Heat and mass transfer in unit of cooling tower filler with advanced gas-liquid contact surface

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Abstract. On a global scale, many cooling towers and contact elements occur in a variety of types. In this paper, a new design of the tower with the technology of contactless evaporation cooling has been presented. Experimental studies of the efficiency of heat and mass transfer processes in the inclined-corrugated element with the advanced gas-liquid contact surface as metal mesh were performed. Results of the change in the efficiency of heat and mass transfer processes from various gas velocity and the ratio of mass flow ratio of liquid and gas phases were reported. Comparative analysis of the influence of specific surface of phase contact on the efficiency of cooling circulating water was carried out. It was found that the use of additional contact surface of the phases allows increasing the efficiency of thermal and mass transfer on average of 44.8% and 54.2%, respectively. The mean-flow air velocity without entrainment of liquid from the apparatus reaches 2.7 m/s.

1. Introduction

Cooling of circulating water is an essential process in various industrial systems (power industry, chemical and petrochemical industries, and others). Currently, cooling towers are most often used in this process; for example, an evaporative forced-draft cooling tower compares favorably with its compactness and high cooling efficiency [1–3]. Year after year, the number of cooling towers is growing, because new and modernized designs of cooling elements (fillers) are being developed. Fillers are subject to many requirements, such as high cooling efficiency of recycling water, low energy costs for the process, ease of manufacture and assembly, the low metal consumption of the design, reliability, and extended life cycle [4–7].

Also, cooling in mechanical-draft towers is caused by evaporation of water when direct contact of liquid and air occurs. Thus, there is a need for a constant supply of water from natural sources. Therefore, cooling towers have a good environment for microorganisms: a presence of oxygen, organic substances, and minerals dissolved in water, and temperature conditions. This fact leads to the biofouling of the cooling tower elements and attendant changing the flow patterns, and may adversely affect the throughput capacity of the apparatuses. The result is a decrease in heat transfer and an increase in hydraulic resistance. Besides, biological fouling causes the initiation of corrosion of the metal elements of the device with its further destruction.
Moreover, biological fouling has adverse impacts on the environment due to the emergence and spread of pathogenic bacteria in the air during the evaporation of liquid [8–11], which is a severe problem for industrial enterprises. So, increasing the cooling efficiency of the circulating tower through solving the problem of biological contamination of water and devices themselves is a pressing issue [12–16]. Generally, it is possible to prevent biological fouling by using chemicals, but in this case, there is a negative impact on the environment. Also, the purchase of reagents is not economically feasible. In addition, it is well known that when chemicals are used for a long time, some microorganisms can adapt to them and proceed to grow. Therefore, we aim to develop the new design of the cooling tower so that the cooling of circulating water can be quite effective, and the use of chemicals can be significantly decreased [17–19].

To solve the proposed problem, in this paper, we developed a cooling tower that operates based on contactless evaporative cooling technology. This technology provides a significant reduction in the use of chemicals or abandonment of use at all. In our previous investigations [20–22], the results of using the inclined corrugated plates for liquid cooling were reported. In order to extend the study of the proposed filler of the cooling tower, new physical experiments are performed with an intensification of the processes occurring in the developed design.

The purpose of this paper is to study the processes of heat and mass transfer in the unit of the cooling tower filler with the advanced gas-liquid contact surface.

2. Materials and methods
The filling unit consists of two contact stages with a total height of 340 mm. The contact stage is 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 is executed on the side surfaces and the upper part of corrugations. The sizes of the investigated apparatus in the cross-section are 100x100 mm.

The experimental setup is depicted in figure 1. Air-water system was tested. Water was supplied through a distributing device from above to the central part of the first contact stage. The mean-flow velocity of cooling air per the total cross-section of the contact device changed from 1.47 to 2.77 m/s; the wetting density was equal to 12–37 m³/(m²·h); temperatures varied in the range of 30.8–32.8 °C (air) and 35.1–41.9 °C (water). The relative air humidity in the course of the experiments ranged between 32 and 36.1 %. Measurements of the temperature and relative humidity at the inlet of the apparatus were taken by a thermohygrometer (TESTO 605i). The water temperature was measured at the inlet-outlet of the apparatus with a two-channel meter-regulator (OWEN 2TRM1). The liquid flow rate was measured by a rotameter, the air velocity – by a thermal anemometer (TESTO 405i) with relative accuracy not higher than 5%.

Efficiency of the heat-and-mass transfer apparatus design with the inclined-corrugated plates for cooling the circulating liquid was evaluated through the thermal efficiency and mass transfer efficiency during water evaporation.

We characterize the thermal efficiency of the cooling tower by means of the dimensionless parameter \( \eta_L \):

\[
\eta_L = \frac{t_{L0} - t_{L}}{t_{L0} - t_{T}}.
\]

(1)

where \( t_{L0} \) is the temperature of hot water entering into the cooling tower, °C; \( t_{L} \) is the temperature of the cooled water in the pond of the cooling tower, °C; \( t_{T} \) is the equilibrium water temperature (wet-bulb temperature), °C.

The mass transfer efficiency of the heat and mass transfer apparatus is determined as [23]:

\[
E = \frac{x_{f} - x_{0}}{x' - x_{0}}.
\]

(2)
where \(x_0, x_f\) are the moisture content of the saturated air at the inlet and outlet of the cooling tower, respectively, kg/kg; \(x^*\) is the equilibrium moisture content of the saturated air, kg/kg.

![Figure 1. The experimental setup: 1 – heat and mass transfer apparatus; 2 – casing; 3 – inclined corrugated contact elements; 4 – pump; 5 – tank; 6 – funnel; 7 – liquid filter; 8 – shutoff valves on the water supply line; 9 – camera; 10 – fan; 11 – heating element; 12 – shutoff valves in the air supply line.](image)

3. Results and discussion
From an analysis of the experimental results, the dependencies of the thermal efficiency against various parameters in graphical form were obtained (figure 2).

![Figure 2. Dependences of the thermal efficiency on the mean-flow gas velocity (a) ratio of mass flow ratio of liquid and gas phases (b) at different wetting densities \(q\), m\(^3\)/(m\(^2\)-h): 1 – 12; 2 – 18; 3 – 24; 4 – 31; 5 – 37.](image)
It has been found that the thermal efficiency of the cooling tower with inclined-corrugated contact elements may reach 51%, which is a high value compared to the existing analogs used today in industrial enterprises. The use of this design has excellent efficiency at high gas velocities. The fact is that when the wetting density increases, the liquid occupies an increasing volume of the contact element, capturing the surface of the mesh metal fill. So, in this case, gas needs more velocity to pass through the layer of liquid. Also, the bubbling of liquid in the space of the filling unit occurs as the mean-flow gas velocity increases.

The efficiency of heat and mass transfer processes is shown graphically in figure 3. From the obtained dependences, we notice that the maximum efficiency of heat and mass transfer processes may attain 100%, and its average values are in the range from 70 to 80%.

Using the mesh metal fill in the design of the contact device has a strong influence on the efficiency of the filling unit. It can be seen more clearly in the graphs shown in figure 4.

![Graph 3](image3.png)

**Figure 3.** Dependences of the mass transfer efficiency on the mean-flow gas velocity (a) ratio of mass flow ratio of liquid and gas phases (b) at different wetting densities \( q, m^3/(m^2\cdot h) \): 1 – 12; 2 – 24; 3 – 37.

![Graph 4](image4.png)

**Figure 4.** Change in the thermal efficiency (a) and the mass transfer efficiency (b) vs. the ratio of mass flow ratio of liquid and gas phases at different wetting densities \( q, m^3/(m^2\cdot h) \): 1 – 12; 2 – 24; 3 – 37 (dashed/solid lines – with/without advanced contact surface as metal mesh).
Comparative graphs indicate that the efficiency of heat and mass transfer has increased significantly. It should be noted that the highest increase in efficiency of heat and mass transfer processes is observed at relatively low wetting densities of 12–24 m$^3$/(m$^2$·h), compared with the previous studies on the contact device without the advanced surface.

4. Conclusions
The unit design of the cooling tower filler with the technology of contactless evaporation cooling has been modernized. Experimental studies of the efficiency of heat and mass transfer processes in the inclined-corrugated element with the advanced gas-liquid contact surface as metal mesh were performed. It was found that the use of additional contact surface of the phases allows increasing the efficiency of thermal and mass transfer on average of 44.8% and 54.2%, respectively. The mean-flow air velocity without entrainment of liquid from the apparatus reaches 2.7 m/s. Thus, the use of the developed device with the advanced phase contact surface provides cooling of liquid with high heat and mass transfer efficiency.

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