E3S Web of Conferences **193**, 01044 (2020) https://doi.org/10.1051/e3sconf/202019301044
ICMTMTE 2020

Cooling efficiency of filler unit in non-chemical cooling tower with advanced contact surface

Ilnur Madyshev[1,*], *Vitaly* Kharkov[1], and *Andrey* Dmitriev[2]

[1]Kazan National Research Technological University, 420015, Karl Marx street 68, Kazan, Russia
[2]Kazan State Power Engineering University, 420066, Krasnoselskaya street 51, Kazan, Russia

Abstract. The paper deals with a pressing problem on the effective cooling of circulating water at industrial plants using the evaporative cooling towers. A new design of the cooling tower is developed that prevents the biological fouling of the equipment surfaces without the use of chemicals. The design of the filler unit with the inclined-corrugated plates and the metal mesh provides the advanced gas-liquid contact surface. An evaluation of the cooling efficiency of the inclined corrugated contact elements is performed by means of the volumetric coefficient values of heat transfer in the gas phase. From experimental data, it has been found that with increasing the wetting density, the volumetric heat transfer coefficients also increase at the same mean-flow air velocity. A comparative analysis of Merkel numbers for the developed filler unit with the existing analogs as the characteristic of cooling capacity indicated its superiority.

1 Introduction

Cooling towers are widely used for cooling circulating water in thermal power plants, as well as in petroleum refineries, chemical, and petrochemical plants [1, 2]. Mechanical-draft cooling towers have a wide distribution by virtue of their energy efficiency, accessibility, and upgradability [3–5]. The cooling efficiency of these towers is highly sensitive to design and operating parameters (water temperature, gas and liquid flow rate, type of filler, and others) [6–8]. A deep insight into evaporative cooling of water is needed both for the modernization of the existing cooling towers and for predicting the efficiency of newly developed ones. Therefore, the calculation of high-performance parameters of circulating water in the cooling towers is a pressing issue [9, 10].

Moreover, there is a problem of significant techno-economic importance through the cooling of circulating biological fouling of the surfaces of industrial equipment water in the mechanical-draft cooling towers. The presence in aqueous systems of bacteria (infecting bacteria, iron bacteria, sulfate-reducing bacteria, etc.) causes and pipelines under favorable conditions (temperature, air availability) [11, 12]. This fact results in the clogging of the water flow, reducing the heat transfer efficiency and increasing hydraulic resistance to air, as well as accelerating the corrosion of the metal surface. In industry, the most common method of controlling biological fouling is the chemical method [13, 14]. However, the

* Corresponding author: ilnyr_91@mail.ru

treatment of water with biocides (chlorine, copper sulfate, copper-zinc oxide, etc.) adversely affects the ecosystem and generally increases production costs [15, 16].

Thus, the resolution to the problem of intensive biomass growth for efficient cooling of circulating water in the cooling towers becomes pressing.

2 Design of the cooling tower and test conditions

Figure 1 shows the developed design of the cooling tower for the evaporative cooling of circulating water at industrial plants without the use of chemicals.

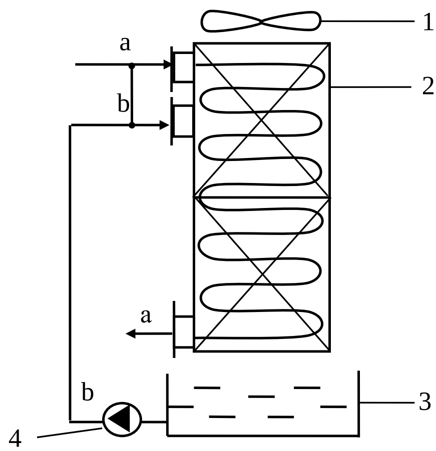

Fig. 1. Schematic diagram of the non-chemical cooling tower with the inclined-corrugated contact elements: 1 – fan; 2 – filler unit; 3 – water-collecting pond; 4 – pump.

The operating principle of the cooling tower is as follows. Hot water entering the filler is divided into two flows. The first one (a) with a higher flow rate is supplied to the tubular radiator without contact with atmospheric air. The second flow (b) is fed to the upper stage of the filler unit, passes through its volume and partially evaporates, contacting with the upward flow of air. It collects at the water-collecting pond, from where it returns to the inlet of the cooling tower. The main first flow is cooled by means of heat transfer with atmospheric air and wetting liquid (b) through the radiator wall surface. In this case, most of the water does not directly contact with air, which corresponds to anaerobic conditions where microorganisms cannot act.

A promising design of the filler unit with the inclined corrugated plates has been developed [17, 18]. The metal mesh is installed over the entire height of the filler unit uniformly, which serves to increase the interphase surface of heat and mass transfer. This design provides the advanced surface of gas-liquid contact during the film flow of water along the surface of the plates and radiator tubes, aa well as the jet flow through holes in the plates. There is also an interaction of air with large droplets formed from jets breakup process and when liquid impacts against the film surface on the plate.

The filler unit consists of two contact stages with a total height of 340 mm. Each stage is made from two corrugated plates inclined at an angle of 45° to the wall. The plates have a rounded profile with a radius of 7.5 mm. Circular perforation 6 mm across is executed on the side surfaces and the upper part of corrugations. The metal mesh is installed over the entire height of the filler unit inside uniformly. The sizes of the investigated apparatus in the cross-section are 100×100 mm.

The air-water system was tested. Water was supplied through a distributing 8 mm tubular device from above to the central part of the first contact stage. Information about the range of parameters and the measuring devices is summarized in Table 1.

Table 1. Details about measuring parameters of the setup.

Parameter	Range	Sensor
Mean-flow velocity of cooling air	1.47–2.77 m/s	Thermal anemometer
Air temperature	30.8–32.8 °C	Thermal hygrometer
Air relative humidity	32.0–36.1 %	
Water temperature	35.1–41.9 °C	Meter-regulator
Wetting density	12–37 $m^3/(m^2{\cdot}h)$	Rotameter

3 Results and discussions

It is possible to evaluate the efficiency of the inclined-corrugated contact elements when the volumetric coefficients of heat transfer in the gas phase are determined. These coefficients characterize the intensity of convective heat transfer and depend on the velocity of the heat-transfer agent, as well as on the geometric parameters of the contact device and other factors. Therefore, the research aims to estimate the volumetric heat transfer coefficients for the developed filler unit of the cooling tower based on the previously obtained criterion relationship of the volumetric mass transfer coefficient [19].

The volumetric mass transfer coefficient in the filler unit with the inclined-corrugated contact elements is found as follows:

$$\beta_{Vx} = 2.53\, q_L \left(\frac{G_m}{L_m} \right)^{0.9}, \tag{1}$$

where β_{Vx} is the volumetric mass transfer coefficient, $kg/(m^3{\cdot}s)$; q_L is wetting density, $kg/(m^2{\cdot}s)$; G_m is the mass flow rate of gas, kg/s; L_m is the mass flow rate of water, kg/s.

It should be noted that the maximum relative calculation error of equation (1) is less than 2.43 % in the range of wetting density of 6.70–10.15 $kg/(m^2{\cdot}s)$ or 24–37 $m^3/(m^2{\cdot}h)$.

The volumetric heat transfer coefficient of air can be found from the Lewis relationship:

$$\alpha_V = c_{PG}\, \beta_{Vx}, \tag{2}$$

where α_V is the volumetric heat transfer coefficient, $W/(m^3{\cdot}K)$; c_{PG} is a specific mass heat capacity of air, J/(kg·K).

The cooling capacity of the contact devices in the cooling towers is determined from the Merkel equation:

$$Me = \frac{\beta_{Vx} h}{q_L} = \frac{\Delta t\, c_L}{K \Delta I_{cp}} \approx A h \left(\frac{G_m}{L_m} \right)^n, \tag{3}$$

where h is filler height, m; Δt is a temperature drop of water, °C; c_L is specific mass heat capacity of water, J/(kg·K); ΔI_{cp} is mean enthalpy difference, J/kg; A is an empirically determined coefficient, characterizing the cooling capacity of the filler unit of the cooling tower; n is a power index, characterizing the dependence of the volumetric mass transfer coefficient on the specific flow rate of gas.

The mean enthalpy difference was determined using the integration rule by the formula:

$$\Delta I_{cp} = \frac{t_{L0} - t_{Lk}}{\int_{t_{Lk}}^{t_{L0}} \frac{dt}{I_s - I}}, \qquad (4)$$

where I_s is saturated air enthalpy; I is air enthalpy.

From the processing of experimental data, the dependence of the volumetric heat transfer coefficient on the mean-flow air velocity was determined (Figure 2). This graph shows that the mean-flow velocity of the gas phase increases in direct proportion to the rise in the volumetric heat transfer coefficient. It should be mentioned that with increasing the wetting density, the volumetric heat transfer coefficients also increase at the same mean-flow air velocity. For example, at the mean-flow air velocity of 1.95 m/s, an increase in the wetting density from 3.25 to 6.70 kg/(m^2·s) results in the volumetric heat transfer coefficient growing by 11 %.

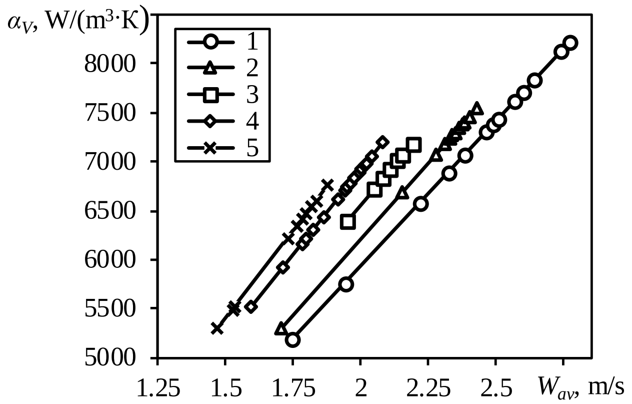

Fig. 2. Dependence of the volumetric heat transfer coefficient on the mean-flow velocity at the different wetting densities q_L, kg/(m^2·s): 1 – 3.25; 2 – 4.97; 3 – 6.70; 4 – 8.42; 5 – 10.15.

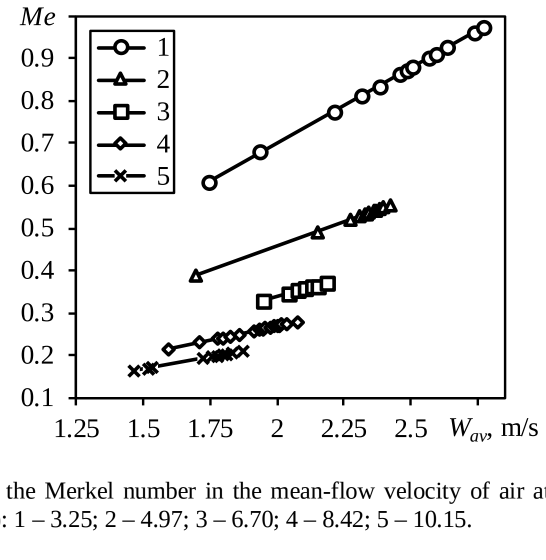

Fig. 3. Dependence of the Merkel number in the mean-flow velocity of air at the different wetting densities q_L, kg/(m^2·s): 1 – 3.25; 2 – 4.97; 3 – 6.70; 4 – 8.42; 5 – 10.15.

Figure 3 shows the experimental results in terms of the Merkel number of the developed filler unit of the cooling tower, obtained by equation (3). It has been found that the highest cooling capacity of the inclined-corrugated elements with the advanced contact surface occurs at low wetting densities. This can be explained by the fact that, at the low flow rate of liquid, there is a higher contact of gas-liquid flows with the minimum number of dead zones. Moreover, the developed design of the contact elements provides a uniform distribution of liquid in the cross-section of the apparatus.

Besides, as the wetting density increases, the critical velocity of gas decreases. This velocity characterizes the initiation of the entrainment of liquid droplets from the internal devices of the cooling tower. However, in the developed filler unit of the cooling tower, the critical gas velocity reaches 2.2 m/s at the wetting density of 24 $m^3/(m^2 \cdot h)$.

A comparative analysis of the cooling capacity of the developed filler unit in the cooling tower with existing analogs showed its superiority. So, at the height of the filler unit equal to 1 m, the wetting density q_L = 2.5 $kg/(m^2)$, and the mean-flow air velocity W_{av} = 1.35 m/s, the Merkel number is 1.6. Under the same conditions, for the wavy asbestos-cement sheets Me equals 0.61, for the polyethylene corrugated sheets – 0.38, for the jet-film contact devices – 1.15 [20]. This proves that the developed inclined-corrugated contact elements have a high specific contact surface of the phases and, as a result, high cooling capacity.

4 Conclusion

The findings of the study showed high values of the heat transfer coefficients in the developed filler unit of the cooling tower. So, there is an intensification of heat and mass transfer processes due to the magnification in the phase contact surface using the metal mesh filling. Thus, the developed design of the inclined-corrugated contact element with the advanced phase surface has a high cooling capacity at low-pressure losses. Also, using the closed-circuit for cooling industrial water can exclude or significantly reduce the number of chemicals added to the water recirculation system.

The reported study was funded by the grant of the President of the Russian Federation, project number MK–417.2019.8.

References

1. A. Bahadori, in *Essentials Oil Gas Util.* (Elsevier, 2016), pp. 159–192
2. A. G. Laptev, V. A. Danilov, and I. V. Vishnyakova, Therm. Eng. **51**, 661 (2004)
3. S. P. Fisenko, A. A. Brin, and A. I. Petruchik, Int. J. Heat Mass Transf. **47**, 165 (2004)
4. A. Golovanchikov, N. Merentsov, and V. Balashov, Chem. Pet. Eng. **48**, 595 (2013)
5. M. Rahmati, S. R. Alavi, and M. R. Tavakoli, Int. J. Refrig. **88**, 229 (2018)
6. P. Shahali, M. Rahmati, S. R. Alavi, and A. Sedaghat, Int. J. Refrig. **65**, 80 (2016)
7. M. Lemouari, M. Boumaza, and A. Kaabi, Energy Convers. Manag. **50**, 1610 (2009)
8. N. Merentsov, V. Balashov, D. Bunin, V. Lebedev, A. Persidskiy, and M. Topilin, MATEC Web Conf. **243**, 00011 (2018)
9. N. A. Merentsov, V. N. Lebedev, A. B. Golovanchikov, V. A. Balashov, and E. E. Nefed'eva, in *IOP Conf. Ser. Earth Environ. Sci.* (2018), p. 12017
10. E. S. Mohammed, Q. K. Jasim, and M. W. Kanbar, Adv. Nat. Appl. Sci. **11**, 36 (2017)
11. T. S. Rao, in *Miner. Scales Depos.* (Elsevier, 2015), pp. 123–140
12. H.-C. Flemming, Appl. Microbiol. Biotechnol. **59**, 629 (2002)

13. M. Al-Bloushi, J. Saththasivam, S. Al-Sayeghc, S. Jeong, K. C. Ng, G. L. Amy, and T. O. Leiknes, J. Ind. Eng. Chem. **59**, 127 (2018)
14. I. S. M. Pinel, D. H. Moed, J. S. Vrouwenvelder, and M. C. M. van Loosdrecht, Water Res. **172**, 115505 (2020)
15. K. D. Demadis, E. Mavredaki, A. Stathoulopoulou, E. Neofotistou, and C. Mantzaridis, Desalination **213**, 38 (2007)
16. W. K. Dodds and M. R. Whiles, in *Freshw. Ecol*. (Elsevier, 2020), pp. 453–502
17. I. N. Madyshev, A. V. Dmitriev, and A. I. Khafizova, in 2019 *Int. Multi-Conference Ind. Eng. Mod. Technol.* (IEEE, 2019), pp. 1–4
18. I. N. Madyshev, A. I. Khafizova, and O. S. Dmitrieva, E3S Web Conf. **126**, 00031 (2019)
19. I. N. Madyshev, O. S. Dmitrieva, and A. V. Dmitriev, MATEC Web Conf. **194**, 1013 (2018)
20. A. V. Dmitriev, I. N. Madyshev, and O. S. Dmitrieva, Ecol. Ind. Russ. **24**, 4 (2020)