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Construction of autonomous buildings with wind power plants

Строительство автономных зданий с ветроэнергетическими установками

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Ключевые слова: ветроэнергетика; ветроэнергетические установки; увеличение коэффициента использования энергии; эффективные преобразователи; здания; структурное проектирование; строительство; возобновляемый ресурс; энергоэффективность

Abstract. The use of renewable energy converters, including local wind power plants to provide private households and houses with electricity, is gaining popularity, especially in countries where there are appropriate state subsidies. In this paper considered approach to the use of the building roof in the conversion of the kinetic energy of the incoming wind into electrical energy by a closed wind power plant (WPP). The construction of the WPP and the roof are converted into a finite element model for aerodynamic calculations. The model of WPPs and roofs is investigated by changing the angle of attack of the roof, with different roofing applications, and also some other elements of the WPP design in order to find the most optimal conditions for increasing the energy efficiency factor (EEF) of the energy carrier. The described approach with the use of a roof in the conversion of wind energy into electrical energy can be used in the structural design and construction of autonomous houses and buildings.

Аннотация. Использование преобразователей энергии возобновляемых источников, в том числе локальных ветроэнергетических установок для обеспечения частных хозяйств и домов электрической энергией приобретает популярность, особенно в странах, где существуют соответствующие государственные дотации. В настоящей работе рассмотрен подход к применению кровли здании при преобразовании кинетической энергии набегающего ветра в электрическую энергию ветроэнергетической установкой (ВЭУ) закрытого типа. Конструкция ВЭУ и кровля преобразуются в конечно-элементную модель для проведения аэродинамического расчета. Модель ВЭУ и кровли исследуются изменением угла атаки кровли, при различных вариантах применения кровли, а также некоторых других элементов конструкции ВЭУ с целью поиска наиболее оптимальных условий для увеличения коэффициента использования энергии (КИЭ) энергоносителя. Описываемый подход с использованием кровли при преобразовании энергии ветра в электрическую энергию может быть использован при структурном проектировании и строительстве автономных домов и зданий.

1. Introduction

Wind energy in the world is developing in three separate areas:

- wind power complexes of low power of 2–100 kW for feeding autonomous objects that do not require significant capital investment and are easy to operate;

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- energy complexes of average power of 200–800 kW for feeding concentrated load in territories with low population density, which require large capital investments and depreciation charges (renovation costs);

- power complexes of high power of 1000–5000 kW for generating power in centralized power systems that do not pay off and constantly require investment for renovation [1].

Therefore, from the point of view of practicality and efficiency of operation, wind energy needs to be developed for local power supply of autonomous objects [2]. In turn, a local WPP for autonomous power supply can be used in tourist recreation areas, farms, oil pumping stations and other similar organizations located in remote areas from a unified electrical system (UES) [3].

The most common converters of renewable resources are wind and solar energy converters, which are practically present in all parts of the world and apply various conversion methods [4]. In addition, to increase the reliability of power supply used diesel generators, along with renewable resources converters [5]. In order to increase the energy efficiency in the converter, it is necessary to conduct research to find the best construction of the WPP, which allows increasing the air mass flow velocity, since even an insignificant increase in the air mass flow velocity will have a great effect, because the kinetic energy of the stream depends on the velocity in the third degree [6].

The study of the construction of WPPs using the roof of the building was conducted out in the software of engineering analysis COMSOL Multiphysics, which performs calculations using the finite element method. This method is widely used in modeling the processes of diffusion, heat conduction, hydrodynamics, mechanics and expanding its scope with increasing the capacity of computing systems [7].

Usually, the Euler formulation of problems is used to solve the equations of hydrodynamics. The grid applied to the calculated area remains fixed during the entire process of the solution. However, when using this approach, difficulties arise in approximating the convective terms [8].

These difficulties are eliminated by using the Lagrangian description of the field. The essence of this approach is that the grid nodes move with the field, which allows us to consider them as particles of the field; in this case the mesh itself is deformed or rearranged at each step of the solution. One of the methods using the Lagrangian description of the field is the PFEM – method of finite elements with particles [9, 10]. This method is used in software of engineering analysis COMSOL Multiphysics [11].

The finite element method with particles is used to simulate fluid flows in areas of complex shape, fluid flows with a free surface, splash processes, and solutions of the adjoint hydroelasticity problems. To solve these problems Lagrangian methods of various types are used traditionally and very effectively: in conjugate problems of hydroelasticity – the methods of vortex elements [12, 13], in the simulation of flows with a free surface – the method of smoothed particles SPH [14, 15]. Advantages and disadvantages of using grid methods and particle methods for solving various problems are discussed in detail in the paper [16].

To simulate the flow is widely used the Navier-Stokes differential equations system. The main problems in the solution of the Navier-Stokes equation are related to differential equations for the laws of conservation of mass and momentum. To solve these problems are used methods to determine the pressure of the Poisson equation [17], the equations for the corrections [18], the penalty functions [19], the addition of the continuity equation by the no stationary member [20], the regularization of the matrix coefficients for time derivatives [21–26]. In addition, there is the problem of the existence and smoothness of the Navier-Stokes equations for solutions which use different methods [27–34].

The aim of this work is to develop the most efficient converter of wind energy that would optimally convert the kinetic energy of the wind and increase the operating range of its work by lowering its lower threshold. When the WPP construction uses a building roof, where it is located, it additionally enfolds the oncoming wind. In this way, the roof of the building becomes an active element in the transformation of energy.

The task that must be solved: the model of the construction of WPPs and roofs, as well as the flow in simulation of the software of engineering analysis should be sufficiently approximate to the natural model. For this, the model should give the same and convergent results in grids, the grid should be sufficiently shallow on important areas of the construction to avoid errors in hydrodynamic calculations, and the calculation area over the model of the WPP should be high enough to avoid a narrowing of the airflow, which can distort the natural flow conditions.

2. Methods

A three-dimensional model of a closed-type WPP construction and a building roof is shown in Figure 1 and consists of the following elements:

1. the directive cone, located in the middle of the construction on one axis with the WPP housing, directs the air flow to the turbine blades area of the WPP;
2. the housing of the WPP, consisting of a front cavity, made in the form of a truncated cone, and an expanding back cavity, which contribute to the acceleration of the air flow in the area of the turbine blades of the WPP;
3. the ejector which is the outer part of the construction of WPPs, the inner side of which is constant at a small angle relative to the WPP housing, narrows and directs the air flow at the outlet to create a low pressure region behind the turbine by entrainment with a flow of exhaust air molecules. Thus, it additionally contributes to the acceleration of the air flow in the turbine blades area of the WPP.

This design contributes to an increase in the speed of the wind flow due to the use of the confuser and diffuser, which makes it possible to obtain a coefficient of wind energy use from 0.4 to 0.45.

Orientation to wind is carried out due to the shank of the wind turbine located behind the body.

A DC generator is used to convert the rotational mechanical energy into electrical energy and is located behind the guide cone at the border of the confuser and diffuser.

The blades of the proposed low-power WPP are made of light composite materials, so the calculation of the load on them was not considered.

Since a local WPP can be used in tourist recreation areas, farms, etc., where large capacities are not required, it is sufficient to install it on standard buildings without special strengthening of the building elements.

Figure 2 shows a cross-sectional view of a closed-type WPP construction model and a building roof. Since the WPP construction and the roof of the building are rotational bodies, to simplify the calculation, computational operations and analysis of the most effective areas of construction applied cross section model. This model is built in the interface "Geometry" of the software of engineering analysis COMSOL Multiphysics. Further selects the material, depending on the model, in this case air is selected as the flow field and iron is used as a material for the construction of the WPP and the roof of the building. Then the boundary conditions are set: input speed, outlet pressure, symmetrical walls. In this interface, the flow of a fluid with any velocities is modeled on the basis of the solution of the Navier-Stokes equations in various formulations. This interface is intended for modeling the low-velocity streams, creeping (Stokes) flows, laminar and turbulent fluid flows. To describe turbulent flows are used Reynolds-averaged Navier-Stokes equations (RANS), supplemented with the different models of turbulence: standard and low-Reynolds type k-ε models, k-ω and SST (Menter) models and the Spalart-Allmaras model [11]. The Reynolds averaging method for the Navier-Stokes equation consists in replacing the randomly changing flow characteristics (velocity, pressure, density) by the sums of the averaged and pulsating components. The Reynolds equations describe the time-averaged flow of a fluid, their peculiarity (in comparison with the original Navier-Stokes equations) lies in the fact that new unknown functions appear in them that characterize the apparent turbulent stresses.

For calculation is chosen a standard k-ε model to describe the turbulent flow, where the equation of motion is transformed to the form in which the effect of average velocity fluctuations (in the form of turbulent kinetic energy) is added and the process of reducing this fluctuation at the expense of viscosity (dissipation). In this model solved two additional transport equations for the turbulent kinetic energy and turbulent dissipation transport. This model is most often used in solving real engineering problems.

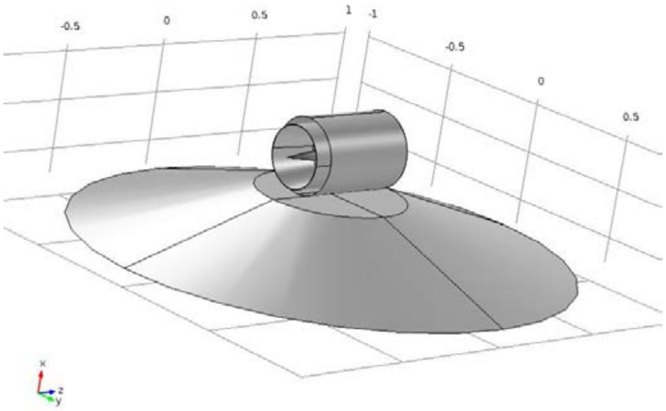

Figure 1. The three-dimensional model of the construction of closed type WPPs and roof of the building

In the grid building interface is selected a method for dividing a model from four types of calibration for each of its sections. There are: “general physics”, “fluid dynamics”, “plasma” and “semiconductor”. Then it specifies a predefined size of the grid. For the flow field area of the model is selected the second type of calibration, namely "fluid dynamics", and for the construction of the WPP and the roof of the building - the first type of calibration, namely "general physics". The constructed grid for one of the variants of the model of closed type WPP construction and the building roof is shown in Figure 3. It can be seen from the figure that the grid near and around the edges of the construction is crushed, which will allow to take into account the changes in the parameters in these important zones for a sufficiently accurate description of the flow processes.

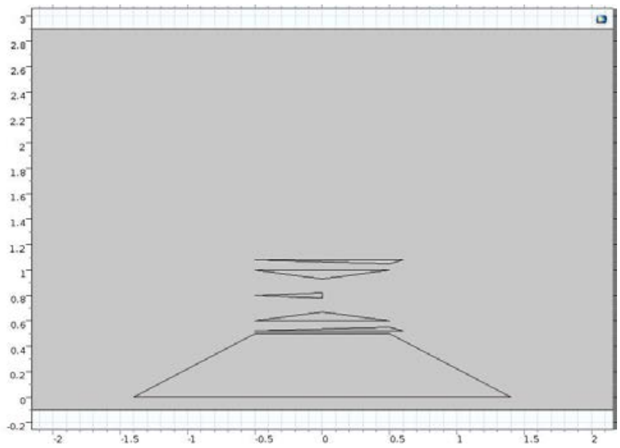

Figure 2. The cross-section of model of the construction of closed type WPPs and roof of the building

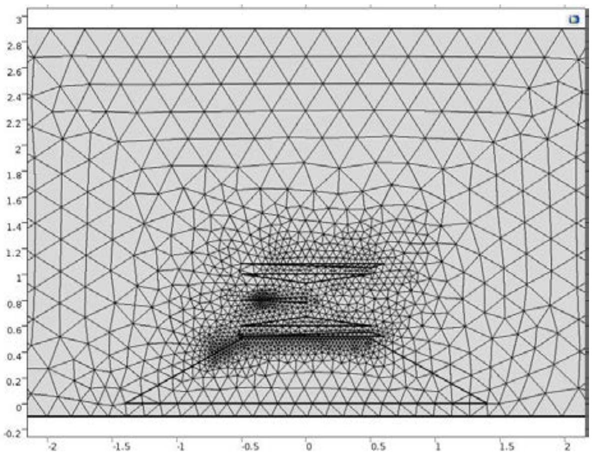

Figure 3. Estimated grid of one of model of the construction of closed type WPPs and roof of the building

3. Results and Discussion

In work [35] the architecture of low-rise buildings with use of wind power installations and principles of form-building in architecture of low-rise buildings is considered. There shaping effect on the increase in the power of wind turbines. The proposed hypotheses on the new formation of residential buildings are not effective enough due to the lack of research on finding the effective angle of the roof of the building. For this, it is necessary to perform calculations under different conditions for each parameter.

The results of the calculations can be obtained in the form of various diagrams and graphs on the necessary parameters for the analysis. Figure 4 shows a diagram of the airflow velocity contours throughout the construction of closed type WPPs and the roof of the building. It shows that in the area of the turbine where the flow is narrowing with the housing and the directive cone of the WPP, the flow velocity reaches a maximum value, behind this zone the flow velocity begins to decrease. A slight decrease in the airflow velocity is observed along the outer edges of the WPP housing, since the ejector creates a low-pressure region in these zones. In this case, the flow velocity reaches 10.2 m/s with its initial value of 5 m/s.

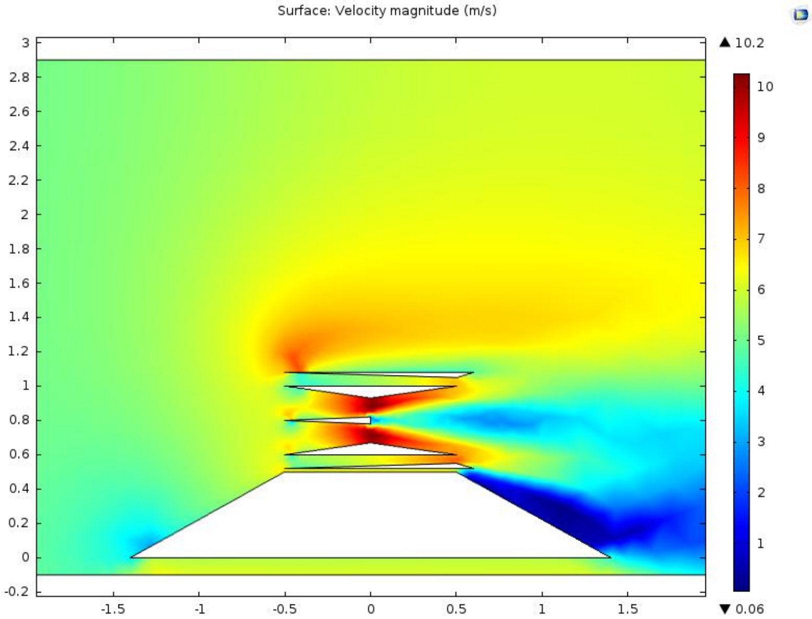

Figure 4. The diagram of the airflow velocity contours throughout the construction of closed type WPPs and roof of the building

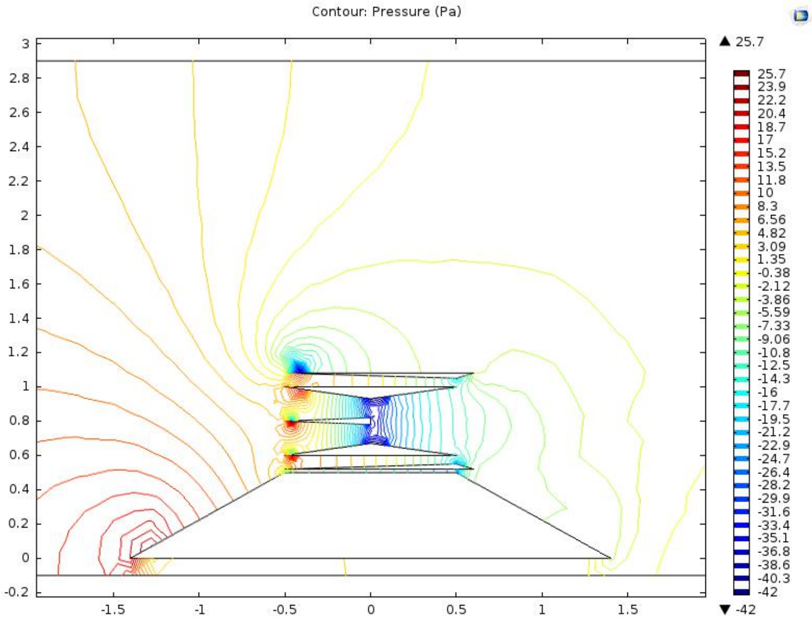

Figure 5. Diagram of airflow pressure contours throughout the construction of closed type WPPs and roof of the building

A diagram of the pressure contours for these conditions is illustrated in Figure 5, where the pressure difference in the construction reaches 67.7 Pa. It can be seen from this figure that the low-pressure zone is behind the turbine of the WPP, especially in the area of the blades of the turbine of the WPP, where achieved the maximum airflow velocity.

To obtain velocity data in the turbine zone (a vertically arranged red line in Figure 6), a graph of the airflow velocity is plotted on the length of this zone, which is shown in Figure 7. The decrease of the velocity of airflow in the middle of the graph shows the shaded area of the closed-type WPP directive cone, where the generator and the turbine housing are located, and also the velocity growth on the both sides – the turbine blade area, where reached the maximum airflow velocity in the construction.

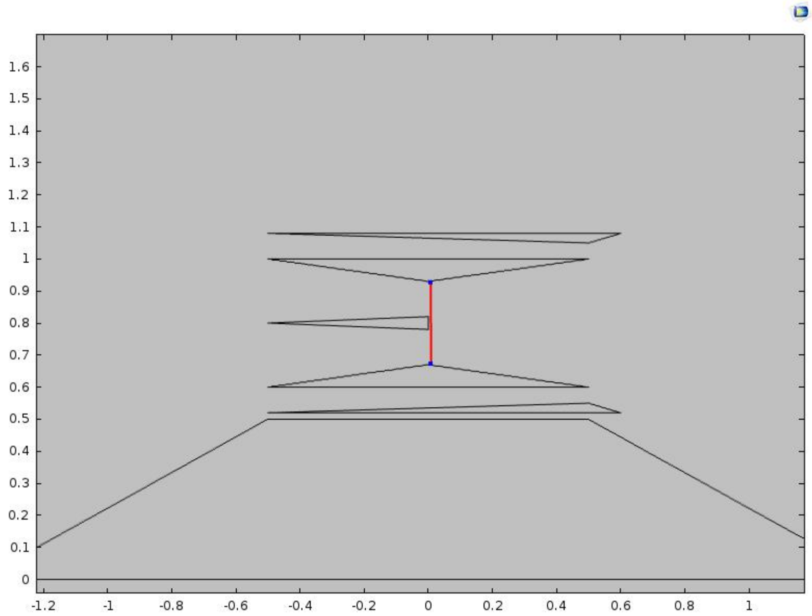

Figure 6. Plot removal area of the airflow velocity

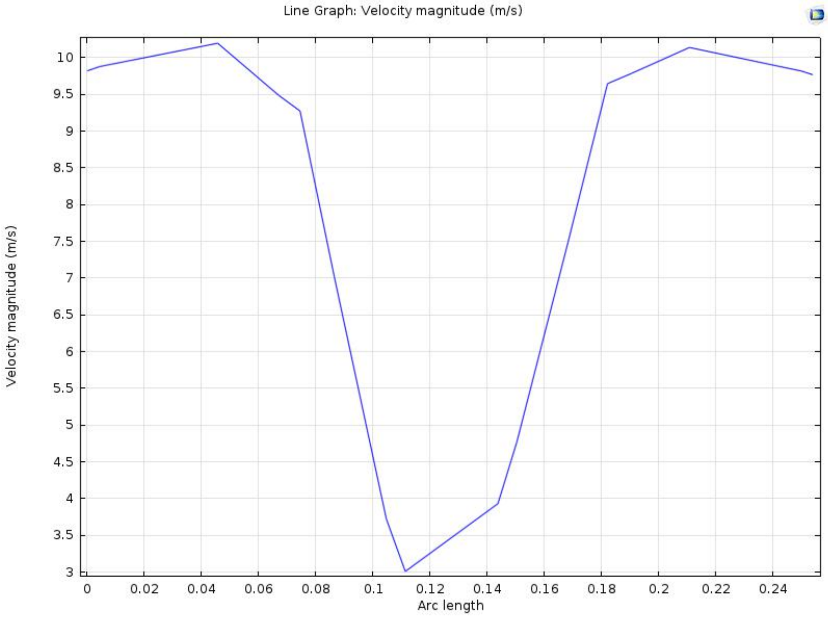

Figure 7. The airflow velocity graph at the location of turbine blades of a closed type WPP

The closed type WPP was also investigated in the absence of an ejector $\vartheta_{w.e.}$ at different angle attack of inclination of the roof of the building α, where the air velocity reaches 10.16 m/s (Figure 8). In addition, her research was conducted in the absence of the roof of the building $\vartheta_{w.r.}$, where a speed of 7.85 m/s is achieved (Figure 9). The results of the calculations performed for different variants with an initial wind velocity of 5 m/s are given in Table 1.

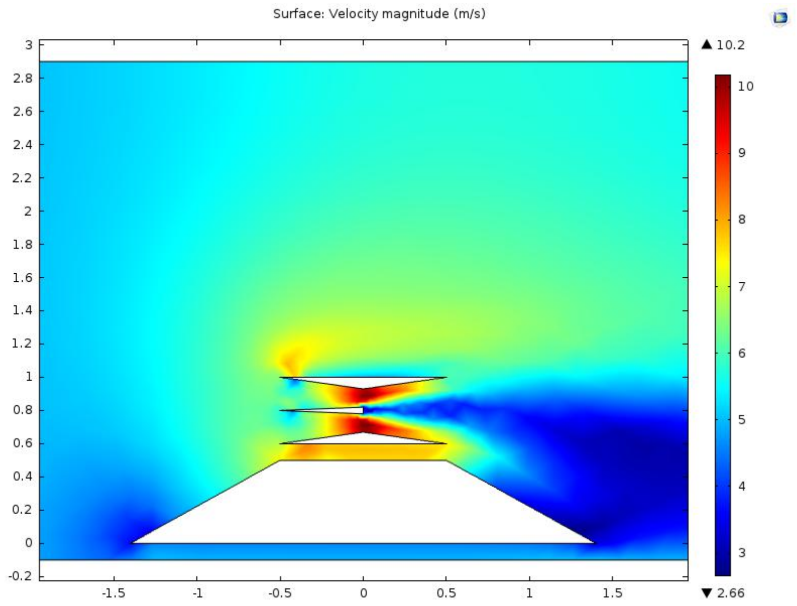

Figure 8. Diagram of airflow velocity contours in the absence of an ejector

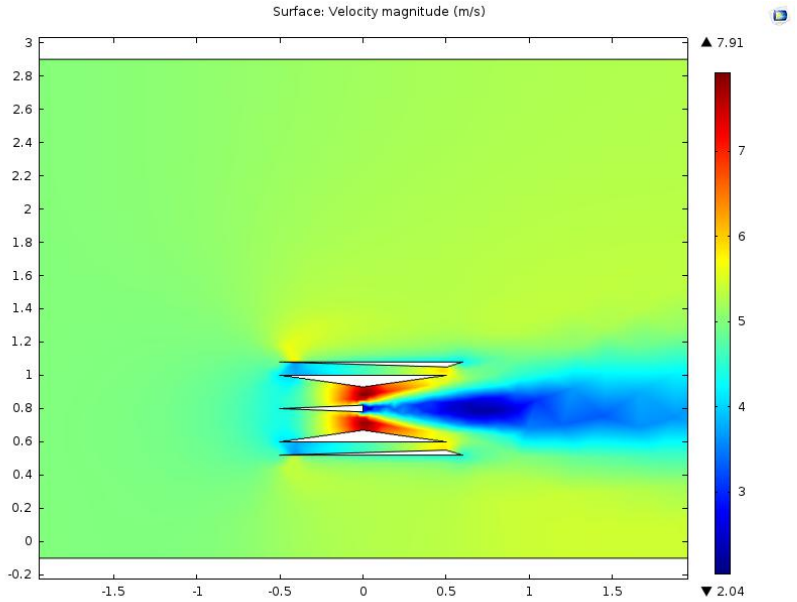

Figure 9. Diagram of airflow velocity contours in the absence of a building roof

Table 1. The results of wind velocity in the zone of the turbine

α, ^{0}	ϑ_{max}, m/s	$\vartheta_{w.e.}$, m/s	$\vartheta_{w.r.}$, m/s
11.31	9.4	9.01	7.85
16.7	9.4	9.01	
26.56	9.5	9.01	
29.1	10.2	10.16	
32	10.14	10.06	
35.5	10.1	9.97	
45	10.01	9.48	

It can be seen from Table 1 that the maximum acceleration of the air flow through the construction in the turbine zone is achieved at an angle of inclination of the roof of the building 29.1^0. Therefore, when designing and building autonomous houses and buildings, it is recommended to take the angle of inclination of the roof in the area 30^0.

4. Conclusions

1. The forms of the WPP construction elements have been developed to effectively increase the velocity of the incoming air flow, such as the directive cone, the installation housing and the ejector.

2. The analysis of the mutual arrangement of the elements of the WPP construction was carried out in the absence of some elements, in the absence of the roof of the building and at various angles of attack of the roof of the building.

3. Based on the results of the analysis an effective version of the construction of the WPP and the roof of the building is identified, where the greatest acceleration of the incoming airflow is achieved.

4. It is recommended to take the angle of inclination of the roof of the building in the area 30^0.

5. Substantiated the construction of a closed type WPP, consisting of a housing of the installation, a directive cone and an ejector, and the roof of a building.

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