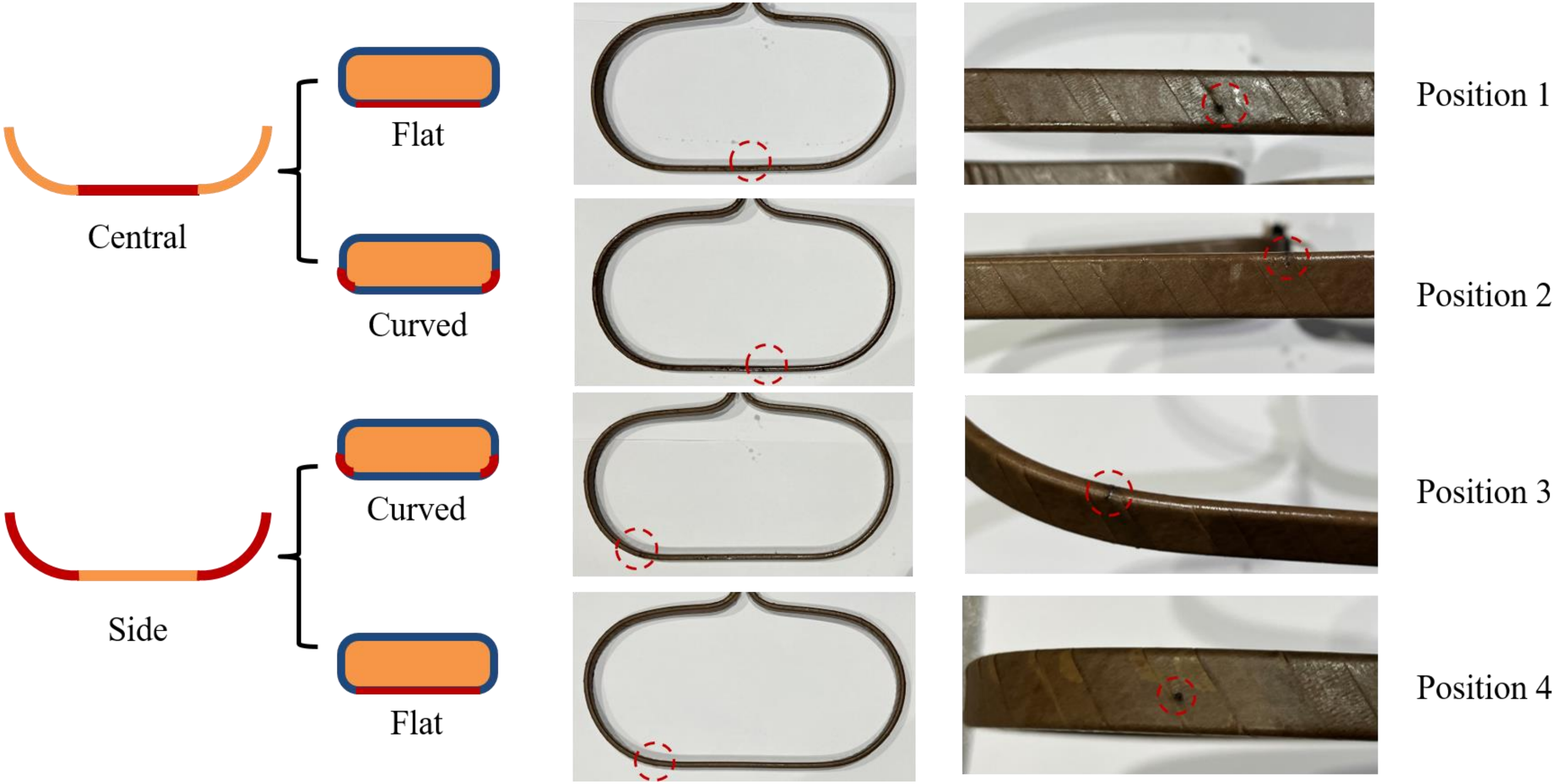
- Overall, with the insulated electrode, the breakdown voltages are also comparable among the three transformer liquids at the investigated electrode geometry.



Breakdown voltage and withstand voltage comparisons among transformer liquids under lightning impulse with insulated electrode, 10 mm gap

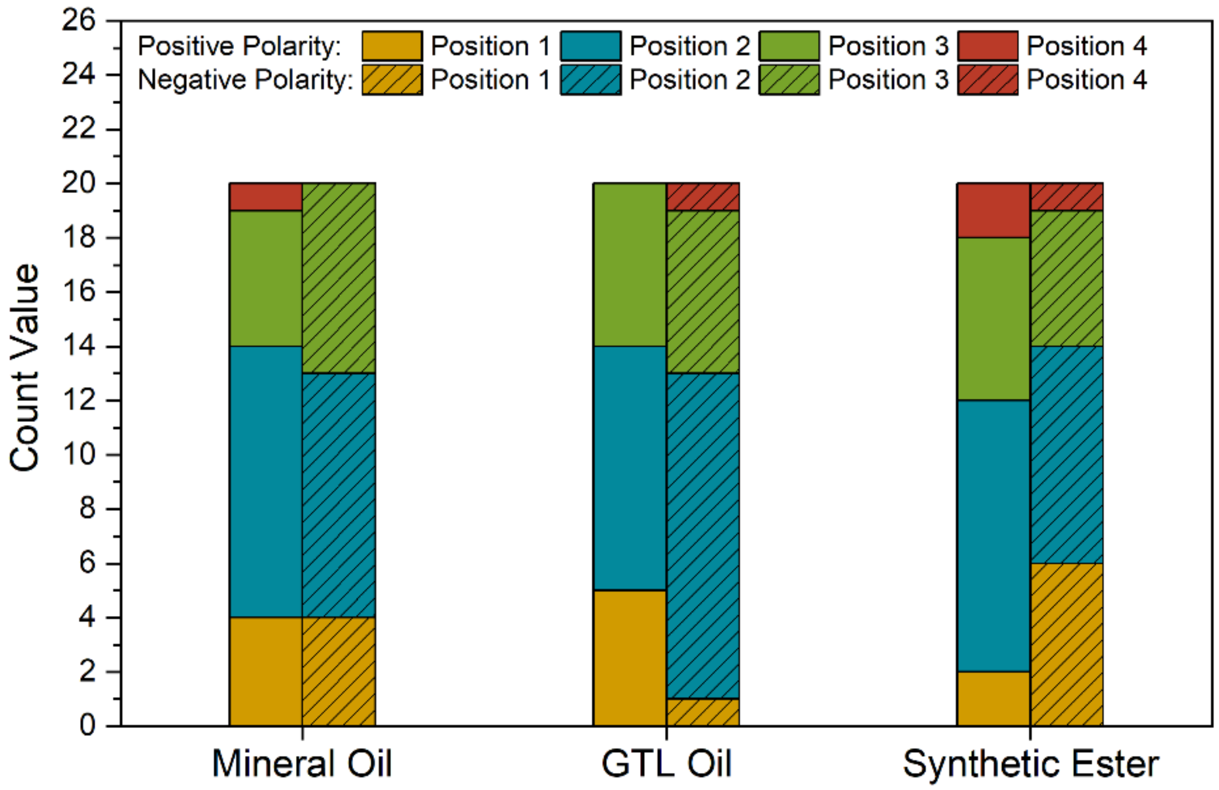
Breakdown Location

- Locations of breakdown are grouped into four categories.

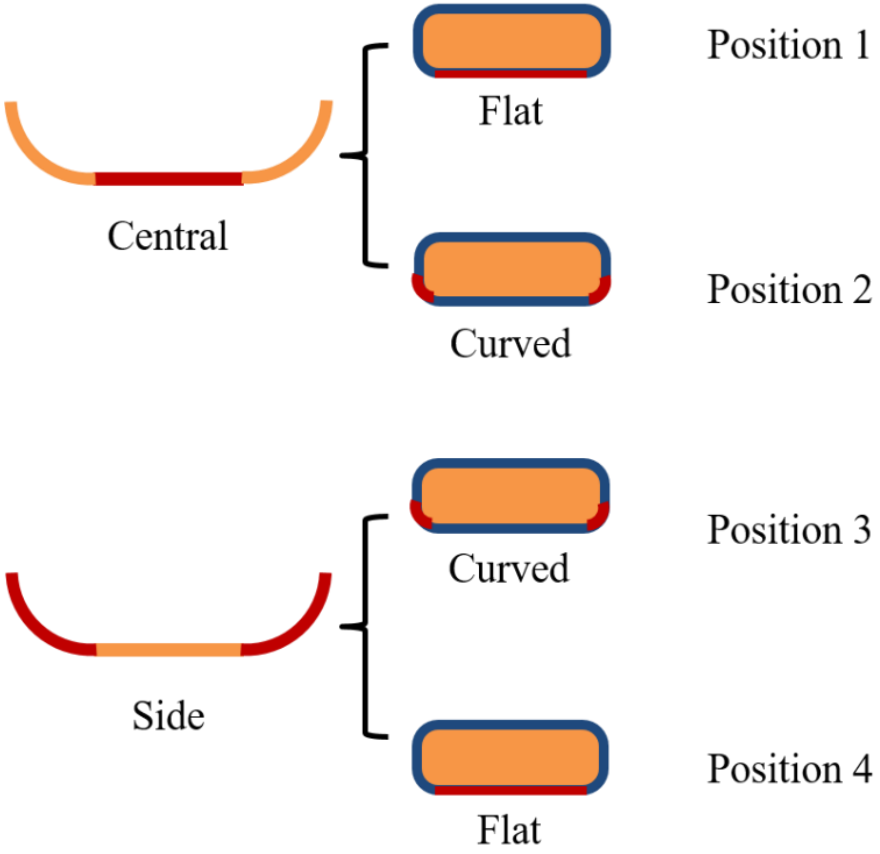


Classification of breakdown locations of transformer liquids with insulated electrode under lightning impulse

- There is no polarity effect on the breakdown streamer initiation position. The breakdown locations are similar among transformer liquids.
- Breakdown location ranking: Position 2 > Position 3> Position 1 > Position 4

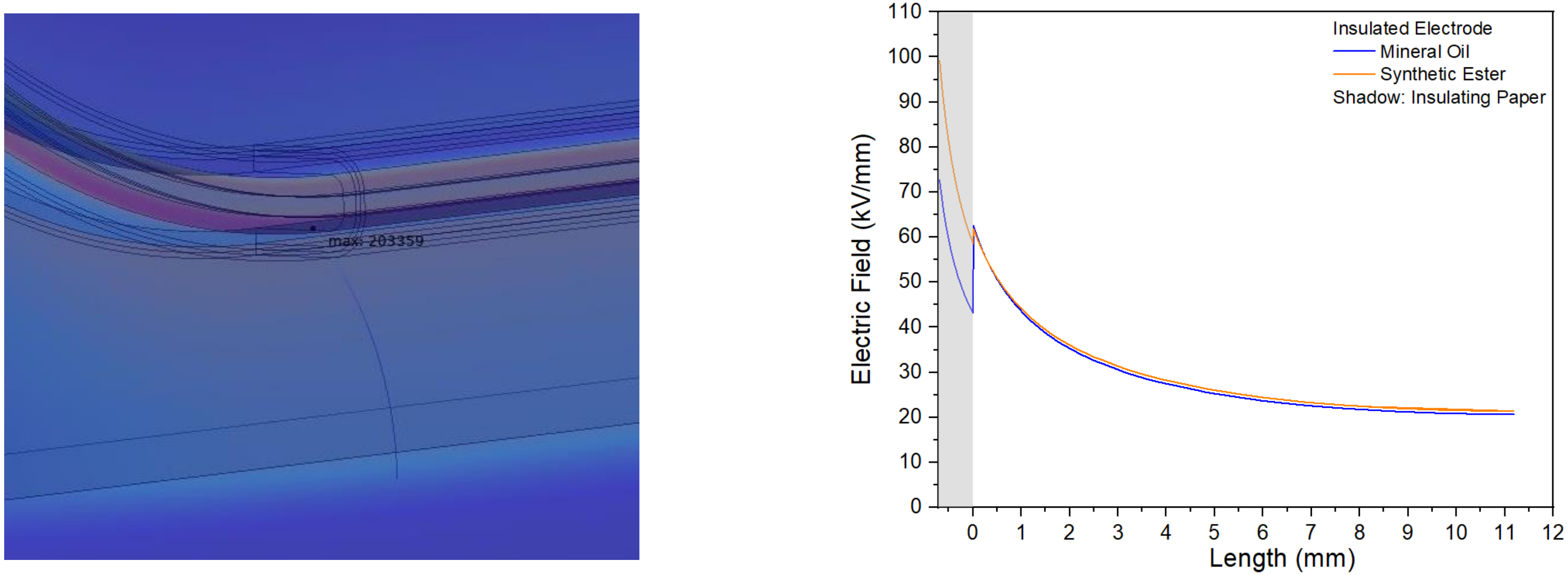


Count value of each type breakdown location of transformer liquids with insulated electrode under lightning impulse



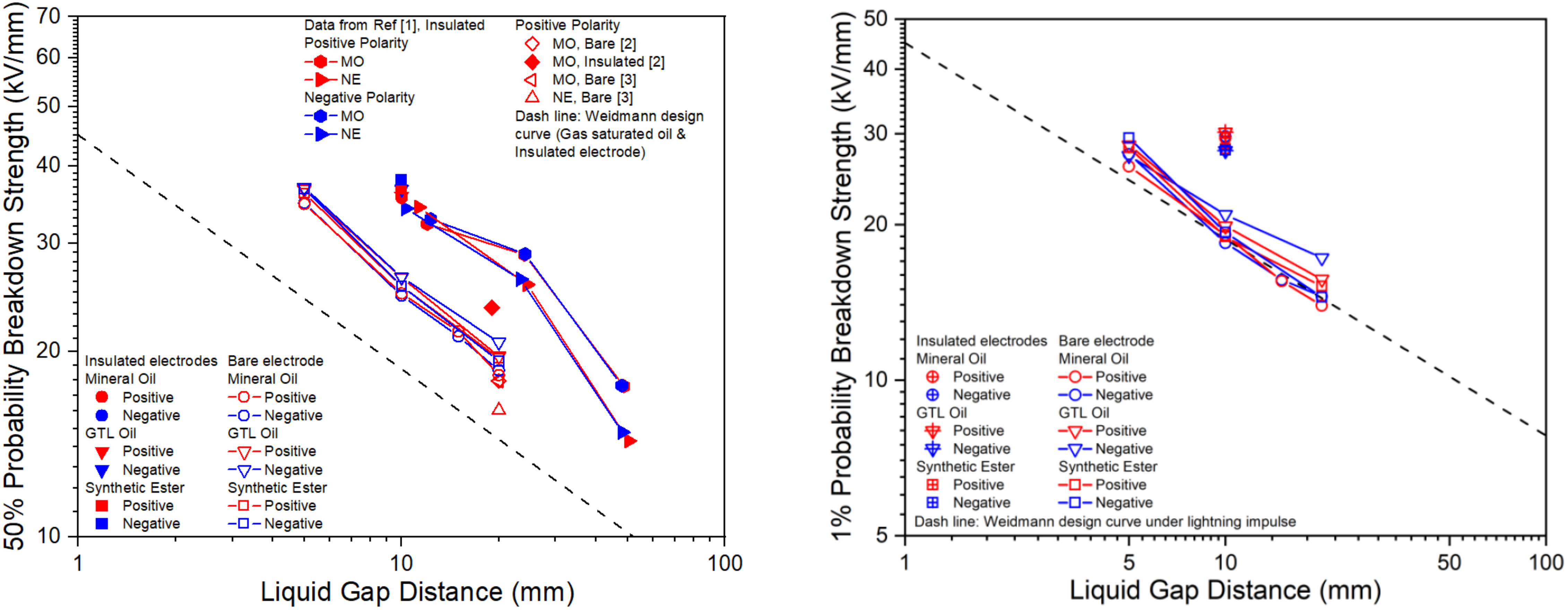
Underlying Breakdown Mechanism

- Maximum electric field at the electrode/paper interface at the breakdown voltage is much higher in the synthetic ester than in the mineral oil.
- Electric fields at the paper/liquid interface under the breakdown voltages are however comparable between the mineral oil and the synthetic ester. This implies that the breakdown for insulated electrodes could be dominated by the electric field at the paper/liquid interface.



Electric field distribution along electric field line considering the effect of liquid type under the breakdown voltage (359.3 kV for mineral oil and 380.6 kV for synthetic ester; liquid gap distance of 10 mm)

Comparison with Literature Data

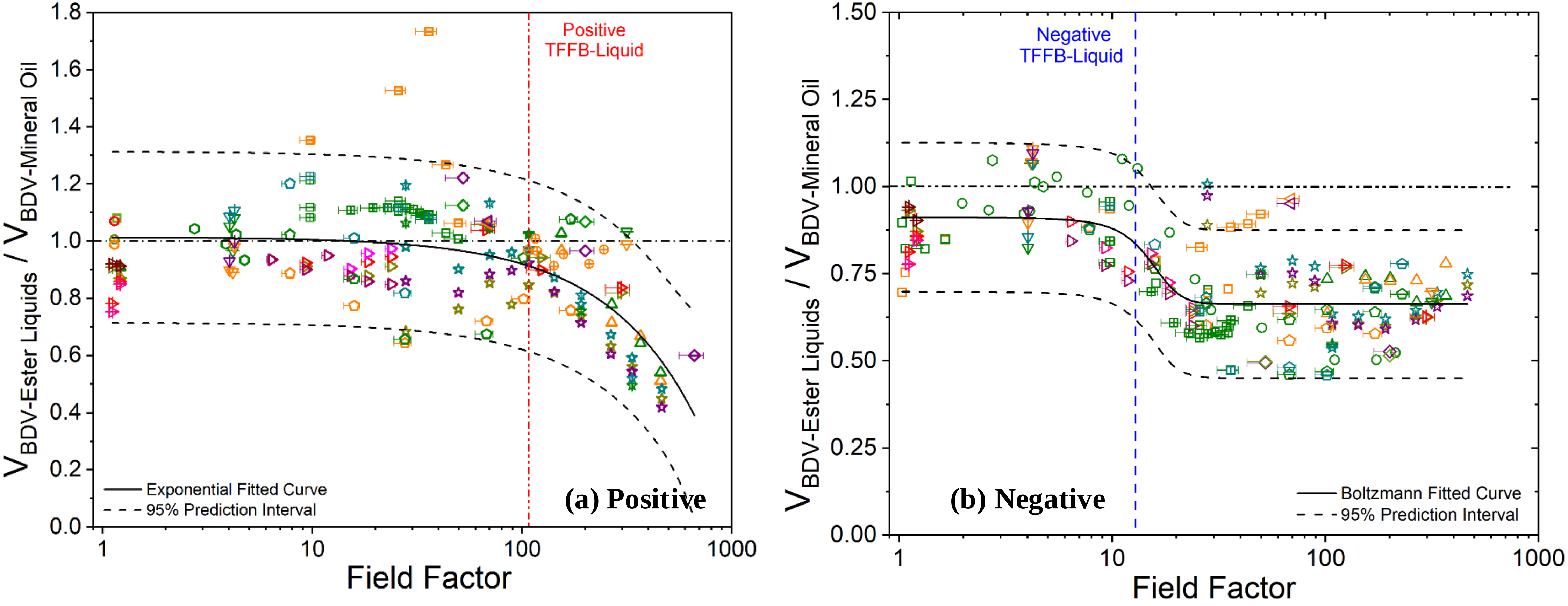


Breakdown strength comparison with references (Left: 50% breakdown field; Right: withstand field with 1% B.P.)

[1] K. J. Rapp, J. Corkran, C. P. Mcshane, and T. A. Prevost, "Lightning Impulse Testing of Natural Ester Fluid Gaps and Insulation Interfaces", IEEE Transactions on Dielectrics and Electrical Insulation, vol. 16, pp. 1595-1603, 2009.
[2] D. Vuković, M. Jovalekic, S. Tenbohlen, J. Harthun, C. Perrier, M. L. Coulibaly, and H. Fink, "Comparative experimental study of dielectric strength of oil-cellulose insulation for mineral and vegetable-based oils", 2012 IEEE International Symposium on Electrical Insulation, pp. 424-428, 2012.
[3] S. Haegele et al, “Lightning impulse withstand of natural ester liquid,” Energies, vol. 11, no. 8, p. 1964, 2018.

Effect of Field Uniformity on Breakdown

- Larger differences between mineral oils and ester liquids are observed at higher field factors (divergent fields).



Comparison of LIBDV between mineral oils and ester liquids at various field factors

Summary

- Thermal and insulation designs of transformers when considering different insulating liquids were investigated in this study through both experiments and simulations.
- A CCL CFD model was developed by incorporating the reduced radiator model, which enables comparative studies on the thermal profiles of different insulating liquids under ON/KN cooling mode.
- Insulation design knowledge has been accumulated mainly based on the experience of using mineral oils, which may not be readily appliable for emerging dielectric liquids.
- Design of breakdown tests and interpretation of breakdown results must consider the effects of electric field uniformity and the underlying breakdown mechanisms.

Acknowledgement

For more details:

[1] S.C. Zhao, H. Yu, Q. Liu, Z.D. Wang, M. Wilkinson, M. Negro, C. Krause, A. Hilker, E. Schaik, M. Daghrah and A. Gyore “Thermal and Electrical Designs of Transformers by Considering Different Insulating Liquids”, CIGRE Paris Session, paper A2-10402, 2024.

[2] S.C. Zhao, Q. Liu, M. Wilkinson, G. Wilson and Z.D. Wang, “A Reduced Radiator Model for Simplification of ONAN Transformer CFD Simulation”, IEEE Transactions on Power Delivery, 2022.

[3] S.C. Zhao, X. Zhang, Q. Liu, Z.D. Wang, M. Negro, M. Daghrah and E. Schaik, “Investigation of Liquid Temperatures and Velocities at Winding Inlet in Natural Cooled Transformers through Complete-Cooling-Loop based CFD Simulations and Experiments”, IEEE Transactions on Power Delivery, 2024.

[4] H. Yu, Q. Liu and Z.D. Wang, “Statistical analysis and interpretation on lightning impulse breakdown voltages of ester liquids under varying field uniformity,” High Voltage, 2023.

[5] H. Yu, Q. Liu, Z.D. Wang, C. Krause and M. Wilkinson, “Lightning impulse breakdown characteristics of transformer liquids with large scale winding conductor model,” IEEE Transactions on Dielectrics and Electrical Insulation, 2024 (under review).