

INDUSTRIAL COOLING TOWER DESIGN AND OPERATION IN THE MODERATE-CONTINENTAL CLIMATE CONDITIONS

by

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A large number of producers offer a wide choice of various types of industrial cooling towers. Usually, a proper choice of pre-fabricated cooling tower satisfies end-user needs. However, if there are specific end-user requirements, it is necessary to design cooling tower according to those requirements. For the adhesive factory located in southern region of Serbia, 350 kW mechanical draught wet cooling tower was designed and built. Dimensioning of the cooling tower was done according to parameters of the ambient air, higher than the standard recommendations given in the literature. In this paper, the reasons for deviation from recommendations are given. The analysis of the cooling tower operation based on real meteorological parameters for 2015 is also shown in this paper. According to this analysis, cooling tower provides required water temperature in any season, and gives opportunity for energy savings in winter, with opportunity for heat capacity enlargement if production capacity is raised as it is planned in the factory.

Key words: cooling tower, ambient air, choice of design parameters, cooling water

Introduction

Industrial processes generate large amounts of heat that must be continuously dissipated if those processes are to continue to operate efficiently. Although this heat is usually transferred to a cool, flowing volume of water, final rejection is always to the atmosphere and, invariably, is accomplished by some form of heat exchanger. Cooling towers are heat exchangers used to dissipate large heat loads to the atmosphere. By applying recirculation cooling system (fig. 1), up to 98% savings in water consumption can be achieved. Payback period depends on the capacity of the plant, cost of equipment, automation, etc. [1].

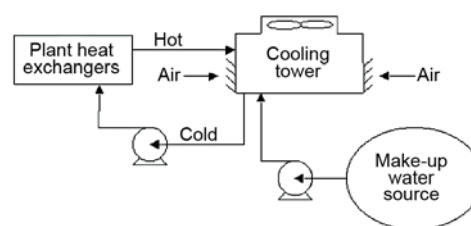


Figure 1. Closed loop cooling system [2]

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Cooling towers are designed and manufactured in several types, with numerous sizes (models) available in each type. Not all types are suitable for application to every heat load configuration. Wet cooling towers may be categorized by the method of generating air flow, air-to-water flow arrangement and by physical shape. Cooling towers fall into two main subdivisions: natural draft and mechanical draft. Natural draft designs use very large concrete chimneys to introduce air through the media. Due to the tremendous size of these towers they are generally used for large water flowrates above 45000 m³/h. Usually these types of towers are only used by utility power stations. Mechanical draft cooling towers are much more widely used. These towers utilize large fans to force air through circulated water. The water falls downward over fill surfaces which help increase the contact time between the water and the air. This maximizes heat transfer [3].

Cooling towers are also divided by the relative flow relationship of air and water within the tower, as follows: in counter-flow towers, fig. 2(a), air moves vertically upward through the fill, counter to the downward fall of water. Cross-flow towers, fig. 2(b), have a fill configuration through which the air flows horizontally, across the downward fall of water.

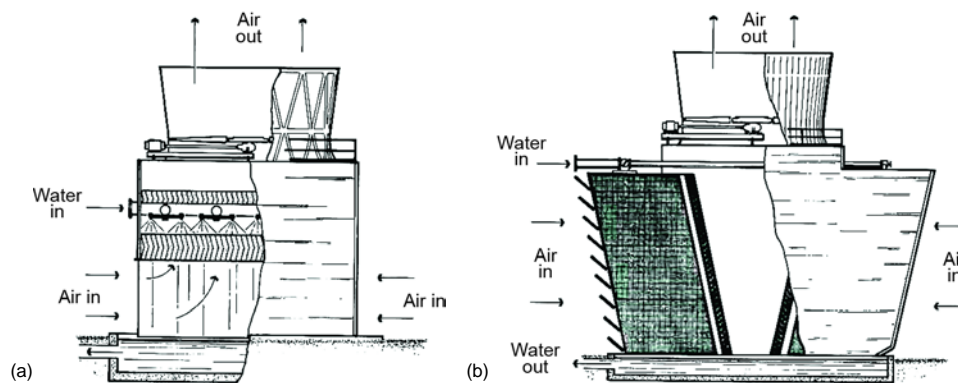


Figure 2. Counter-flow (left) and cross-flow (right) cooling towers

Counter flow cooling towers have theoretically, a uniform exit air wet bulb temperature. Cross-flow towers exhibit a large variation of exit air wet bulb temperature, which is responsible for further evaporation loss. In addition, cross-flow towers require more airflow in order to meet the same cooling capacity and overall evaporation losses are slightly higher [4].

All cooling towers that are used to remove heat from an industrial process or chemical reaction are referred to as industrial process cooling towers [5].

In general, the design solution of cooling systems with wet cooling towers depends on the power and type of plant, thermodynamic parameters, techno-economic conditions, cost of equipment, *etc.* The required tower size will be a function of: cooling range, approach to wet bulb temperature, mass flow rate of water, wet bulb temperature, air velocity through tower or individual tower cell and tower (fill pack) height.

The principles of calculation and analysis of the cooling tower

The cooling of water is carried out in direct contact with atmospheric air due to convection and evaporation of water in the moist air. Since a cooling tower is based on evaporative cooling, the maximum cooling tower efficiency is limited by the wet bulb temperature of

the cooling air. The performance of cooling tower is often expressed in terms of cooling range and approach (fig. 3). Cooling range is the temperature difference between the hot water coming to the cooling tower and the temperature of the cold water leaving the tower. Approach is the temperature difference between the temperature of the cold water leaving the tower and the surrounding air wet bulb temperature. Both, the range and approach must be greater than zero in normal cooling tower operation. In practice, the actual temperature of water cooling is higher than wet bulb temperature for 5-10 K [6].

Heat is transferred from water drops to the surrounding air by the transfer of sensible and latent heat.

The cooling characteristic of the cooling tower is represented by the Merkel equation [7, 8]:

$$\frac{\beta_{xv} V}{G} = \int_{t_1}^{t_2} \frac{c_w dt}{h'' - h} \quad (1)$$

The Merkel equation primarily states that at any point in the tower, heat and water vapour are transferred into the air due (approximately) to the difference in the enthalpy of the air at the surface of the water and the main air stream. Thus, the driving force at any point is the vertical distance between the two operating lines. Therefore, the performance demanded from the cooling tower is the inverse of this difference.

For technical calculations, it can be considered with sufficient accuracy that unsaturated moist air obeys the laws of a mixture of ideal gases.

The relative humidity, ϕ of an air-water mixture can be calculated:

$$\phi = \frac{p_{wp}(t)}{p_{ws}(t)} = \frac{\omega}{0.622 + \omega} \frac{p_a}{p_{ws}(t)} \quad (2)$$

The enthalpy of moist and humid air includes the enthalpy of dry air – the sensible heat – and the enthalpy of evaporated water – the latent heat. Specific enthalpy of moist air on the tower inlet can be expressed:

$$h = h_a + xh_w = 1.0048t + \frac{0.622 p_{ws}(t) \phi}{p - p_{ws}(t) \phi} (2500 + 1.86t) \quad (3)$$

where h [kJkg⁻¹] is the specific enthalpy of moist air, h_a [kJkg⁻¹] – the specific enthalpy of dry air, x [kgkg⁻¹] – the humidity ratio, h_w [kJkg⁻¹] – the specific enthalpy of water vapor, and t [°C] – the dry bulb air temperature.

The analytical relation of ambient air enthalpy vs. wet bulb temperature can be represented by an analytical expression [4]:

$$h = 1.6184 \cdot 10^{-3} t_{WB}^3 - 2.704 \cdot 10^{-2} t_{WB}^2 + 2.512 t_{WB} + 4.574 \quad (4)$$

The saturated vapor pressure can be calculated by different methods. In this paper, the IAPWS-97 method is used [9].

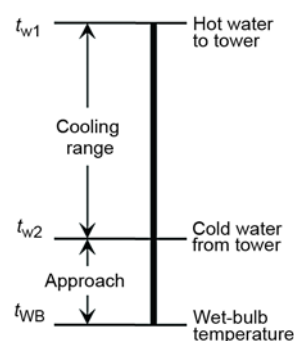


Figure 3. Diagram showing definition of cooling range and approach

Determination of the volumetric heat and mass transfer coefficients is done for cooling devices in which water is sprayed through nozzles or in the form of drops flows on the grid.

Criteria equations do not include changing the surface of liquid, so in the absence of exact methods it is common use of the purely empirical formulation. In [7] for the 38-46 °C inlet water temperature empirical formula is given:

$$\beta_{xv} = A(w\rho)^m q_1^n \quad (5)$$

where q_1 [$\text{kgm}^{-2}\text{s}^{-1}$] is the specific mass flow rate, w [ms^{-1}] – the air velocity, and $A = 1050$, $m = 0.62$, and $n = 0.38$ are the constants. Although there are lot of empirical formulas for the volumetric mass transfer coefficient [7, 10], eq. (5) is proven to be useful in this type of calculation by comparing numerical results with experimental data [11-13].

For the analytical solution of Merkel integral, it is necessary to find appropriate dependence of specific enthalpy of saturated air and temperature. For this temperature range, the parabolic dependence (7) is obtained:

$$h'' = 0.019t^2 - 1.575t + 40, \quad (6)$$

Solving the Merkel integral, the following equation can be written:

$$V = HF_{cs} = \frac{Gc_w \Delta t}{\beta_{xw} \Delta h_m} \quad \text{or} \quad H = \frac{Gc_w \Delta t}{\beta_{xw} \Delta h_m F_{cs}}$$

$$\Delta h_m = \frac{1}{2} (\Delta h_1 + \Delta h_2) - \delta h_m''$$

$$\Delta h_1 = h_1'' - h_2, \quad \Delta h_2 = h_2'' - h_1, \quad \delta h_m'' = \frac{h_1'' + h_2'' - 2h_m''}{4} \quad (7)$$

where $h_{1,2,m}$ is the specific enthalpy of saturated air at inlet, outlet, and mean temperature, $h_{1,2}$ – the specific enthalpy of saturated air at inlet and outlet temperature, and $h_{1,2}''$ – the specific enthalpy of saturated air at inlet and outlet wetted-surface temperature.

Fan power consumption:

$$P = \frac{dpV}{\eta}, \quad dp = \frac{\xi H \rho w^2}{1.4} \quad (8)$$

Thermal analysis should be done as a control in the case of determining the temperature of cold water, depending on various atmospheric conditions. In that case, the following equation can be written, as a result of Merkel integral solution [10]:

$$0.045t_{w,out}^2 + \left(0.03t_{w,in} + \frac{c_w}{2\lambda} + \frac{Gc_w}{V\beta_{xv}} - 0.785 \right) t_{w,out} +$$

$$+ \left[0.045t_{w,out}^2 - \left(0.785 + \frac{c_w}{2\lambda} + \frac{Gc_w}{V\beta_{xv}} \right) t_{w,in} + h_{in} + 40 \right] = 0 \quad (9)$$

Solution of this equation is water temperature on the outlet of the cooling tower, as function of atmospheric air parameters, inlet water temperature, flow rate of the water, and air

flow rate. This dependence gives an opportunity for overall consideration of the influence of different parameters on the outlet water temperature.

For the practical analysis of cooling tower operation, the following losses influencing the operation have to be defined: blow-down, evaporation loss, drift loss, and make-up loss. In this paper, analysis of these losses is not included.

Meteorological data

Meteorological data are very important for design and energy analysis of the cooling tower system. For thermal calculation of the cooling tower, the following atmospheric air parameters are necessary:

- dry bulb temperature, t_a , [°C],
- relative humidity, φ , [%], or
- wet bulb temperature, t_{WB} , [°C].

These values are defined for a specific climate: for example, the design wet bulb temperature for San Francisco, Cal., USA, is 18 °C, while for Hanoi, Vietnam, is 30 °C [4]. Wet bulb temperature, at first greatly influences the dimensions and, later, the operation of cooling tower. These data can be obtained from a local meteorological institution. The relevant institution in Serbia is Republic Hydrometeorological Service of Serbia [14].

Mostly used recommendation for value of the air temperature in the design of cooling tower is mean air temperature for three hottest months (June, July, August in our climate zone). The explanation for this recommendation is that very high wet bulb temperatures (24-26 °C) appear in a very short period of time (0.1-0.2%) [15]. Several authors recommends cooling tower design according to the “worst case scenario” – highest geographic wet bulb temperatures. This temperature will dictate the minimum performance available by the tower. As the wet bulb temperature decreases, the available cooling water temperature will decrease too [16].

In our opinion, both recommendations are not appropriate solutions in this particular case. In the first recommendation, during hot summer months, the cooling capacity will decrease and due to lack of appropriate cooling the whole process in the industrial plant could be threatened. Following the other recommendation can lead to high investment and operating costs.

We have decided to find a solution that will be appropriate for both, performances and costs point of view. The first criterion is to ensure continuous production process *i. e.* adequate cooling under all atmospheric conditions. The second criterion is to ensure energy efficient operation during the less harsh atmospheric conditions.

In order to meet these two criteria, the climatic parameters for the specific geographic area are considered. The temperature regime of the region in which the factory is located shows all the characteristics of continental climate. Mean monthly and mean annual air temperature, extreme values of air temperature and mean number of days with characteristic values of air temperature, for the period from 2005 to 2012, is shown in tab. 1 [14].

The mean relative humidity, absolute minimum and the number of days when the relative humidity was $\leq 30\%$, $\leq 50\%$, and $\geq 80\%$ are shown in tab. 2. Most of the values show that the relative humidity decreases from winter to summer months and then rises again from summer to winter. A small increase in relative humidity was recorded in May and June because these are the months with the highest rainfall. Monthly relative humidity ranges from 62% (July and August) to 85% (December), while the average annual value is 71%.

The most important data in the selection of design parameters of atmospheric air for the cooling tower system are values for summer months (June, July, and August) 2005-2012.

Table 1. Average monthly and yearly air temperature, air temperature extremes, and average number of days within specified values of air temperature

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Average monthly and yearly air temperature	1.1	1.4	7.5	13.3	17.7	21.3	23.7	22.9	18.6	12.5	7.4	2.7	12.6
Average maximum of air temperature	4.4	5.0	12.2	18.7	23.1	26.6	29.3	28.8	24.1	17.8	12.0	5.6	17.3
Average minimum of air temperature	-2.1	-2.2	2.6	7.5	11.9	15.2	17.1	16.5	12.8	7.6	3.1	-0.3	7.5
Absolute maximum of air temperature	17	24	25	29	35	36	43	40	37	33	25	19	43
Absolute minimum of air temperature	-18	-24	-13	-2.0	1.0	6.0	11	8	4	-2	-6	-22	-24
Average number of days with air temperature < 0 °C	17.1	16.5	7.4	0.1	0.0	0.0	0.0	0.0	0.0	1.0	6.3	14.6	63.0
Average number of days with air temperature ≥ 35 °C	0.0	0.0	0.0	0.0	0.1	1.1	5.1	3.5	0.5	0.0	0.0	0.0	10.4

Table 2. Average monthly and yearly relative humidity, absolute minimum of relative humidity, average number of days within specified values of relative humidity

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Mean relative humidity (RH)	84	79	67	63	67	67	62	62	66	73	78	85	71
Absolute minimum of RH	37	19	13	16	18	18	7	15	15	21	22	42	7
Average number of days with RH ≤ 30%	0	0.1	1.1	1.7	0.8	0.8	2.2	2.9	1.4	0.3	0	0	11.4
Average number of days with RH ≤ 50%	0.3	1.6	7	9	7.2	7.4	10.5	10.3	8.4	4.3	1.6	0.5	68
Average number of days with RH ≥ 80%	0.6	0.4	0.2	0.1	0.1	0.1	0	0.1	0.1	0.2	0.3	0.7	2.9

The average dry bulb temperature, relative humidity and wet bulb temperature statistic for summer period 2005-2012 is given in tab. 3. The average maximum dry bulb temperature, relative humidity and wet bulb temperature statistic for summer is given in tab. 4.

According to this climate statistics, the dry bulb temperature of 29 °C and relative humidity of 64% *i. e.* wet bulb temperature of 23 °C was adopted as designed ambient air parameters.

Analysis of the industrial cooling tower performance in operation

Industrial cooling tower is designed for the needs of adhesive factory, which is located in the southern region of Serbia. In the adhesive production process it is necessary to provide continual cooling of the reactor, using constant flow rate of water with initial tempe-

Table 3. Average ambient air parameters

Month	June	July	August
Dry bulb temperature [°C]	21.3	23	18.6
Mean	21		
Relative humidity [%]	67	62	62
Mean	64		
Wet bulb temperature [°C]	17.3	18.1	14.4
Mean	16.7		

Table 4. Average maximum ambient air parameters

Month	June	July	August
Dry bulb temperature [°C]	26.6	29.3	28.8
Mean	28.3		
Relative humidity, mean [%]	64		
Wet bulb temperature [°C]	21.6	24	23.6
Mean	23		

perature of 35 °C. Input parameters for calculation of the cooling tower and selection of necessary equipment were: the required heat capacity 350 kW, specific customer requirements and meteorological parameters for the relevant geographical area, as described previously.

The characteristics of the chosen fill type are: contact area for heat exchange: 240 m²/m³, maximum capacity (hydraulic load of fill): 30 t/m²h, calculated dimensions of fill: 1.8 × 1.8 × 0.9 m.

For cooling towers of this type, heat capacity and cooling range, the recommended values of air velocity are 2-5 m/s. These recommendations by the standards meet the requirements of stability in operation and efficiency of the cooling process in the tower. Nominal air velocity is 3 m/s. Variable-frequency drive fan is chosen. Air flow rate can be changed in the range 4-15 kg/s. Specification of other equipment is not of relevance for the considerations shown in this paper.

Designed cooling tower is built and put into operation in November 2014. Photography of constructed cooling tower and its cross section is shown in fig 4.

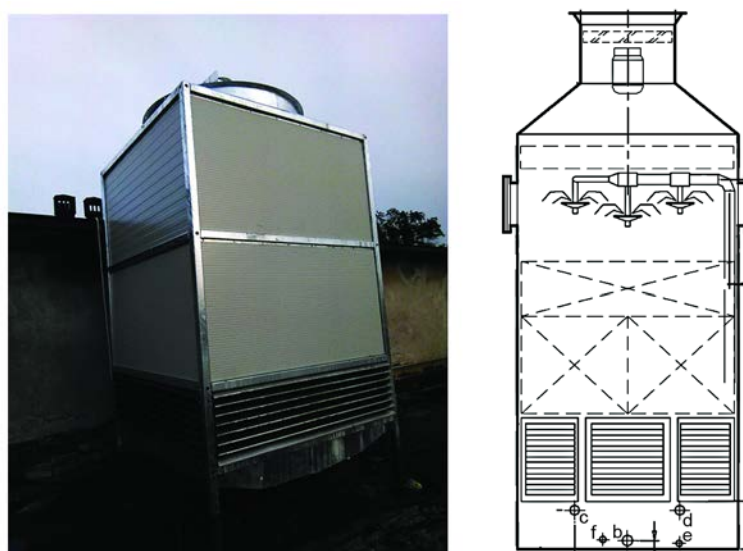


Figure 4. Cooling tower in factory Chemis

Performance and energy efficiency of the cooling system in the adhesive factory are tested during the winter and especially during the very hot summer in 2015. Required cooling

water parameters, necessary for undisturbed production process are provided in any season, together with savings in energy demand during the seasons with lower ambient air temperature [17].

The cooling tower performance during the three month winter and three month summer period is analyzed, according to meteorological data obtained from Republic Hydro-meteorological Service of Serbia [14]. In order to perform the analysis and give a real presentation of the cooling tower operation in extended period of time, mean temperature and relative humidity are used, calculated by using following formulae:

$$t_{\text{mean}}(\text{daily}) = \frac{1}{8} \sum_{n=1}^8 t_n \quad (10)$$

and

$$RH_{\text{mean}}(\text{daily}) = \frac{1}{8} \sum_{n=1}^8 RH_n \quad (11)$$

Table 5. The mean daily atmospheric air dry bulb temperature, RH and wet bulb temperature in every five days

Summer 2015						
Period	I	II	III	IV	V	VI
June						
T , [°C]	20.8	23	22.3	18.5	15.3	17.5
RH , [%]	68	78	74	72	68	72
July						
T , [°C]	23.5	26.5	20	28	27	25.5
RH , [%]	62	64	66	62	64	62
August						
T , [°C]	25.5	27.5	27	28.3	26.3	25.3
RH , [%]	66	65	60	64	63	62
Winter 2014/2015						
	I	II	III	IV	V	VI
December 2014						
T , [°C]	3.3	4.6	7	4.8	-2	-3.8
RH , [%]	89	90	89	87	85	82
January						
T , [°C]	1	9	6	10	0.5	8
RH , [%]	84	86	90	84	82	87
February						
T , [°C]	5	-2	4.5	3.2	10	7
RH , [%]	89	72	87	90	82	87

where t_n and RH_n are the dry bulb temperature and relative humidity, respectively, of the ambient air measured every 3 hours starting from 00:00. For the calculation of cooling water outlet temperature, mean daily dry bulb temperature of the atmospheric air and mean daily relative humidity on every five days is used, as it is shown in tab. 5. The five-day mean dry bulb temperature and relative humidity are calculated as average daily mean temperature and relative humidity:

$$t_{\text{mean}}(\text{period}) = \frac{1}{5} \sum_{m=1}^5 t_{m,\text{mean}}(\text{daily})$$

and

$$RH_{\text{mean}}(\text{period}) = \frac{1}{5} \sum_{m=1}^5 RH_{m,\text{mean}}(\text{daily})$$

Using nominal value of air flow *i. e.* air velocity and mean ambient dry bulb air temperature and mean relative humidity from tab. 5, the change of water temperature at the outlet of the cooling tower is obtained. Inlet water temperature is defined by adhesive production process and it is considered as constant. The results obtained for the three hottest and three coldest months in 2015 are shown in figs. 5 and 6, respectively.

It is mentioned that for the continuous production process, this plant needs

cooling water temperature 35 °C, in any time of the year. As it can be seen, during the winter period, due to favorable atmospheric conditions, temperature of the cooling water is always under the limit value of 35 °C. During the critical period of three hottest summer months, with nominal air velocity of 3 m/s, temperature of the cooling tower outlet water was near to designed value, the highest value was 35.9 °C. It means that even in the season with atmospheric conditions above the average values for the specific geographic region, this cooling tower can provide continuous operation of the reference plant. Figure 7 shows a comparison of the results obtained in the winter and summer mode, with the required value of cooling water temperature 35 °C.

Figure 5. The change of outlet water temperature, summer 2015

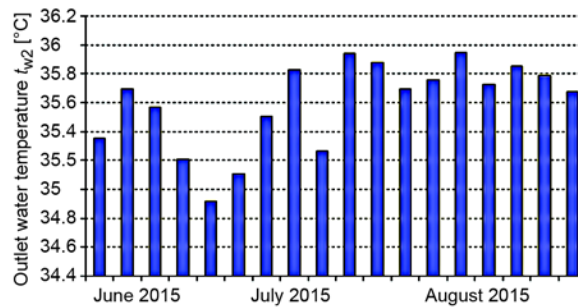


Figure 6. The change of outlet water temperature, winter 2014/15

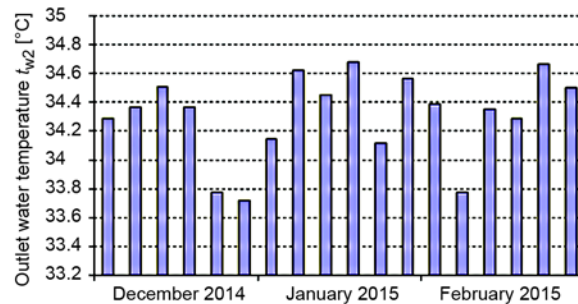
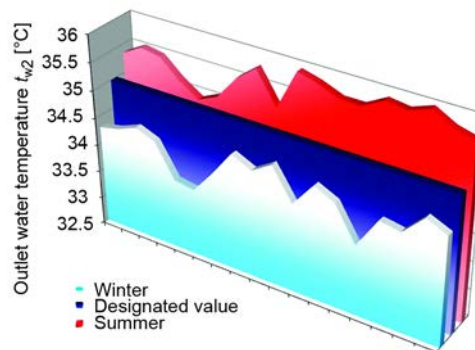


Figure 7. Winter/summer mode and designated value comparison



Although deviations from the reference value are not large (less than 1 °C), there is a possibility for improvement of cooling tower efficiency by regulation of air flow rate and fan power. The objective of regulation is to achieve the required temperature of outlet water at minimum costs.

In winter mode, the atmospheric air temperature is low enough to achieve adequate cooling capacity of the cooling tower. Since the lower temperature of the cooling water is not needed for the production process, there is a possibility for energy savings by adjusting air flow rate.

The reduction of air flow leads to an increase in outlet water temperature. Weather conditions during the cold period gives opportunity for lower air flow rate, thereby achieving satisfactory water temperature with a lower fan power consumption. Figure 8 shows outlet water temperature at different air flow rates for the winter 2014/15. The results obtained for air flow rate 5 kg/s, 7 kg/s, and 10 kg/s are represented with upper, middle, and lower curve in the diagram, respectively.

In summer, the ambient air temperature increase aggravates cooling conditions in the cooling tower, which results in higher temperatures of the cold water leaving the tower. Required water temperature of 35 °C can be achieved by increasing the air flow rate. This increase was possible due to an increase in fan power consumption. With cooling tower dimensioning according to higher wet bulb temperature, this increasing in power consumption is relatively low – with 25% increase of power consumption compared to designed value, the required temperature of the cooling water is achieved, as it is shown in fig. 9. The results obtained for air flow rate 10 kg/s, 12.5 kg/s, and 15 kg/s are represented with upper, middle and lower curve in the diagram, respectively.

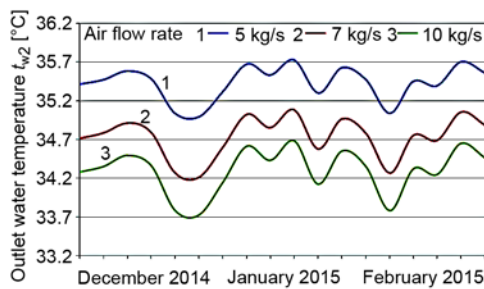


Figure 8. Outlet water temperature at different air flow rates, winter 2014/15

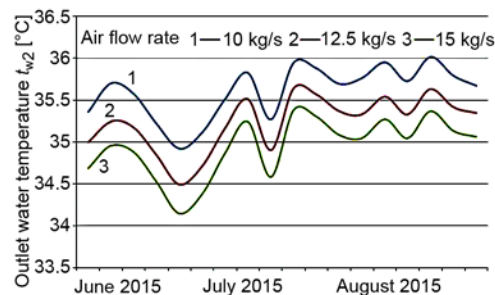


Figure 9. Outlet water temperature at different air flow rates, summer 2015

Air flow rate is directly proportional to the velocity, while the pressure is proportional to the square of the velocity. From energy savings standpoint of view, the most important issue is that the consumed power is proportional to the third gear. Thus, for example, 75% of the speed produces 75% of the air flow, but it has only about 42% of the force necessary for full flow. When the flow is reduced to 50%, power consumption is only 12.5% [18].

Thus, regulation of air flow rate in winter mode generates energy savings, while in summer mode the desired temperature of the cooling water is achieved, regardless of atmospheric conditions. Figure 10 shows the fan power consumption in percent for different periods of the year, while the referent value is power consumption for air flow rate of 12.5 kg/s.

One of the specific requirements of the user is the possibility to raise the production capacity of adhesive, and thus to increase the heat capacity of the cooling tower, in terms of increased water flow for unchanged referent temperature. Therefore, calculation of possibility to increase the flow rate of cooling water and heat capacity for a given configuration of the cooling tower was made. The obtained results for the constant air flow rate and nominal ambient air parameters are shown in fig. 11. According to calculation, this cooling tower will provide satisfactory cooling capacity for 60% enlargement of the capacity.

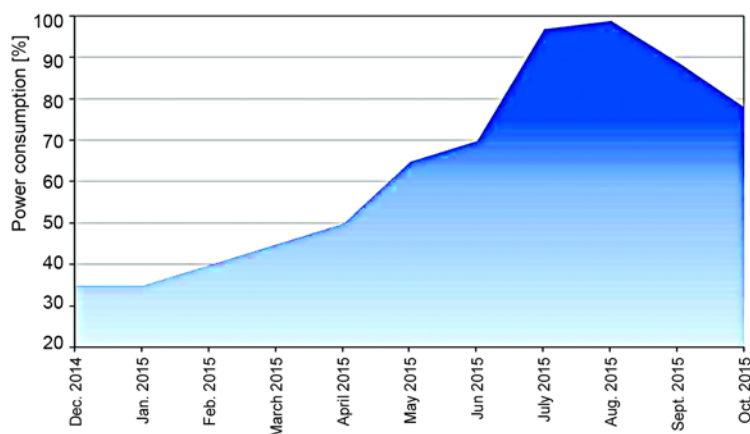
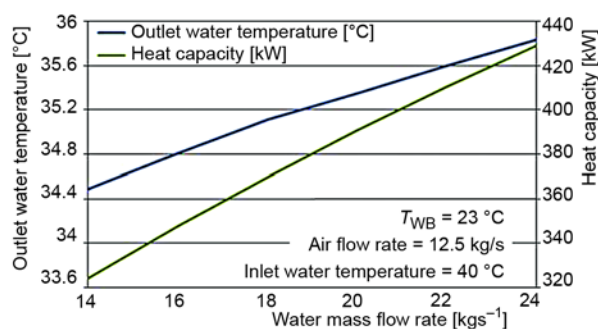


Figure 10. Fan power consumption for 35 °C outlet water temperature

Figure 11. Heat capacity and outlet water temperature vs. flow rate of water



Conclusion

Industrial cooling tower with capacity of 350 kW was dimensioned according to ambient air parameters that are higher than standard recommendations, in order to ensure required cooling water temperature during the hottest period of the year. According to detailed ten-years meteorological statistics for the factory location, design wet bulb temperature is adopted to be 23 °C. This cooling tower is built and put into operation in November 2014. The efficiency of the cooling system in the adhesive factory is tested during winter and especially during very hot summer in 2015. The results of the analysis of cooling tower operation in real conditions are shown in this paper. Required cooling water parameters, necessary for undisturbed production process are provided in any season, together with savings in energy demand during seasons with lower ambient air temperature. By regulation of air flow rate in winter mode, great energy savings are achieved, while in summer mode the desired temperature of the cooling water is achieved, regardless of atmospheric conditions. This justifies the choice of design parameters. In addition, because of the planned increase in production capacity of the factory, the demand for cooling water will increase. It is shown that this cooling tower will provide satisfactory results for an increase of cooling water flow rate by 60%, without additional investments.

Nomenclature

c – specific heat, [kJkg⁻¹K⁻¹]
 G – water flow rate, [kgs⁻¹]

H – fill height, [m]
 h – specific enthalpy of moist air, [kJkg⁻¹]

h'' – specific enthalpy of saturated air, [kJkg⁻¹]
 p – pressure, [Pa]
 q_l – specific mass flow rate, [kgm⁻²s⁻¹]
 t – temperature, [°C]
 V – fill volume, [m³]

Greek symbols

β_{wv} – volumetric mass transfer coefficient,
[kgm⁻³s⁻¹]

λ – air/water flow rate ratio, [-]
 ρ – density, [kgm⁻³].

Subscripts

a – air
in – inlet
out – outlet
w – water

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