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# FLOW STRUCTURE DEFINITION IN THE BUNDLES OF FLAT-OVAL TUBES WITH INCOMPLETE FINNING UNDER CONDITIONS OF NATURAL DRAFT

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***The expediency of using "dry" cooling systems for technological products is considered. The expediency of using flat-oval tubes with incomplete finning as heat exchange surfaces of air coolers is shown. The transfer of the operating mode of air coolers to the operating mode with the fans turned off during a certain time of the year is substantiated. Installation of an additional exhaust tower can lead to energy savings for the fan drive up to 55 %.***

***The technique of numerical modeling and experimental study of the flow structure in a package of flat-oval tubes with incomplete finning under natural draft conditions is presented. Experimental studies and computational fluid dynamics (CFD) – modeling of the flow structure and averaged velocity fields in a package of flat-oval tubes with incomplete finning under natural draft conditions are carried out. The obtained numerical and experimental distributions of velocities and temperatures near the surface of the tubes and in the wake behind them give an idea of the features of the flow around the tubes and the effect of the flow structure on the intensity of their heat transfer. It was found that the hydrodynamic flow pattern in a stack of flat-oval tubes according to the results of CFD modeling corresponds to the classical concepts of hydrodynamics. The absence of a part of the finning in the aft part of flat-oval tubes with incomplete finning, where the formation of the aft circulation zone is observed, is substantiated. The verification of the CFD-modeling data and the data of the experimental study on the determination of the average velocities and temperatures in the flow behind the pack of flat-oval tubes with incomplete finning is carried out. The verification results indicate that the average numerical simulation error does not exceed 18 %. It is shown that to determine the optimal, from the point of view of heat transfer, geometric parameters of a number of flat-oval tubes under natural draft conditions, it is advisable to use CFD modeling***

***Keywords: energy saving, heat transfer, flat-oval tube, transverse finning, package, natural draft***

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## 1. Introduction

Today there is a need to meet the needs of the Ukrainian market with new effective cooling systems for technological products (air coolers, "dry" cooling towers, etc.). The available literature on the state of the art in air cooling technology shows the following. Creation of "dry" cooling systems with weight and size characteristics and cost acceptable for their wide distribution is directly related to the thermal and dynamic efficiency of their heat exchange surface. As such surfaces, it is advisable to use the new ones proposed in the Igor Sikorsky KPI, surfaces with flat-oval tubes with incomplete finning [1].

These tubes have a number of significant advantages over finned tubes currently used in industry. These advantages include: a higher degree of surface decomposition, ideal thermal contact between the fins and the main tube, low aerodynamic resistance and high manufacturability.

Taking into account the above, it is advisable to carry out studies of heat transfer and features of the flow around such tubes under conditions corresponding to the possible modes of operation of air coolers.

## 2. Literature review and problem statement

The operation of "dry" cooling systems is accompanied by significant costs for the drive of the fan motors, which provide the required air flow rate to remove the heat flow from the heat exchange surfaces. The total electricity consumption for one air-cooled unit with a thermal capacity of 1 MW is about 100 MWh of electricity per year, which corresponds to about 224 thousand UAH of the company's cash costs.

As shown in [2], it is possible to transfer air coolers to the operating mode with the fans turned off during a certain time of the year. Saving energy for the fan drive in this case is up to 37 % per year [3, 4]. In this case, the removal of the heat flow from the heat exchange surface of the air cooler (AC) is carried out using free convection.

However, as indicated in [5], it is possible to install an additional exhaust tower above the heat exchange surface and transfer the AC operation mode to the natural draft mode. With this, it is possible to significantly expand the range of ambient temperatures at which it is possible to operate the AC in the operating mode with the fans turned off.

This method requires practically no capital expenditures and can increase the overall energy savings for the fan drive up to 55 %.

Incomplete finned flat-oval tubes operate effectively under forced convection conditions. The works [1, 6] show their significant advantages over tubes with a round finned profile and the possibility of their use as heat exchange sections of air coolers. But the features of the AC operation, given above, make it necessary to check the possibility of using flat-oval tubes with incomplete finning under natural draft conditions.

The works [7–9] are devoted to the study of heat exchangers with a built-in exhaust tower. In [7], a numerical and experimental study of the influence of the location of the heat exchange beam on the efficiency of the dry cooling tower model was carried out. In [8, 9], the influence of the installation of an exhaust tower on the intensity of heat exchange of air cooling devices based on bimetallic finned tubes is considered. However, the data given in the sources [7–9] can be applied only for those types of heat transfer surfaces, which are devoted to these works. At the same time, studies of the flow structure and heat transfer of precisely flat-oval tubes with incomplete finning under natural draft conditions have not been carried out at the moment.

Based on the analysis of works [10, 11], it should also be noted that the highest heat transfer rate of the finned surfaces is achieved when they are located across the incident flow. As indicated in [12], when using finned telescopic tubes, the best heat and dynamic performance is achieved when they are located with a smaller radius towards the flow. Considering the above, this work does not consider a change in the angle of attack and a change in the variant of the arrangement of finned tubes relative to their longitudinal axis.

All this allows to state that it is expedient to study the flow structure in packets of flat-oval tubes with incomplete finning under natural draft conditions. These studies will provide new data for the development of recommendations for the use of flat-oval tubes with incomplete finning in the design of modern air coolers.

## 3. The aim and objectives of research

The aim of research is to obtain new data on the flow structure in the interfin channels of flat-oval tubular-finned heat exchange surfaces for natural draft conditions. These data are required to conduct an in-depth analysis of the feasibility of using such tubes in dry air cooling systems.

To achieve this aim, the following objectives are set:

– to perform CFD-modeling of heat transfer of a package of flat-oval tubes with incomplete finning under natural draft conditions;

– to conduct an experimental study of velocities and temperatures near the surface of the tubes and in the wake behind them using a hot-wire anemometer in accordance with the conditions of natural draft;

– to check the possibility of using CFD-modeling of heat transfer of a package of flat-oval tubes with incomplete finning, verify the numerical and experimental data.

## 4. Methods for studying the flow structure in packets of flat-oval tubes with incomplete finning under natural draft conditions

To study the temperature distribution, averaged velocity fields and flow structure in packets of flat-oval finned tubes under natural draft conditions using CFD modeling, a finite element model of a number of research tubes was developed, which made it possible to numerically visualize the flow near the surface of the tubes and in the wake behind them. and also to obtain the distributions of temperatures and fields of averaged velocity in the interfin channels of finned tubes.

In the numerical simulation of the flow structure, the Boussinesq approach [13] was used. When using this approach, it is believed that the physical parameters of the medium are constant, the density depends only on temperature, and this dependence must be taken into account only in the expression for the force of gravity.

$$\bar{\rho}\left(\frac{\partial u_i}{\partial \tau}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\beta\vartheta\bar{\rho}F_i+ \\ +\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]-\frac{\partial p}{\partial x_i}, \tag{1}$$

$$\frac{\partial u_i}{\partial x_j}=0, \tag{2}$$

$$\bar{\rho}C_p\left(\frac{\partial\vartheta}{\partial\tau}+u_j\frac{\partial\vartheta}{\partial x_j}+u_j\left(\frac{\partial\bar{T}}{\partial x_j}-\beta T\frac{F_j}{C_p}\right)\right)=\Delta Q_\upsilon+ \\ +\beta T\frac{\partial p}{\partial\tau}+\beta T u_j\frac{\partial p}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\lambda\frac{\partial\vartheta}{\partial x_j}\right)+\frac{\mu}{2}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)^2, \tag{3}$$

where $\rho$ –density, $u$ – component of the velocity vector, $\tau$ – time, $x$ – coordinate along the generatrix of the distorted body, $\beta$ –thermal coefficient of volumetric expansion, $\theta$ – excess temperature, $F$ –bulk force, $\mu$ –coefficient of dynamic viscosity, $p$ – pressure, $C_p$ – isobaric heat capacity, $T$ – temperature, $Q_\upsilon$ – specific power of volumetric heat sources, $\lambda$ – thermal conductivity coefficient, index $i$ – along the projection on the $x$, $y$, $z$ axes, index $j$ – according to the number of solid boundary surfaces of the body.

The Boussinesq approximation does not impose restrictions on the change in thermophysical characteristics and the influence of the work of compression and energy dissipation on the flow and heat transfer [14].

The calculations were carried out in a stationary setting. The geometry of the CFD model of the finned flat-oval tube, as well as the pitch between the tubes ($S_1$=60 mm) and the height of the exhaust tower above the ends of the fins (1 m) correspond to the physical experiment [15]. The numerical model is based on a full 3D model of the elements of a series of flat-oval tubes with incomplete finning. The task is external, the calculations were carried out in a stationary setting. The hydrodynamic picture of the fluid flow in half-open rectangular channels formed by the fins and the supporting tube is the same in all interfin channels along the tube. Taking into account the above, for the simulation, a tube with an average width of a row, bounded by two adjacent guard tubes, was chosen. In these tubes, an average fin along the width of the tube was considered, bounded by fins of the same type, which were chosen as security ones.

The mutual influence of the boundary layers developing on the surfaces of the fins forming a flat half-open channel was taken into account by symmetric boundary conditions.

An example of a 3D computational grid is shown in Fig. 1.

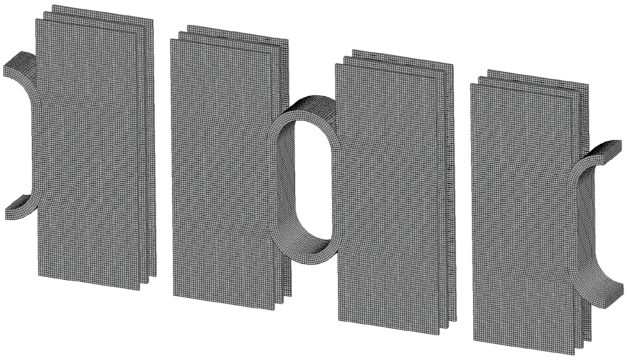


Fig. 1. Three-dimensional model of the solution area of the heat conduction problem

The construction of the computational model was based on the development of a geometric model of the computational domain, discretization of the computational domain in accordance with the concept of the influence of the characteristics of the finite element mesh on the stability and convergence of the solution, and the application of boundary conditions. The computational area was covered with an uneven rectangular mesh with thickening to the walls of the base and heating elements. The number of elements in the computational grid was 3,720,000. The temperature of the external environment and the density of the heat flux on the inner surfaces of flat-oval tubes were set as boundary conditions. The mentioned values coincide with the input data of the physical experiment [15].

An experimental device for carrying out experimental studies is shown in Fig. 2, 3.

Detailed information on the design of the experimental device is given in [15]. However, to conduct experimental studies on the measurement of local velocities and temperatures of the air flow under natural draft conditions, a German-made Testo 425 hot-wire anemometer (pos. 2, Fig. 2, pos. 5, Fig. 3) was used, which was introduced into the flow using a telescopic probe. The sensing element of the hot-wire anemometer was able to move in a plane above the heat exchange section using a coordinate device (element 3, Fig. 2).

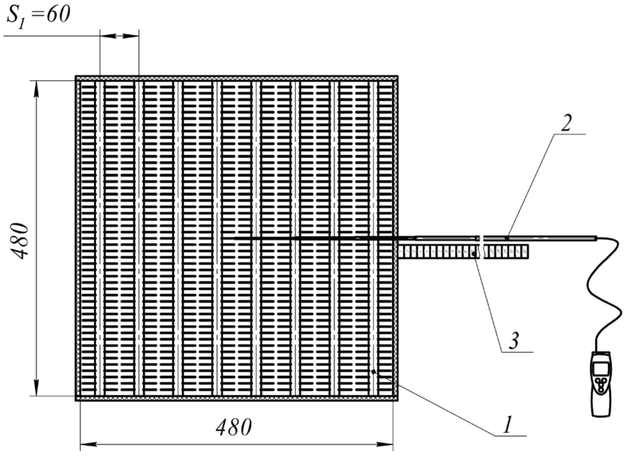


Fig. 2. Diagram of an experimental device for research under conditions of free convection and natural draft (top view): 1 – package of finned tubes; 2 – hot-wire anemometer; 3 – coordinate device

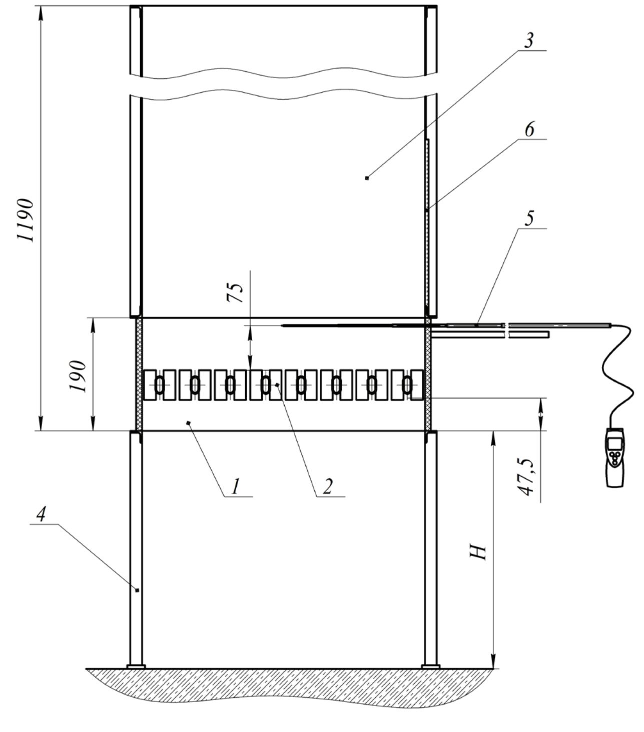


Fig. 3. Diagram of the experimental device for conducting research in conditions of free convection and natural draft (front view): 1 – thermal insulation section; 2 – package of profiled finned tubes; 3 – exhaust tower; 4 – support posts 5 – hot-wire anemometer; 6 – Plexiglas window

## 5. Results of studying the flow structure in packets of flat-oval tubes with incomplete finning under natural draft conditions

### 5. 1. Results of CFD-modeling of heat transfer of a pack of flat-oval tubes with incomplete finning under natural draft conditions

Fig. 4 shows a numerical visualization of temperature fields and instantaneous flow rates in the interfin channel of a number of flat-oval tubes with incomplete finning.

The given temperature distribution corresponds to the temperature distribution in the interfin space of the channel of a single flat-oval tube under forced convection [16]. On the surface of the flat-oval tube, the most heated zone is aft along the flow direction, and the zone with the minimum temperature is located at the frontal point. As in the case of forced convection under natural draft conditions, a thermal boundary layer begins to develop on the surface of a flat-oval tube and its fins, the thickness of which increases as the flow moves deeper into the interfin channel. The maximum thickness of the boundary layer can be estimated visually (the near-wall region near the bearing tube (Fig. 4, *a*). Such analysis shows that with an increase in the supplied power, the thickness of the boundary layer decreases, which in turn indicates an increase in the local flow velocity.

The above is confirmed by the results of the distribution of instantaneous velocities in the central plane of the interfin canal (Fig. 4, *b*). The analysis of the figure confirms the predicted tendency to increase the velocity in places of high temperature. Form Fig. 4 it can be seen that the flow that moves from bottom to top under the influence of the difference in air densities is primarily directed into the gap between the ends of the fins of adjacent tubes, where the maximum flow rate is observed. In this case, with an increase in the supplied heat flux, an increase in the flow rate is observed.

Analysis of Fig. 5, which shows the air flow lines in the near wake behind the tube, indicates that the formation of two oppositely swirled vortices is observed in the aft part along the flow. Further, the movement of the flow forms a Karman vortex street, which is consistent with the generally accepted picture of the flow with a transverse flow around tubes [17].

In addition, it should be noted that the created aft circulation zone is smaller in terms of its relative size than for round finned tubes with a similar cross-section perimeter. This zone is distinguished by a low intensity of circulation currents, and, accordingly, a low intensity of heat exchange with the surface of the fins. Therefore, the aft part of the fins of traditional fully finned tubes practically does not work as a ballast one. This indicates that the absence of a part of the finning in the aft zone of flat-oval tubes with incomplete finning is quite justified. It leads to a significant decrease in the metal consumption of the finned surface and a significant simplification and improvement of the manufacturability.

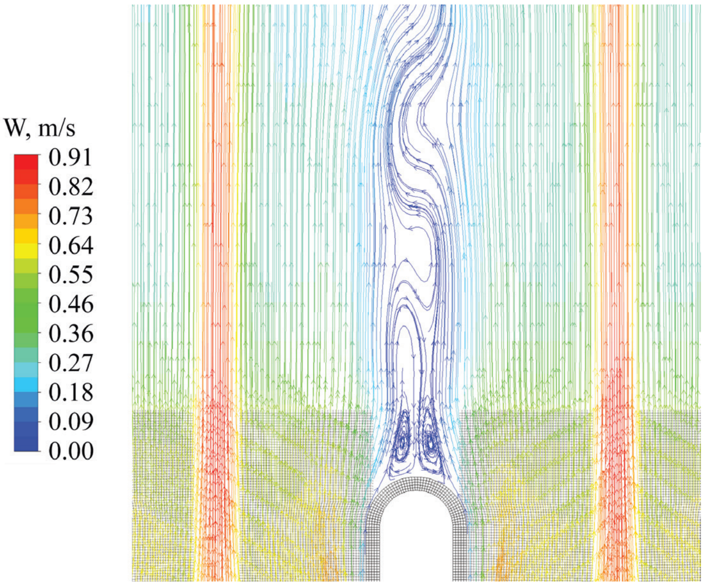
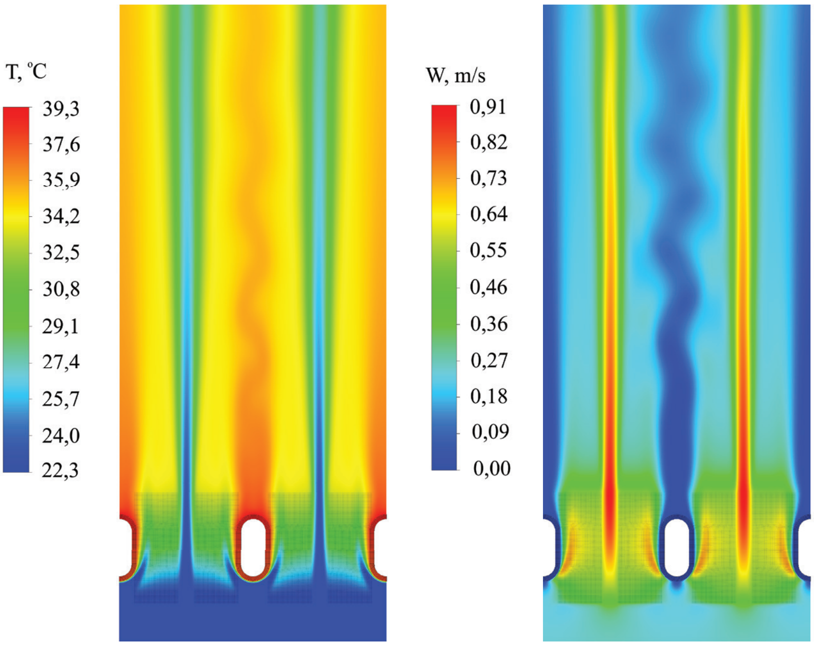


Fig. 5. Trajectories of motion of particles in the near wake with a heat load on one tube $Q$=100 W



*a* *b*

Fig. 4. Distribution of temperatures and flow rates in the interfin space of the channel at a heat load on one tube $Q$=100 W: *a* – temperature distribution; *b* – velocity distribution

### 5. 2. Results of an experimental study of velocities and temperatures near the surface of tubes and in the wake behind them under natural draft conditions

The physical experiment aimed to analyze the flow structure and its representation in the form of velocity and temperature flow fields with the tubes of the heat exchange section. The flow structure was measured above the heat-exchange section at a distance of 75 mm from the upper end of the fin of the flat-oval tube (Fig. 2, 3). Based on the results of the experimental study, the distributions of the temperature head (Fig. 6) and velocities (Fig. 7) were obtained along the width of a single-row stack of flat-oval tubes with incomplete finning *L*.

The presented dependences are of extreme nature. The parameter that the delamination data is given is the heat load $Q$ supplied to one tube ($Q$=50, 100, 150, 175 W). The minimum temperature value is in the center of the gap between the fins, where the maximum velocity is in compliance. The graphs clearly show the temperature-velocity relationship: that is, the higher the flow rate, the lower its temperature.

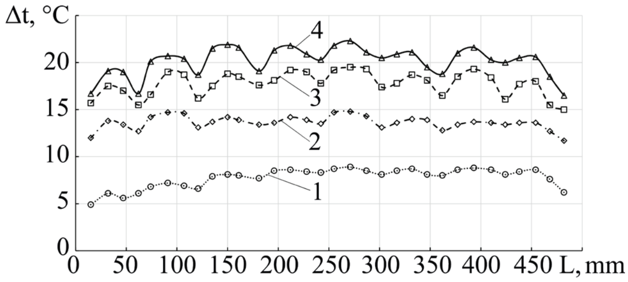


Fig. 6. Distribution of the temperature head over the width of a single-row package according to the results of experimental studies: 1 – $Q$=50 W; 2 – $Q$=100 W; 3 – $Q$=150 W; 4 – $Q$=175 W

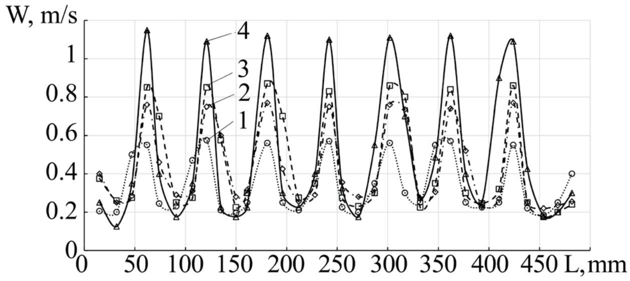


Fig. 7. Velocity distribution along the width of a single-row packet according to the results of experimental studies: 1 – $Q$=50 W; 2 – $Q$=100 W; 3 – $Q$=150 W; 4 – $Q$=175 W

### 5. 3. Verification of numerical and experimental data

In order to visually assess the relationship between the physical and computational experiment, graphical dependences of verification of temperature head (Fig. 8) and instantaneous flow rates (Fig. 9) along the width of the interfin channel L are presented. 8, 9, solid lines represent the results of CFD modeling, and the dots represent the results of experimental studies.

Verification of the values of temperature heads and instantaneous flow rates and the construction of their two-dimensional graphical dependencies took place on a line drawn in the center of the interfin channel at a distance of 75 mm from the end of the fin. This corresponds to the performed physical experiment [15].

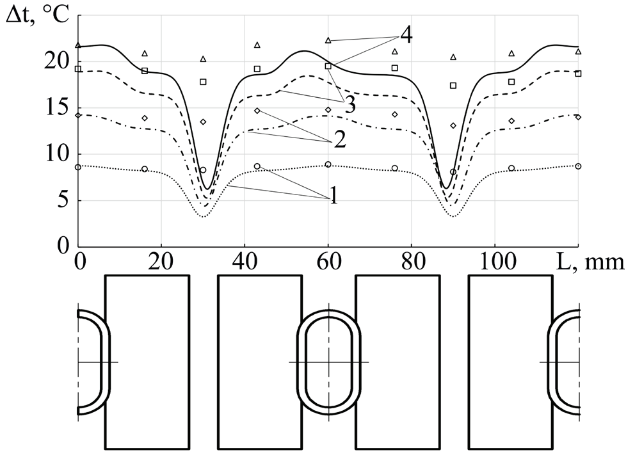


Fig. 8. Verification of the temperature head distribution over the width of a single-row package: 1 – $Q$=50 W; 2 – $Q$=100 W; 3 – $Q$=150 W; 4 – $Q$=175 W

The given verification of numerical data (Fig. 8, 9) indicates that the average error between numerical and experimental data is 18 %. At the same time, the greatest deviations in the distributions of velocities and temperature differences are observed in the space between the fins of adjacent tubes. It should be noted that the distributions of velocities and temperature heads determined from the results of experimental studies and CFD modeling have an identical character.

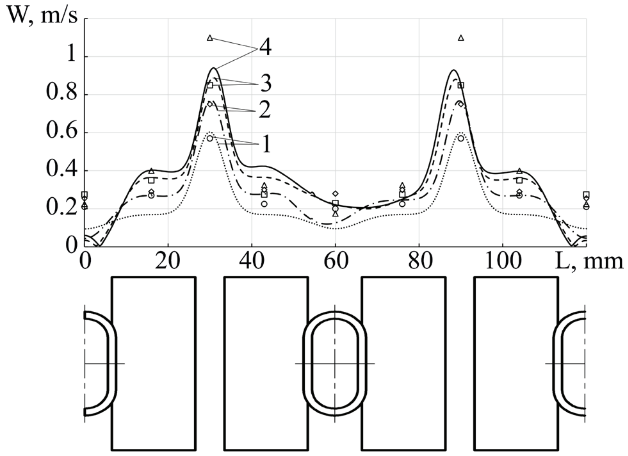


Fig. 9. Verification of the velocity distribution over the width of a single-row package: 1 – $Q$=50 W; 2 – $Q$=100 W; 3 – $Q$=150 W; 4 – $Q$=175 W

## 6. Discussion of the research results of the flow structure in packets of flat-oval tubes with incomplete finning under natural draft conditions

CFD modeling of heat transfer of a package of flat-oval tubes with incomplete finning under natural draft conditions made it possible to obtain a numerical visualization of the temperature fields and instantaneous flow rates in the interfin channel of a number of such tubes. A detailed analysis of the obtained distributions (Fig. 4, 5) made it possible to conclude that the obtained flow pattern is in good agreement with the generally accepted flow pattern for a transverse flow around tubes [17].

The data of an experimental study of velocities and temperatures near the surface of tubes and in the wake behind them under natural draft conditions indicate the following. The distributions of temperature heads and flow rates (Fig. 6, 7) are stratified in accordance with the change in the supplied heat flow Q. In this case, the temperature heads and flow rates change in opposite directions. Temperature minimums and velocity maxima coincide with the center of the gap between the fins of adjacent tubes. Temperature maxima and velocity minima are located in the aft circulation zone, which is formed directly behind the flat-oval tube.

The above verification of the numerical data (Fig. 8, 9) indicates a sufficient correlation between the results of experimental and numerical distributions of velocities and temperature heads. This makes it possible to use the developed technique to determine the geometric and step characteristics of a number of flat-oval tubes with incomplete finning under natural draft conditions, which are optimal in terms of heat transfer intensity. This allows to minimize the cost of experimental research by reducing the number of options for their geometric characteristics and step characteristics of their location.

The technique considered can be used for CFD modeling of the intensity of heat transfer of flat-oval tubes with incomplete finning under natural draft conditions in the range of Rayleigh numbers Ra=2.8 $10^3$...13.2·$10^3$.

The disadvantage of the studies carried out is that, according to the results of numerical modeling, the value of the temperature head in the space between the fins of adjacent tubes is slightly less than the corresponding values obtained in the physical experiment (Fig. 6). This is due to the fact that during the physical experiment, when the temperature field of the flow was fixed behind the tubes, significant fluctuations of the temperature values were observed, and their averaged values were taken into account when constructing the graphical dependencies.

Further studies are planned to be carried out in the direction of studying the influence of changes in the geometric parameters of tubes on the intensity of heat transfer under natural draft conditions.

## 7. Conclusions

1. Based on the results of the CFD simulation of heat transfer of a pack of flat-oval tubes with incomplete finning under natural draft conditions, it was determined that the flow pattern corresponds to the classical concepts of hydrodynamics.

2. An experimental study of the velocities and temperatures near the surface of the tubes and in the wake behind them using a hot-wire anemometer under natural draft conditions. This study made it possible to obtain data on experimental distributions of velocities and temperature heads, which give an idea of the peculiarities of the flow around tubes and the effect of the flow structure on the intensity of their heat transfer. The data obtained are used to verify the developed numerical model.

3. The data obtained by CFD modeling on the flow structure in packets of flat-oval tubes with incomplete finning under natural draft conditions are consistent with the results of experimental studies with an average error of 18 %. This indicates that the developed CFD modeling technique can be used to determine the geometric and step characteristics of a number of flat-oval tubes with incomplete finning under natural draft conditions, optimal in terms of heat transfer. This makes it possible to significantly simplify the corresponding experimental studies.

## References

1. Pis'mennyi, E. N. (2016). Study and application of heat-transfer surfaces assembled from partially finned flat-oval tubes. Applied Thermal Engineering, 106, 1075–1087. doi: http://doi.org/10.1016/j.applthermaleng.2016.06.081
2. Kuntysh, V. B., Sukhotskii, A. B., Samorodov, A. V. (2013). Inzhenernii metod teplovogo rascheta apparata vozdushnogo okhlazhdeniia v rezhime svobodno-konvektivnogo teploobmena. Khimicheskoe i neftegazovoe mashinostroenie, 12, 3–6. Available at: https://elib.belstu.by/handle/123456789/6624
3. Kamaletdinov, I. M. (2001). Raschet svobodnokonvektivnogo teploobmena v apparatakh vozdushnogo okhlazhdeniia (AVO) gaza s uchetom vliianiia vetra na ikh rabotu. Izvestiia VUZov. Neft i gaz, 5, 71–74.
4. Vasilev, Iu. N., Zolotarevskii, B. C., Margolin, G. A., Kriukov, N. P. (1972). Ekspluatatsiia sistem vozdushno-vodianogo okhlazhdeniia v rezhime estestvennoi konvektsii. Gazovaia promyshlennost, 6, 23–25.
5. Pysmennyi, Ye. M., Terekh, O. M., Rudenko, O. I., Nishchyk, O. P., Vozniuk, M. M. (2016). Pat. No. 110702 UA. Sposib enerhozberezhennia v aparati povitrianoho okholodzhennia. No. u 2016 02427. declareted: 14.03.2016; published: 25.10.2016, Bul. No. 20. Available at: https://uapatents.com/4-110702-sposib-energozberezhennya-v-aparati-povitryanogo-okholodzhennya.html
6. Pismennii, E. N., Bagrii, P. I., Terekh, A. M., Semeniako, A. V. (2013). Optimizatsiia orebreniia novoi teploobmennoi poverkhnosti na osnove ploskoovalnykh trub. Inzhenerno-fizicheskii zhurnal, 86 (5), 1002–1007. Available at: https://www.researchgate.net/publication/313724066_INZENERNO-FIZICESKIJ_ZURNAL
7. Tanimizu, K., Hooman, K. (2012). Natural draft dry cooling tower modelling. Heat and Mass Transfer, 49 (2), 155–161. doi: http://doi.org/10.1007/s00231-012-1071-1
8. Milman, O. O., Aleshin, B. A. (2005). Eksperimentalnoe issledovanie teploobmena pri estestvennoi tsirkuliatsii vozdukha v modeli vozdushnogo kondensatora s vytiazhnoi shakhtoi. Teploenergetika, 5, 16–19. Available at: http://95.164.172.68:2080/khportal/DocDescription?docid=KhHAI.BibRecord.510157593
9. Sukhotskii, A. B., Marshalova, G. S. (2019). Features of Gravitational Flow of Heated Air in an Exhaust Shaft Above a Multirow Finned Bank. Journal of Engineering Physics and Thermophysics, 92 (3), 619–625. doi: http://doi.org/10.1007/s10891-019-01967-x
10. Abed, W. M., Amer, J. S., Ahmed, A. N. (2010). Natural Convection Heat Transfer in Horizontal Concentric Annulus between Outer Cylinder and Inner Flat Tube. Anbar Journal for Engineering Sciences, 3 (2), 31–45.
11. Chen, H.-T., Chou, J.-C. (2006). Investigation of natural-convection heat transfer coefficient on a vertical square fin of finned-tube heat exchangers. International Journal of Heat and Mass Transfer, 49 (17-18), 3034–3044. doi: http://doi.org/10.1016/j.ijheatmasstransfer.2006.02.009
12. Suyi, H., Shizhou, P. (1995). Convection and heat transfer of elliptical tubes. Heat and Mass Transfer, 30 (6), 411–415. doi: http://doi.org/10.1007/bf01647445
13. FLUENT 5.5 UDF User's Guide (2000). Fluent Inc., 563.
14. Martynenko, O. G., Sokovishin, Iu. A. (1982). Svobodno-konvektivnii teploobmen. Minsk: Nauka i tekhnika, 400.
15. Vozniuk, M. M., Terekh, O. M., Rudenko, O. I., Reva, S. A., Baraniuk, O. V. (2016). Heat transfer of flat-oval tubes with incomplete fining under conditions of free convection and natural draft. ScienceRise, 2 (2 (19)), 10–15. doi: http://doi.org/10.15587/2313-8416.2016.60029
16. Rudenko, A. Y., Terekh, A. M., Semeniako, A. V., Nyshchyk, A. P., Baraniuk, A. V. (2011). The method of flow visualization of gas flow on the surface of bodies of various shapes. Eastern-European Journal of Enterprise Technologies, 1 (9 (49)), 51–55. Available at: http://journals.uran.ua/eejet/article/view/2448
17. Van-Daik, M. (1986). Albom techenii zhidkosti i gaza. Moscow: Mir, 184. Available at: https://www.c-o-k.ru/library/document/13685