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Jet-film contact devices for heat and mass transfer processes in heat power engineering

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Abstract. One of the main production processes for many branches of industry is cooling of recycled\circulating water, which takes place in the cooling towers. The most important parameter to determine the cooling efficiency of water in the cooling tower is the contact surface of air and water. The existing designs of contact devices are highly effective in cooling the liquid, but they are complex to manufacture and expensive. In this regard, a new design of the jet-film contact device was developed, which allows creating a highly developed contact surface of liquid and gas phases. Mathematical model of the element of jet-film contact device was built by means of specialized software package and numerical calculations were carried out. Paper includes the study of behaviour of liquid and gas phases in the device element, and the mathematical dependences were obtained. Dependency of the liquid entrainment from device when changing the water flow rate was studied. Also, the comparison of designs with different location of holes within the wall elements was also carried out. Modernization of the studied jet-film contact device was carried out in order to identify the direction which to follow for improvement of design properties. This paper proposes an engineering method for calculating the jet-film contact device.

1. Introduction

In the recent years, water reserves have been sharply reduced due to the fact that people cannot rationally use the useful resources. For example, the developed countries spend a huge amount of water for the industrial needs, and the used water from these enterprises is returned back into natural reservoirs, that causes irreparable harm to the environment. In this regard, energy, chemical, petrochemical and many other industries use the recycled water for water cooling. This is due to the fact that the removal of low-temperature industrial waste heat by circulating water allows to reduce the consumption of fresh water and thermal emissions into the environment by several times [1–3].

Circulating water is cooled in cooling towers. The most common type is a fan evaporative cooling tower, which has high cooling efficiency and small dimensions. However, such cooling towers are much more expensive, and the most part of costs is required for the cooling tower fillers. Manufacture of them is very cost-intensive, as well as replacement with new ones. In this regard, there is a need to reconstruct the known devices or develop new designs [4–8].

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The most important parameter to determine the water cooling efficiency in the cooling tower is the contact surface of air and water. Designs of contact devices, developed in the recent years, have high efficiency in cooling the liquid, but the manufacture of many of them is expensive and quite complex. Also, many elements have to be replaced with new ones in case of large biological deposits on the device [9–12].

As of today the main task is to develop new high-performance contact devices that will meet all the above requirements, as well as have a large contact area of the liquid and gas phase, good throughput capacity and low hydraulic resistance [13–23].

The authors of this paper created a contact device, which has a high efficiency of heat and mass transfer, and its hydraulic resistance is not inferior to analogues [24–30].

2. Results of studies and discussion of them

The studied device is a stage of a square shape with width of 100 mm and vertical walls of 50 mm high, chequerwise arranged. Distance between the rows of neighboring stages is 25 mm. Geometrical parameters of each element are selected in such a way that the air movement acquires a circular profile. The upper part of the trays is open, there are holes in the lower part. 8 holes with a diameter of 5 mm were executed in the lower part of the walls of each drain cup. Distance from the center of holes to the bottom of drain cup is 2.5 mm. Holes with a diameter of 10 mm were executed within the bottom, which were located in the center of the drain cup.

When conducting experimental studies with two-phase flows, it is almost impossible to observe the processes, taking place in the inner part of the contact element. Reliable data can be obtained only at the input and output of the device, as when introduced into the working area of the measuring devices, they introduce disturbances and distort the flow structure. In this regard, in order to identify the features of interaction between the gas and liquid phases, numerical simulation is used.

In order to calculate the processes, taking place in the element of the device, the ANSYS Fluent software package (figure 1), the liquid volume method (VOF) were used, allowing to take into account the interaction of two immiscible phases. The studied module was divided into 130690 cells. There are 48644 cells at the interface with solid walls. It should be noted that the previous calculations showed satisfactory convergence of the results of modeling and experimental studies. In the course of calculation, the boundary conditions were set by water and air pressures. Air pressure in the lower part of the device was set equal to 101425 Pa, and in the upper part – 101325 Pa. The unsteady issue was being resolved. After 0.9 seconds a quasi-stationary mode was detected, so the calculation was stopped.

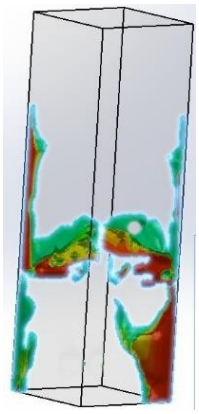


Figure 1. Numerical simulation of liquid and gas phase interaction in the device element.

A recess was executed in the upper drain cup, which had the shape of a circle quarter with a radius of 5 mm and size of 0.1 mm. The water pressure was set equal to 101800 Pa, that corresponded to the level of liquid in the drain cup of 48.57 mm. Calculations were carried out at the temperature of air and water of 20°C.

In the course of numerical calculation of the contact element, the liquid level in the drain cups was changed. Changing the liquid level, the dependency of the liquid flow rate out of the hole on the maximum average air flow rate (figure 2) was observed.

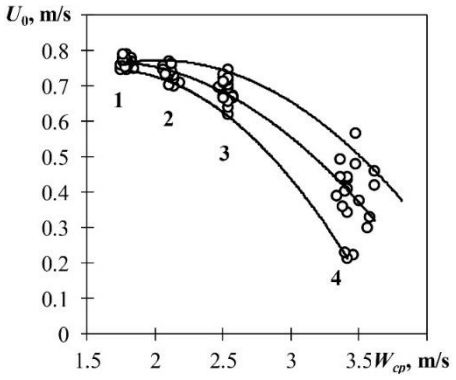


Figure 2. Dependency of the liquid flow rate out of the hole on average air flow rate at different levels of liquid in the trays *h*, m: 1 – 0.0051; 2– 0.0071; 3 – 0.0101; 4 – 0.0204.

The graph shows that with an increase of the liquid level, the limit value of the average air flow rate also increases, which can be set provided that the liquid will not be entrained. It should also be noted that the low liquid flow rates out of the hole correspond to high average air flow rate, otherwise, there is a large percentage of liquid entrainment. Mathematical dependency was obtained by approximation method for this process:

$$U_0 = -0.1126W_{cp}^2 + 0.3647W_{cp} + 0.4753, \quad (1)$$

where U_0 – liquid flow rate out of the hole, m/s; W_{cp} – average air flow rate, m/s.

Equation (1) is an equation of a quadratic polynomial, where the value of the approximation reliability is 0.8954. This equation allows to determine the average air flow rate, at which there is a complete liquid entrainment, its value is equal to 4.2 m/s.

It was also found that the device operates quite effectively at the air flow rate of 3.2 m/s (figure 3), that is a quite high value. This shows a large throughput capacity of the device.

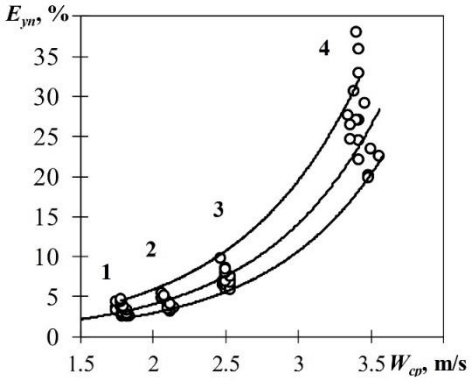


Figure 3. Changing of the entrained liquid amount if the average air flow rate is also changed at different levels of liquid in the trays *h*, m: 1 - 0.0051; 2 - 0.0071; 3-0.0101; 4 - 0.0204.

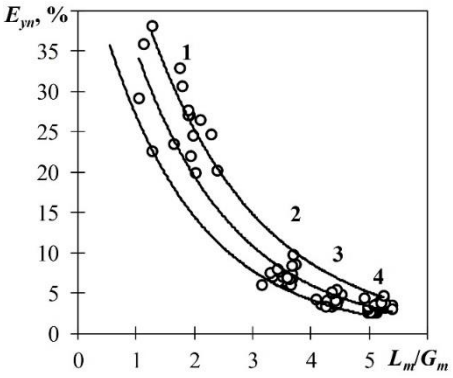


Figure 4. Dependency of the water entrainment on ration of mass water flow rate and mass air flow rate at different levels of liquid in the trays h, m: 1-0.0051; 2 - 0.0071; 3 - 0.0101; 4 - 0.0204.

Dependency of the entrained liquid amount on the average flow rate can be recorded as follows:

$$E_{yn} = 0.3319e^{1.2502W_{cp}}. \quad (2)$$

Then, the ration of mass flow rates of liquid and gas can be set, based on the mathematical balance (figure 4).

The graph in figure 4 shows that with an increase of the mass water flow rate in relation to the mass air flow rate, there is a decrease of the water entrainment.

Water entrainment from the device is not significant, this is due to the fact that the upper stages of the contact device prevent the entrainment of liquid drops, caught into the air stream, that in fact serves as a collector of drops. This is an additional advantage among many other contact devices.

After the ratios of mass flow rates, as well as the maximum average air flow rate are determined, it is possible to determine the cross-sectional area of the apparatus, required not to entrain the liquid by the gained air flow rate and the apparatus will work quite effectively. If the body of the apparatus is already assembled and the cross-sectional area is known, it is possible to determine the maximum air flow rate that can be set.

If we know the liquid flow rate out of the hole (equation (1)), and the mass liquid flow rate is set, it is possible to determine the central diameter of the hole as per the well-known formula:

$$d_0 = \sqrt{\frac{4L_m}{\pi\rho U_0}}. \quad (3)$$

where L_m – mass liquid flow rate, kg/s; ρ – liquid density, kg/m^3.

Thus, this paper introduces an engineering procedure for calculating the jet-film contact device, including the determination of the liquid flow rate out of the hole in the drain cup, average air flow rate, as well as determination of geometrical parameters of the device.

The developed design operates quite effectively, the processes, taking place inside of the device, show that the development of designs of jet-film contact devices is going in a right direction and holes, which had been added within the walls, made a great contribution to operation of device. In this regard, the design can still be finalized.

During the process of design modernization, influence of the holes within the walls of elements on the processes of interaction between two phases, was also studied. These studies were carried out in order to show how the holes affect the movement of flows, as well as to show the direction to follow in order to improve the design.

The next device is a stage of a square shape with width of 100 mm and walls of 50 mm high, chequerwise arranged. Moreover, the walls of the drain cup are arranged so that the bottom of the drain cup passes through the middle of the walls, and the tray has upper and lower walls. Distance between the rows of neighboring stages is 25 mm. Holes with a diameter of 10 mm are executed within the bottoms of the drain cups, and such hole is located directly in the middle of drain cup. One hole with a diameter of 10 mm is also executed within the middle of the wall of each drain cup.

The boundary conditions remained the same: the air pressure in the lower part of device was set equal to 101425 Pa, and in the upper – 101325 Pa. The calculations were carried out at a temperature of the air and water of 20°C. Water flow rate varied from 0.5 m/s to 1.5 m/s. When the liquid flow rate was changed, the percentage of liquid entrainment from the device also changed. We analyzed the obtained data and came to the conclusion that with an increase of the liquid flow rate, the percentage of its entrainment from the device reduces, as well as at the average air flow rates from 1 to 2 m/s, the liquid entrainment is not significant (figure 5). However, the average air flow rate of this contact device is much lower than that of its predecessor, that does not allow to give a high assessment of its properties

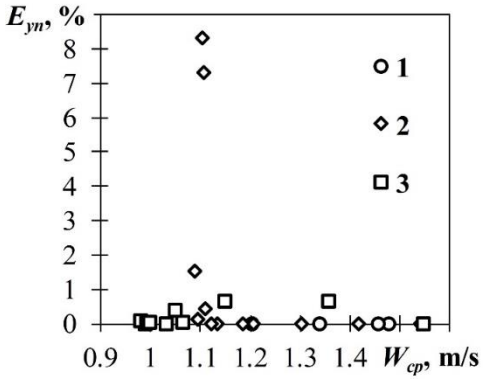


Figure 5. Changing of the entrained liquid amount if the average air flow rate is also changed at different water flow rates *U*, m/ s: 1 – 0.5; 2 – 1; 3 – 1.5.

The next step to improve the design was the addition of a partition over the hole within the center of the bottom (figure 6). This element was introduced in order to reduce the air carrying capacity, since air bubbles were observed in the previous design, that flew out of the hole.

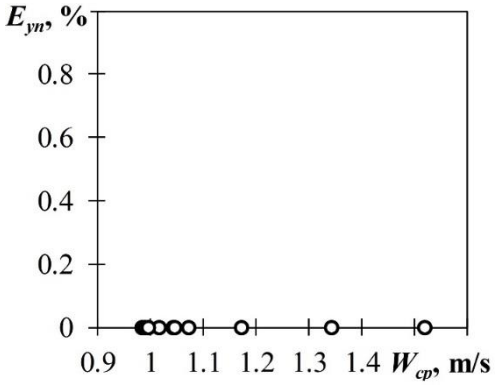


Figure 6. Changing of the entrained liquid amount if the average air flow rate is also changed when the partition over the central hole within the bottom is added into design.

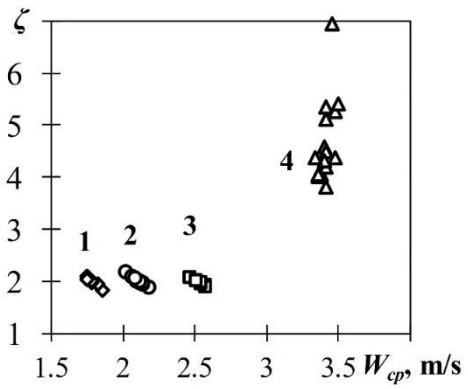


Figure 7. Dependency of the hydraulic resistance coefficient *ζ* on the average air flow rate at the following pressure drop *dp*, Pa: 1 – 50; 2 – 70; 3 – 100; 4 – 200.

It was assumed that the partition will hold the air and not allow it to carry out the water up, however, this modernization has not provided a significant effect and we believe that addition of it into design is not worthwhile, due to the fact that it will only bring complexity to the design [31].

Another indicator of the effective operation of contact devices in thermal power plants is the hydraulic resistance that occurs when the air flow passes through the contact device. High values of heat and mass transfer coefficients can be achieved by using the device, having low hydraulic resistance.

Figure 7 shows the dependency of hydraulic resistance on the average air flow rate at different pressure drop between the pressure at the inlet and outlet of the device. As can be seen from the graph, if the average gas flow rate is up to 3 m/s, the hydraulic resistance coefficient remains practically unchanged and fluctuates in the range of values about 2 and the spread of values is minimum. When the rate is more than 3 m/s, the hydraulic resistance coefficient increases sharply, due to the liquid entrainment from the device. In this case, the range of values is between 4 and 6. The proposed device has a relatively low hydraulic resistance at sufficiently high values of the average flow rate and minimum entrainment of liquid drops. All this shows good prospects of its application for heat and mass transfer processes. It should also be noted that at high operational rates of the device there was no distribution between the rows, therefore, there will be no need to install redistributive devices.

For comparison, a device within which the bottom of elements was located in the middle, was studied. As a result of studies, it is found that the hydraulic resistance considerably increases. Moreover, the unacceptable entrainment is observed already at the values of average flow rate of 1.5 m/s. It can be concluded that changing of design in this way is not advisable.

3. Conclusions

Having analysed all three designs and considered their pros and cons, the following conclusions can be drawn:

1) Contact device with holes within the lower part of the wall allows to cool the liquid effectively enough and to gain the air flow rate up to 4.2 m/s, that is a high value among the existing analogues.

2) The average air flow rate within the second variant of design of the contact device reaches 2 m/s.

3) Water entrainment in the devices is observed at an acceptable level, about 15%. In reality, the water entrainment will be much less because of the merging of drops, which is not provided in the model.

4) Water entrainment in the second contact device is lower, however, it should be noted that this data is only at average air flow rates from 1 to 2 m/s.

Acknowledgments

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