fire

MDPI

Article

Research on Fire Suppression Characteristics of Compressed Air Foams in Full-Scale 220 kV Converter Transformer

Yike Guo [1], Tao Chen [2,*], Biao Zhou [1], Peng Zhang [2], Yuwei Wang [2], Xuyao Wang [1] and Danping Hao [1]

[1] School of Emergency Management and Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China
[2] Tianjin Fire Science and Technology Research Institute of MEM, Tianjin 300381, China
* Correspondence: chentao@tfri.com.cn

Abstract: To study the fire behavior of UHVDC (ultra-high-voltage direct current) converter transformers and the effectiveness of CAFs (compressed air foams) in suppressing fires, a full-scale model of a 220 kV converter transformer fire was constructed. The model mainly considered the oil pool fires and oil spill fires that form after explosions, causing the casing to completely fall out. The hot oil fire tests were conducted on the physical converter transformer. The fire suppression characteristics of the CAF system for converter transformer fires were studied. The temperature and changes in various locations of the fire model were analyzed under different foam supply strengths. The fire in a converter transformer is characterized by intense heat, high temperatures, and strong radiation. The highest temperature can exceed 1000 °C in cases of complete combustion. The fire in the converter transformer involves a dynamic oil spill and a large pool of oil, making it challenging to extinguish. The fire extinguishing performance and cooling effect of CAFs are outstanding. The recommended foam supply strength for the actual project is more than 8 L/(min·m^2).

Keywords: CAF; converter transformer; fire extinguishment system

Academic Editor: Jinlong Zhao

Received: 3 December 2024
Revised: 23 December 2024
Accepted: 28 December 2024
Published: 31 December 2024

Citation: Guo, Y.; Chen, T.; Zhou, B.; Zhang, P.; Wang, Y.; Wang, X.; Hao, D. Research on Fire Suppression Characteristics of Compressed Air Foams in Full-Scale 220 kV Converter Transformer. *Fire* **2025**, *8*, 12. https://doi.org/10.3390/fire8010012

1. Introduction

UHVDC converter transformers have high voltage levels, large oil storage capacity, and complex layouts. The insulating oil inside the transformer is prone to leakage and combustion when the transformer is under failure or high temperatures and other abnormal conditions [1]. The accident cases of recent years have shown that normal conventional fire extinguishment technology has difficulty meeting the fire extinguishment requirements of UHVDC converter transformers. CAF has the advantages of high fire extinguishing efficiency, uniform and stable foam, and environmentally friendly chemicals [2–5]. Therefore, it is important to investigate the characteristics of the CAF to suppress transformer fires. It is of great significance for controlling transformer fire accidents.

In recent years, researchers have conducted several studies on the fire properties of transformers and the effectiveness of CAF in extinguishing. The main focus of current research is on the evaluation of fire extinguishing methods [6–8], fire risk assessment [9], factors influencing fire extinguishing performance such as different mixing ratios of air and foam solution [10], qualities and application rates of CAF [11], variable fuel thicknesses of oil [12], the coupling effect of CAF and other fire extinguishing methods [13], and transportation characteristics in pipe networks [14]. Several researchers have focused on the characteristics of transformer fires of large or small sizes. Wu [15] investigated the fire characteristics of transformer oil fires in a 100 m^2 tank and identified differences in the effectiveness of two firefighting methods: a hand-held fire water branch and a fire water monitor. Zhao [16] studied the correlation between burning rate and pool diameter and concluded that pool size does not affect the boiling layer in oil pool tests. Li [17] explored the characteristics of continuous spill fires and established a prediction model for the burning area and radiation of transformer oil spill fires. Zhang [18] investigated the burning process and fire characteristics of transformer oils using a cone calorimeter. The study found that both external radiative heat flux and oil type have an impact on fire hazards. Sun [19] conducted experiments on transformer oil jet fires using various nozzle diameters to investigate the characteristics of transformer oil jet flames. They also developed a prediction model for the radiant heat flux of oil-filled equipment in substations. Zhu [20] conducted a study on the suppression of transformer oil pool fires in a $3 \times 3 \times 3$ m room by water mist. They found that flame intensification occurred at the initial stage during water mist injection, which was related to fire size and the size of the pressure. Although the effectiveness of CAF in extinguishing transformer oil fires has been verified, there are few reports available on the behavior of full-scale transformer oil fires and the fire extinguishing characteristics of such incidents. The development and extinguishing process of the oil-immersed transformer fire model are not clear.

In this study, a full-scale 220 kV converter transformer solid fire model was developed, which includes simulations of oil pool fires and oil spill fires in a 1:1 proportion. Furthermore, the suppression characteristics of CAF systems for full-scale converter fires are discussed for the first time.

2. Experiment and Method

2.1. Apparatus Layout Introduction

A full-size solid fire model was developed and constructed following the structure and dimensions of a 220 kV oil-immersed transformer in the State Grid Beijing Power Company (China, Beijing). The model is depicted in Figure 1. The energy level and explosion power of 220 kV oil-immersed transformer during fault conditions are significantly lower than those of UHVDC converter transformers. The model is primarily concerned with oil pool fires and oil spill fires that result from explosions and falling tubes. The fire model includes a main tank top pool fire, a burn hole fire, an oil spill fire, and a bottom pool fire. The transformer in this model consists of a main oil tank that measures 6.5 m in length, 3.5 m in width, and 1.5 m in height. Additionally, there are two radiators situated at either end of the main tank. The oil conservator measures 2.5 m in length, 1.0 m in width, and 1.0 m in height. The arrangement of the model is based on the typical layout of a 220 kV oil-immersed transformer room in real-world projects. For safety reasons, the model is situated in the center of a pit that measures 14.5 m in length and 9.5 m in width, as illustrated in Figure 2.

2.2. Materials

The KI25X transformer oil, produced by Petro China's Karamay Lubricating Oil Plant (China, Xinjiang, Karamay), was used as the test fuel. The density is 884.6 kg/m^3, the kinematic viscosity is 9.652 mm^2/s and the flash point is 143 °C. This transformer oil has the characteristics of rapid heat transfer, good oxidation stability, and excellent electrical properties. The amount and temperature of transformer oil are key factors that affect fire extinguishing performance. The higher the temperature of the oil, the more challenging it becomes to put out the fire. The oil dosage and temperatures for various locations in the test were determined through a comprehensive analysis that included case studies of fire accidents, temperature analysis of actual operating oil, and theoretical calculations for a typical 220 kV oil-immersed transformer. The results are presented in Table 1. Film-forming CAF extinguishing agents, which have a fire extinguishing performance level of Class I and a burn resistance level of Class A, were used in conjunction with a fixed CAF-generating device called FCAFS1200 (China, Tianjin) during the test. The release device adopted a self-developed CAF spraying pipe. The arrangement of the pipe network is illustrated in Figure 3. The CAF spray pipes have a length of 12 m on each side, with a distance of 9.5 m between them and a height of 6.4 m from the ground.

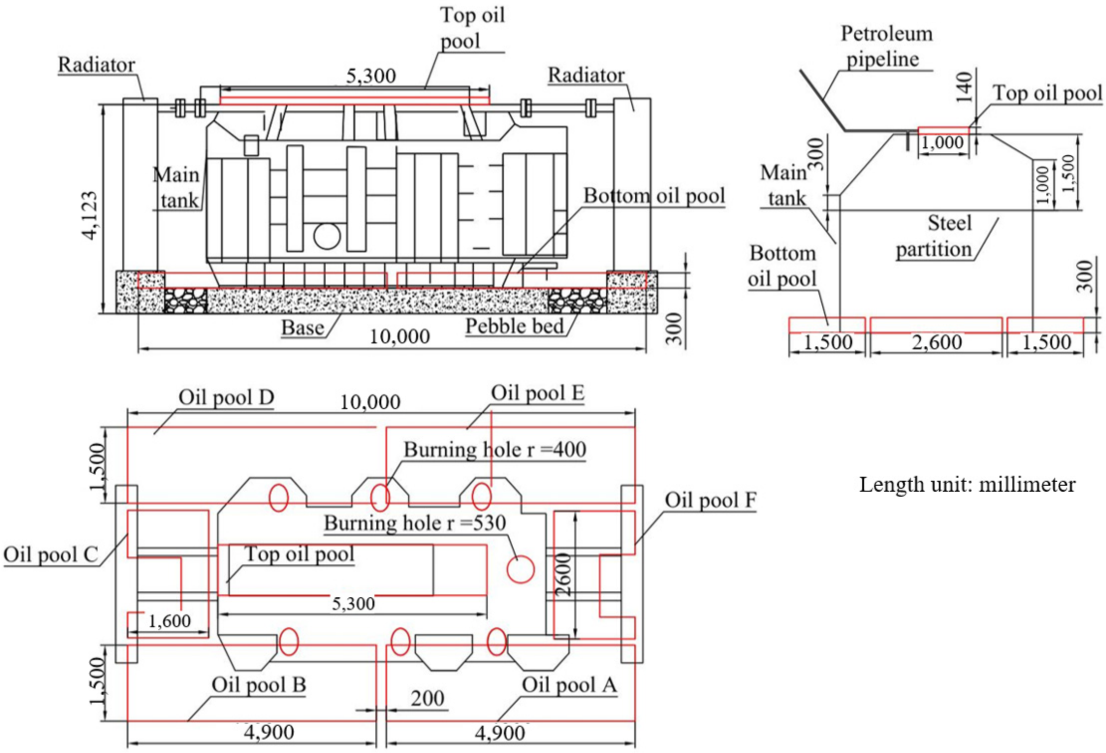


Figure 1. Schematic diagram of 220 kV oil-immersed transformer.

Figure 2. Fire model fact map of 220 kV oil-immersed transformer.

Table 1. Test oil quantity and test oil temperature.

No.	Model Position	Oil Consumption		Oil Temperature/°C
		Oil Layer Thickness/mm	Oil Volume/m^3	
1	Main oil tank	150	3.5	≥85
2	Top oil pool	140	0.8	≥85
3	Bottom oil pool A	70	0.5	≥85
4	Bottom oil pool B	70	0.5	≥85
5	Bottom oil pool D	70	0.5	≥85
6	Bottom oil pool E	70	0.5	≥85
7	Bottom oil pool C	70	0.2	≥85
8	Bottom oil pool F	70	0.2	≥85

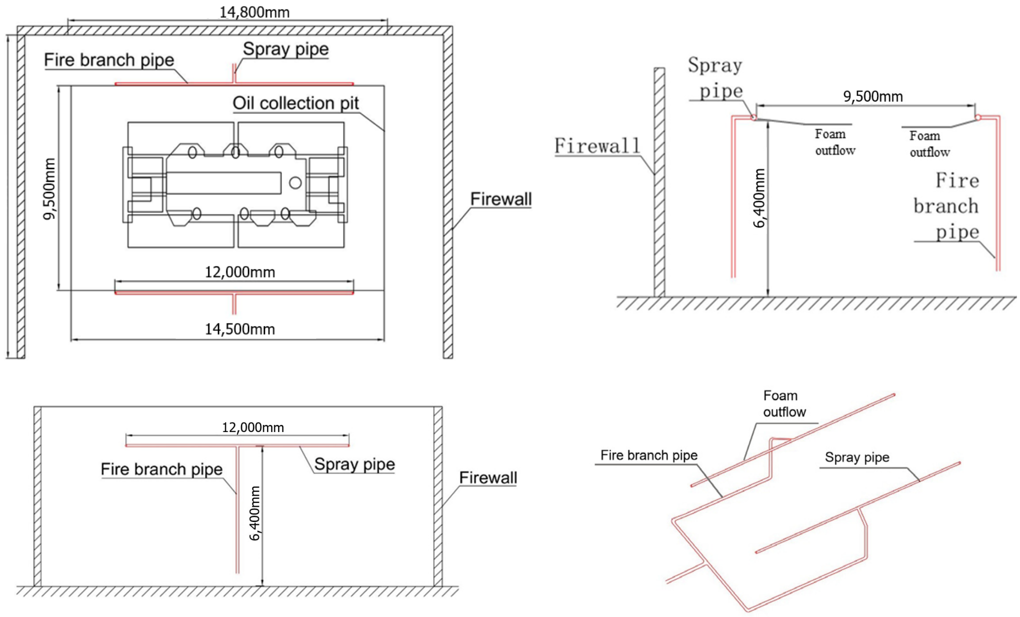


Figure 3. Layout of CAF spray system.

2.3. The Configuration of Thermocouples

To investigate the characteristics and development of fire suppression, a multi-channel data acquisition system was utilized along with thermocouples, infrared thermometers, and heat flow meters. These instruments were used to measure crucial thermal parameters, including temperature, distribution, and heat radiation during the experiment. The TP1000 multi-channel data acquisition system was used in real time, supporting the measurement of signals such as thermocouples, resistance temperature detectors and thermistors, DC (direct current) voltages, and DC currents. K-type armored NiCr-NiSi thermocouples with a 3 mm diameter and temperature measurement range of 0 °C to 1200 °C were used in the test. The other test equipment includes two cameras (HF S30 and COOLPIX S8000) (China, Tianjin), a stopwatch, a walkie-talkie, a thermal imaging camera, a radiometric heat flow meter, etc.

A total of 38 thermocouples were arranged in the main tank, the combustion holes, the top tank, and the bottom tank. Among these thermocouples, T1–T3 were evenly distributed inside the main tank 250 mm from the bottom near the center. T4–T10 were located directly above the 7 combustion holes in the main tank, respectively. T11 and T12 were located 50 mm from the bottom, near the center inside the top tank. T13 and T14 were located 200 mm above the top tank, near the center. T15–T18 and T20–T23 were located 50 mm from the bottom, near the center, inside the bottom tanks, and every location—A, B, D, and E—had 2 each. T25–T28 and T30–T33 were arranged 500 mm above the center of the bottom pools, and each point—A, B, D and E—had 2 each. T19 and T24 were arranged 50 mm from the bottom near the center; the points C and F had 1 each. T35–T38 were evenly spaced at a distance of 2.5 m directly above the main tank. A thermocouple was placed 100 mm from the bottom in the high-heat oil conservator outside the firewall to measure the temperature of the oil in the conservator. The arrangement of thermocouples is shown in Figure 4. In addition, four high-definition cameras were set up at each of the four corners of the transformer model to record the development and extinguishing process of the fire of the oil-immersed transformer physical model.

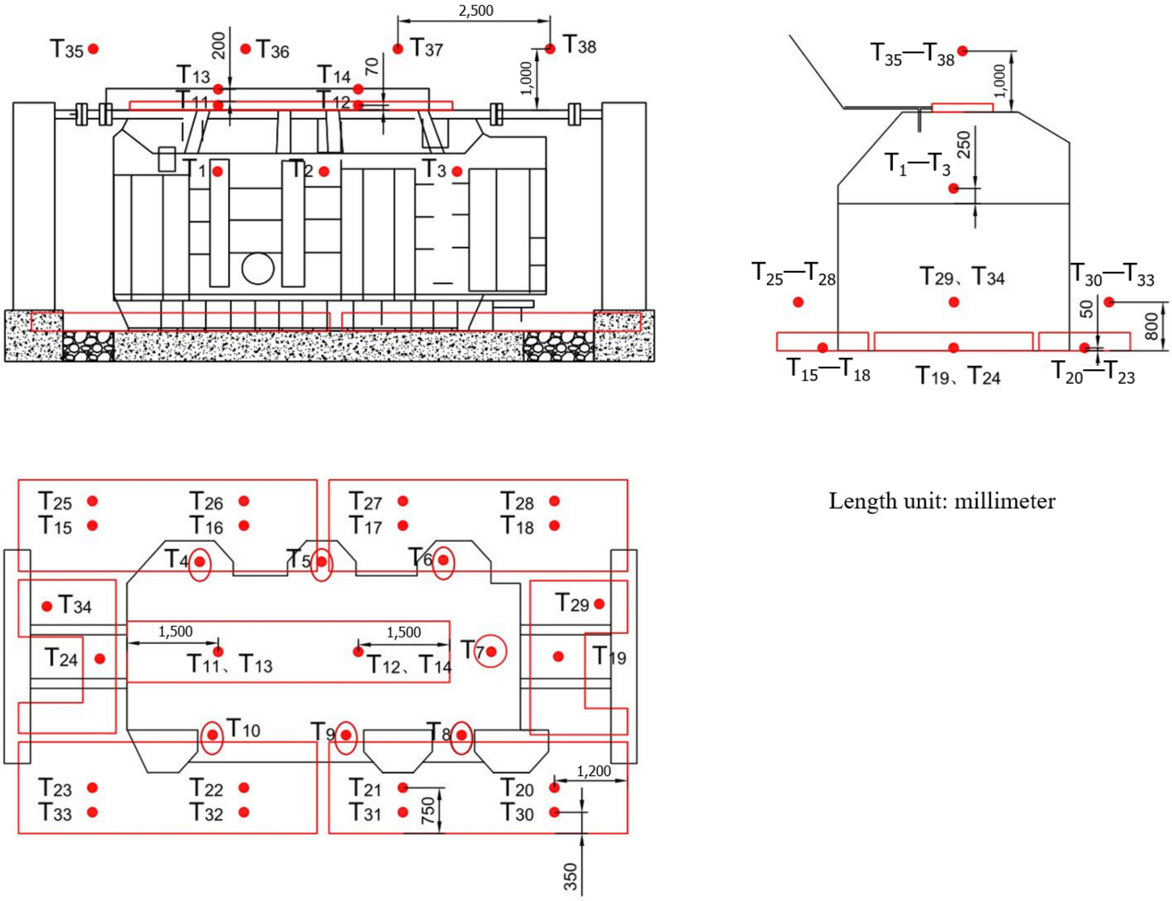


Figure 4. Thermocouple layout T1–T38.

2.4. The Test Procedure

The heating tank and oil conservator were filled with transformer oil according to the program's oil consumption. The tank was then covered with a lid, and the transformer oil was heated in both the heating tank and the oil conservator. When the temperature of the transformer oil in the heating tank and oil conservator reached approximately 160 °C and 110 °C, respectively, the heating was stopped. The hot oil was then injected into the main tank and each oil pool from the heating tank. Meanwhile, the lid of the tank was removed.

By opening the electric control valve connecting the oil conservator and the main oil tank, the transformer oil stored in the oil conservator flowed into both the main oil tank and the top oil pool. When the overflow of oil from the main oil tank and the top oil pool reached approximately 300 L/min, the oil was ignited by electric ignition on both sides of the bottom oil pool and the main oil tank, and the timer was started.

The CAF spraying system was started after the pre-ignition process, which took approximately three minutes. The CAF spraying system uses two supply intensities. The foam solution flow rate is 1100 L/min, the supply intensity is 8 L/(min·m^2), the foam solution flow rate is 1300 L/min, and the supply intensity is 9.4 L/(min·m^2).

The fire extinguishing process was observed and recorded, including the flame pattern, smoke, temperature, heat radiation, foam coverage performance, and other changes, during the fire extinguishing process. After the fire was completely extinguished, foam samples were collected and their performance was determined using the following methods.

Step 1: The interior of the precipitator receiver tank was moisturized with water, cleaned, and weighed (m_1).

Step 2: After extinguishing the fire, the foam collector was promptly positioned beneath the nozzle to collect a sample of the foam using the precipitator. While the stopwatch was running, the excess foam from the precipitator was scraped, wiped away, and weighed (m_2). The mass of the 25% precipitate (m_3) was calculated using Equation (1), where m_1 is the net weight of the liquid analyzer, g; m_2 is the weight of the foam and liquid analyzer, g; and m_3 is the weight of the 25% precipitate, g.

$$m_3 = (m_2 - m_1)/4 \tag{1}$$

Step 3: The precipitation-receiving tank of the precipitation tester was removed and placed on the balance, while the foam-receiving tank was placed on the stand, keeping the precipitation free of foam. When the mass of the precipitated liquid was m_3, we recorded the 25% precipitation time with a stopwatch.

Step 4: The foaming multiplier was calculated according to Equation (2), where E is foaming time, ρ is density of the foam solution (ρ = 1.0 g/mL), and V is the volume of foam receiving tank, mL.

$$E = \rho V/(m_2 - m_1) \tag{2}$$

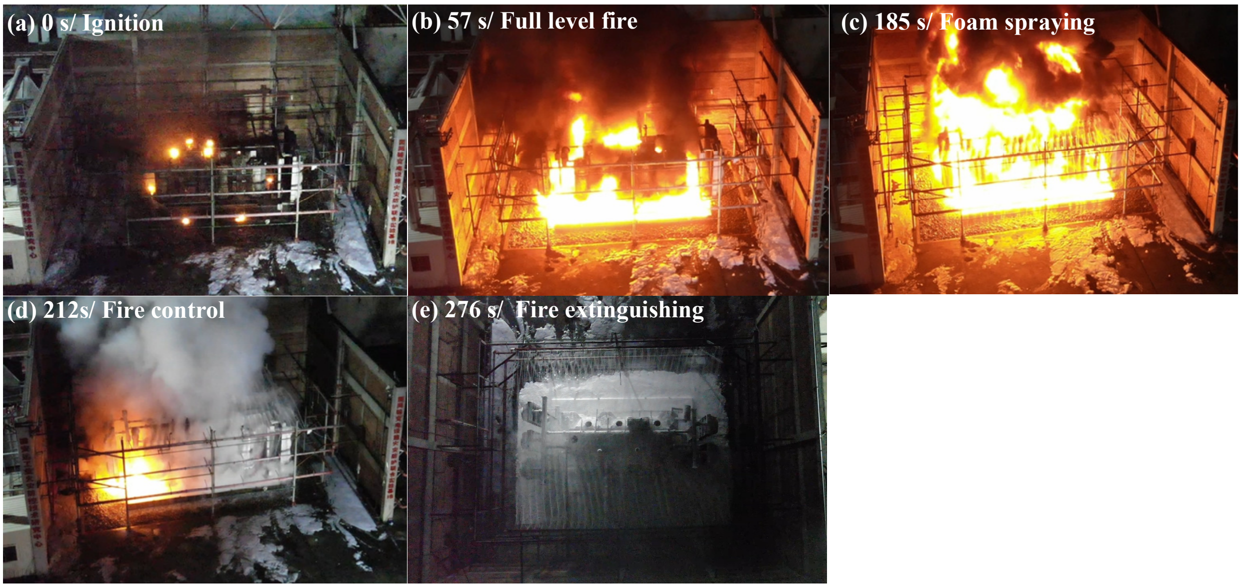
When the oil temperature dropped below 100 °C, the fire extinguishing system was shut down. The application of CAF was stopped. The oil relief valve was closed and the continuous supply time was recorded. When the transformer oil cooled down to ordinary temperature after the test, the remaining transformer oil, the oil tank, and pool were disposed and cleaned up in preparation for the next test.

3. Results and Discussion

3.1. The Influence of Supply Intensity on Fire Suppression Performance

The experimental procedure is shown in Figure 5. After pre-ignition for 60 s, the fire developed into a full liquid fire filling the whole area of the physical model, producing thick black smoke. After approximately 180 s of pre-ignition, the CAF was sprayed to extinguish the fire. When the flow rate of the foam solution was 1100 L/min and the supply intensity was 8 L/(min·m^2), the fire was completely extinguished in 175 s. For transformer oil in the main oil tank, bottom oil pool, and top oil pool, the oil's temperature was reduced to below 100 °C after continuously supplying foam for 468 s. After 480 s of continuously supplying foam, the temperature of transformer oil was reduced to 99.8 °C, 90.7 °C, and 69.6 °C, respectively. When the foam solution flow rate was 1300 L/min and the supply intensity was 9.4 L/(min·m^2), the fire was completely extinguished in 91 s. After 618 s of continuous foam supply, the transformer oil temperature in the main oil tank, bottom oil pool, and top oil pool reduced to 97.6 °C, 87.6 °C, and 62.7 °C respectively. Meanwhile, a thick foam blanket was formed on the surface of the transformer oil throughout the area, which could cool down the temperature and prevent the fire from re-igniting.

(**A**)



(**B**)

Figure 5. Fire extinguishing process diagram with different supply intensities. (**A**) Fire Extinguishing Chart at Supply Intensity of 8 L/(min·m^2). (**B**) Fire Extinguishing Chart at Supply Intensity of 9.4 L/(min·m^2).

When the transformer oil overflows from the tank, the oil moves along the tank wall to form a dynamic oil spill fire close to the wall. With the high temperature of the tank wall, the transformer oil quickly vaporizes into oil vapor, so the fire is very difficult to put out. Cooling down the tank wall requires a large flow of CAF. A large flow of CAF must be used to make the tank wall quickly cool down; after that, the oil spill fire can be extinguished. Under the condition that the foam mixture is supplied at a strength of 8 L/(min·m^2), the CAF spray system can quickly and effectively extinguish hot oil fires of 220 kV oil-immersed transformers. The thick foam blanket on the transformer oil surface throughout the area could quickly cool down the fire and prevent it from re-igniting.

Figure 6 depicts the temperature distribution within the fire zone. With a supply intensity of 9.4 L/(min·m^2), the temperature field in Figure 6 indicates that after burning for 57 s, the fire expanded into a full liquid fire with an oil spill. The temperature throughout the fire area was extremely high. The temperature of the entire area affected by the fire decreased rapidly after the application of CAF. This indicates that CAF possesses not only a potent fire-extinguishing ability but also an exceptional cooling effect.

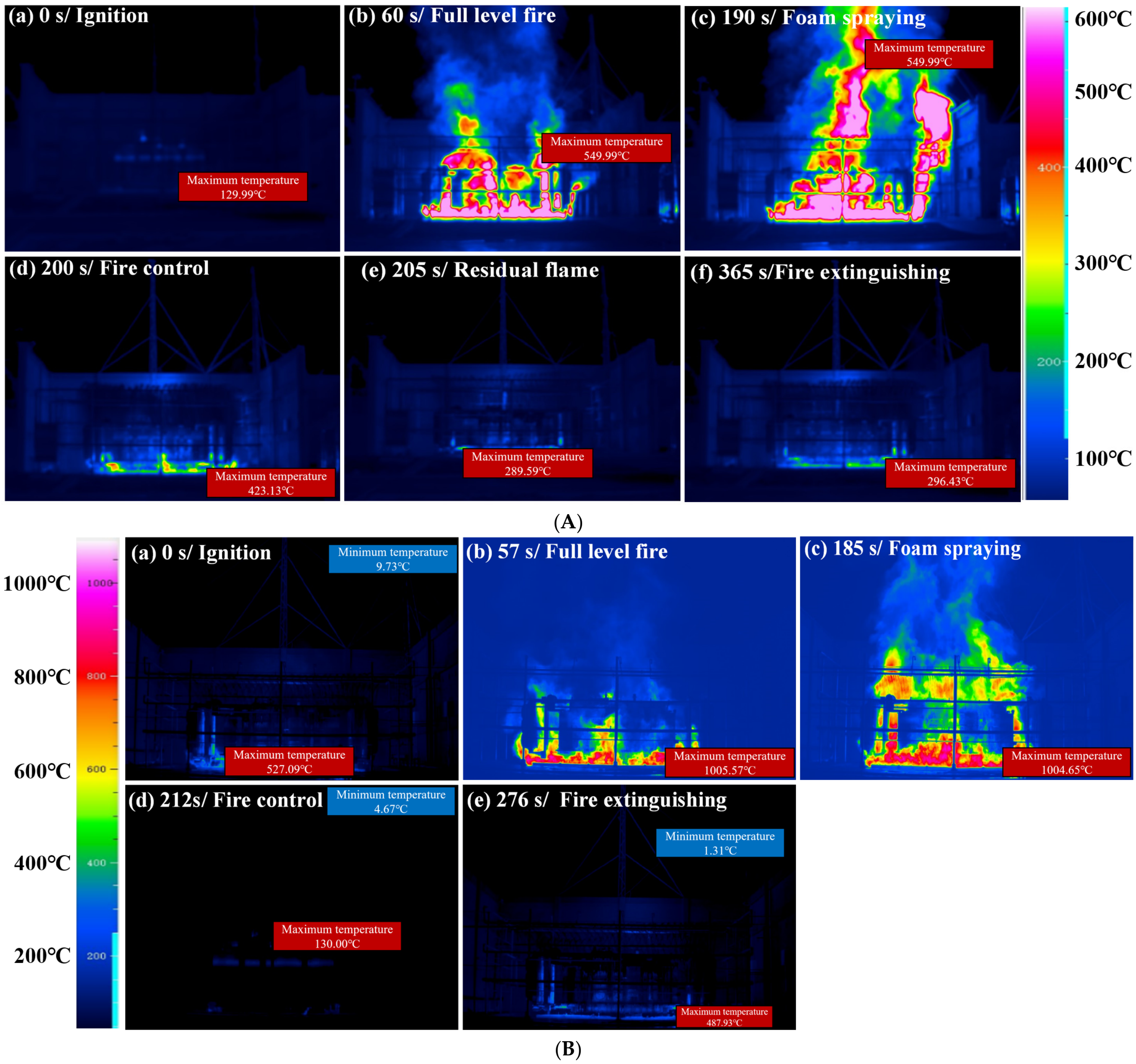
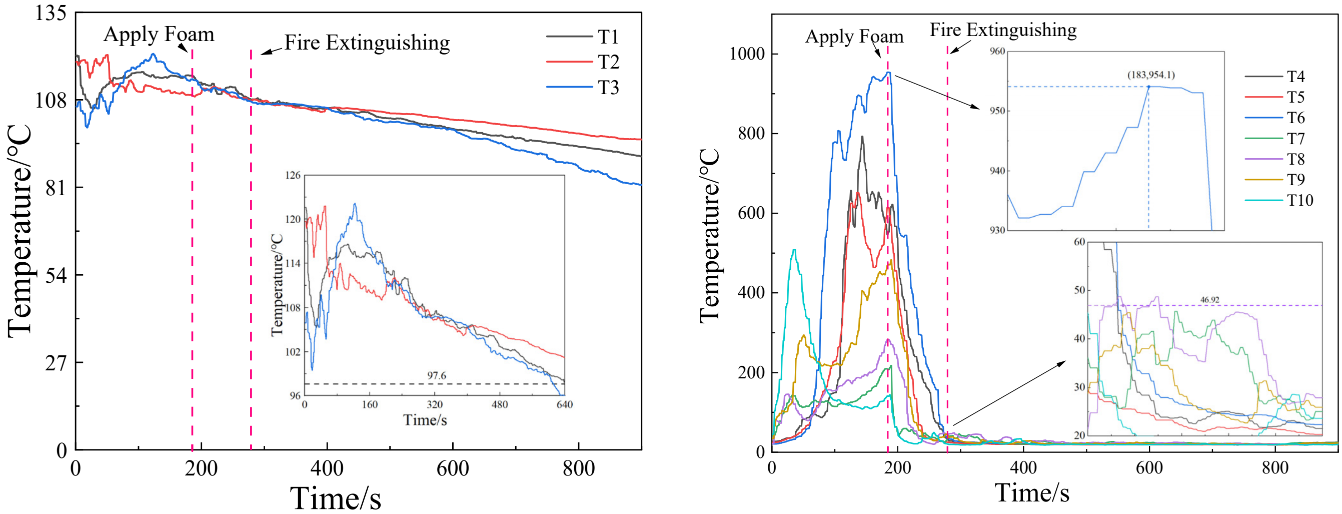


Figure 6. Infrared thermal images of fire extinguishing process under different supply intensities. (**A**) Temperature field Chart at Supply Intensity of 8 L/(min·m^2). (**B**) Temperature field Chart at Supply Intensity of 9.4 L/(min·m^2).

3.2. The Temperature of Various Locations

To investigate the fire characteristics of different positions of the transformer, compressed air foam with a supply intensity of 9.4 L/(min·m^2) was selected for the fire extinguishing test. Figure 7 shows the temperature variation inside the main tank and combustion holes. When ignited, the temperature of the transformer oil inside the main tank was approximately 121.6 °C. After a while, the temperature of the transformer oil gradually increased and began to gradually decrease when applying CAF to the transformer. After a continuous supply of foam for 618 s, the transformer oil temperature was reduced to below 97.6 °C, and the surface of the transformer oil was covered by foam throughout the area. After ignition, the fire reached a stable state of combustion after 168 s. The temperature inside the combustion hole of the main tank rapidly increased, reaching a maximum temperature of 954.1 °C at 183 s. After applying CAF, the temperature inside the combustion hole began to decrease rapidly. After the transformer fire was completely extinguished, the temperature inside the combustion hole dropped to approximately 46.9 °C.

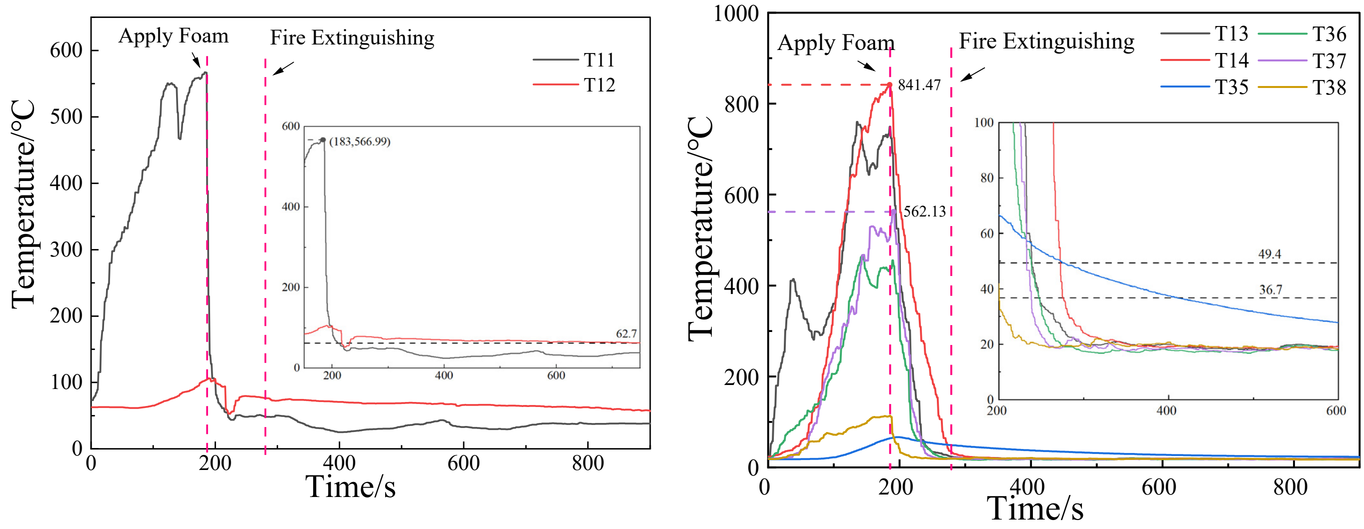


(**a**) Main fuel tank (**b**) Combustion hole

Figure 7. Temperature inside the main fuel tank and combustion hole.

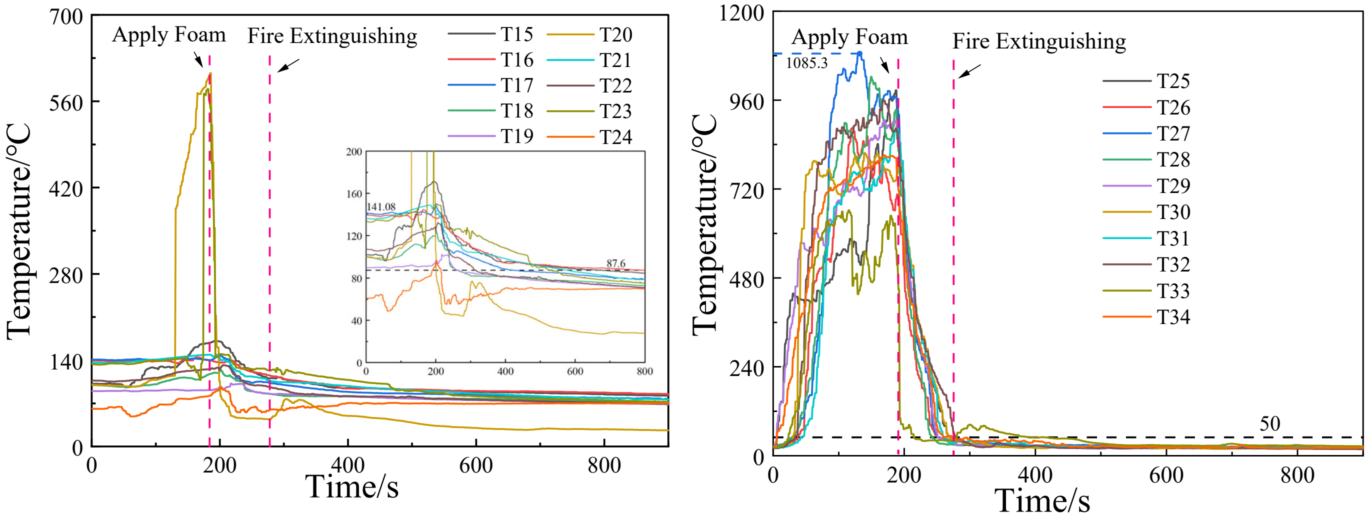
Figure 8 shows the temperature variation of the top oil pool during the fire extinguishing process. The temperature of the oil in the top pool was approximately 76.9 °C at the moment of ignition (0 s). After ignition, the temperature of the transformer oil in the top oil pool continued to rise, and the oil's maximum temperature reached approximately 566.9 °C (T11). After extinguishing the fire in the upper oil pool, the temperature of the transformer oil began to decrease gradually. After continuously supplying foam for 618 s, the temperature of the transformer oil in the top oil pool decreased to 62.7 °C. A layer of foam formed on the surface of the transformer oil. After ignition, the temperature above the main oil tank and the top oil pool rose rapidly. The fire achieved a stable state of combustion after 174 s. The maximum temperature recorded above the main oil tank was 562.13 °C for 191 s, while the top oil pool reached a maximum temperature of 841.47 °C for 185 s. The temperature above the main oil tank and the top oil pool decreased rapidly after the application of CAF. The temperature above the main oil tank and the top oil pool decreased to approximately 49.4 °C and 36.7 °C, respectively, after the transformer fire was completely extinguished.

Figure 9 depicts temperature fluctuations inside and above the bottom tank. In the figure, it can be observed that when ignited, the temperature of the transformer oil inside the bottom pool was approximately 141.08 °C. The temperature of the transformer oil inside the lower pool continued to increase after ignition and decreased after the application of CAF. After 78 s of continuous foam supply, the temperature of the transformer oil inside the lower pool decreased to below 87.6 °C. After ignition, the temperature above the lower tank continued to rise and reached a stable combustion state after approximately 138 s of burning. During the entire combustion phase, the temperature above the bottom tank reached a maximum of 1085.3 °C. After applying CAF, the temperature above the bottom tank continued to decrease. After 96 s of continuous foam supply, all temperatures dropped below 50 °C.



(**a**) The oil temperature (**b**) The temperature above the pool

Figure 8. The temperature of the top oil pool during the fire extinguishing process.



(**a**) The oil temperature (**b**) The temperature above the pool

Figure 9. The temperature of the bottom oil pool during the fire extinguishing process.

4. Conclusions

(1) Full-scale testing has sufficient advantages in terms of realism and fire extinguishing system evaluation. Fires in full-size oil-immersed transformers with 220 kV are complex. It possesses characteristics of high burning heat and temperature, strong thermal radiation, and thick black smoke. After complete combustion, the temperature can reach up to 1000 °C or even higher. The temperature of the transformer oil reached 120 °C or even higher. The dynamic oil spill fire and the large area pool fire, which overflowed from the oil tank and spread along the wall of the tank, caused the fire to rapidly intensify and become difficult to extinguish.

(2) The CAF spray system is capable of rapidly and efficiently extinguishing hot oil fires in 220 kV oil-immersed transformers. During the fire extinguishing process, the compressed air foam monitor can quickly cool down the box wall temperature, preventing the oil spill from gasifying. The thick foam blanket established on the surface of the transformer oil can quickly cool down the temperature and effectively prevent re-ignition. The slow application of foam can also reduce the impact of the compressed air foam jet on the foam layer and transformer oil.

(3) Under the condition that the foam mixture supply strength is 8 L/(min·m^2), the CAF spraying system can extinguish a fire in a 220 kV oil-immersed transformer within 180 s. The temperature of the transformer oil can be cooled to below 100 °C by continuously supplying foam for approximately 468 s.

(4) Under the condition that the foam mixture supply strength is 9.4 L/(min·m^2), the CAF spraying system can extinguish a hot oil fire in a 220 kV oil-immersed transformer within 90 s. Continuous foam supply for approximately 510 s can reduce the temperature of the transformer oil to below 100 °C.

(5) We can respond quickly at the early stage of a fire and quickly control the fire using the CAF spray system, which helps reduce the risk of fire spread and the cost of firefighting. In practice, it is recommended that the foam mixture supply strength of a CAF spraying system should not be less than 8 L/(min·m^2).

Author Contributions: T.C. and P.Z.: methodology; B.Z.: project administration; X.W.: Software; Y.G. and D.H.: writing—original draft preparation review and editing; Y.W.: supervision. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the National Key Research and Development Program of China (2022YFC3004900, 2022YFC3004903), the Tianjin Natural Science Foundation Project (22JCZDJC00880), the Beijing Municipal Natural Science Foundation (No.8222029), the Key Laboratory of Fire Protection Technology for Industry and Public Building, the Ministry of Emergency Management (No.2023KLIB02) and the State Key Laboratory Cultivation Base for Gas Geology and Gas Control (Henan Polytechnic University) (No. WS2021A01).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Keim, T.; Bindra, A. Recent Advances in HVDC and UHVDC Transmission [Happenings]. *IEEE Power Electron. Mag.* **2017**, *4*, 12–18. [CrossRef]
2. Shakhov, S.; Vinogradov, S. Fire Extinguishing Efficiency of Compressed Air Foam, Water and Gel Forming Agents in a Standard Class A Test Fire. *Saf. Fire Technol.* **2020**, *55*, 154–160. [CrossRef]
3. Wang, K.; Fang, J.; Shah, H.R.; Lang, X.; Mu, S.; Zhang, Y.; Wang, J. Research on the influence of foaming gas in compressed air/nitrogen foam on extinguishing the n-heptane tank fire. *J. Loss Prev. Process Ind.* **2021**, *72*, 104533. [CrossRef]
4. Xu, Z.; Guo, X.; Yan, L.; Kang, W. Fire-extinguishing performance and mechanism of aqueous film-forming foam in diesel pool fire. *Case Stud. Therm. Eng.* **2020**, *17*, 100578. [CrossRef]
5. Sheng, Y.; Jiang, N.; Lu, S.; Wang, Q.; Zhao, Y.; Liu, X. Study of Environmental-Friendly Firefighting Foam Based on the Mixture of Hydrocarbon and Silicone Surfactants. *Fire Technol.* **2020**, *56*, 1059–1075. [CrossRef]
6. Liu, Y.; Li, B.; Wu, C.; Chen, B.; Pan, B. Effectiveness Test and Evaluation of Transformer Fire Extinguishing System. *Fire Technol.* **2022**, *58*, 3167–3190. [CrossRef]
7. Guo, Y.; Zhang, J.; Ke, Y.; Huang, W.; Liu, R.; Huang, Y.; Su, W. Research on Performance Evaluation Method of Compressed Air Foam Fire Extinguishing System in UHV Converter Station. In Proceedings of the 2022 7th Asia Conference on Power and Electrical Engineering (ACPEE), Hangzhou, China, 15–17 April 2022; pp. 1204–1208.
8. Fu, X.; Zhang, J.; Xie, J.; Tan, T.; He, L.; Guo, Y. Research on Compressed Air Foam System Performance Diagnosis Combined with Engineering Practice. In Proceedings of the 2022 Asian Conference on Frontiers of Power and Energy (ACFPE), Chengdu, China, 21–23 October 2022; pp. 172–177.
9. Feng, J.R.; Yu, G.; Zhao, M.; Zhang, J.; Guo, Y.; Lu, S. A Dynamic Fire Risk Assessment Framework of Critical UHV Converter Transformer. In Proceedings of the 2022 4th International Conference on System Reliability and Safety Engineering (SRSE), Guangzhou, China, 15–18 December 2022; pp. 271–277.

10. Rie, D.-H.; Lee, J.-W.; Kim, S. Class B Fire-Extinguishing Performance Evaluation of a Compressed Air Foam System at Different Air-to-Aqueous Foam Solution Mixing Ratios. *Appl. Sci.* **2016**, *6*, 191. [CrossRef]
11. Chen, T.; Fu, X.-C.; Bao, Z.-M.; Xia, J.-J.; Wang, R.-J. Experimental Study on the Extinguishing Efficiency of Compressed Air Foam Sprinkler System on Oil Pool Fire. *Procedia Eng.* **2018**, *211*, 94–103. [CrossRef]
12. Wang, K.; Fang, J.; Shah, H.R.; Mu, S.; Lang, X.; Wang, J.; Zhang, Y. A theoretical and experimental study of extinguishing compressed air foam on an n-heptane storage tank fire with variable fuel thickness. *Process Saf. Environ. Prot.* **2020**, *138*, 117–129. [CrossRef]
13. Tu, J.; Pau, D.; Yang, T.; Nan, S.; Zhang, J.; Shang, F.; Li, K. Effect of foam air mixing on flame intensification—Comparative experimental study of foam and water sprays extinguishing transformer oil pool fire. *Fire Saf. J.* **2022**, *133*, 103664. [CrossRef]
14. Tan, T.; Zhang, J.; Luo, S.; Xie, J.; Guo, Y.; Shang, F.; Liu, R. Study on Transportation Characteristics of Compressed Air Foam Pipe Network. In Proceedings of the 2022 7th Asia Conference on Power and Electrical Engineering (ACPEE), Hangzhou, China, 15–17 April 2022; pp. 1198–1203.
15. Wu, C.; Zhou, T.; Chen, B.; Liu, Y.; Liang, P. Experimental Study on Burning Characteristics of the Large-Scale Transformer Oil Pool Fire with Different Extinguishing Methods. *Fire Technol.* **2021**, *57*, 461–481. [CrossRef]
16. Zhao, J.; Wang, S.; Zhang, J.; Zhou, R.; Yang, R. Experimental Study on the Burning Characteristics of Transformer Oil Pool Fires. *Energy Fuels* **2020**, *34*, 4967–4976. [CrossRef]
17. Li, L.; Zhai, X.; Wang, J.; Chen, P.; Shi, C. Experimental study on vertical spill fire characteristics of transformer oil under continuous spill condition. *Process Saf. Environ. Prot.* **2021**, *156*, 521–530. [CrossRef]
18. Zhang, B.; Zhang, J.; Huang, Y.; Wang, Q.; Yu, Z.; Fan, M. Burning process and fire characteristics of transformer oil. *J. Therm. Anal. Calorim.* **2020**, *139*, 1839–1848. [CrossRef]
19. Sun, R.; Wang, J.; Yang, X.; Chen, P. Experimental research on the combustion characteristics of transformer oil jet fires in oil-filled equipment under heat. *ACS Omega* **2021**, *6*, 31843–31853. [CrossRef] [PubMed]
20. Zhu, P.; Wang, X.; Wang, Z.; Cong, H.; Ni, X. Experimental Study on Transformer Oil Pool Fire Suppression by Water Mist. In *Fire Science and Technology 2015*; Harada, K., Matsuyama, K., Himoto, K., Nakamura, Y., Wakatsuki, K., Eds.; Springer: Singapore, 2017; pp. 895–901.