

Investigation of cooling temperature heterogeneity in evaporative cooling towers [†]

Ayrat Badriev*

Kazan Federal University, Kazan 420008, Russia;

* Correspondence: AlBadriev@gmail.com;

† Presented at the 4th International Electronic Conference on Applied Sciences (Online), 27 Oct–10 Nov 2023

Abstract: In this paper, we consider the analysis of temperature area heterogeneity in evaporative cooling towers of various types. An experimental study of cooling heterogeneity in several cooling towers has been carried out. Cooled water temperature distribution histograms were plotted and degrees of heterogeneity were established. It was found that each evaporative cooling tower has an individual degree of water - cooling heterogeneity under practically equal operating and environmental conditions. The effect of the water - cooling heterogeneity degree on the evaporative capacity of cooling towers has been analyzed. The analysis of the causes of heterogeneity in the process of water cooling has been carried out. It has been revealed that temperature heterogeneities occur due to the cooling tower design features, its location on the ground, and the distribution of water and airflows inside the device. Measures to reduce temperature heterogeneity of cooling in evaporative cooling towers are proposed.

Keywords: evaporative cooling towers; heterogeneity; temperature distribution

1. Introduction

In thermal and nuclear power plants, evaporative cooling towers are most commonly used for cooling circulating water. According to the construction and commissioning of cooling installations data, today about 40 % of thermal and nuclear power plants all over the world use and implement evaporative cooling towers. This is primarily due to the fact that cooling towers, in comparison with other cooling methods, such as cooling by means of a reservoir or splash pool, eliminate water pollution and occupy much less production area.

Cooling towers are considered to be the main equipment of the recycled water supply system, because they perform one of the main tasks of cooling the turbine condensers, the efficiency of which determines the performance of the power plant as a whole. A vivid example in the production, when the water temperature rises by 34 °F at the cooling tower outlet, the steam turbine output decreases by 0.4 % on average [1]. Therefore, maintaining the standard recycled water temperature in plants is often a critical issue.

Another feature of evaporative cooling towers is their large size. The huge size is necessary to cool large volumes of recycled water with air drawn inside the tower by natural draft or with the help of fan. The hydraulic load per cooling tower can range from 8,500 to 30,000 t/h, and the biggest cooling towers reach heights of up to 202 meters with diameters of up to 142 meters [4, 12]. However, the feature in the form of large size can pose a problem in cooling towers. Studies by scientists show that large apparatuses are characterized by flow heterogeneities [2]. Therefore, we wonder whether process heterogeneities can originate in large - size evaporative cooling towers? How do they affect the cooling efficiency of the installation? The scientific novelty of this work is the experimental determination of the degree of process heterogeneity and its effect on the cross-sectional cooling capacity in a comparison of several evaporative cooling towers.

Citation: To be added by editorial staff during production.

Academic Editor: Simeone Chianese

Published: date



Copyright: © 2023 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

2. Previous studies

Considering installations that are characterized by their large size of different industries branches, it can be said that they have in common the property of non - uniformity processes. For example, studies of liquid distribution in a distillation column [5,6] demonstrate significant flow irregularities and their significant impact on column efficiency. Similar results have been obtained, among others, by scientists who have devoted their research to the peculiarities of scale transition in the development of apparatuses in the chemical industry [2, 3]. From the point of view of mathematical modeling, the authors' research [9] are interesting, the results of which were the detection of irregularity in heat and mass transfer apparatuses and mathematical proof of the two - phase flows non - uniformity influence on the efficiency of heat and mass transfer.

The results of the research on non - uniformity of flows in large - sized apparatuses should be taken into account, but cannot be strictly attributed to evaporative cooling towers in spite of the fact that they belong to heat and mass transfer apparatuses. The reason for this is the design features of cooling towers, their modes of operation as well as their operating conditions. Since the main process in evaporative cooling towers is heat and mass transfer, the efficiency of which depends on the density of contact between the two phases, namely water and air, it is appropriate to consider the works that are devoted to the study of non - uniformity of air and water flows.

Considering evaporative cooling towers in cross - section, the air distribution in evaporative cooling towers occurs below the filler and above the filler. Studies show that the airflow distributions in both spaces are dissimilar. Due to the aerodynamic drag occurrence in the filler, the flow velocities at the outlet are equalized, hence above the filler the air velocities are almost uniform. However, the air behavior at the cooling tower inlet below the filler is quite different. Studies [7] show that from the periphery to the center of the cooling tower, the air velocities are non - uniform. Hence, the researchers conclude that the draft in the cooling tower is also non - uniform, and hence the cooling efficiency of the unit has decreased. Based on the research results, the following authors propose to layout the filler in such a way to reduce the non - uniformities [8].

Research on the evaporation process efficiency improving in cooling towers by means of airflow swirling deserves special attention [10]. Scientists conducted an interesting experiment, which consists in feeding smoke to the cooling tower inlet, which allowed visualizing the airflow in the apparatus. As a result, irregularities in the vertical and radial direction were found. The authors proposed to reduce the irregularities by using special duct baffles. Chinese scientists [11] have also conducted similar studies. The experiments were conducted on a laboratory model of a cooling tower. The results also demonstrate the phenomenon of non - uniformity of air at the cooling tower inlet. The effect of wind baffles under wind - induced conditions has also been investigated in studies [13, 14], and the results show the occurrence of air non - uniformity in cooling towers.

Along with the development of airflow non - uniformities, irregularities of water irrigation can also occur. Since the water irrigation mainly depends on the operation of water distribution system, there are different approaches to scientific works taking into account the non - uniformity of its local or general irrigation. For example, the authors investigate the development of local non - uniformity of a single nozzle along the radius and circumference, and a coefficient to estimate the degree of non - uniformity is introduced [15]. Other scientists believe that estimation by a single nozzle will lead to large calculations and propose to estimate the group nozzles operation irrigation irregularities, using assumptions in calculations. There are also approaches for estimation of water irrigation non - uniformity according to the length of the main pipeline [16], as well as the scientists who investigated irregularities using CFD modeling of hydrodynamics, which require complex preparatory stages before calculations [17, 18].

Analyzing the studies in the field of water and air distribution non - uniformity, it is worth noting that the flow non - uniformities are of heterogeneous nature and depend on many internal and external factors, which certainly affects the cooling efficiency of

evaporative cooling towers. Therefore, we decided to do research in evaluating the effect of flow non - uniformity on the temperature distribution of cooling water in evaporative cooling towers.

The analysis of known works allowed us to determine the research directions devoted to the non-uniformity of water and air flows, which are presented in Table 1.

Table 1. Research directions of non-uniformity of water and air flows.

Air distribution non - uniformity	Water distribution non - uniformity
Analyzing the effect on tower thrust	Analyzing the impact of nozzle distribution
Analysis of the influence of the filler layout	Pipeline distribution impact analysis
Analyzing the influence of wind at the tower inlet	CFD analysis of the influence of radial distribution
Analyzing the effect of air on a laboratory model	CFD analysis of the impact of nozzle distribution

3. Materials and Methods

Three tower - type evaporative cooling towers with irrigation areas of 1600, 2600, and 3200 m² were chosen as the objects of the study. Water and air flow non - uniformities have been previously found in them [19, 20]. The cooling towers are monolithic natural draft towers that are equipped with a polymer filler. Experimental investigations of the cooling tower with an irrigation area of 1600 m² showed that the degree of air distribution non - uniformity was 28.4 % with an average air velocity of 3.75 m/s, and the non - uniformity of water irrigation was 15 % with an average hydraulic load of 6.8 m/hr. The air distribution non - uniformity of the 2600 m² cooling tower was 20.8 % and the water irrigation non - uniformity was 33 % with an average of 3.41 m/h. Finally, the air distribution non - uniformity of the 3200 m² cooling tower was 37 % with an average air velocity of 4.1 m/s, and the cooling water distribution non - uniformity was 24 % with an average hydraulic load of 7.1 m/h.

The experimental studies of the distribution of the temperature area of cooling water were carried out under the summer mode conditions of installations operations. Measurements of final temperatures of water irrigated in the form of rain were carried out. The measurement points of $\frac{1}{4}$ of the cooling tower cross - sectional area are schematically shown as an example in Figure 1.

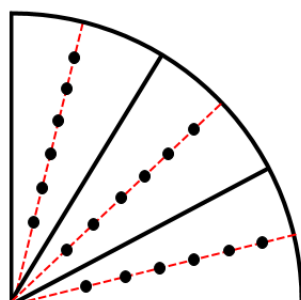


Figure 1. Temperature area measurement points across the cross - section of the cooling tower.

The methodology of the experiments was as follows: using a telescopic tube, at the end of which a measuring vessel was fixed, the filling of the vessel with water was recorded. The water temperature was measured in real time using a temperature sensor with a remote display. In order to eliminate random errors, parallel experiments were performed 4 times and the temperature readings were averaged. During the experiment, the measurement error amounted to 2.5 %, considering that the error of the measurement device according to the passport was ± 0.05 %.

Further, it was decided to evaluate the obtained data set for the results reproducibility. The experimental data were checked using the Cochran's criterion. As a result of processing, the calculated value of Cochran's criterion was $G_c = 0.136$. Comparing the result with the tabulated value of $G_{cr} = 0,326$ at a confidence interval of 0.95, it should be concluded that $G_c < G_{cr}$. This means that the condition according to the Cochran criterion is fulfilled, and we can consider the data reproducible.

4. Results and Discussion

The experimental data obtained from each evaporative cooling tower were processed and normalized to average values. The results are presented as histograms of the distribution for each cooling tower section.

Processing of the temperature area statistics over the CT - 1600 cooling tower section showed that the standard deviation was 4.67 °F from the average value of 47.64 °F. Consequently, the irregularities in the water and airflows resulted in a non - uniform inlet and outlet temperature difference distribution of 9.8 %. Figure 2 shows a histogram of the distribution of water temperature differences.

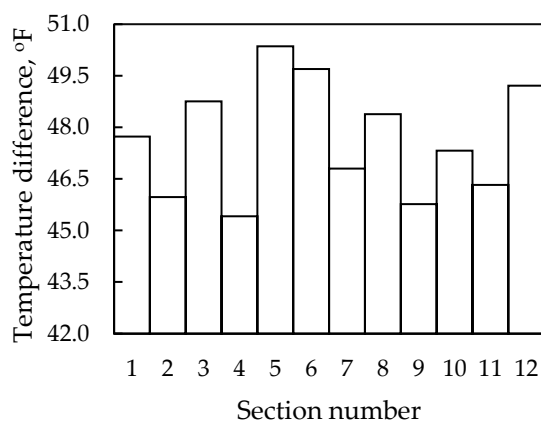


Figure 2. Temperature area distribution across the cross - section of an evaporating cooling tower with an irrigation area of 1600 m².

Figure 3 shows the temperature difference distribution of the CT - 2600 cooling tower. According to the statistical the data processing, the value of the cooling temperature readings was 50.46 °F and its standard deviation was 5.25 °F, which corresponds to 10.4 % non - uniformity from the average value.

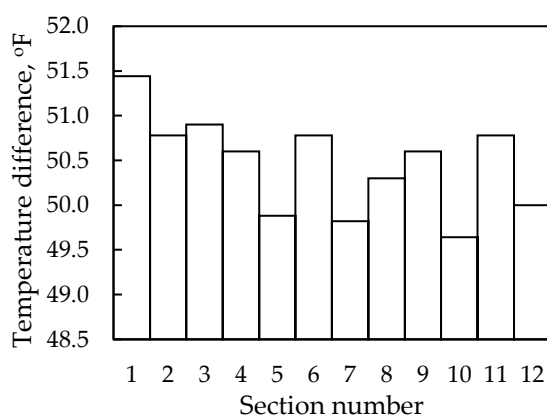


Figure 3. Temperature area distribution across the cross - section of an evaporating cooling tower with an irrigation area of 2600 m².

The following Figure 4 shows the distribution of the CT - 3200 evaporative cooling tower cooled water temperature differentials. In this case, static processing showed that the average of the temperature area distribution was 46.97 °F and the standard deviation was 5.64 °F, indicating a degree of non - uniformity of 12 % of the average value.

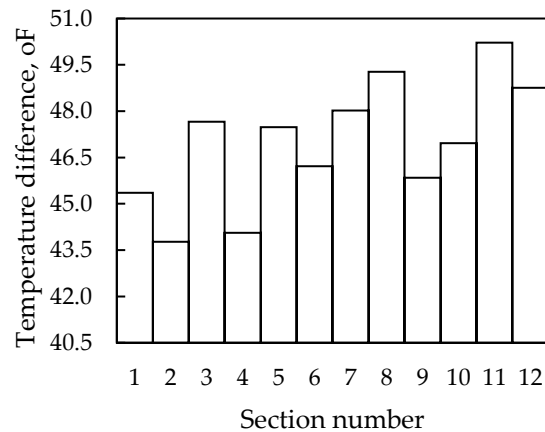


Figure 4. Temperature area distribution across the cross - section of an evaporating cooling tower with an irrigation area of 3200 m².

The results of studies of the heterogeneity of the water-cooling process in evaporative cooling towers demonstrate significant non-uniformity of the temperature field distribution, which is a consequence of the occurrence of non-uniformity of water and air flows. Compared to other studies of flow non-uniformity in localized zones, the new results suggest a complex non-uniformity of cooling temperature distribution in the cross-section of evaporative cooling towers.

5. Conclusion

The results of an experimental study to evaluate the temperature area distribution by the cross section of evaporating cooling towers demonstrate that non - uniformities in water and airflows result in heterogeneity water - cooling. Moreover, each evaporating tower has an individual degree of heterogeneity. Experiments show that the increase in the non - uniformity of water and airflows leads to non - uniform temperature dispersion, and thus to a decrease in cooling efficiency. The analysis of the temperature area heterogeneities shows that the main reasons for its occurrence are the design features of the installations. The water and airflows non - uniformities can arise due to poor operation of water distribution system, poor regulation of duct windows, fillers state and other elements, as well as due to location of neighboring cooling towers. Based on the findings, the measures are developed to reduce heterogeneities in evaporative cooling towers.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Ponomarenko V.S., Arefiev Yu.I. Cooling towers of industrial and power enterprises: reference manual. Publisher: Energoatomizdat, Russia, 1998; 376 p.
2. Rosen A. M. Martyushin E.I., Olevsky V.M. Scale transition in chemical technology: development of industrial apparatuses by the method of hydrodynamic modeling. Publisher: Chemistry, Russia, 1980; 320 p.
3. Timonin A.S., Baldin B.G., Borshev V.Y., Gusev Y.I. Machines and apparatuses of chemical productions: textbook for universities. Publisher: N.F. Bochkareva Publishing House, Russia, 2008; 872 p.
4. Busch D., Harte, R., Kratzig, W. B., Montag, U. New natural draft cooling tower of 200 m of height. Engineering Structures, 2002; Volume 24, № 12, pp. 1509 - 1521. DOI: 10.1016/S0141 - 0296(02)00082 - 2.

5. Pavlenko A.N., Pecherkin N.I., Chekhovich V.Yu., Zhukov V.Yu., Sander S., Hopeton P., Serov A.F., Nazarov A.D. Mixture separation and liquid distribution on a structured nozzle in a large - scale model of a distillation column. *Theoretical Foundations of Chemical Technology*, 2006; Volume 40, № 4, pp. 355 - 365.
6. Pavlenko A.N., Pecherkin N.I., Chekhovich V.Yu., Zhukov V.Yu., Sander S., Hopeton P. Experimental study of the influence of irregularity of irrigation at the inlet of a structured nozzle on the separation efficiency of a freon mixture. *Theoretical Foundations of Chemical Technology*, 2009; Volume 43, № 1, pp. 3 - 13.
7. Nedviga Yu. S., Pilipenko K. V. Field studies of the work of spray nozzles with hydroventilators on the cooling tower № 5 of CHPP - 22 of "MOSENERGO". *Izvestiya VNIIG im. B.E. Vedeneev*, 2000; Volume 236, pp. 248 - 253.
8. Pushnov A. S., Ryabushenko A. C. Composition of cooling tower sprinkler taking into account non - uniformity of air flow velocity field. *Teploenergetika*, 2016; № 7, pp. 74 - 79.
9. Bratuta E. G., Ganja A. N., Borovok S. V. Influence of non - uniformity of discrete phase distribution on heat and mass transfer in disperse flow. *Bulletin of NTU "KHPI": Energy and Heat Engineering Processes and Equipment*, 2004; № 11, pp. 37 - 42.
10. Vlasov A. V., Davidenko V. F., Dashkov G. V., Martynenko O. G., Solodukhin A. D., Stolovich N. N., Tyutyuma V. D.. Intensification of Evaporative Cooling in Tower Cooling Towers with Inlet Air Flows Swirling. *Proceedings of the IV Minsk International Forum*, 2000; Volume 10, pp. 192 - 201.
11. Wang K., Sun, F., Zhao Y., Gao M., Ruan L. Experimental research of the guiding channels effect on the thermal performance of wet cooling towers subjected to crosswinds - Air guiding effect on cooling tower. *Applied Thermal Engineering*, 2010; Volume 30, № 5, pp. 533 - 538. DOI: 10.1016/j.applthermaleng.2009.10.015.
12. Zhao L., Chen H., Hu X., Ge Y. Distribution pattern of fluctuating wind pressures on cooling towers in grouped rectangular arrangement, *Journal of Wind Engineering and Industrial Aerodynamics*, 2022; Volume 224, 104975. DOI: <https://doi.org/10.1016/j.jweia.2022.104975>.
13. Ma H., Si F., Zhu K., Wang J. The adoption of windbreak wall partially rotating to improve thermo - flow performance of natural draft dry cooling tower under crosswind, *International Journal of Thermal Sciences*, 2018; Volume 134, pp. 66 - 88, DOI: <https://doi.org/10.1016/j.ijthermalsci.2018.08.005>.
14. Chen X., Sun F., Li X., Song H., Zheng P., Lyu X., Yan L. Field measurement on the three - dimensional thermal characteristics of a single air inlet induced draft cooling tower, *Applied Thermal Engineering*, 2020; Volume 172, 115167, DOI: <https://doi.org/10.1016/j.applthermaleng.2020.115167>.
15. Dobrego K. V. V. Davydenko V. F., Koznacheev I. A. Use of splashing nozzles for giving rotation to steam - air flow in the supernatant space of a cooling tower. *Engineering and Physics Journal*, 2016; Volume 89, № 1, pp. 148 - 157.
16. Gilfanov K. H., Davletshin F. M., Gilyazov D. R. Increasing the efficiency of water cooling and cooling towers research as a control object: monograph. Publisher: Kazan State Power Engineering University, Russia, 2009; 213 p.
17. Williamson N., Behnia M., Armfield S. Comparison of a 2D axisymmetric CFD model of a natural draft wet cooling tower and a 1D model. *International Journal of Heat and Mass Transfer*, 2008; Volume 51, pp. 2227 - 2236.
18. Zhang G., Zheng Y., Chen Q. Water distribution below a single spray nozzle in a natural draft wet cooling tower. *The 14th IFToMM World Congress*. Taiwan, October 25 - 30, 2015; pp. 582 - 588.
19. Sharifullin V.N., Badriev A.I. Aerodynamic characteristics of the cooling tower under the non - uniform distribution of the water and airflows. *Thermal Engineering*, 2019; Volume 66, pp. 569 - 574. DOI: <https://doi.org/10.1134/S0040601519080081>.
20. Sharifullin V.N., Badriev A.I., Sharifullin A.V. Analysis of influence of irrigation density distribution non - uniformity on the processes in a tower cooling tower. *Problems of Power Engineering*, 2013; № 11 - 12, pp. 24 - 26.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.