Abstract

Monitoring cooling towers have shown that one of the decisive factors leading to premature failure of the concrete shell is migration of vaporous moisture from the inside to the outer surface, condensation and freezing of the surface layer, which results in the destruction of the shell. The purpose of research is to determine the optimal values of the temperature in ventilated air gap. It is necessary to provide the required thrust and the air throughput to maintain the mode of heat and humidity. Temperature and air velocity affect heat-moisture mode. The calculation was made for the three cases of developing thrust in the gap. First case thrust is created using the heated air by heat exchange with the warm surface of the screen. Second case thrust is created using heated air by dint of a smooth pipe with a diameter of 100 mm, which supply the circulating water. Third case heating is carried out by two ribbed pipes with a diameter of 50 mm with round or square edges, the diameter (side) of 100 mm and increments 100 mm.

As a result of research the following conclusions were obtained: air temperature in the gap depends on the outdoor temperature $t_{ext}$ and it is as higher, as higher the $t_{ext}$; medium temperature in height gap $t_{med}$ was lower in the case of additional heater than at natural convection; the temperature difference $t_0-t_{ext}$ decreases with increasing $t_{ext}$; air temperature at the inlet of the gap $t_0$ decreases with increasing thickness of the gap; the temperature in the air gap increases from $t_0$ to $t_b$. Difference $t_0-t_b$ as height, as smaller the thickness of the air gap and outdoor temperature.

It is necessary to provide the required thrust in air gap for the effective protection of reinforced concrete cooling tower. Thickness and shape of the gap, the outdoor temperature and the temperature inside the cooling tower depends on it.

Keywords: air gap, air velocity, cooling tower, mode of heat and humidity, temperature in the air gap.

1. Introduction

Cooling towers are applied in circulation water supply system, where cooling of water must be deep and steady while the hydraulic and thermal loads are high. The complexity of heat-exchange processes, when water passes a cycle from converting into steam to its subsequent condensation, is caused by many factors. Influence of environment and internal intensive process.

Damp-proof covering is usually applied to protect interior surface. However, experience of cooling towers application shows that these method is not rather effective [1]. Installation of screen that is made of vapor proof elements is further more effective protective option. The screen should have gap with interior surface. The accounting of feature of the heat-moisture and aerodynamic modes was begun by Barabanshchikov [2]. This article is deep research of the aerodynamic mode in a cooling tower.
2. Calculation of the temperature and speed of air in ventilated air gap

The calculation of temperature and speed of air in a gap was made for three trust creation cases. Air temperature in the ventilated gap depends on air speed in a gap. Air speed in a gap is unknown and it depends on a difference of temperatures of external and internal air. Calculation was made by an iteration method.

2.1 First case (absence of heating)

Trust arises at the expense of a natural gravitational pressure in the absence of heating. It is determined as a difference of middle temperatures of air in a gap and outside of cooling tower ($t_{med}$−$t_{ext}$). The increase of $t_{med}$ in comparison with $t_{ext}$ takes place due to the heat exchange of air in a gap with screen and shell. Because of $S_s = S_{sh}$ the total amount of heat, which air receives, equal:

$$Q = \alpha S_s \left( t_2 + t_3 - 2t_{med} \right) \quad (1)$$

where $\alpha$ – heat transfer coefficient; $S_s$ and $S_{sh}$ – the areas of gap’s walls from the screen and shell; $t_2$ and $t_3$ – temperatures of surfaces of screen and shell in gap. Express the warmth $Q$ according to the:

$$Q = c_{air} v_{med} \rho S_{ext} \left( t_{med} - t_{ext} \right) \quad (2)$$

from where:

$$t_{med} = \frac{(t_2 + t_3 - at_{ext})}{(a - 2)} \quad (3)$$

where $t_{ext}$ – temperature of external air; $S_{ext}$ – area of air inlet; $c_{air}$ – specific heat of air in the gap;

$$a = c_{air} v_{med} \rho S_{int} / (\alpha S_s) \quad (4)$$

The air consumption in the ventilated layer is determined by a difference of pressure $\Delta p$. The movement of air is influenced by this difference. Hydraulic losses in a layer are equal $\Delta p$ at a design consumption. The pressure $P$ in the layer with natural circulation is equal to the sum of the wind $\Delta p_v$ and gravitational $\Delta p_t$ pressures:

$$\Delta p = \Delta p_v + \Delta p_t \quad (5)$$

$\Delta p_v$ is equal to the difference of the pressures created by wind on an entrance and exit from a layer:

$$\Delta p_v = \rho_{ext} (k_1 - k_2) v_w^2 / 2 \quad (6)$$

where $k_1$ and $k_2$ – aerodynamic coefficients on an entrance and an exit of a layer; $v_w$ – velocity of air. Gravitational pressure $\Delta p_t$ arises due to the difference in density between the outside air and the air in layer.

$$\Delta p_t = Hg(\rho_{ext} - \rho) \quad (7)$$

where $H$ – difference of height of inlet and outlet of air in layer. Air velocity through the gap is obtained from the condition of equality of available pressure (5) and hydraulic losses.

$$v = (2\Delta p / \rho)^{0.5} = [(k_1 - k_2)v_w^2 / \Sigma \zeta + 2Hg(\rho_{ext} - \rho_{int}) / (\rho_{int} \Sigma \zeta)]^{0.5} \quad (8)$$

where $\Sigma \zeta$ – sum of frictional and local resistance coefficients. Mass air rate $j$ through 1 rm of gap length on perimeter is equal:
where $\delta$ – thickness of an air layer. As the wind direction is changeable, in this case it is advisable to take $k_1=k_2$, which will simplify the formula (8). Calculation model is shown in Fig. 1. The air enters into the gap with a temperature $t_0$ and changes its temperature, passing through it. Heat exchange $h_e$ at some distance with walls gains stationary character and air steam gets the invariable temperature of $t_{\text{const}}$ which is not connected with its reference temperature. The task consists in determination of air temperature in any section of a layer and heat exchange through a construction. Temperature of $t_{\text{const}}$ can be determined according to a formula:

$$t_{\text{const}} = \frac{t_{\text{ext}} + (t_{\text{int}} - t_{\text{ext}}) R_{\text{ext}}}{(R_{\text{ext}} + R_{\text{int}})} = \frac{(R_{\text{ext}} R_{\text{int}} + R_{\text{int}} R_{\text{ext}})}{(R_{\text{ext}} + R_{\text{int}})}$$

(10)

where $R_{\text{ext}}$ and $R_{\text{int}}$ – resistance to a heat exchange of external and internal parts of a structure with surrounding air layers. Into a gap between surfaces of the screen and shell a radiant heat exchange is effected with coefficient of radiant heat exchange $\alpha_r$, depending on temperature. Coefficient $\alpha_r$ is determined by formula:

$$\alpha_r = e_{\text{red}} C_0 b \phi$$

(11)

where $C_0$ – blackbody coefficient; $e_{\text{red}}$ – reduced power of blackness of surfaces ; $\phi$ – radiation factor; $b=0.81+0.01 t_{\text{med}}$ – temperature coefficient; $t_{\text{med}}$ – medium temperature between surfaces. Heat transmission resistance of screen $R_{\text{int}}$ and shell $R_{\text{ext}}$ is defined:

$$R_{\text{int}} = \frac{1}{\alpha_{\int} + 1/ \alpha_f + 2/ \alpha_r}$$
$$R_{\text{ext}} = \frac{1}{\alpha_f + 2/ \alpha_r + R_{\text{sh}} + 1/ \alpha_{\text{ext}}}$$

(12)

where $\alpha_i$ – coefficient of convective heat exchange of one surface to the air, moving in the layer with velocity $v$. Convective heat exchange in a layer can be calculated on the following dependences based on M.A. Mikheyev's recommendations [3]. For the laminar mode of the movement ($Re<2\cdot10^3$) in the channel, use dependence:

$$Nu = 1.4 \left( \frac{Re \cdot d}{l} \right)^{0.4} Pr^{0.33} \left( \frac{Pr}{Pr_w} \right)^{0.25}$$

(13)

where $P_r/P_{w}$ takes into account the dependence of physical properties on temperature and direction of thermal stream. The average value of the coefficient of convective heat exchange for air along the length of layer is equal to:

$$\alpha_f = e \left( 0.896 + 1.51\cdot10^{-3} t \right) (v\rho)^{0.2} \Delta T^{0.1} / d^{0.5}$$

(14)

where $v$ – velocity, m/s; $\Delta T$ – temperature difference between the air and the surface air layer; $t$ – average of these temperatures; $d$ – equivalent diameter, which is equal to $F/P$ ($F$ – the area and $P$ – channel perimeter). For layer $d$ is equal to width of the gap $d=\delta$.

Table 1. Values $\epsilon$ depending on $l/d$.

<table>
<thead>
<tr>
<th>$l/d$</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50 and more</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon$</td>
<td>1.9</td>
<td>1.7</td>
<td>1.44</td>
<td>1.28</td>
<td>1.18</td>
<td>1.13</td>
<td>1.05</td>
<td>1.02</td>
<td>1.0</td>
</tr>
</tbody>
</table>
For channels of very big length \( l/d > 0.067 \text{RePr}^{5/6} \) (in this case holds for all \( \delta \)) the \( \text{Nu} \) becomes almost constant:

\[
\text{Nu} = 1 \text{Nu} = 4\left( \frac{\text{Pr}}{\text{Pr}_{\infty}} \right)^{0.25}
\]  

(15)

In an air layer of the enclosure when for air \( \text{Pr}=\text{Pr}_{\infty} \), \( \text{Nu}=4 \), and \( \alpha_l \) at \( \text{t}_{\text{ext}}=0 \) °C is equal:

\[
\alpha_l = 4\lambda_{\text{air}}/d
\]  

(16)

Table 2. Average value of \( \alpha_l \) for air at \( \text{t}_{\text{ext}}=0 \) °C at various thickness of a gap.

<table>
<thead>
<tr>
<th>( \delta )</th>
<th>( \alpha_l=4\lambda_{\text{air}}/d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.976</td>
</tr>
<tr>
<td>0.15</td>
<td>0.651</td>
</tr>
<tr>
<td>0.2</td>
<td>0.488</td>
</tr>
<tr>
<td>0.3</td>
<td>0.325</td>
</tr>
<tr>
<td>0.4</td>
<td>0.244</td>
</tr>
<tr>
<td>0.5</td>
<td>0.195</td>
</tr>
<tr>
<td>0.7</td>
<td>0.139</td>
</tr>
<tr>
<td>1</td>
<td>0.098</td>
</tr>
</tbody>
</table>

For the turbulent area of flow (\( \text{Re}>2\cdot10^3 \)) according to the [3] we have:

\[
\text{Nu} = 0.021\text{Re}^{0.8}\text{Pr}^{0.43}\left( \frac{\text{Pr}}{\text{Pr}_{\infty}} \right)^{0.25} \varepsilon_l
\]  

(17)

At the beginning of the gap \( \varepsilon_l \) accepts values up to 1.65 and then decreases and at \( l/d>50 \) it becomes equal to 1.0.

In technical calculations it is possible to neglect changes of convective heat exchange on a stabilization site (at the beginning of a layer) in this mode. Consider the change in heat exchange on layer length by method of V.N. Bogoslovsky [4]. All values are related to the gap width of 1 m. In a random cross-section \( x \) the equation of the heat balance of the air in the air layer within the element \( dx \) (Fig. 1) can be represented as:

\[
dQ_1 - dQ_2 = dQ_3
\]  

(18)

d\( Q_1 \) (warmth transmitted through a protective screen) is equal:

\[
dQ_1 = \left[ \left( t_{\text{int}} - t \right) / R_{\text{int}} \right] dx
\]  

(19)

Through external part of construction (shell of cooling tower) passes \( dQ_2 \) that is equal:

\[
dQ_2 = \left[ \left( t - t_{\text{ext}} \right) / R_{\text{ext}} \right] dx
\]  

(20)

The part of heat through a construction is lost on air heating. Air temperature increases by \( dt \) on length \( dx \) by changing heat content on \( dQ_3 \):

\[
dQ_3 = c\lambda_{\text{air}} dt
\]  

(21)

The difference between the heat flows through the inner and outer parts of the construction to the air in the layer with the formula (10) can be written as:

\[
dQ_1 - dQ_2 = \left[ (R_{\text{ext}} + R_{\text{int}}) / R_{\text{ext}}R_{\text{int}} \right] (t_{\text{const}} - t)dx
\]  

(22)

After substitution (21) and (22) we will receive the differential equation (18) in a look:

\[
\left[ \left( R_{\text{ext}} + R_{\text{int}} \right) / R_{\text{ext}}R_{\text{int}} \right] (t_{\text{const}} - t)dx = c\lambda_{\text{air}} dt
\]  

(23)

After division of variables and integration from \( t_0 \) to \( t \) and from 0 to \( x \) the solution of this equation is:
\[ \theta_x = e^{-Kx} \]  

(24)

As an example we will calculate temperature in a gap at a thickness \( \delta = 0.15 \) m and temperature of external air \( t_{ext} = 0 \) °C. The values of thermal resistance \( R_s = d_s/\lambda_s \) and \( R_{sh} = d_{sh}/\lambda_{sh} \), included in \( R_{int} \) and \( R_{ext} \), are given in table 3.

Table 3. Thermal resistance of elements of construction.

<table>
<thead>
<tr>
<th>Type of construction</th>
<th>Work material</th>
<th>Coefficient of heat conductivity ( \lambda ), W/(m·°C)</th>
<th>Average thickness of ( d ), m</th>
<th>Thermal resistance, m²·°C/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unitized screen</td>
<td>Fiberglass of cold curing</td>
<td>0.33</td>
<td>0.0005</td>
<td>1.52 \times 10^{-3}</td>
</tr>
<tr>
<td>Precast screen</td>
<td>Glass fibre laminate</td>
<td>0.29</td>
<td>0.002</td>
<td>6.90 \times 10^{-3}</td>
</tr>
<tr>
<td>Shell</td>
<td>Reinforced concrete</td>
<td>2.04</td>
<td>0.7</td>
<td>0.343</td>
</tr>
</tbody>
</table>

Average value for \( \alpha_{int} = 10.8 \), for \( \alpha_{ext} \) according to [5]. For winter conditions \( \alpha_{ext} = 23 \) W/(m²·°C), for summer conditions according to a formula:

\[ \alpha_{ext} = 1.16(5 + 10\cdot v^{0.5}) = 17.4 \]  

(25)

where \( v \) – minimum from average speeds of a wind on rhumbs for July. Their repeatability makes 16% and more and is accepted according to [6], but not less than 1 m/s. The heat exchange coefficient by radiation is determined by the general formula:

\[ \alpha_r = e_{red}\varphi C_r b = 0.541 \cdot 0.577 \cdot 0.93 = 2.9 \]  

(26)

By calculations it is established that depending on temperature of external air: \( t_{med} = -25.2 \pm 23.6 \) °C and \( b = 0.81 + 0.01 t_{med} = 0.56 \pm 1.05 \). For the winter period it is possible to accept \( b = 0.93 \).

\[ Nu = 0.021 \cdot 6629^{0.8} \cdot 0.83^{0.43} \cdot (0.83 / 0.83)^{0.25} = 22.1 \]  

(27)

For unitized screen:

\[ R_{int} = 1 / \alpha_{int} + R_s + 1 / \alpha_s + 2 / \alpha_r = 1 / 10.8 + 1.52 \cdot 10^{-3} + 0.15 / (22.1 \cdot 0.0244) + 2 / 2.9 = 1.06 \]  

(28)

For precast screen \( R_{int} = 1.07 \). As the difference is very small, for the screen we will accept the last value. For winter conditions:

\[ R_{ext} = 1 / \alpha_{int} + R_{sh} + 1 / \alpha_{ext} + 2 / \alpha_r = 0.278 + 0.386 + 0.690 = 1.35 \]  

(29)

For summer conditions:

\[ R_{ext} = 1 / \alpha_{int} + R_{sh} + 1 / \alpha_{ext} + 2 / \alpha_r = 0.278 + 0.400 + 0.690 = 1.37 \]  

(30)

Table 2. Dependence \( \theta \) from \( x \).

<table>
<thead>
<tr>
<th>( x, m )</th>
<th>0</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.780</td>
<td>0.609</td>
<td>0.475</td>
<td>0.371</td>
<td>0.289</td>
<td>0.226</td>
<td>0.176</td>
<td></td>
</tr>
</tbody>
</table>

This shows that with increasing \( x \) the value of \( \theta \) tends to zero. The temperature of the air in the gap approaches a constant value \( t_{const} \). It allows to determine the height of the initial section \( h_c \). Air temperature in a layer practically does not change in its limits. We will calculate \( t_{const} \) (for \( \delta = 0.15 \) m and \( t_{ext} = 0 \) °C):
\[ t_{\text{const}} = \left( R_{\text{ext}} t_{\text{int}} + R_{\text{int}} t_{\text{ext}} \right) / \left( R_{\text{ext}} + R_{\text{int}} \right) = \left( 1.35 \cdot 21 + 1.07 \cdot 0 \right) / \left( 1.35 + 1.07 \right) = 11.7 \, ^\circ C \]  
(31)

For practical purposes it is enough to consider \( t_x \approx t_{\text{const}} \) with a small error. For example, \( t_x - t_{\text{const}} = \pm 0.05 \, ^\circ C \) that is even excess accuracy. Then the critical height and temperature \( t_x \) can be calculated according to:

\[ h_{cr} = -\ln \left[ 0.05 \left( \frac{t_{\text{const}} - t_0}{t_x} \right) \right] / K_x, t_x = t_{\text{const}} - (t_{\text{const}} - t_0) e^{-K_x}. \]  
(32,33)

At small expenses of air \( t_{\text{const}} \) is established at a short distance from gap entrance and remains invariable on all height of a layer. The average air temperature in a layer differs little from \( t_{\text{const}} \). If height of a layer is commensurable with \( h_{cr} \) the average temperature is much different from \( t_{\text{const}} \). In this case average air temperature in a layer:

\[ t_{\text{med}} = \frac{\int_0^H t(x) dx}{H} = \frac{\int_0^H \left[ t_{\text{const}} - \left( t_{\text{const}} - t_0 \right) e^{-K_x} \right] dx}{H} = t_{\text{const}} + \left( t_{\text{const}} - t_0 \right) \frac{e^{-KH} - 1}{KH} \]  
(34)

where \( H \) – gap height. The described method allows to carry out joint calculation of the inter-related thermal and aerodynamic modes of the ventilated layer.

2.2 Second case (heating of air inlet by single smooth pipe)

Air on an entrance to inlet needs to be warmed up to ensure sufficient air flow rate. The heating is carried out by heat exchange with the pipe. This pipe is installed along the perimeter of the cooling tower between the shell and the protective screen and brings recycled water. Nusselt's criterion for convective heat exchange for \( Re \) in the range \( 4000 \div 40000 \) (preliminary calculations showed that Reynolds's numbers are in these limits) is calculated as:

\[ Nu = (0.43 + 0.20 Re^{0.62} Pr^{0.38}) \varepsilon \]  
(35)

where \( \varepsilon \) – correcting coefficient, which considers degree of turbulence of the running stream. In this case \( (l/\delta >> 50) \) \( \varepsilon = 1.0 \). \( Pr = \nu / a \) – Prandtl number; \( \nu \) – kinematic viscosity of air; \( a \) – temperature conductivity coefficient of air. The heat exchange coefficient \( \alpha \) is calculated according to:

\[ \alpha = Nu \lambda_t / d \]  
(36)

where \( d \) – diameter of the warming-up pipe; \( \lambda_t \) – heat conductivity of air at temperature \( t \). Amount of heat \( Q \), which is given to air by a pipe during time \( \tau \) at the stationary mode, is equal:

\[ Q = \alpha S_p \tau (t_p - t_{\text{ext}}) \]  
(37)

where \( S_p \) – area of an external surface; \( t_p \) – temperature of the warming-up pipe (accept \( t_p \approx 40 \, ^\circ C \)). The same amount of heat \( Q \) can be expressed through a thermal capacity of external air \( c_{\text{out}} \):

\[ Q = c_{\text{out}} \lambda_t \rho_{\text{out}} \tau (t_0 - t_{\text{ext}}) \]  
(38)

where \( S_{\text{inl}} \) – area of an inlet; \( t_0 \) – air temperature at the beginning of a gap. By equating the right parts of the equations (37) and (38) and replacing relation \( S_p / S_{\text{out}} = \pi d / \delta \), we receive:

\[ t_0 = \pi d a \left( t_p - t_{\text{ext}} \right) / (\delta c_{\text{out}} \lambda_t \rho_{\text{out}}) + t_{\text{ext}} \]  
(39)
From (39) it is visible that $t_0$ does not depend on diameter of the warming-up pipe, because the product $d\alpha$ remains to constants at any values of diameter. We will enter designation $\alpha_d=\pi d\alpha$, where $\alpha_d$ is heat exchange coefficient of one rm of a pipe. Heat exchange coefficients at a cross flow of the isothermal cylinder were established experimentally for various values of Nu and Re in research [7]. Experimental values for similar conditions are close to our settlement.

2.3 Third case (heating of air inlet by bunches of ridge pipes)

Calculation of heat exchange in bunches of the pipes with round and square edges, which are flowed round by a cross flow of air, is made on the following equations valid in the range $3\cdot10^3<Re<25\cdot10^3$:

$$Nu = CRe^m (d / b)^{-0.54} (h / b)^{0.14}$$

where $Nu=\alpha b/\lambda$; $Re=vb/\upsilon$; $b$ – step of edges; $d$ – outer diameter of a pipe; $h=0.5(D-d)$; $D$ – diameter or side of an edge. Calculation was done for a chess bunch of pipes with round edges, for which $C=0.223$, $m=0.65$. Accept: $b=0.1$; $d=0.05$; and $D=0.1\text{ m}$.

3. Conclusion

Temperature of air in the gap depends on the outdoor temperature $t_{\text{ext}}$ and it is as higher, as higher the $t_{\text{ext}}$. Medium temperature in height gap $t_{\text{med}}$ was lower in the case of additional heater than at natural convection. This, paradoxical at first sight, situation has the following simple explanation. The heating of air on gap’s inlet increases the initial temperature of air $t_0$. The consumption of air $j$ increases as a result of increase of speed of the movement. At the same amount of the absorbed heat increasing of air temperature is smaller, according to a formula (21). Furthermore, as a result of change of thermal resistance $R_{\text{ext}}$ and $R_{\text{ext}}$ temperature of a cold concrete wall $t_1$ goes down more strongly, than temperature of a warm fiberglass wall $t_2$ increases. At the same air temperature $t_1>t_2>t_3$ it reduces the total amount of heat $dQ_3$ that also results to a decrease of $dt$. The temperature difference $t_0-t_{\text{ext}}$ decreases with increasing $t_{\text{ext}}$. Air temperature at the inlet of the gap $t_0$ decreases with increasing thickness of the gap, that also leads to falling of velocity. The heating of air allows to increase value of initial temperature, but this measure is effective only at the big area of contact with the warming-up surface. Critical length, on which air temperature becomes constant ($t_{\text{cont}}$), makes thousands of meters, which significantly exceeds the height of the cooling tower ($l_{\text{cr}}>H$), therefore the temperature in the air gap increases from $t_0$ to $t_0$. Difference $t_{\text{0}}-t_{\text{0}}$ as height, as smaller the thickness of the air gap and outdoor temperature.

Along with increase of gap width: losses on air stream resistance are decreased, but it is not very significant; heat emission of warming-up pipes is decreased due to deterioration of ambient velocity; initial temperature at inlet of a gap and average temperature in the gap decreases due to increase consumption of air; initial air velocity is lowered due to decrease of its temperature and according increase of density (it leads to loose of gravitational head).

References

[5] SNiP II-3-79* (Construction Norms and Regulation), Stroitel'naia teplofizika.
[6] SNiP 2.01.01-82 (Construction Norms and Regulation), Stroitel'naia klimatologija i geofizika.