Comparative evaluation of flow-through and counter-flow indirect-evaporative air coolers and their influence on the heat balance of transformer underground substations

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Abstract. In order to optimize the air environment temperature of the underground engineering equipment premises, it is necessary to conduct a comparative assessment of the operation of flow-through and counter-flow indirect-evaporative air coolers. Based on the previous mathematical models that describe the thermophysical processes in the channels of indirect evaporative coolers, an analysis of the structural and standard parameters of their operation is carried out. The most rational ratios of flows through the “wet” and “dry channels” are revealed and they ensure the maximum station cooling capacity. The transformer substation of the underground illustrates the effectiveness of their use. According to the result of the studies, it has been proved that the most rational ratio of air flows through wet and dry channels for flow-through indirect-evaporative coolers is 2.1-2.2, for counter-flow heat exchangers it is 3.0. The advantage of recuperation coolers is established by such indicators as: cooling capacity - 53.5%, air cooling range - 41%.

1. Introduction

Modern ventilation systems of transformer underground substations designed in 40-50 years of the last century often can not satisfy the requirements for normalizing the temperature condition of their air environment. This is caused by the increased passenger traffic flow and the intensity of train movement. The installation of higher power transformers at substations leads to a significant increase in heat generation. The temperature in the engineering equipment premises of the underground in this case reaches 35-40°C, which makes the work of the staff extremely difficult and worsens the equipment operation practices.

To neutralize the heat generations which are performed by the operation of power units, as well as the braking and driving of the underground trains, the application of water evaporative air coolers is the most promising [1-3]. Being environmentally friendly, such stations are favorably distinguished by efficiency and low material consumption [4–8]. Installations that cool the processed air flow without increasing its moisture content are especially in high demand. Two types of such coolers are known: flow-through and counter-flow recuperative (CFR).
In earlier works [9-11], the principal schemes and design features of such coolers were considered, and mathematical modeling of thermophysical processes in their channels was carried out [11, 12].

At the same time, the question of the effectiveness of these devices and the impact of their work on the heat balance of transformer underground substations requires a deeper study. This is due to the fact that the stations are characterized by different cooling range and air flow rates, the mutual influence of which determines their cooling capacity [13-16]. In this regard, it is necessary not only to compare the indicated coolers, but also to determine the most rational modes of their operation, ensuring the maximum value of their cooling capacity.

2. Materials and methods

Often, during cooling some technical premises, it is necessary to maintain the moisture content of their environment. For this purpose, it is advisable to use the indirect evaporation units from the previously mentioned water evaporative coolers.

Schematic diagrams of flow-through and counter-flow installations are considered in [17, 18]. To assess the effectiveness of their work, we use mathematical models proposed earlier in [9-12]. They are based on parabolic equations:

\[
- \rho \cdot V_t(x,y) \cdot C \cdot \frac{\partial T}{\partial x} = \frac{\partial}{\partial y} \left( \lambda(T) \frac{\partial T}{\partial y} \right), \quad x \in (0,L), \ y \in (Hp,Hp+H)
\]

(1)

\[
\rho \cdot V_t(x,y) \cdot C \cdot \frac{\partial t}{\partial x} = \frac{\partial}{\partial y} \left( \lambda(t) \frac{\partial t}{\partial y} \right), \quad x \in (0,L), \ y \in (-h,0),
\]

(2)

where \( \rho, \ C, \ - \) air density, kg / m\(^3\) and its specific heat, respectively, J/kg\(\cdot\)°C, \( V_t \) is the air velocity in the “dry” channels, \( L \) is the length of the channels, \( m, h \) is the width of the channels, \( m \).

The mass exchange process in a “wet” channel is described by the following equation:

\[
V_t(x,y) \frac{\partial W}{\partial x} = \frac{\partial}{\partial y} \left( D(t) \frac{\partial W}{\partial y} \right), \quad x \in (0,L), \ y \in (-h,0)
\]

(3)

where \( V_t \) is the air flow velocity in the “wet” channels, \( W \) is the vapor density, kg / m\(^3\).

The temperature distribution in the plates characterizes the Laplace equation:

\[
\frac{\partial^2 T_p}{\partial x^2} + \frac{\partial^2 T_p}{\partial y^2} = 0, \quad x \in (0,L), \ y \in (0,Hp).
\]

(4)

Let us consider the premises of transformer underground substations with overall sizes \(6m \times 6m \times 3m\). The heat generation of the power units located in it is 16.5 kW. In the hot season, the ventilation system provides a total air flow of 4100 m\(^3\) / h at a temperature of 27°C. This system provides a room temperature of 39.8°C.

Compare the work of two units of the same sizes 1.8 m wide and 0.8 m high with a channel length of 0.4 m. The total air flow is 7500 m\(^3\) / h. One of these units works on the principle of flow-through, and the other one on the principle of counter-flow cooling. The initial parameters of the inlet air: temperature \( T_{in} \) = 39.8°C, relative humidity 30%. The performance indicator is the cooling capacity, determined by the formula:

\[
C \rho G_{dry} (T_{in} - T_{out}) = Q,
\]

(5)

where \( T_{out}, \ G_{dry} \) are, respectively, the temperature and flow rate of “dry” air at the output of the cooler.
3. Discussion

Let us consider the work of a flow-through indirect cooler. One of the main controlled parameters during operation of the cooler is the nature of the redistribution of the total air flow through the “dry” and “wet” channels. Fig. 1 shows a dependency graph of the cooling capacity of the installation on the redistribution coefficient $k$, which is equal to the ratio of “dry” to “wet” flow.

This curve behavior is due to the fact that when the air flow through the “dry” channels increases to a certain value, the cooling capacity increases due to an increase in air flow. With a further increase in the volume of air passing through the “dry” channels, the cooling capacity value decreases caused by a decrease in the cooling depth due to a decrease in the intensification of thermophysical processes in the cooler channels.

Thus, it has been established that for flow-through indirect evaporative coolers, maximum cooling capacity is achieved with a ratio of air flows through the “dry” and “wet” channels $k = 2.15$. For the considered example of air through the “dry” channels it is $5156 \text{ m}^3/\text{h}$, and the cooling capacity of the installation is $Q = 17284 \text{ W}$.

![Figure 1. The effect of air redistribution on cooling capacity of the direct indirect evaporative cooler.](image)

For the established ratio of channels, a dynamic analysis of air temperature changes along their length was made (Fig. 2). The studies have shown that the cooling depth is $10.3^\circ\text{C}$ at maximum cooling capacity. In addition, the nature of the curves is clearly illustrated by the fact that the length of the plates can be reduced to 30 cm in order to reduce the material consumption of the installation, as the temperature practically does not decrease on the line from 30 cm to 40 cm. This decrease will lead to a decrease in “transport” aerodynamic drag that provides additional opportunities for increasing air flow.

We will conduct similar research for a counter-flow (recuperative) cooler. Applying mathematical modeling, we establish the optimal redistribution of “dry” and “wet” air flows in terms of cooling capacity. Figure 3 shows a graph of the independence cooling capacity of the installation on the redistribution coefficient $k$ equal to the ratio of “dry” to “wet” flow. As we can see from this graph, the maximum cooling capacity of $Q = 26544 \text{ W}$ is achieved at a value of $k = 3$, which corresponds to an air flow rate of $G = 5625 \text{ m}^3/\text{h}$. 


Figure 4 shows the change in air temperature along the length of the recuperative cooler. As we can see from this graph, the air is cooled at maximum cooling capacity; the air is cooled at 14.5°C. It should be noted that in an indirect cooler the “wet” air flow exhausted outside the room has almost the same temperature as the “dry” flow, which leads to a loss in the cooling capacity of the installation.

The graph in fig. 4 shows that the temperature of the exhausted “wet” air is much higher in the recuperative cooler, which leads to an increase in cold savings.

The installation of these coolers gives the following results (table 1) for the considered premises.

![Figure 2](image1.png)

**Figure 2.** Change in air temperature in the “dry” (- - - -) and “wet” (––––) channels along the length of the flow-through indirect-evaporative cooler

![Figure 3](image2.png)

**Figure 3.** The effect of air redistribution on cooling capacity of the counter-flow, indirect-evaporative cooler.
Figure 4. Change in air temperature in “dry” (- - - -) and “wet” (–––––) channels along the length of the counter-flow indirect-evaporative cooler.

Table 1. Comparison of the efficiency of indirect-evaporative air coolers at $T_n=39,8^\circ$C.

| Cooler type   | Air cooling depth, $\Delta t$, $^\circ$C | Air flow through dry channels, $G$, m$^3$/h | Cooling capacity, $Q$, kW |
|---------------|------------------------------------------|---------------------------------------------|---------------------------|
| Flow-through  | 10.3                                     | 5156                                        | 17284                     |
| Recuperative  | 14.5                                     | 5625                                        | 26544                     |

The premises temperature stabilizes at a value of 32°C using a flow-through indirect-evaporative cooler, and the temperature stabilizes at a value of 26°C during the work of a counter-flow heat exchanger.

4. Conclusion.
The most rational ratio of air flow rates through “dry” and “wet” channels has been determined. It is 2.1-2.2 for flow through indirect-evaporative coolers and it is 3.0 for counter-flow heat exchangers.

1. It has been established that with optimal flow ratios, the cooling depth of the processable air by recuperative stations is 41% higher than indirect-evaporative coolers of the flow-through type.
2. With optimal ratios of air flow through the “dry” and “wet” channels, the air flow of “dry” air from recuperative coolers is 9% higher.
3. Comparing the cooling capacity of the stations, it was concluded that the recuperative cooler is more efficient than the indirect one by 53.5%.
4. For the premises under consideration, the use of recuperative coolers will reduce the air temperature from 35-40°C to 24-26°C, while flow-through indirect-evaporative coolers reduce it only to 30-32°C in similar conditions.

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