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Article

Experimental Evaluation of Gas-Dynamic Conditions of Heat Exchange of Stationary Air Flows in Vertical Conical Diffuser

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Abstract: Conical diffusers are widely used in technical devices (gasifiers, turbines, combustion chambers) and technological processes (ejectors, mixers, renewable energy). The perfection of flow gas dynamics in a conical diffuser affects the intensity of heat and mass transfer processes, the quality of mixing/separation of working media and the flow characteristics of technical devices. These parameters largely determine the efficiency and productivity of the final product. This article presents an analysis of experimental data on the gas-dynamic characteristics of stationary air flows in a vertical, conical, flat diffuser under different initial boundary conditions. An experimental setup was created, measuring instruments were selected, and an automated data collection system was developed. Basic data on the gas dynamics of air flows were obtained using the thermal anemometry method. Experimental data on instantaneous values of air flow velocity in a diffuser for initial velocities from 0.4 m/s to 2.22 m/s are presented. These data were the basis for calculating and obtaining velocity fields and turbulence intensity fields of the air flow in a vertical diffuser. It is shown that the value of the initial flow velocity at the diffuser inlet has a significant effect on the gas-dynamic characteristics. In addition, a spectral analysis of the change in air flow velocity both by height and along the diffuser axis was performed. The obtained data may be useful for refining engineering calculations, verifying mathematical models, searching for technical solutions and deepening knowledge about the features of gas dynamics of air flows in vertical diffusers.

Keywords: conical flat diffuser; stationary air flow; velocity field; turbulence intensity field; spectral analysis; thermal anemometry method

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1. Introduction

Conical diffusers of various designs are widely used in technical devices (for example, channels and flow sections in hydraulic turbines [1], the working space of flow gasifiers [2] and other machines and devices) and technological processes (ejectors for separating steam and air [3], separators for separating liquid droplets from a steam flow [4], wind energy recovery [5] and other technologies). The design features and perfection of the gas dynamics of a liquid or gas flow in a conical diffuser affect the intensity of heat and mass transfer processes, the quality of mixing/separation of working media and the flow characteristics of technical devices. These parameters largely determine the efficiency and productivity of the final product. Therefore, the experimental study of the gas dynamics of air flow in a conical diffuser remains an important and pressing problem for the development of science and technology.

Many scientists and specialists study the features of physical processes in conical diffusers from various points of view [6–10]. Thus, Mfon S.A. et al. developed an original mathematical model for assessing and predicting the pressure drop in a conical diffuser for various flow parameters and for various geometric dimensions of the diffuser [6]. The proposed method quickly and accurately determines the pressure drop coefficient of the diffuser for various boundary conditions. Teshnizi E.S. and Momeni F. proposed a new analytical method for calculating the turbulent boundary layer in diffusers to analyze and predict the flow separation point [7]. The proposed method may be useful for designing devices with conical diffusers. Mamoudou A. et al. created a mathematical model to estimate the distribution of the flow temperature field inside the diffuser for different geometric dimensions and initial conditions [8]. The main objective of this study was to obtain the most uniform temperature field in the diffuser for use in a drying chamber. Zhou X. et al. developed an original diffuser design for the Francis turbine to smooth out (soften) flow pressure fluctuations [9,10]. The selection of the optimal shape for the conical diffuser resulted in a decrease in the amplitude of the flow pressure fluctuations by 18.6% compared to the basic design of the gas-dynamic system. Accordingly, the determination and prediction of the parameters of liquid and gas flows is a key factor in the process of creating highly efficient machines and devices with conical diffusers.

Scientists and specialists often use methods of swirling or turbulizing the flow in a conical diffuser to intensify heat and mass transfer and to improve the processes of mixing/separating working media in gas-dynamic systems with a diffuser [11–14]. Liu Z. et al. studied the influence of diffuser geometry on the gas dynamics of swirling air flow (the flow was swirled by an axial swirler) using an optical method (PIV method) [11]. The authors obtained detailed data on the gas-dynamic characteristics of the flow with an emphasis on the evolution of the precessing vortex core. Buron J.-D. et al. performed a similar study inside a draft diffuser tube in relation to a turbine [12]. The obtained results improve engineering methods for calculating diffusers and create more efficient power devices. Modern approaches based on machine learning algorithms are actively used to analyze and predict flow characteristics in conical diffusers [13,14]. The authors created tools for predicting the profiles of the average velocity, kinetic energy of turbulence and frequency response of swirling flows in diffusers for different boundary conditions based on experimental data, mathematical modeling and machine learning. This direction of scientific research is popular and rapidly growing today. Additional research results on this topic are given in articles [15–17]. Thus, swirling the flow in front of the diffuser is an effective method for intensifying thermophysical processes both inside the diffuser and downstream from it.

There are scientific and technical studies on the development of methods for controlling the gas dynamics of flows in conical diffusers to optimize thermogas-dynamic processes in machines and devices [18–20]. Yang J. et al. used a Karman-vortex generator to reduce flow separation in conical diffusers with large opening angles (more than 18 degrees) [18]. This made it possible to avoid early flow separation (collapse) in the expanding section of the diffuser. Shukri Askari E.S. et al. used a spiral ribbon insert in a diffuser to create additional flow recirculation [19]. This contributed to a significant improvement in the distribution of air flow velocity throughout the volume of the conical diffuser. Plotnikov L. and Ryzhkov A. proposed various designs of inlet channels to control the air flow structure in a conical diffuser [20]. The design (in particular, the cross-section shape of the inlet channel) has a significant effect on the flow velocity field in the diffuser and cylindrical section. Accordingly, the development of active and passive methods for controlling the gas-dynamic flow structure in conical diffusers remains a promising and technologically advanced task in science and technology.

Fine-tuning the design (opening angle, diameter, length, degree of displacement, etc.) of the diffuser is also a pressing issue among scientists and specialists to improve the efficiency of technical and technological devices [21–23]. Kale S.A. et al. studied the influence of the diffuser diameter (from 0.6 to 6.0 m) on the gas-dynamic and consumable characteristics of the flow for a constant velocity of 6.5 m/s [21]. Yan Y. et al. studied the influence of a set of geometric dimensions of a conical diffuser on gas dynamics and performance [22]. Mihailowitsch M. et al. refined the design of the turbine outlet diffuser to improve flow characteristics and increase the efficiency of the turbine [23]. The geometric dimensions of the conical diffuser have a noticeable effect on the integral gas-dynamic characteristics of the flows. Therefore, the design of the diffuser must be calculated and selected very carefully for each specific case, taking into account both the purpose and objectives of operation.

The properties of the working media also have a noticeable impact on the gas-dynamic, consumable and heat-exchange characteristics of flows in conical diffusers [24–27]. Benavides-Moran A. and Lain S. studied the detailed gas-dynamic characteristics of gas and solid particles in a vertical conical diffuser for different boundary conditions based on mathematical modeling [24]. The main goal was to create the most uniform distribution of solid particles in the diffuser volume. Chou Y.-W. and Liao C.-C. also modeled the distribution of solid particles inside a conical diffuser [25]. The aim of the study was to find the diffuser geometry and flow parameters required to eliminate the accumulation of particles in the corners of the diffuser. There are also studies of flow characteristics for working media in the form of incompressible fluid [26] and nanofluids [27]. The physicochemical properties of fluids have a significant impact on the thermogas-dynamic characteristics of flows in conical diffusers.

The importance of further research into the gas dynamics and heat transfer of flows in conical diffusers is determined by its wide application in hydraulic turbines [28], gas turbines [29], Francis turbines [30], power plants based on the Organic Rankine Cycle [31], ventilation and air conditioning systems [32] and many other applications.

It should be emphasized that scientists do not pay enough attention to the detailed study of gas dynamics in diffusers based on experimental data. There is a small amount of work available to identify the physical mechanisms of the evolution of gas dynamics in vertical conical diffusers. This work is aimed at eliminating this problem. Thus, the objectives of this study are as follows:

- to create an experimental setup and select a measuring base for studying the gas dynamics of the air flow in a vertical, conical, flat diffuser;
- to obtain experimental data on the instantaneous values of the air flow velocity in a vertical diffuser for different initial conditions;
- to describe the distribution of the velocity fields in a vertical diffuser for different boundary conditions;
- to present the turbulence intensity fields of the air flow in a vertical diffuser for different initial conditions;
- to obtain the dependences of the change in turbulence intensity along the downstream diffuser axis for different initial velocities at the inlet;
- to perform a spectral analysis of the change in the local flow velocity over time along the height of the vertical diffuser for different boundary conditions.

The scientific novelty of this study consists in establishing the patterns of evolution of the gas-dynamic characteristics of stationary flows in a vertical, conical, flat diffuser for different boundary conditions. The data obtained can be used to verify mathematical models and design diffusers for various technical applications.

This article has a classic structure: (1) an introduction with a brief overview of the current state of research; (2) a description of the measurement methods and tools, and the formulation of the research problem; (3) the research results, analysis and discussion; (4) a conclusion with the key findings; and (5) the literature references.

2. Statement of the Research Problem and Measurement Tools

The experimental setup was designed and manufactured to study the gas-dynamic characteristics of stationary flows in a vertical flat diffuser (Figure 1).

The main elements of the experimental setup were as follows: (1) a blower for creating air movement in the gas-dynamic system with the ability to control consumable characteristics by changing the rotation frequency of the blower rotor; (2) a receiver for equalizing and stabilizing the flow after the centrifugal blower; (3) a vertical conical diffuser with holes for hot-wire anemometer sensors; and (4) an automated measuring system based on a constant-temperature hot-wire anemometer, an analog-to-digital converter, and specialized software. The receiver had a volume of about 0.04 m^3 with a leveling grid inside. The receiver served to reduce the amplitudes of the pulsations of the speed and pressure of the flow after the centrifugal blower. The stabilized air flow entered the vertical diffuser.

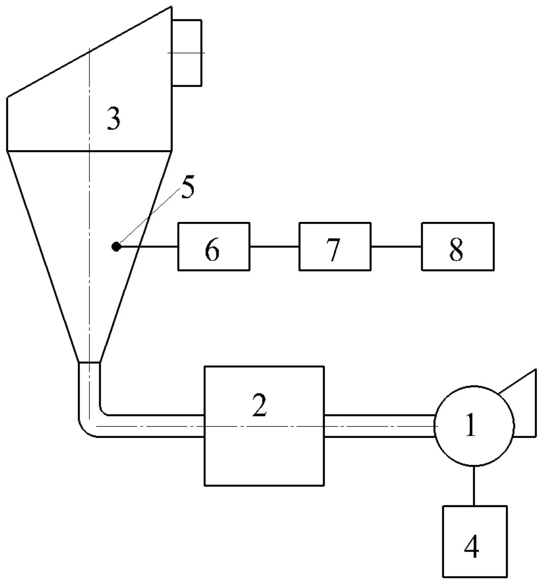

Figure 1. Experimental setup diagram: 1—air blower; 2—receiver with equalizing grate; 3—vertical conical diffuser; 4—frequency converter (air flow control through the system); 5—hot-wire anemometer sensor for measuring air flow velocity; 6—constant-temperature hot-wire anemometer; 7—analog-to-digital converter; 8—computer with specialized software.

The geometry of the vertical diffuser under study and its photograph are shown in Figure 2a,b.

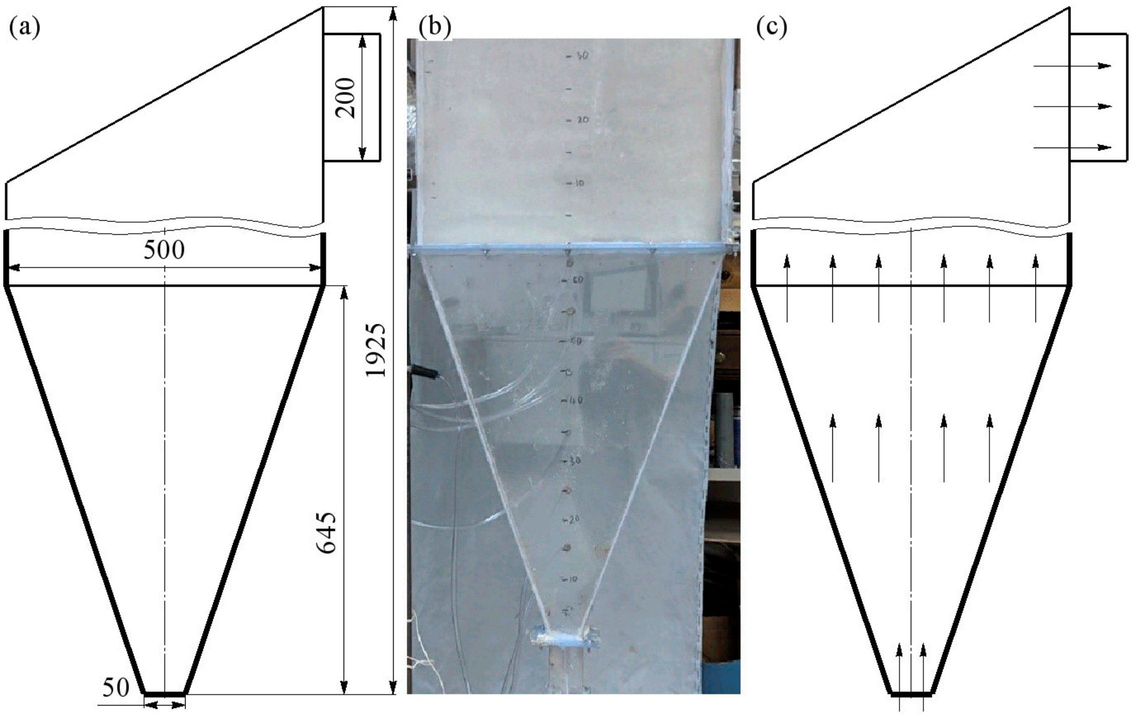

Figure 2. The main geometric dimensions of the diffuser under study (**a**), its photograph (**b**) and the approximate direction of air flow in the diffuser (**c**).

The main geometric dimensions of the diffuser were as follows: the height of the diffuser was h = 645 mm, the height of the straight section was 1280 mm (the total height of the installation was H = 1925 mm), the width of the inlet section was 50 mm, the width of the straight section was L = 500 mm, and the thickness of the installation was 20 mm. Accordingly, the cross-section of the air inlet channel into the diffuser was a rectangle with sides of 50 mm and 20 mm. The main elements of the stand (diffuser) were made of transparent polystyrene with a wall thickness of 2 mm.

The approximate movement of the air flow in the diffuser is shown in Figure 2c. It should be noted that the air exited the diffuser from the right side of the straight section of the installation and not vertically upwards. The size of the outlet section was 200 mm (the thickness was also 20 mm).

The design and geometric dimensions of the experimental setup were chosen based on the potential application of the results of this study to a flow gasifier, i.e., a device for producing synthetic gas from wood waste. This device has the same geometric dimensions but is made in a three-dimensional (volumetric) configuration.

The air flow velocity at the diffuser inlet varied from 0.4 m/s to 2.22 m/s, which corresponded to Reynolds' numbers from 750 to 4160. These flow regimes also correspond to the flow velocities in the designed in-line gasifier for synthetic gas production. The industrial gasifier has similar geometric, speed and regime characteristics to air flow during operation [33]. Therefore, it is impractical to investigate higher initial flow velocities in the diffuser. Accordingly, the laboratory results can be transferred to a real-life sawdust gasification plant. Air with a temperature of 22 °C was used as the working medium in these studies. The problem statement was isothermal, i.e., the air temperature was constant during the experiments.

The main components of the measuring system are shown in Figure 3. The gas-dynamic characteristics of the air flow in the diffuser were assessed using the thermal anemometry method [34,35]. Constant-temperature hot-wire anemometer IRVIS TA-5.1 (Kazan, Russia) with a single-filament sensor was used for these purposes. The main technical characteristics of the constant-temperature hot-wire anemometer are presented in Table 1. The analog signal from the sensor was fed to the analog-to-digital converter LCARD E14-300 (Moscow, Russia) for transformation into a digital code. The analog signal was recorded at a frequency of 3 kHz. Digital signals from the analog-to-digital converter were processed in specialized software LGraph2 version 2.35.20 (Moscow, Russia). The digital signal was visualized in real time and also stored in tabular form in the specified program. The data in tabular form could be exported to various programs for processing, analysis and visualization.

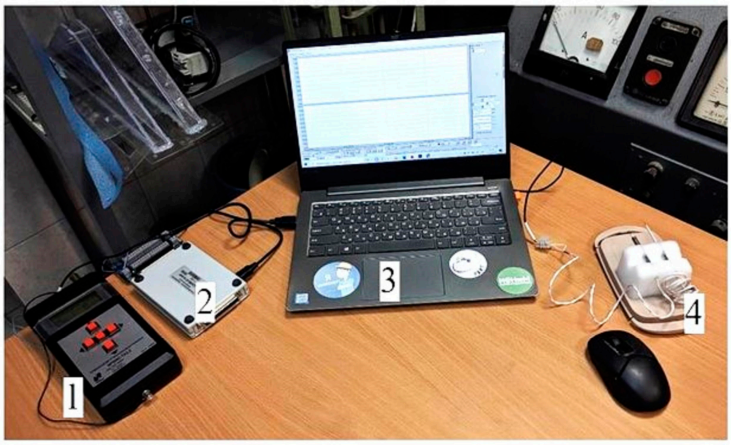

Figure 3. Main elements of measuring system based on thermal anemometry method: 1—constant-temperature hot-wire anemometer; 2—analog-to-digital converter; 3—computer with specialized software; and 4—hot-wire anemometer sensors.

Table 1. The technical characteristics of the hot-wire anemometer.

Hot-Wire Anemometer Parameter	Quantitative Value of the Parameter
Power consumption, W	5
Output signal of the hot-wire anemometer channel, V	0. . .5
Absolute pressure value of the measured medium, kPa	83.7. . .1600
Average flow velocity measurement range, m/s	0. . .100
Frequency characteristics of the hot-wire anemometer channel, kHz	10
Ambient air temperature, °C	0. . .+45
Relative humidity, % at a temperature of 35 °C	no more than 95%
Barometric pressure, kPa	84. . .106.7
Overall dimensions, mm	195 × 100 × 40
Weight of the device, kg	0.5

The determination of experimental uncertainty in measuring instantaneous air flow velocities is based on taking into account the errors of the following devices: a barometer with an error of 0.1%, a thermocouple with an error of 1.0%, a micromanometer with an error of 2.5%. The relative uncertainty of air flow velocity measurement w was 4.8%. The uncertainty is given by taking into account the calibration error (1.1%) and then converting the analogue signal into a digital code (2.2%). The measuring system was regularly checked.

The design of the single-thread constant-temperature hot-wire anemometer sensor and the method of its installation in the diffuser are shown in Figure 4. The sensor's sensitive element (thread) was made of tungsten and had a length of 4 mm and a diameter of 4 μm. The thread (sensitive element) of the sensor was positioned perpendicular to the incident flow. The sensor thread was located in the middle of the flat diffuser. The small dimensions of the sensor and sensitive element made it possible to avoid significant flow deformation in the measuring zone.

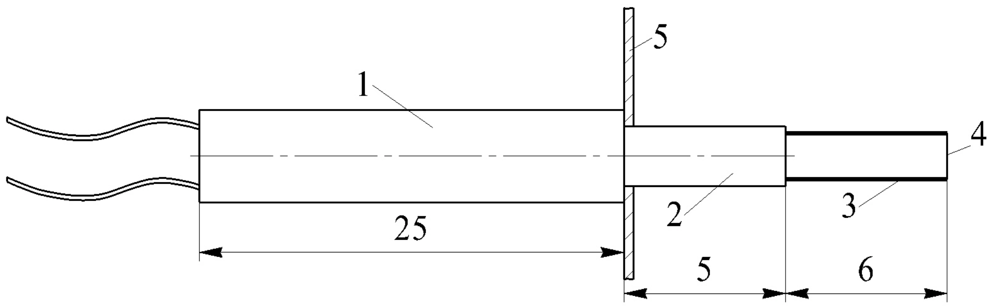

Figure 4. Design of single-thread constant-temperature hot-wire anemometer sensor for determining air flow velocity: 1—sensor base; 2—ceramic insert; 3—conductive holder; 4—thread (sensitive element); and 5—vertical diffuser.

The diameter of the ceramic insert in the sensor was 2 mm, the diameter of the holder was 0.5 mm and the diameter of the thread was 4 μm. One sensor was installed sequentially at each measuring point. Thus, the miniature dimensions of the sensor and the sensitive element did not introduce significant changes in the gas dynamics of the flow in the diffuser.

The installation locations of the hot-wire anemometer sensors for measuring the air flow velocity in the diffuser are shown in Figure 5. The measurements were carried out in the diffuser section of the experimental setup (Figure 5). The first control section for height was located at a height of h = 50 mm from the inlet section of the diffuser. The distance between the sensors was l = 32 mm in this section. The distance between the sensors along the width of the diffuser starting from a height of 150 mm was l = 50 mm and the step in height was h = 100 mm. The distance from the extreme point to the wall was 10 mm at heights of h = 50 mm; 150 mm; 250 mm; 350 mm; and 550 mm (not shown in the diagram).

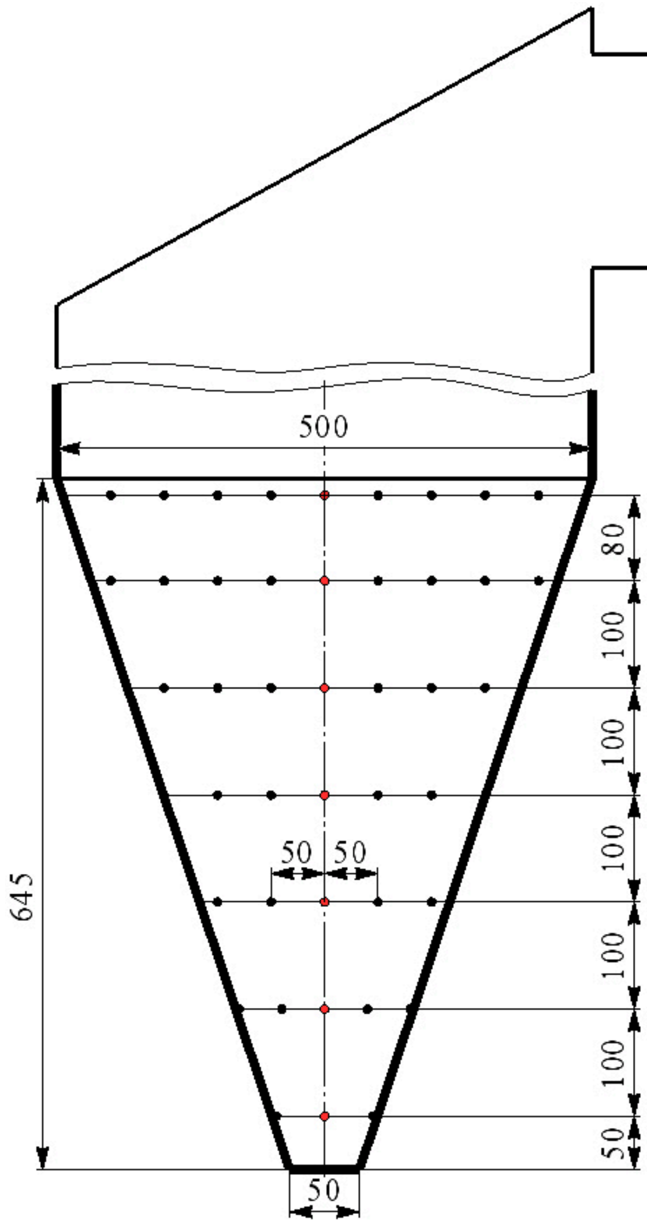

Figure 5. Installation locations for constant-temperature hot-wire anemometer sensors in flat vertical diffuser (43 measuring points).

The total number of measurement points was 43. Instantaneous values of air flow velocity w_x were determined at each point using the measurement system described above. Measurements were carried out sequentially in the stationary air flow mode. The average flow velocity w was calculated as the mathematical expectation of the function $w_x = f\ (\tau)$ for all 43 measuring points. The initial flow velocity w_o in the diffuser was calculated by determining the arithmetic mean of the velocities in the first control section (three measuring points at a height of h = 50 mm).

Spectral analysis of the functions $w_x = f\ (\tau)$ was carried out to clarify the gas-dynamic characteristics of the flow in the diffuser using the Scilab version 6.1.1 (France) program. Discrete Fourier transform was used. Each discrete frequency f_n was calculated using the following formula:

$$f_n = \frac{n}{N\Delta t}, \tag{1}$$

where N is the number of points in the studied data series; Δt is the time interval between two consecutive points in the data series; and n is the index that denotes the discrete frequency number ($n = 0, 1, 2, \ldots, N - 1$). The spectral component X_n for each frequency was calculated using the following formula:

$$X_n = \sum_{q=0}^{N-1} x_q \exp\left(-j\,\frac{2\pi n q}{N}\right), \quad (2)$$

where q is the number of the point in the data series ($q = 0, 1, 2, \ldots, N-1$); x_q is the point of the data series; and j is the imaginary unit.

The first half of the spectrum was considered, which corresponded to positive frequencies ($n \leq N/2$). The spectral component (2) was normalized by the following formula to obtain the signal amplitude (A_w):

$$A_w = \frac{2}{N} X_n. \quad (3)$$

The assessment of the pulsating component of the air flow was carried out by determining the turbulence intensity TI for each measuring point. TI was calculated as the ratio of the mean square pulsating component of the velocity to the average velocity of the flow under study. The method for calculating TI is described in detail in the article [36].

Thus, an experimental stand was created to study the gas-dynamic characteristics of a stationary air flow in a vertical, flat, conical diffuser. A measuring system with the required accuracy and speed was selected to obtain information about the gas-dynamic features of flows in the system under consideration. This design, including geometric dimensions and physical processes, is characteristic of flow gasifiers for wood waste.

3. Experimental Research Results, Analysis and Discussion

The changes in the instantaneous values of the air flow velocity w_x for time τ at different heights h for the installation of the hot-wire anemometer sensor and for different initial flow velocities w_o are presented in Figures 6 and 7.

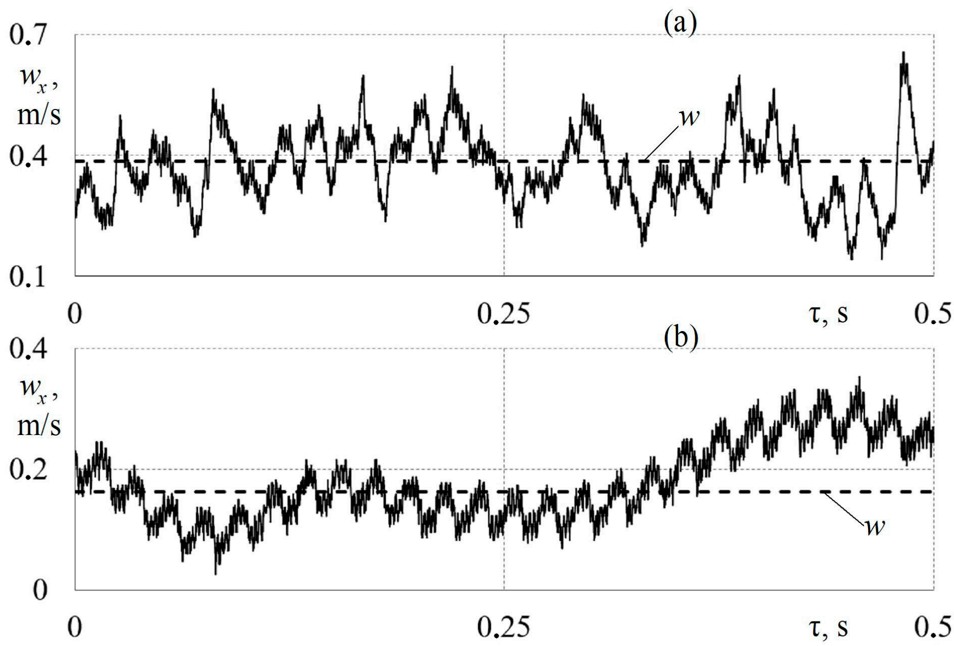

Figure 6. Dependences of instantaneous values of flow velocity w_x on time τ for initial w_o = 1.12 m/s in a vertical conical diffuser at different heights h (along diffuser axis): (**a**) h = 150 mm and (**b**) h = 450 mm (w is average flow velocity at measured point).

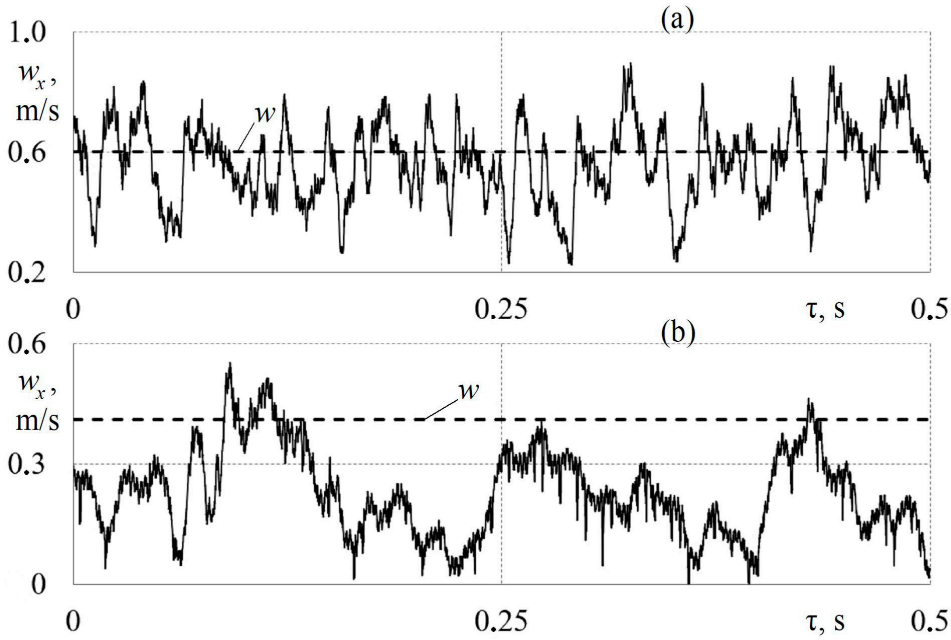

Figure 7. Dependences of instantaneous values of flow velocity w_x on time τ for initial w_o = 2.22 m/s in a vertical conical diffuser at different heights h (along diffuser axis): (**a**) h = 150 mm and (**b**) h = 450 mm (w is average flow velocity at measured point).

Figure 6a shows that the spread of the air flow velocity oscillation amplitude is up to 0.6 m/s for w_o = 1.12 m/s and h = 150 mm. At the same time, air flow velocity fluctuations are observed on the function $w_x = f$ (τ). In general, the function $w_x = f$ (τ) does not have a clearly expressed trend and is similar to white noise. The function $w_x = f$ (τ) is transformed downstream for h = 450 mm (Figure 6b). There is a decrease in the spread of the velocity fluctuations to 0.35 m/s. The velocity fluctuations become more orderly. There is also a decrease in the average flow velocity at the measurement points under consideration from 0.39 m/s (h = 150 mm) to 0.175 m/s (h = 450 mm).

An increase in the initial air flow velocity (w_o = 2.22 m/s) at the diffuser inlet causes a slight increase in the amplitude of the flow velocity oscillations to 0.7 m/s for h = 150 mm (Figure 7a). An increase in the initial flow velocity led to an increase in the flow velocity oscillations by 14% for h = 150 mm. Speed fluctuations are also observed in the $w_x = f$ (τ) dependencies, which is typical for all measurement points. The spread of the air flow speed fluctuations is 0.55 m/s for h = 450 mm (Figure 7b). Accordingly, an increase in the initial velocity from w_o = 1.12 m/s to w_o = 2.22 m/s causes an increase in the amplitudes of the w_x pulsations by 36%. This indirectly indicates an increase in large- and small-scale flow turbulence with an increase in the initial velocity w_o. Turbulization of the flow should have a positive effect on the heat and mass transfer processes in the vertical diffuser. In the applied aspect, turbulization of the flow can improve the mixing and combustion processes in the flow gasifier.

The velocity fields w were obtained by averaging the instantaneous values of w_x at each measurement point and the velocity fields in the vertical diffuser were obtained for different initial velocities to assess the evolution of the flow structure under different boundary conditions (Figure 8).

Figure 8a shows that the air flow moves mainly along the diffuser axis at an initial velocity of w_o = 0.4 m/s. It can be assumed that the location of the flow outlet does not affect the direction of air movement at low initial velocities w_o. This is since the flow energy is insufficient to set the trajectory of the air movement direction. Accordingly, the air flow is dispersed throughout the entire volume of the diffuser.

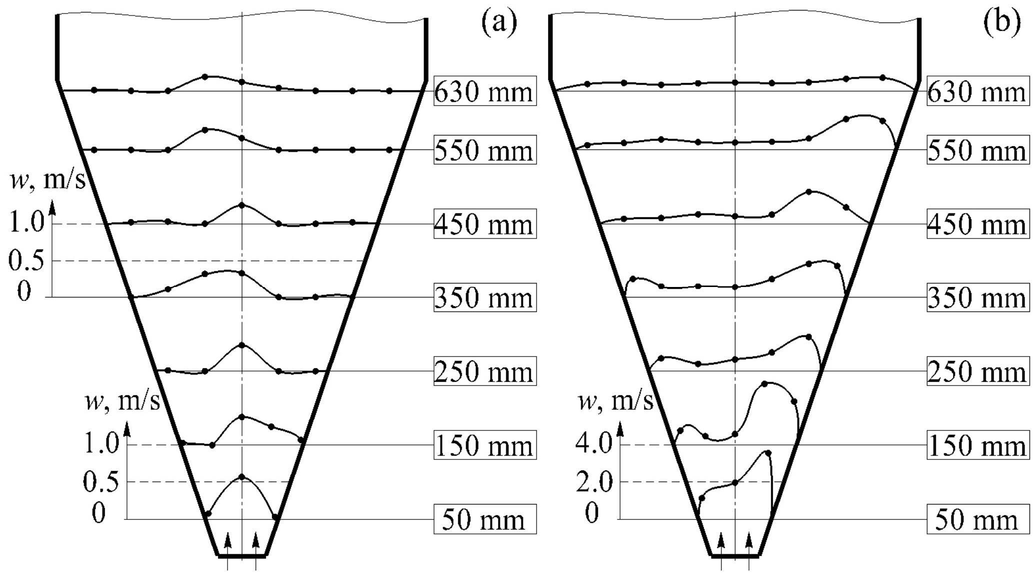

Figure 8. Velocity fields w of stationary air flows in vertical conical diffuser for different initial velocities w_o: (**a**) w_o = 0.4 m/s and (**b**) w_o = 2.22 m/s.

An increase in the initial velocity to w_o = 2.22 m/s causes a significant change in the air flow structure in the vertical diffuser under study (Figure 8b). There is a clearly expressed "sticking" of the flow to the right side of the diffuser. The flow movement along the right side of the diffuser is caused by the presence of an air outlet on this side. It should be noted that the gravitation of the main movement of the air flow is characteristic of all initial velocities under study except w_o = 0.4 m/s.

Velocity fields with their main movement along the right wall can have a negative effect on the uniformity of heat and mass exchange in the diffuser. This can lead to a deterioration in the mixing of working bodies in the flow gasifier and, accordingly, to a decrease in its efficiency and productivity.

The flow turbulence intensity TI was calculated at each measurement point based on the instantaneous velocity data w_x and the TI fields in the vertical diffuser were obtained based on these calculations (Figure 9).

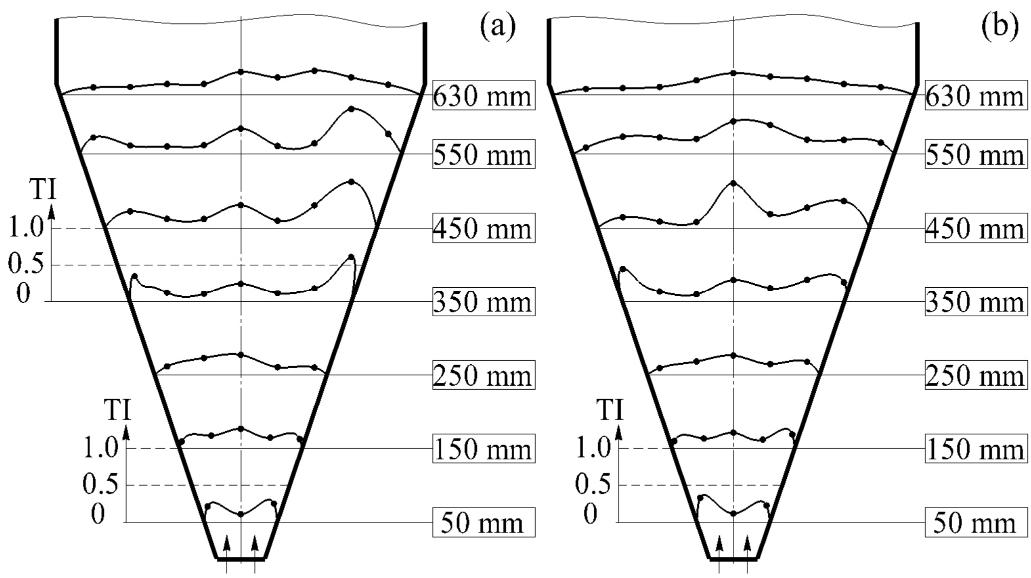

Figure 9. Turbulence intensity fields TI of stationary air flows in vertical conical diffuser for different initial velocities w_o: (**a**) w_o = 1.12 m/s and (**b**) w_o = 2.22 m/s.

The following conclusions can be drawn from the analysis of Figure 9a:

- a wide range of flow turbulence TI variation is observed from near-zero values to 0.9 in a vertical diffuser for a given initial flow velocity (w_o = 1.12 m/s);
- there is an increase in TI along the downstream diffuser axis;
- the highest TI values are characteristic of areas near the side walls and along the diffuser axis in control sections along the diffuser height.

It should be noted that the increase in the initial flow velocity w_o causes a noticeable change in the turbulence intensity field in the diffuser (Figure 9b). The following conclusions can be made based on the analysis of Figure 9b:

- the range of TI variation is from approximately zero values to 0.75 for w_o = 2.22 m/s (accordingly, it can be stated that the flow turbulence decreases by an average of 15% in the diffuser with an increase in the initial velocity of the supplied air);
- the TI fields have a more uniform distribution over the entire volume of the diffuser for w_o = 2.22 m/s compared to the fields for w_o = 1.12 m/s;
- there is no correlation between the velocity fields and the TI fields for the wo under consideration (comparison of Figures 8b and 9b);
- there is also an increase in TI along the downstream diffuser axis;
- the highest TI values are characteristic only of sections along the diffuser axis in the control sections along the diffuser height.

It is known that TI characterizes the level of small-scale turbulence in the gas flow and affects the quality of the mixing of working media, the amount of heat transfer and the intensity of heat exchange in various technical devices [37,38]. Accordingly, it can be assumed that the intensity fields of the flow turbulence in the vertical diffuser affect the efficiency of the flow gasifier and its productivity.

The dependences of the change in TI along the height of the studied vertical diffuser along its axis for different initial flow velocities were obtained to analyze more detailed information about the gas-dynamic characteristics of the flow (Figure 10).

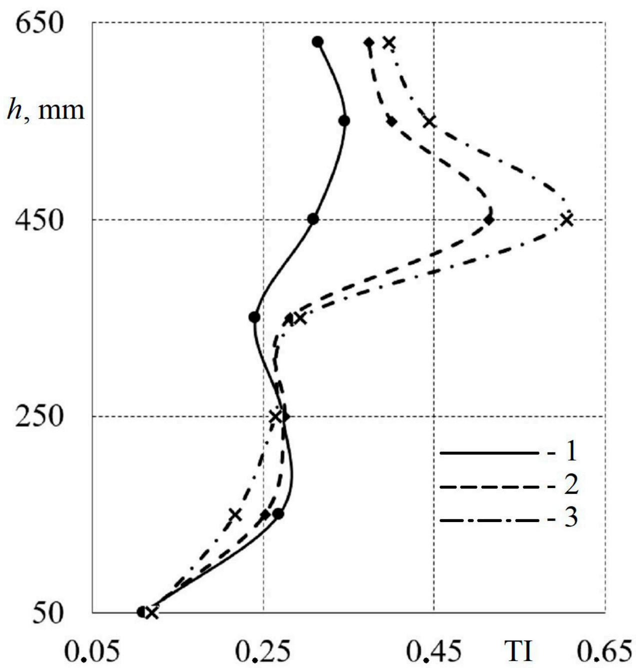

Figure 10. The dependences of the turbulence intensity TI of a stationary air flow along the diffuser height h (along the diffuser axis) for different initial velocities w_o: 1—w_o = 1.12 m/s; 2—w_o = 1.75 m/s; and 3—w_o = 2.22 m/s.

Figure 10 demonstrates that the change in TI along the height *h* and along the diffuser axis is nonlinear. At the same time, the initial flow velocity at the diffuser inlet has a significant effect on the TI values, which is especially characteristic at heights $h > 350$ mm. An increase in the initial velocity leads to a slight decrease in TI for $h < 250$ mm. The differences in TI values do not exceed 8% for *h* up to 250 mm. In turn, an increase in the initial velocity at the diffuser inlet causes a significant increase in TI in the range of 14 to 48% for $h > 350$ mm. The greatest differences are characteristic of $h = 450$ mm.

The obtained data can be used to find technical solutions for controlling the gas-dynamic characteristics of air flow to improve the heat and mass exchange of working media in a vertical diffuser (for example, as applied to a flow gasifier). For example, it is known that the level of air flow turbulence affects the position and parameters (length, opening angle, etc.) of the flame in diffuser-type combustion chambers [39]. The obtained data are also used to improve the design of a flow gasifier with similar geometric dimensions and similar boundary conditions [33]. Moreover, the revealed patterns are applicable to other technical devices with similar diffuser designs.

Spectral analysis of the functions $w_x = f\ (\tau)$ along the height and along the diffuser axis was performed to clarify the gas-dynamic characteristics of the air flow (Figure 11). The dominant frequencies and their amplitudes were identified based on the obtained spectrograms (Figure 12).

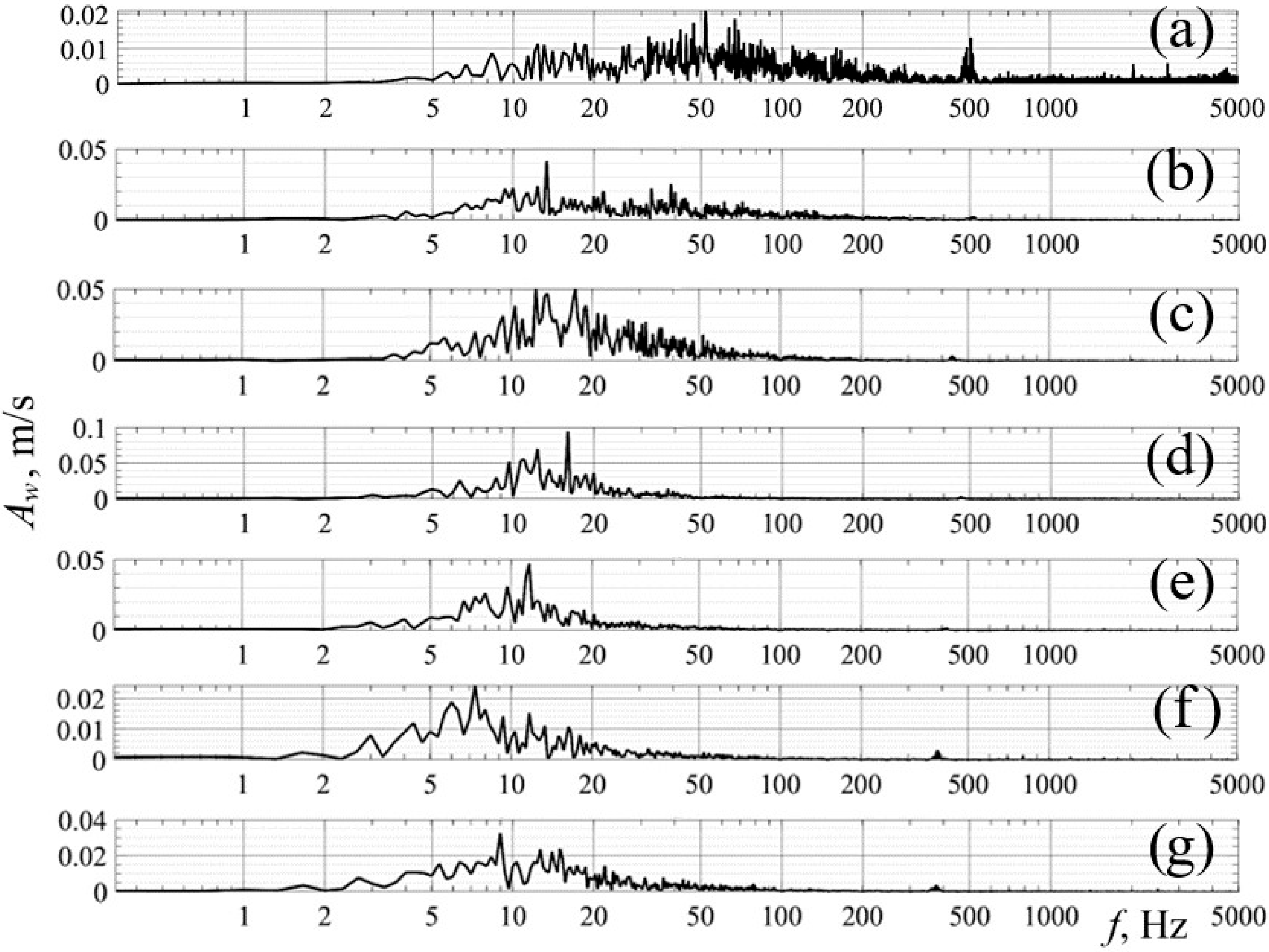

Figure 11. Graphs of the amplitudes of air flow velocity spectrum A_w at different heights *h* of diffuser (along diffuser axis) for initial velocities w_o = 2.22 m/s: (**a**) h = 50 mm; (**b**) h = 150 mm; (**c**) h = 250 mm; (**d**) h = 350 mm; (**e**) h = 450 mm; (**f**) h = 550 mm; and (**g**) h = 630 mm.

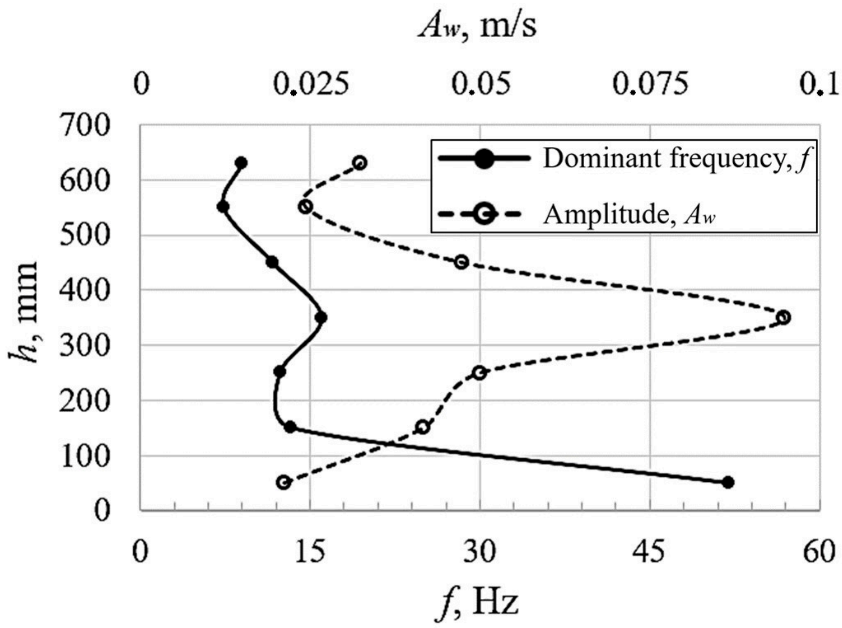

Figure 12. Dominant frequencies f (solid line and filled markers) and their amplitudes A_w (dashed line and hollow markers) at different heights h of diffuser (along diffuser axis) according to spectrograms in Figure 11.

The graphs of the spectrum amplitudes of the function $w_x = f\ (\tau)$ at all heights have a similar pattern (except for h = 50 mm), with a prevalence of frequencies of 5–20 Hz in the spectrum (Figure 11). This indicates the prevalence of large-scale turbulent structures, the sizes of which are comparable with the characteristic sizes of the flow or channel. This also indicates the presence of reverse flow or recirculation zones in the area of the diffuser axis. Indeed, the peaks of the flow velocity profiles are located to the right of the diffuser axis, which means that the flow core also passes to the right of the axis (according to Figure 8b).

The spectrogram for the height h = 50 mm is notable for the fact that the spectrum of the predominant frequencies is much wider and lies in the range of 5–200 Hz, as well as in the vicinity of 500 Hz. This indicates the mutual coexistence of large- and small-scale structures in the flow with a clear predominance of the latter. Indeed, the point under consideration is located at the inlet section of the diffuser. Therefore, large-scale turbulence has not yet formed in this area, but small vortices have already been generated. Accordingly, the turbulence intensity has decreased, and the frequency spectrum has shifted to a higher-frequency region. The flow core partially passes through the point under consideration at a height of h = 50 mm (according to Figure 8b).

Figure 12 shows that the dominant frequency f decreases from 52 Hz at h = 50 mm to 9 Hz at h = 630 mm (except for the point at h = 350 mm with the dominant frequency f = 16 Hz, which is out of the general trend). This indicates that there is an increase in the length scale of the turbulent structures downstream, which can contribute to the intensification of the heat and mass transfer processes in machines and devices with a conical diffuser. The amplitude of the velocity pulsations A_w increases from 0.021 m/s at h = 50 mm to a maximum of 0.095 m/s at h = 350 mm. The peak value of the amplitude may be due to the development of hydrodynamic instabilities associated with the strongest recirculation. Indeed, the highest velocities w and turbulence intensities TI are observed at a height of h = 350 mm at the extreme left points (except for the extreme left points at a height of h = 50 mm) according to Figures 8b and 9b. A decrease in amplitude is observed for h > 350 mm, which may be associated with a further dissipation of turbulence and a decrease in the intensity of large structures. A decrease in large-scale turbulence may lead to the deterioration of heat and mass transfer processes. The influence of gas flow dynamics on the characteristics of mass transfer, mixing and combustion processes is shown in [40,41].

There are stable relationships between the flow parameters, mixing features of working media and flame characteristics for various technical devices.

The obtained data refine the knowledge base on gas-dynamic conditions of heat exchange in a vertical, conical, flat diffuser and can be used in various technical devices to find engineering solutions to improve its performance and efficiency.

4. Conclusions

The key findings of this study are as follows:

- the experimental data on the instantaneous values of air flow velocity in a vertical, conical, flat diffuser for different initial conditions using the thermal anemometry method were obtained;
- the fields of averaged velocities in a vertical diffuser for different boundary conditions were presented, where the initial flow velocity had a noticeable effect on the velocity distribution in the vertical diffuser;
- the turbulence intensity fields TI in the vertical diffuser were presented; the TI values had a wide range of variation from 0.05 to 0.92; an increase in the initial flow velocity (from 0.4 m/s to 2.22 m/s) caused a drop in TI by an average of 15%; and the value of the initial flow velocity modified the turbulence intensity fields in the vertical diffuser;
- the change in TI along the downstream diffuser axis was shown, where the dependence TI = f (h) was nonlinear and was determined by the initial flow velocity;
- the spectral analysis of the function $w_x = f$ (τ) along the vertical diffuser height was performed. The dominant frequencies of the velocity pulsations f decreased from 52 Hz at h = 50 mm to 9 Hz at h = 630 mm. This indicates the predominance of large-scale turbulent structures downstream. The amplitudes of the velocity pulsations A_w at the dominant frequencies increased from a minimum of 0.021 m/s at h = 50 mm to a maximum of 0.095 m/s at h = 350 mm. This is due to the development of hydrodynamic instabilities and recirculation zones. The amplitude decreased due to turbulence dissipation for h > 350 mm.

The obtained data can be used in various fields of science and technology to refine the design methods of devices with vertical conical diffusers. The described results also deepen the database on the gas-dynamic characteristics of flows in a vertical diffuser. The described results capture the relationship between the initial flow velocity, the turbulence intensity and the frequency spectrum of pulsations. This data is necessary to improve the methods of calculation and the design of diffusers for various purposes.

Directions for further research on this topic include studying the gas dynamics of flows in a three-dimensional vertical diffuser, creating a physical and mathematical model, and obtaining data on the flow structure using an optical method—the PIV method. The development of active and passive methods (technical solutions) for controlling the gas dynamics of flows in a vertical diffuser is also a possible scientific task related to this topic.

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