Study on Heat Transfer and Water Temperature Influencing Factors of Transformer Water spray System Pipeline in Cold Area Booster Station Projects

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Abstract. Water spray system is one of the most commonly used fire extinguishing systems for oil-immersed transformers in booster stations. However, research on weather the water in water spray system pipeline will freeze behind the deluge valve is rare. In this paper, the calculation formula of water heat transfer and temperature change rules in the transformer water spray pipe has been analyzed and deduced. The water temperature and freezing risk in the water spray pipelines under different water source temperatures and ambient temperatures has been calculated. The importance of the above two variables on the freezing of the water spray system has been analyzed, and the relevant points that should be paid attention to in the design of the transformer water spray fire extinguishing system has been put forward.

Keywords: Oil immersed transformer, Water spray fire protection system pipeline, Heat transfer, Cold region

1 Introduction

Water spray fire extinguishing system has been widely used in the fire extinguishing of oil-immersed transformers [1-3]. For severe cold area booster station projects, it is also worth discussing whether the water spray water will freeze during the flow process in the pipeline behind the deluge valve. Considering the wide application of water spray in oil immersed transformer fire extinguishing in booster stations, it is necessary to conduct in-depth research on evaluating the freezing risk of outdoor transformer water spray fire extinguishing system pipelines in severe cold area booster station projects, discuss the feasibility, safety and applicability of water spray system for transformers in such cold areas, and put forward points needs to been attention in design, operation and maintenance for cold area booster station projects, so as to improve the fire extinguishing guarantee rate of their water spray systems.However, existing studies and engineering cases only have related design requirements for antifreezing and insulation of the pipe section in front of the deluge valve[4]. For example, the deluge valve and the pipe in front of the deluge valve should be set in the room where the temperature is not lower than 4 °C, so as to ensure that the water in

© The Author(s) 2025
Y. Qiu et al. (eds.), *Proceedings of the 2024 7th International Conference on Civil Architecture, Hydropower and Engineering Management (CAHEM 2024)*, Advances in Engineering Research 256,
https://doi.org/10.2991/978-94-6463-650-5_5

the pipe section in front of the deluge valve is not frozen. For the pipe section behind the deluge valve, it is only flushed when extinguishing the fire, so it is generally believed that it will not freeze. However, for extreme cold areas, due to the heat transfer process, there may still be problems of gradual cooling and freezing during the flow of water in the pipelines. In this article, the heat transfer and cooling patterns of water inside the pipelines after the deluge valve have been studied , and the factors influencing the water temperature in the water spray system pipelines have been analyzed. Finally, corresponding measures in the design of the transformer water spray fire extinguishing system in cold area booster station projects have been proposed based on the above research results, in order to improve the safety, effectiveness and environmental adaptability of this fire extinguishing system.

2 Calculation Methods

In order to facilitate the reader to retrieve the definition of the parameters and variables, the nomenclature table is listed below.

Table 1. Nomenclature table.

Parameters	Definition
K	Total heat transfer coefficient of pipeline ($W\cdot(m\cdot°C)^{-1}$)
D	Pipe diameter (m)
T	The water temperature at a section of the pipe (°C)
T_0	Ambient temperature (°C)
G	Flow rate of water in the pipeline ($m^3\cdot s^{-1}$)
C	Specific heat of water (4200 $J\cdot(kg\cdot°C)^{-1}$)
T_Z	Water temperature at the end section of the pipe (°C)
T_R	Water temperature at the starting section of pipe section (°C)
L	Pipe length (m)
v	Water flow velocity ($m\cdot s^{-1}$)
Re	Reynolds number
X	The ratio of the solidified water in the pipe to the total water volume(%)

In order to study the temperature change of the water in the pipelines, the pattern of heat exchange between the water in the pipeline and the ambient air should be determined first. Take a pipe section as the research object, and assume that the water temperature at this section is T, and the water temperature change after the water flow passes through the dL length is dT, so the water temperature at the L+dL pipeline section is T+dT. The calculation diagram is shown in Fig. 1.

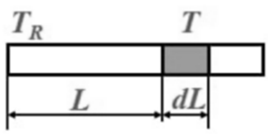

Fig. 1. Pipe section heat transfer calculation diagram.

The heat balance equation of dL tube section is as follows:

$$K\pi D\,(T - T_0)dL = -GCdT \tag{1}$$

$$\frac{-dT}{T-T_0} = \frac{K\pi D}{GC}dL \tag{2}$$

Integrating the pipeline section

$$\int_{T_R}^{T_L}\frac{-dT}{T-T_0} = \frac{K\pi D}{GC}\int_0^L dL \tag{3}$$

$$\ln\frac{T_R-T_0}{T_L-T_0} = \frac{K\pi D}{GC}L = aL \tag{4}$$

$$T_Z = T_0 + (T_R - T_0)e^{-aL_R} \tag{5}$$

The key of the above formula is to determine the value of total heat transfer coefficient of pipeline.

According to the research results of Ran[5] and literature [6], it can be concluded that the lower the water temperature inside the pipeline, the smaller the total heat transfer coefficient of the pipeline. When the water temperature inside the pipeline is 70 °C and the Reynolds number of the water flow inside the pipeline is greater than 5 $\times$ 10^4, the heat transfer coefficients of steel pipes with different diameters are shown in Table 2. The research result of Neale [7] are basically consistent with those described in Table 2. Therefore, it is safe and dependable to use the heat transfer coefficient listed in the following figure to calculate the water temperature change in the water spray water supply pipeline.

Table 2. Relationship between pipe diameter and total heat transfer coefficient of pipeline.

D (mm)	15	20	25	32	40	50	70	80	100	150	200
K (W • (m • ℃)$^{-1}$)	0.95	1.15	1.4	1.71	1.91	2.31	2.81	3.22	4.02	5.69	7.42

When the water temperature is calculated to be below 0 °C using the above method, it is considered that some water will transform from liquid to solid, while releasing latent heat of solidification. Due to the fact that the latent heat of solidification per unit mass of water is 3.36×105 J, which is 80 times the heat released per unit mass of liquid water for every 1 °C decrease, it can be estimated based on this proportional relationship that when the water temperature inside the pipeline drops to 0 °C and continues to generate heat exchange with the outside world to release heat, the ratio of water that solidifies into ice in the pipeline to the total water volume can be estimated.

Figure. 2 to Figure. 5 shows the water spray system of a main transformer. At the rated working pressure, the flow rate of spray nozzle for the main transformer surface is 1.05L/s, the flow rate of spray nozzle for the main transformer oil pit is 0.50L/s, and the flow rate of spray nozzle for the main transformer oil pillow is 2.10L/s. The design flow rate of each pipe section is calculated based on the basic data.

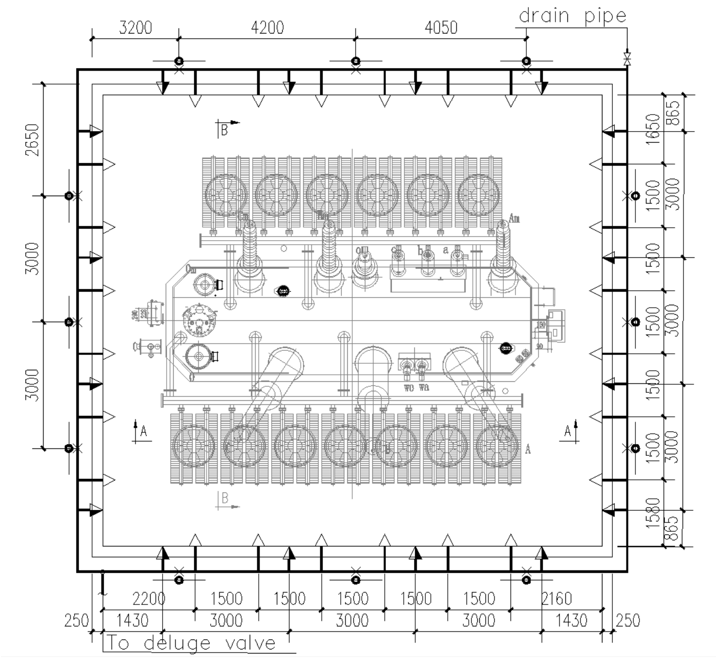

Fig. 2. Layout of water spray at 1.00m.

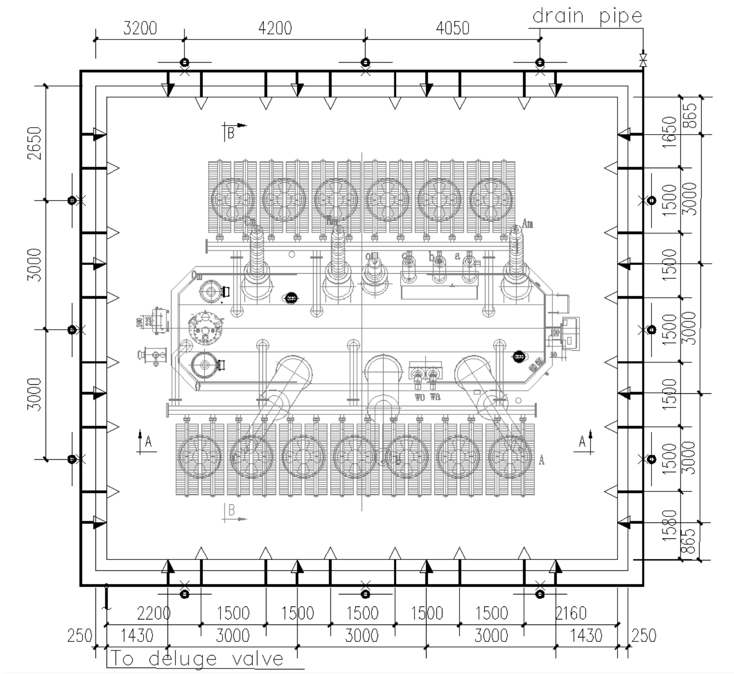

Fig. 3. Layout of water spray at 2.50m.

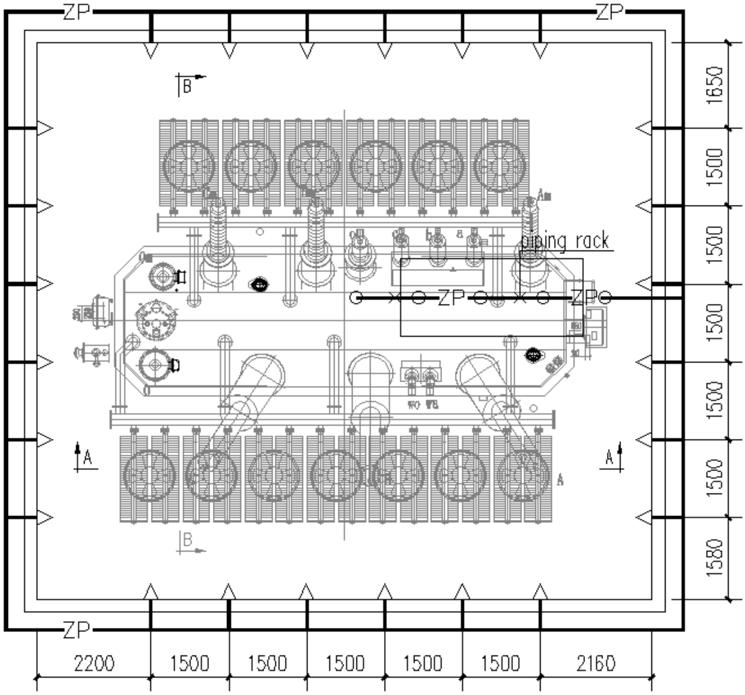

Fig. 4. Layout of water spray at 4.00m.

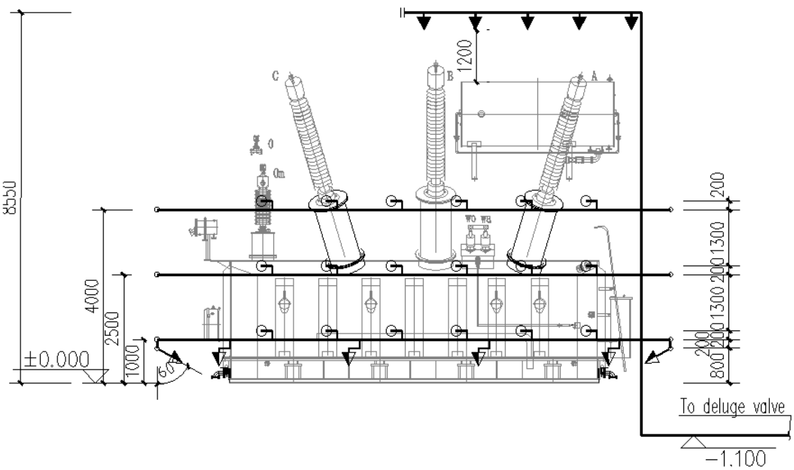

Fig. 5. Elevation of water spray.

The hydraulic and thermal characteristic parameters of each section from the main pipe to the farthest spray nozzle branch pipe are shown in Table 3.

Table 3. Hydraulic and thermal characteristic parameters table in water spray pipes.

Pipe section	D (mm)	L (m)	G ($m^3 \cdot s^{-1}$)	v ($m \cdot s^{-1}$)	Re ($\times 10^4$)	K ($W \cdot (m \cdot °C)^{-1}$)
A-B	200	5	0.1000	3.12	62.0	7.42
B-C	150	1.5	0.0610	3.36	50.1	5.69
C-D	100	9.5	0.0357	4.34	43.1	4.02
D-E	65	10.5	0.0105	3.16	20.4	2.81

Substituting the values of the hydraulic and thermal characteristic parameters in Table 3 into formula (5), the temperature of the water inside the end of each pipe section can be obtained, so as the water temperature and the freezing condition in the farthest spray nozzle branch pipe section at different starting point water temperature of the pipeline section and ambient temperature can be obtained.

3 Analysis of Water Temperature and Freezing inside Pipelines under Different Conditions

3.1 The Influence of Water Temperature at the Starting Point of the Pipeline Section

According to the calculation method described above, the heat transfer calculation of the water flow in the water spray pipe network after the deluge valve shown in Figure. 2 to Figure. 5 has been carried out.

Set the ambient temperature to -20℃, set the initial water temperature at the starting section of pipe section to different values, and calculate the water temperature in the farthest spray nozzle branch pipe section. The result is shown in Figure 6 and Figure 7.

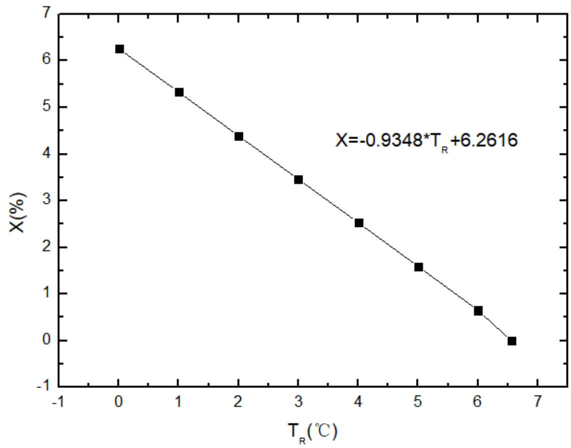

Fig. 6. Diagram of relationship between T_R values and X values.

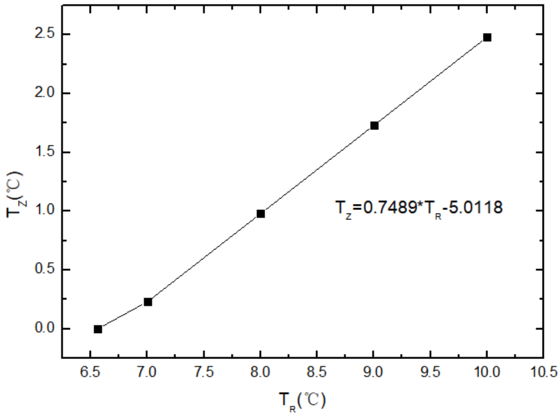

Fig. 7. Diagram of relationship between T_R values and T_Z values.

As shown in the above figure, with the increase of water temperature at the starting section of pipe section, the proportion of solidified water gradually decreases. When the water temperature rises to about 6.6 °C, there is no more solidified water in the pipeline. As the water temperature continues to rise, the water temperature in the farthest spray nozzle branch pipe section also increases. According to the functional relationship between T_R and Tz, for every 1 °C increase in T_R, Tz correspondingly increases by about 0.7 °C.

3.2 The influence of ambient temperature

Set the initial water temperature at the starting section of pipe section at 5 ℃, set the ambient temperature to different values, and calculate the water temperature in the farthest spray nozzle branch pipe section at different ambient temperatures. The results are shown in Figure 8 and Figure 9.

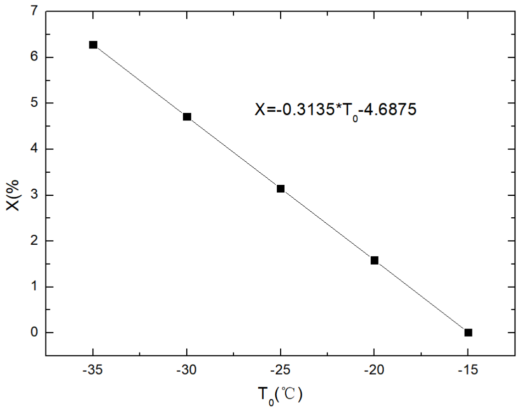

Fig. 8. Diagram of relationship between T_R values and X values.

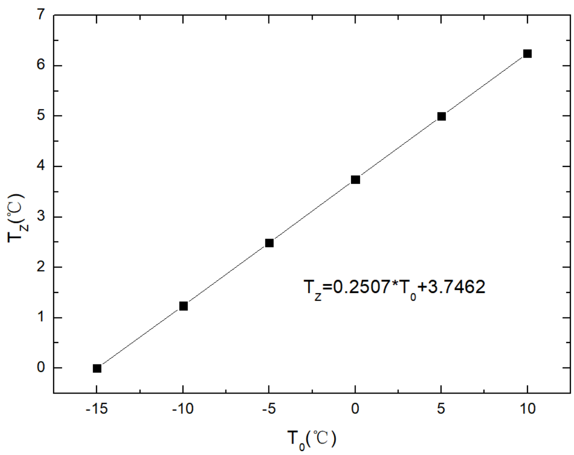

Fig. 9. Diagram of relationship between TR values and TZ values.

As the ambient temperature decreases, the water temperature in the farthest spray nozzle branch pipe section decreases accordingly. When the ambient temperature drops to -15 ℃, the water inside the pipeline begins to freeze. As the ambient temperature continues to decrease, the proportion of solidified water gradually increases. When the ambient temperature drops to -35 ℃, about 5% of water in the farthest spray nozzle branch pipe section transforms into solid state.

4 Conclusions and Recommendations

As an effective fire extinguishing system, water spray is widely used in transformer fire extinguishing. This paper discussed the heat transfer and water temperature influencing factors of transformer water spray system pipeline in cold area. According to the above discussion, it can be seen that the temperature of the water source has the greater impact on the water temperature of the water spray system pipelines, followed by the ambient temperature.

Therefore, anti freezing and thermal insulation measures need to be taken into account in the fire pool for storing water for spray system in severe cold areas. For example, a fire water tank can be installed in a heated room to store water, or the fire pool can be buried deep outdoors and an electric heating rod can be installed in the tank for regulating the water temperature in extreme weather conditions.

In addition, although the ambient temperature cannot be artificially controlled, it is possible to strengthen communication with the local meteorological station, empty the stored water in the pipelines behind the deluge valve before the onset of extreme cold weather, check the integrity of the fire protection pipeline and valve insulation facilities, debug the working performance of the electric heating or water pool electric heating rod, and ensure that the fire protection system water supply Maintain good operating condition in extreme cold weather.

In future research, the total heat transfer coefficients of pipeline (K value) with different ambient temperatures, wind speeds, water temperatures inside pipelines, pipeline materials, and wall thicknesses are worth to take future investigation. In addition, it is suggested to carry out full-scale test of transformer water spray extinguishing system in severe cold areas booster stations, so as to further verify the reliability and effectiveness of water spray system applied to transformer extinguishing in severe cold areas.

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