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GENERALIZATION OF THE LOCAL APPROACH APPLICATION TO THE ASSESSMENT OF TRANSFER PROCESSES IN HEAT POWER EQUIPMENT

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Abstract. *In order to develop measures to improve the thermal efficiency of working surfaces and the coolant supply system, it is necessary to examine and analyze the results of comprehensive studies of transfer processes under complex conditions of interaction of external (increased turbulence) and internal (separation) turbulent effects typical for heat power equipment. The aim of the work is to develop methods for assessing transfer processes in such equipment based on local control of thermophysical parameters in characteristic zones of the working environment. The object of the study is heat exchange surfaces of power, chemical and electronic equipment, as well as coolant supply systems. The research method is physical modeling of turbulent effects of various natures and processes of heat, momentum and mass transfer using hot-wire, electro-calorimetric methods, and heat and mass analogy methods. The article considers the generalization of the local approach application on examples of assessing the influence of increased turbulence, local closed separations and unsteady flows on transfer processes in the flow part of heat power equipment for various purposes. A local approach to the development of an effective coolant supply system for the technology of final drying of plant waste fragments is also considered. The use of a local approach, which allows recording thermophysical parameters in any characteristic zone of the working space, provides the ability to control the most thermally stressed areas. These results are the basis for developing measures to increase the thermal efficiency of working surfaces.*

Keywords: local thermophysical parameters, local aerodynamic characteristics, heat exchange surfaces, coolant supply system.

2. Introduction

It is known that processes in heat power, technological and electronic equipment occur under complex conditions of interaction of various natures turbulent effects. On the one hand, external disturbances caused by turbulence of the medium, pressure gradients, velocity non-stationarity, etc. are primarily associated with the geometry and design of the flow part. On the other hand, there are internal sources of disturbances on the working surface, caused by both natural causes (e.g., roughness, separation) and special artificial measures aimed at improving the transfer process (e.g., blowing to cool the surface, holes to increase heat dissipation, riblets to reduce hydraulic resistance, etc.). In addition, many technical applications are characterized by the installation of prismatic elements on a flat surface.

The progressive trend of increasing the efficiency and operational reliability of equipment requires constant improvement of methods for control and management of working processes. This is achieved by penetrating into the complex mechanism of boundary layers (BL) development on streamlined surfaces and targeted impact on their internal structure. Based on the above, it follows that it is relevant to conduct complex experimental studies in laboratory conditions on controlling the structure of boundary layers by means of different nature disturbances, in particular, studying the features of a bypass laminar-turbulent transition. It concerns first gas turbine engines. The blade boundary layers are subjected to a combination of variables including free-stream turbulence, pressure gradient, unsteady periodic wakes of the upstream blade rows. These conditions have a significant influence on the BL transition process.

The increased interest of the electronics industry in the development of methods for calculating heat exchange of elements and units of electronic equipment confirms the relevance of studying the features of heat exchange in a pseudolaminar boundary layer developing on the surface of a prismatic element. Previously, the calculation of electronic equipment units was based on the average flow rate determined by the fan performance and constant for all prisms installed on a flat surface. This approach ignores information about the velocity and temperature fields and does not sufficiently take into account the influence of the size and location of the prismatic elements on the hydrodynamic structure of the flow. The local approach allows us to determine the temperature state of individual prismatic elements and the entire structure as a whole.

Due to the rapid development of computer technology in the last decade, there has been a disproportionate increase in numerical modeling compared to physical experiment, in particular direct numerical modeling of separated flow [1]. Therefore, experimental studies of heat transfer and hydrodynamics of complex flows, including separated flows, are of particular relevance. Analysis of the results of these studies helps to determine the characteristics of transfer processes when separations occur, allows evaluating the actual course of processes and helps to improve numerical modeling.

The organization of optimal distribution of the coolant flow for various heat technologies, in particular for the technology of final drying of plant waste fragments, is an important factor in energy saving. Improving the aerodynamic characteristics of the drying process based on a local approach is an urgent task.

2. Analysis of recent research and publications

As the analysis of recent studies and publications shows, the number of studies devoted to the influence of disturbances of various nature on the laminar-turbulent transition has now significantly increased. The relevance of this part of the work is evidenced by the volume of studies devoted to the problems of the bypass transition due to its wide distribution in various technical applications, primarily in gas turbines [1, 2]. In particular, the review [3] describes models of various types transition for flows in the boundary layer of streamlined surfaces in turbomachines. Unsteady flow initiates special type of laminar-turbulent boundary layer transition: wake-induced transition, which is also typical for gas turbine engines. The conclusions of the works [4, 5], which present a study of the simultaneous influence of the intensity and scale of turbulence on the onset of the bypass laminar-turbulent transition, indicate that the intensity of turbulence is the main factor affecting the transition, and the scale of turbulence has a secondary effect. Studies devoted to the problems of the bypass transition mainly relate to the numerical modeling of the hydrodynamic bypass transition using various turbulence models.

Most of the experimental and computational work deals with the case of momentum transfer. The problems associated with the influence of turbulence, periodic velocity non-stationarity and separation on heat transfer remain unclear.

Despite numerous attempts to penetrate into the separation mechanism in the recirculation, reattachment and relaxation zones, some aspects of complex separated flows remain unpredictable to date. Thus, universal criteria for assessing the intensity of separation and methods for diagnosing its type (laminar, transitional or turbulent) have not been developed. There are no reliable recommendations for determining the size (length and height) of the separation bubble and the length of the relaxation zone behind it. Data on the influence of the degree of turbulence on the formation of separation and the development of BL in the relaxation zone behind it are limited. Since friction practically disappears in the separation zone, there is a significant violation of the Reynolds analogy in it, extending to the relaxation zone.

There are enough articles devoted to the development of effective methods for drying various agricultural products and fragments of plant waste. In the study [6], an indirect solar dryer was proposed and developed, which accelerates the drying process of agricultural products. The work [7] describes an automatic control system for the drying process, which ensures sufficient heat flows depending on the type of product being dried. Impact jets, as in the present study, are often used in industry to dry, cool or heat various products. Impact drying and cooling is especially common for continuous sheets such as paper, textiles and metals. For example, results described in [8] for heat transfer mechanism of a slit jet impingement, will help to optimize cooling equipment and controlled parameters for the industrial-scale hot steel strip/plate cooling technology.

To determine the patterns of this complex transfer process, careful experimental data obtained under conditions as close as possible to the conditions in the flow section of full-scale equipment are required. Taking into account all of the above, the purpose of the study is to develop methods for assessing transfer processes in such equipment based on local control of thermophysical parameters in characteristic zones of the working environment.

3. Materials and research methods

The research method is physical modeling of turbulent effects of various natures and processes of heat, momentum and mass transfer using hot-wire, electro calorimetric methods, and heat and mass analogy methods. Since physical modeling is one of the most promising methods for studying transfer processes occurring under complex conditions, the studies were carried out in specially manufactured experimental samples of installations that completely reproduce the operating conditions of a full-scale installation in terms of geometric parameters and air supply system. The studies of the influence of increased turbulence, local closed separations, and velocity non-stationarity on the transfer processes in the flow path of heat power equipment were conducted in the T-5 wind tunnel of the IET NASU. The generator for creating turbulence had the form of a perforated plate. The working surface was a flat plate, the length of which made it possible to implement a mixed flow regime in the boundary layer. The velocity of the external flow, the shape of the leading edge of the plate and the length of the interceptor installed at the end of the wind tunnel test section controlled the type of separation (laminar, transitional or turbulent). Experimental investigations of a flat plate heat transfer in the presence of unsteady flows were carried out in a wind tunnel using various wake generators (a still and hesitating cylinder, a still and rotating "squirrel" wheel).

The studies of the transfer processes in the pseudolaminar boundary layer developing on the surface of a prismatic element were carried out in the aerodynamic stand ADS-1. The layout included four rows of prismatic elements installed on a flat surface (Fig.1). To study the heat transfer of prismatic elements, the method of heat and mass analogy was used, in particular the method of sublimation of matter in air.

The design of the experimental model, specially manufactured for the aerodynamic improvement of final drying of plant waste fragments, completely reproduced the operating conditions of the full-scale installation in terms of geometric parameters and air supply system (Fig.4) [9].

4. Results and discussion

4.1 Local approach for assessing the impact of increased turbulence

Such studies were conducted under conditions of nonlinear interaction of external (increased turbulence) and internal (separation at the leading edge) disturbances on two types of different working surfaces – flat and prismatic, therefore the results of two parts of the studies are considered.

For the first part, when studying the bypass laminar-turbulent transition, the local approach means determining the local coefficients of heat transfer and friction at the local velocity, as well as the fields of velocity, temperature and their pulsations in various sections along the length of the flat working surface.

The use of a local approach made it possible to explain the reason for the formation of a pseudolaminar boundary layer (PLBL), which precedes the bypass transition. This is caused by the simultaneous manifestation of two mutually related processes: selective penetration of turbulent pulsations from the external flow into the boundary layer (BL) and the development of powerful pulsations within the BL itself. Depending on the scale of turbulence, the development of PLBL at $Tu > 0$ can be accompanied by an increase in the coefficients of friction and heat transfer due to an increase in the velocity and temperature gradients near the wall with a simultaneous change in the internal structure of the BL. This also allowed us to evaluate the fact that in the pseudolaminar boundary layer the increase in heat transfer (up to 70%) significantly outpaces the increase in friction (up to 17%). The reasons for the intensification of heat transfer in the pseudolaminar boundary layer, significantly outstripping friction, are associated with higher rates of growth of the energy loss thickness compared to the momentum loss thickness; closer to the wall location of the temperature pulsation maxima compared to the longitudinal velocity pulsation maxima; high degree of correlation (up to 90%) between them. Methods for predicting the type of flow in the boundary layer and determining the coordinates of the bypass laminar-turbulent transition were also developed. Control of heat removal in the pseudolaminar boundary layer and monitoring of the length and location of the bypass transition zone make it possible to avoid the occurrence of dangerous heat-stressed areas.

The second part of the work is devoted to the features of heat transfer in the pseudolaminar boundary layer developing on the surface of a prismatic element. As is known, prisms are typical elements of electronic equipment boards. To develop an effective cooling system for such equipment, it is necessary to assess the thermal state of the elements of a specific layout and develop measures to improve it.

The thermal efficiency of individual prismatic elements was tested for the arrangement shown in Fig. 1, which included four rows of prismatic elements. Turbulence in the first row was created by the input conditions and in the second, third and fourth rows - by the traces of the previous rows; flow separation occurred when flowing around the input edges of the elements.

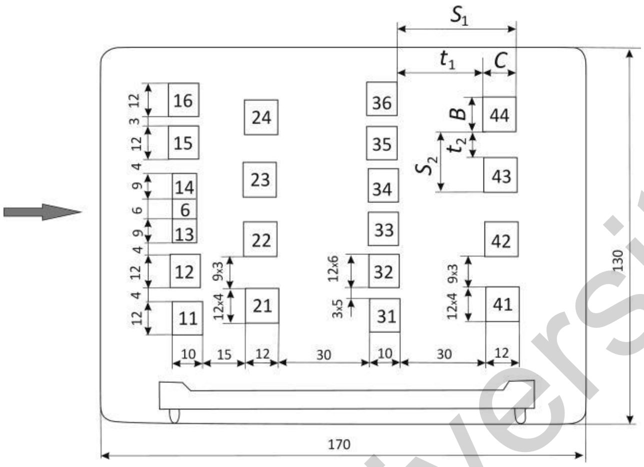

Fig.1. Flat surface with prismatic elements

The local approach for this part of the work is to determine the average surface heat transfer coefficient from the local velocity measured over each prismatic element. The analysis of the results showed that the intensity of the average heat transfer for the prisms located in positions 1 (prism No. 23) and 2 (prism No. 43) is different, which is associated with the aerodynamic features of their flow. The average heat transfer of the last row of prisms is less intense than for the first three rows. Thus, when constructively developing a flat surface with prismatic elements, the most heat-stressed of them should be located in conditions of maximum heat removal. In this case, such conditions turned out to be the flow conditions 1. This is a very important practical conclusion. Similarity equations were proposed for calculating the local heat transfer of each face of the prism separately and the average surface heat transfer Tabl. 1.

Table 1. Recommendations for calculating the average heat transfer of a prismatic element and its faces in 1-3 rows gap-free installed on a flat surface in a stream

General view of the similarity equation	$\overline{Nu} = C\,\mathrm{Re}^n$			
Average heat transfer	Defining size	Heat exchange surface	C	n
The element as a whole	C	$\sum F$	0.536	0.6
The upper face	C	$C \times B$	0.536	0.6
The side face	C	$C \times h$	0.487	0.6
The frontal face	h	$B \times h$	0.75-0.89	0.5
The back face	h	$B \times h$	0.116	0.667

This approach allows us to single out the role of each face in the total heat transfer and leads to the fact that the total heat transfer coefficient practically coincides with the average heat transfer coefficient on the upper face. This allows us to estimate the spatial temperature heterogeneity of the layout and carry out measures to change the temperature in the required direction. The use of a local approach contributed to the implementation of a more accurate prediction of the reliability of electronic equipment components, taking into account their operating conditions in uneven temperature fields. Thus, the use of a local approach leads to a reduction in product development costs, allows for a more accurate selection of the required power for the cooling system, improves the design of equipment, and increases their reliability and service life [10].

4.2 Local approach for assessing the impact of flow separation

In the flow part of heat power equipment, conditions are often created that promote the occurrence of local closed separations. The occurrence of separations leads to a redistribution of heat transfer coefficients and a change in hydrodynamic resistance along the length of the working surfaces and is accompanied by significant disruptions in the structure of the thermal and hydrodynamic BL in the relaxation zones and the separation itself. Experiments using a local approach, conducted at the IET NAS of Ukraine, confirmed extremely slow recovery to" classical" turbulent boundary layer after various types of a separation with various rates of this gradual process, which made it possible to identify zones of "fast" and "slow" relaxation in the outer and inner parts of the BL. The separation "works" as a generator of external turbulence, because of which the length of the relaxation zone in the outer part of the BL is much greater than in the inner one. Moreover, the relaxation zone of the thermal BL is shorter than the hydrodynamic one due to the conservative reaction of the thermal BL to various disturbances, including separation.

A generalization of experimental data on heat transfer intensification confirmed the effectiveness of using turbulent viscosity to assess the transport properties of complex flows. Due to this approach, the turbulent viscosity at the outer boundary of the dynamic boundary layer in the section of reattachment $\nu_{t\delta r}/\nu$ is chosen as the main criterion determining, in the first approximation, the type of separation (laminar, transitional or turbulent) and its intensity. Laminar separation occurs at $\nu_{t\delta r}/\nu$=5, with increasing $\nu_{t\delta r}/\nu$ transitional separation occurs and, finally, at $\nu_{t\delta r}/\nu$>30 - turbulent separation. The value of this viscosity can be calculated based on the "energy-dissipation" turbulence model. For this purpose, it is advisable to use the decay law of longitudinal velocity pulsations at the outer boundary of the dynamic boundary layer developing behind the separation. In the first approximation, in the relaxation zone, the intensification of heat exchange can be described by the following equation:

$$St / St_o = f(\nu_{t\delta r} / \nu_{to}) \tag{1}$$

where St_o are determined by equation (2) for a turbulent boundary layer:

$$St_o = 0.0144 \cdot \mathrm{Re}^{**-0.25} \tag{2}$$

Equation (1) also contains the turbulent viscosity generated near the wall in the turbulent boundary layer, which can be calculated based on known recommendations:

$$\nu_{to} = 0.0168 \cdot U_e \cdot \delta^* \tag{3}$$

It should be noted that the choice of comparison conditions is very important when assessing the intensification of heat transfer and generalizing the experimental results. Relation (3) is recommended for the condition $Re^{**} = const$, the use of which is more acceptable for local representation of experimental data, when many uncertainties associated with the initial conditions are eliminated by using the momentum thickness δ^{**} as the determining dimension, rather than the current length x. The application of the local approach expanded the ideas regarding the non-traditional and sometimes unpredictable transformation of many important characteristics of the dynamic and thermal BL in the relaxation zone: distributions of friction and heat transfer coefficients, average velocities and temperatures, velocity and temperature pulsations at the outer boundary of the BL.

4.3 Local approach for assessing the impact of unsteady flow

It should be noted that there are different types of wake generators [11]. As already noted in the section "Materials and research methods", for modeling the unsteady flow with wake in this work such types of generators were installed in a wind tunnel: a still and hesitating cylinder, a still and rotating "squirrel" wheel. Based on the application of a local approach to determining the distribution of local heat transfer coefficients on a flat surface, the occurrence of a wake-induced laminar-turbulent transition initiated by stationary and moving wakes is confirmed. In this case, pre-transitional BL was pseudolaminar and characterized by substantial heat transfer growth in comparison with laminar boundary layer. By means of such wakes, it is possible to change the intensity of heat transfer in the pseudo laminar boundary layer up to 80%, while simultaneously controlling the location and length of the wake-induced transition.

As experimental results have shown, a peripheral shear zone and a non-uniform turbulence field characterize the external flow with periodic non-stationarity. To evaluate the characteristics of such an external flow, it was replaced by a shear equivalent and a method for separating the total pulsations into turbulent and non-stationary components was proposed. For dividing turbulent and nonstationary components the additional measurement was conducted after still "squirrel cage". The method of dividing was based on two following assumptions: 1. rotation does not substantially influence on turbulent component; 2. energies of disturbances of different nature are not correlated, i.e. $\overline{u_e'^2} = \overline{u_t'^2} + \overline{u_n'^2}$.

The distributions of total fluctuations (u_e') including turbulent (u_t') and nonstationary (u_n') components differ by peaks (fig.2), amplitude of which decreases downflow. As shown at fig.3 the decay law of averaged total fluctuations $u_e'/U_e = f(x)$ was similar to the one after traditional still grids widely used for generation of turbulence in aerodynamic tubes. The values of total fluctuations changed from $u_e'/U_e \approx$ 15% to $u_e'/U_e \approx$ 4.3% at x=50 and 600 mm respectively.

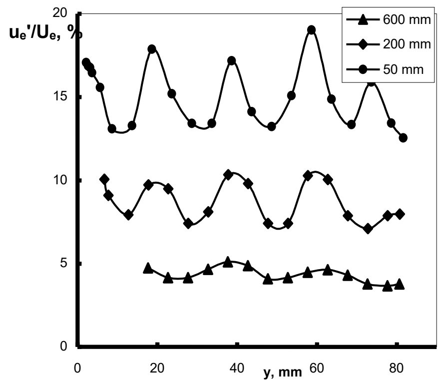

Fig.2. Total velocity fluctuations behind rotating "squirrel cage"

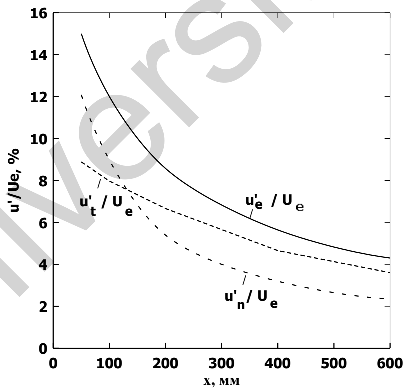

Fig.3. Distribution of components of velocity fluctuations

The decay law of total energy of longitudinal velocity fluctuations of shearless equivalent permits to estimate the transport properties of turbulized flow in the working part of aerodynamic tube. For that, it is possible to use the traditional form of decay laws behind stationary generators of turbulence:

$$\frac{U_e^2}{\overline{u_e'^2}} = A(x + x_0)^m , \quad (4)$$

where the exponent values (m) usually are chosen in the range of m =1,2-1,4, while virtual distance (x_0) and coefficient (A) are determined in the results of experimental investigations. On the base of decay law (4) it is possible to calculate the kinetic energy of fluctuations, their dissipation and characteristic scale as well as to estimate turbulent viscosity of turbulized flow ν_{te} in the frames of "energy – dissipation" turbulence model. Preliminary calculations show that values of the latter change from $\nu_{te} \approx 2{,}7.10^{-3}$ to $\nu_{te} \approx 1{,}4.10^{-3}$ м^2/c along the length of working part, i.e. exceed values of molecular viscosity almost into 200 times at x =50 mm.

The analysis of the obtained results (Fig. 3) demonstrates that the non-stationary component decreases significantly faster than the turbulent one. In the initial sections of the plate, the main contribution to the longitudinal fluctuations in the external flow is made by the non-stationary component, while in the middle and final sections of the plate, the turbulent component became prevailing. The revealed fact is important from a practical point of view, since it allows one to control the intensity of transfer processes using separately the parameters of non-stationarity (frequency, amplitude) or turbulence. The application of the local approach allows one to calculate the kinetic energy of fluctuations, dissipation and characteristic scale, and to estimate the turbulent viscosity of a turbulized flow with periodic non-stationarity. These data are necessary for calculating transfer processes in flows with periodic non-stationarity, for example, in turbomachines, based on turbulence models.

4.4 Local approach to improving the coolant supply system

Another example of the local approach application to the control of transfer processes in heat power equipment was the work to improve the aerodynamic characteristics of the coolant supply system in the technology of final drying and technological conditioning of plant materials [9]. The design of the full-scale installation was preceded by an aerodynamic calculation of the coolant supply system. However, as further tests showed, this calculation did not sufficiently take into account the influence of the installation structural elements on the hydrodynamic structure of the flow. To improve the aerodynamic characteristics of the coolant supply system, studies were conducted on a specially manufactured experimental model of the installation, which completely reproduces the operating conditions of a full-scale installation in terms of geometric parameters and air supply system (Fig. 4). The main difference was that the experiments were carried out without heating the coolant (air) and with a fixed working line.

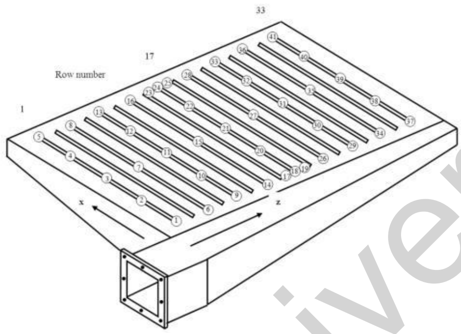

Fig. 4. Scheme of air supply to the working line

The processed plant material is placed on a fixed working line, which is a thin metal plate perforated with holes. The working line is blown with vertical air jets flowing from the system of longitudinal slots. The non-uniformity of the flow velocity field as well as the degree of turbulence were estimated based on the results of measurements at characteristic points of the working space. The results of the experiments confirmed that the initial design of the installation does not satisfy the optimal parameters of the coolant supply system. For this installation, the recommended values are U_{av}~0.5-0.8 m/s with a permissible degree of non-uniformity of velocity field 0.6-1.8.

Specific measures are proposed to improve the design of this system, namely: significant changes have been made to the size of the slots; the sections of the slots are partially covered at the ends of the rows; minimized leakage in the distribution box and others. As a result of these measures in final modification the velocity field non-uniformity coefficient k changed by no more than ~1.8 at an average velocity U_{av}=0.77 m/s (Fig. 5a). Thus, a significant improvement in the velocity field was observed both along the rows and along their length. The measurement results also showed that in final modification there is an increase in the degree of flow turbulence, reaching at some points u'/U = 52% at an average level of ~30% (Fig. 5 b).

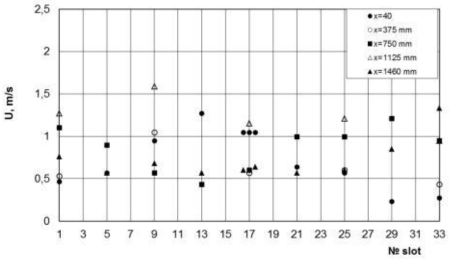

Fig.5a. Velocity distribution in final modification

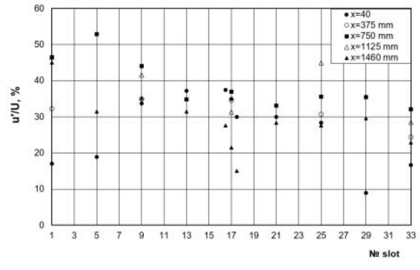

Fig.5b. Longitudinal pulsations distribution in final modification

An increase in both the average flow velocity of the coolant and its degree of turbulence contributes to the intensification of the heat and mass transfer process. This will improve the quality of the product and reduce the drying time. Analysis of the results of these studies allows us to develop a more rational design option for a full-scale installation. The use of the local approach consisted in estimating the value of average velocities and non-uniformity in local velocity distributions, as well as determining the degree of flow turbulence at characteristic points of the working space. Aerodynamic improvement of the coolant supply system contributes to the intensification of heat and mass transfer, and, as a result, increases productivity while reducing the time of the final drying process of plant raw materials.

5. Conclusion

The article presents a generalized study of a local approach application to assessing transfer processes in heat power equipment for various purposes. The advantage of the local approach is the possibility of fixing the thermophysical parameters of the process in any characteristic zone of the working space. Based on the data obtained, methods for calculating complex flows were developed and methods for monitoring and controlling work processes in heat power equipment were improved.

The scientific novelty and practical significance of the application of the local approach is as follows:

1) To generalize data on heat transfer intensification using turbulent viscosity in assessing the transport properties of complex flows.

2) The reason for the formation of a pseudolaminar boundary layer is formulated, which is caused by the simultaneous manifestation of two mutually related processes: selective penetration of turbulent pulsations from the external flow into the boundary layer (BL) and the development of powerful pulsations inside the BL itself.

3) The reasons for the significantly faster intensification of heat transfer in a pseudolaminar boundary layer compared to friction are substantiated.

4) Methods for predicting the type of flow in the boundary layer and determining the coordinates of the bypass laminar-turbulent transition region have been developed.

5) Conditions for controlling the most dangerous heat-stressed areas during the development of mixed flow regimes are created.

6) A bank of new experimental data on the intensity of the processes occurring for a flat surface with prismatic elements has been obtained, which allows taking into account the spatial unevenness of the temperature field and organizing measures to eliminate the unevenness.

7) To obtain many important characteristics of the dynamic and thermal BL in the relaxation zone, which can be used in the development of promising engineering and numerical methods for calculating complex flows in heat power equipment.

8) To justify the possibility of controlling the location and length of the wake-induced transition using stationary and moving wakes.

9) To evaluate the turbulent viscosity of a turbulent flow with periodic non-stationarity for the development of numerical methods for calculating flow transfer processes in heat power equipment.

10) To improve the aerodynamic characteristics of the coolant supply system, to ensure the required quality of material processing while reducing the time for the final drying process of plant raw materials.

Conflict of interest statement
The author declares that she has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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