Modeling of heat and mass transfer processes in cooling towers and structure optimizing of polymer filler

V G Afanasenko*, P A Kulakov, Yu L Galimova and D I Sidorkin
Department of Technological Machines and Equipment, Ufa State Petroleum Technological University, 1, Kosmonavtov St., Ufa, 450062, Russia

* afanasenko.v.g@yandex.ru

Abstract. The closed water recycling systems with the main element being the evaporative water cooling devices or cooling towers are used to cool the main equipment of industrial enterprises. During these processes the recycled water is being polluted and lost, therefore it is necessary periodically provide this water volume from natural sources. Improving the efficiency of cooling towers can reduce the negative factors of such systems' operation. This article presents the research of the aerodynamic characteristics of heat-and-mass exchange packs of cooling towers made of vertical polymer pipes. The design of the optimized cooling tower filler unit is described and recommendations for improving the efficiency of evaporative cooling process of the circulating water are given.

1. Introduction
The Water resources are considered to be a national wealth and the level of economic development of any country as well as the health of its population depend on this water condition. In this regard, the problem of cost-effective use and protection of surface water from pollution and depletion requires serious attention, both in practical and scientific terms [1-4].

The growing needs in water resources of national economy do not fulfill this demand only by freshwater from natural sources, so the industrial enterprises should operate autonomous, closed water supply systems. Circulating water having passed the technological cycle is cooled to the required temperature in the air cooling devices or by evaporation of its part cooling towers [5, 6].

Heat-and-mass exchange process in industrial cooling towers is accomplished under conditions of direct interaction of gas and liquid phase, moving counter flow. The supply and spraying of liquid is produced by the flow energy driven by the electric pump. The air flow is most often driven by a fan.

Given that the energy consumption for liquid supply depends mainly on the height of the required pump head and the condition of the pipeline system in the cooling tower, and the energy consumption for water spraying is completely dependent on the type and design of the packs used, as well as the fact that in the block of heat-and-mass exchange pack the liquid flow occurs under the action of mass forces, it can be argued that by the improvement of the sprinkler it is impossible to reduce the energy consumption of the pump for liquid pumping.

Based on the information given above, the most appropriate way to increase the energy efficiency of the process of circulating water cooling is to reduce energy losses to overcome the air flow of the
cooling tower filler. It should be necessary to investigate and optimize the design of the heat-and-mass exchange pack by considering the aerodynamic resistance of the cooling tower sprinkler unit.

2. Objective and research method
The A large group of heat-and-mass exchange devices is unified by the use polymer corrugated pipes, as they have a developed specific surface area, high strength characteristics at low weight, long service life (compared to the structures of asbestos cement and wood), as well as low cost of manufacture, installation and maintenance. An example of such a pack can serve as a cooling tower sprinkler unit, shown in Figure 1 [7-10].

![Figure 1. Block of cooling tower fillers: 1 – corrugated pipes; 2 – support elements](image)

Theoretical research of gas-vapor flow hydrodynamics in the heat-and-mass exchange cooling tower made up of polymer corrugated pipes, is to be carried out by the use of numerical computer modeling techniques with software systems.

The cooling tower filler block has vertical channels where interacting gas and liquid fractions move. These channels can be divided into two types:
* channel limited by the inner surface of the tube;
* channel bounded by the outer surfaces of adjacent tubes.

We research the air flow in each of these channels.

At the initial stage, we neglect the influence of the step and the size of the corrugations on gas dynamics of the flow, as well as the movement of the liquid on the working surfaces, i.e. we consider smooth vertical dry polymer pipes tightly connected with each other by external side surfaces [2, 11-14].

3. Gas dynamics in tube side of the filler
The most common variety of polymer tubes used for producing various packs has a diameter of 65 mm, less common are products made of tube diameter of 45 mm [1, 5].

To research the aerodynamic characteristics, we use a calculation model with a length of 1000 mm and cylindrical surface diameter of 65 mm, as it is shown in Figure 2.

Boundary conditions:
* for the cylindrical wall, imitating the surface of fill element – "wall" with logarithmic law (irregularity 0);
* from the ends – "Input / output" (with a specified normal speed) and "Free output" (zero pressure / output);
* surfaces of the axial cross-sections of the cylinder, located at a right angle – " Symmetry " (Wall with slippage).

**Figure 2.** The calculation model of the tube side of the cooling tower filler for different types:
   a) one-sided-transparent facets; b) opaque facets

The most conformable to the considered problem model of incompressible (ideal) fluid was used for calculations, which includes the Navier-Stokes equations (the law of conservation of momentum), the law of continuity (the law of conservation of fluid mass) and the k-ε model of turbulent motion [15].

In FlowVision, the numerical integration of the equations by spatial coordinates was carried out using a rectangular adaptive locally refined grid. The working medium chosen is "Air", the physical properties of which are available in the integrated database.

As a result of the simulation, the resistance of the cooling tower filler element is determined, the ratio of which to the area of the flow of the design model determines the pressures drop in the air flow. The average value of the coefficient of aerodynamic drag from the Weisbach equation: for tubes diameter of 65 mm – 0.198, and for tubes diameter of 45 mm – 0.320.

In the same way, the aerodynamic processes in the space formed by the outer surfaces of smooth tubes were modeled, with aerodynamic resistance coefficient: for tube diameter of 65 mm – 2,271, and for tube diameter of 45 mm – 2,716.

4. **Increasing the efficiency of the filler unit made of polymer corrugated tubes**

   As it was shown in the aerodynamic researches in the block of the cooling tower filler, made up of vertical tubes, at a constant air flow rate, the pressure difference created by different channels differs several times. Therefore, at a constant pressure of the cooling tower created by the fan, the amount of the cooling agent installed in different channels will be different, that is, the free volume of the filler will be used non-uniformly, and the heat-and-mass exchange process will proceed in a non-optimum mode [16-18].

   Figure 3 shows the result of modeling the air motion with the initial velocity of 6 m/s entering the parallel tube and inter-tube channels of the cooling tower filler unit composed of elements with 45 mm diameter.
To increase the efficiency of air flow energy use, with the air to be driven by the fan, it is advisable to reduce the resistance in the intertubular space by increasing its cross-sectional area. In this regard, it is proposed to increase the distance between adjacent elements in the block of cooling tower filler [7].

Let’s consider the flow area of the channels limited by the outer and inner surfaces of the vertical corrugated tubes arranged in-line. The main geometrical dimensions of the filler unit are shown in Figure 4.

![Diagram of cooling tower filler unit](image)

**Figure 3.** The flow pattern of steam-gas flow in the cooling tower filler unit

**Figure 4.** The cross section of the filler block in the cooling tower made up of vertical polymeric corrugated tubes

The flow area of the channel limited by the inner surface of the corrugated tube in the area of the studied section is determined as:

\[ S_1 = \frac{(D - 2s)^2}{4} \pi \]  \hspace{1cm} (1)
and the flow area of the channel limited by the external surfaces of adjacent tubes with their in-line arrangement:

\[ S_2 = (A + D - d)^2 - \frac{(D + d)^3 \pi}{4} \]  

(2)

Denoting the ratio of the studied flow areas by \( k \), we obtain the following expression:

\[ k = \frac{S_1}{S_2} = \frac{(D - 2s)^2 \pi}{4(A + D)^2 - (D + d)^2 \pi} \]  

(3)

By this expression, you can find the distance between the outer surfaces of corrugated tubes, where the ratio of the cross-sectional area of the passage channels is equal to \( k \):

\[ A = \frac{1}{2} \sqrt{\pi \left( \frac{D - 2s}{k} \right)^2 + (D + d)^2} - D \]  

(4)

where \( D \) – outer diameter of the tube, m; \( s \) – tube wall thickness, m; \( k \) – ratio of the area of the passage sections in the tube and the intertubular space (it is recommended to take it as \( k \approx 1.0 \)); \( d \) – corrugation diameter, m.

5. The gas flow dynamics in the optimized design of the filler

To research the aerodynamic characteristics of the optimized intertubular space, the calculation was made for the channel with 1000 mm length formed by the outer surfaces of the tubes with 45 and 65 mm diameters, having in-line location at the distance of 11.4 and 16.46 mm, respectively. This design of the block corresponds to \( k \) value = 1.0.

The simulation results for comparison of the aerodynamic characteristics of the tube and optimized intertubular space are presented in Figure 6 as a graph of the pressure difference vs. the air flow velocity at 45 and 65 mm diameter of the researched elements.

![Figure 5. Pressure difference - flow rate curve](image-url)
As it follows from the results the pressure difference for different channels formed in the optimized design of the cooling tower filler unit made of vertical parallel tubes are approximately equal to each other (the difference does not exceed 8%), what allows the most efficient use of the free volume of the filler, evenly distributing the flow energy to overcome the block of the heat-and-mass exchange pack.

By analyzing the obtained pressure differences caused by the tube and optimized intertubular space of the filler during the air flow in it, we can consider that the most available for the speed range of 1.5÷8.0 m/s is the following power dependence:

$$\Delta p = 0.0274 \frac{D}{2} \omega^{1.711}$$

(5)

6. Conclusion
The optimization of the design of the heat-and-mass exchange pack of cooling towers made of polymer tubes will reduce the aerodynamic resistance of the filler and, accordingly, the energy loss to overcome the air flow in the filler unit. The article presents the recommendations for designing the internal cooling tower devices, as well as the results of modeling the aerodynamics of optimized heat-and-mass exchange pack made of polymer tubes. In addition, the authors have revealed the empirical dependence of the filler resistance and its geometric dimensions.

Acknowledgments
The research was conducted at Ufa State Petroleum Technological University in the framework of implementation of an initiative scientific project of fundamental nature on the state task of educational institutions of higher education for 2017-2019 (№ 9.7294.2017/8.9, dated 31.01.2017) with the assistance of the Interuniversity center for collective use "Regional research and production complex “Nedra”.

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