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Investigation into Heterogeneity of Cooling Temperature in Evaporative Cooling Towers †

Ayrat Irekovich Badriev

Higher School of Engineering, Kazan Federal University, Kazan 420008, Russia; aibadriev@gmail.com

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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 was 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 on the evaporative capacity of cooling towers was analyzed. An analysis of the causes of heterogeneity in the process of water cooling was carried out. It is revealed that temperature heterogeneities occur due to the cooling tower's 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

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1. Introduction

In thermal and nuclear power plants, evaporative cooling towers are most commonly used for cooling circulating water. According to data for the construction and commissioning of cooling installations, about 40% of thermal and nuclear power plants all over the world today 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. As a vivid example in 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 a 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 a fan. The hydraulic load per cooling tower can range from 8500 to 30,000 t/h, and the biggest cooling towers reach heights of up to 202 m with diameters of up to 142 m [2,3]. However, this 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 [4]. Therefore, we examined 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.

2. Previous Studies

Considering installations that are characterized by their large size in branches of different industries, it can be said that they have in common the property of non–uniform 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 [7]. From the point of view of mathematical modeling, the authors' research [8] is interesting, the results of which were the detection of irregularity in heat and mass transfer apparatuses and mathematical proof of the two-phase flow's non-uniform 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 reasons for this are the design features of cooling towers and 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 [9] 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 decreases. Based on the research results, researchers have proposed to lay out the filler in such a way to reduce the non-uniformities [10].

Research on improving the evaporation process efficiency in cooling towers by means of airflow swirling deserves special attention [11]. Scientists conducted an interesting experiment that consisted of 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 [12] 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 water irrigation mainly depends on the operation of the water distribution system, there have been different approaches to scientific works taking into account the non-uniformity of its local or general irrigation. For example, researchers investigated 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 was introduced [15]. Other scientists believe that estimation using a single nozzle will lead to large calculations and proposed to estimate group nozzles' operational 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 scientists who investigated irregularities using CFD modeling of hydrodynamics, which requires 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 conduct research 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 airflows, and these are presented in Table 1.

Table 1. Research directions of non-uniformity of water and airflows.

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 m^2 were chosen as the objects of this study. Water and airflow 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 m^2 showed that the degree of non-uniformity of air distribution 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/h. The air distribution non-uniformity of the 2600 m^2 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 m^2 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 the cooling water were carried out under the summer mode conditions of installation operations. Measurements of final temperatures of water irrigated in the form of rain were carried out. The measurement points of 1/4 of the cooling tower cross-sectional area are schematically shown as an example in Figure 1.

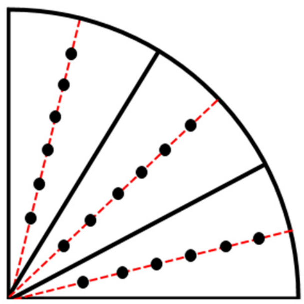

Figure 1. Temperature area measurement points across the cross-section of the cooling tower.

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%.

It was further decided to evaluate the obtained data set for the results' reproducibility. The experimental data were checked using 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 can 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 section of the cooling towers.

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.

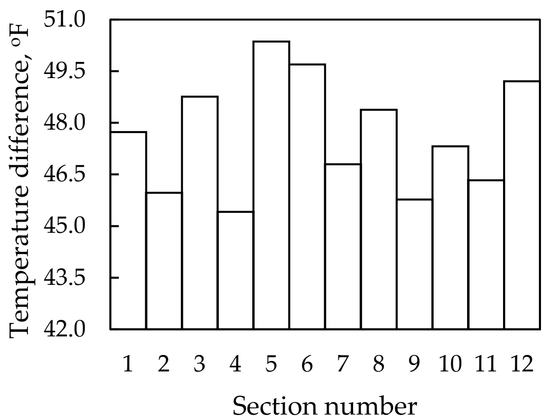

Figure 2. Temperature area distribution across the cross-section of an evaporating cooling tower with an irrigation area of 1600 m^2.

Figure 3 shows the temperature difference distribution of the CT-2600 cooling tower. According to the statistical 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.

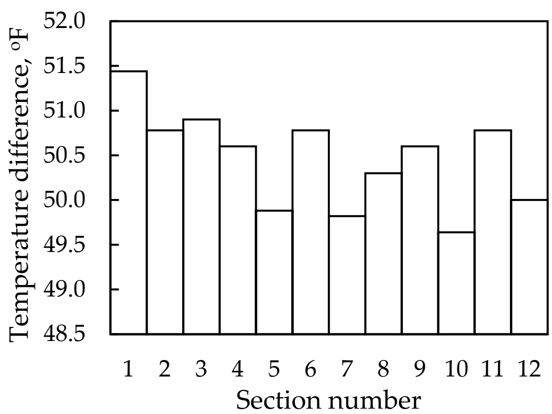

Figure 3. Temperature area distribution across the cross-section of an evaporating cooling tower with an irrigation area of 2600 m^2.

The following Figure 4 shows the distribution of the temperature differentials of the CT-3200 evaporative cooling tower cooled water. 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.

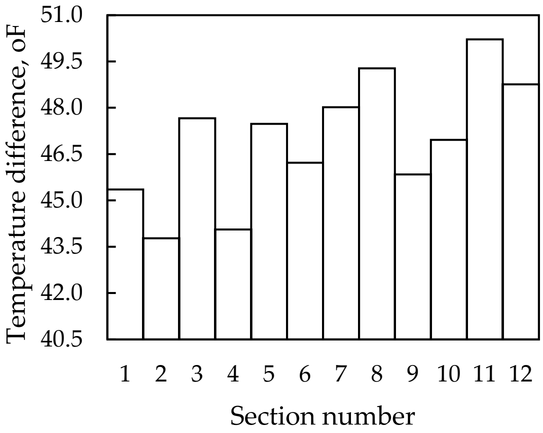

Figure 4. Temperature area distribution across the cross-section of an evaporating cooling tower with an irrigation area of 3200 m^2.

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 airflows. Compared with other studies of flow non-uniformity in localized zones, the new results suggest a complex non-uniformity of cooling temperature distribution in the cross-sections of evaporative cooling towers.

5. Conclusions

The results of an experimental study to evaluate the temperature area distribution in the cross-sections of evaporating cooling towers demonstrate that non-uniformities in water and airflows result in heterogeneous 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 this occurrence are the design features of the installations. The water and airflows' non-uniformities can arise due to poor operation of the water distribution system, poor regulation of duct windows, the condition of fillers and other elements, as well as due to the location of neighboring cooling towers. Based on these findings, measures should be developed to reduce heterogeneities in evaporative cooling towers.

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