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COMPUTATIONAL DESIGN AND OPTIMISATION OF INNOVATIVE, HIGH-EFFICIENCY WIND TURBINE

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Abstract

New concept of innovative, high-efficiency wind turbine has been developed and optimised. The turbine consists of a rotor with a vertical axis of rotation and a ring-palisade casing, which task is to deflect wind stream so that it flows perpendicularly to the rotor plane. The main advantage of such configuration of a wind turbine is that due to the vertical axis of symmetry, it works independently on the wind direction and it does not need any mechanism directing it towards the wind. The greatest challenge when designing the turbine was to minimise losses of energy of the wind stream deflected by 90 degrees by the ring vanes of the casing. This involved optimisation of number, shapes and mutual positions of the ring vanes. The whole optimisation works were done based on computational methods of Computer-Aided Design and Optimisation and Computational Fluid Dynamic. Subsequent variants of the ring-palisade casing were designed using an appropriately adapted in-house-software package supporting design and optimisation of multi-element airfoils. Three-dimensional analysis of flow around and inside the casing was conducted by application of commercial URANS solver ANSYS FLUENT. Eventually designed turbine is characterised by high efficiency in respect of acceleration of the wind stream. On the basis of computer simulations, it is estimated that the average velocity of air stream flowing through the rotor plane may be higher than the wind speed by about 45%. Extent of the acceleration of the wind stream partially depends on the number of ring vanes comprising a casing. Depending on specificity of application, this number of ring vanes may be chosen by a compromise between performance and dimensions of the turbine. The proposed wind turbine seems to be very promising solution, especially within the area of small and moderate renewable-energy sources, which in particular may be placed directly in residential-building areas, e.g. on the roofs of houses. This type of renewable-energy sources may also be successfully used in the field of environmentally friendly transport, in the process of producing hydrogen as fuel for fuel cell vehicles.

Keywords: *green power, wind turbine, computational fluid dynamics, computer-aided design and optimisation*

1. Introduction

It seems that a fuel cell vehicle will become the future of road transport. Fuel cells create electricity to power an on-board electric motor and they need compressed hydrogen [1]. That kind of propulsion emits only water and heat therefore is considered a zero-emissions system. Hydrogen can be industrially derived, but unfortunately, the process takes a lot of energy. If the energy does not come from renewable sources, then fuel-cell cars are not as clean as they theoretically seem. Only solar and wind energy can provide clean electricity for producing of hydrogen [2]. The paper presents new type of wind turbine able to generate electricity for industrial purposes in low wind speed conditions.

Wind turbine is a common name of devices that convert kinetic energy from the wind into electrical power. Such sources of renewable energy are being widely developed and utilised, especially in countries or regions with favourable weather conditions.

There are many different solutions and inventions of wind-turbine concepts. Most of them utilise specially designed rotors to drive the electrical generator. They may be categorised with regard in orientation of the rotor shaft.

Horizontal-axis wind turbines (HAWT) have the main-rotor shaft oriented horizontally. Usually, in such a case, the rotor and electrical generator are placed at the top of a tower, and the rotor shaft must be pointed into the wind. The mechanism directing the rotor plane towards the wind may be passive (e.g. wind vane) or active, utilising a wind sensor coupled with a servomotor. The former solution is usually applied in small turbines, while large turbines utilise the latter concept.

Vertical-axis wind turbines (VAWT) have the main-rotor shaft oriented vertically. One advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective. In addition, the generator and gearbox can be placed near the ground, using a direct drive from the rotor assembly to the ground-based gearbox, improving accessibility for maintenance. The key disadvantages of VAWT include the relatively low rotational speed with the consequential higher torque and hence higher cost of the drive train, the inherently lower power coefficient, the 360 degree rotation of the aerofoil within the wind flow during each cycle and hence the highly dynamic loading on the blade, the pulsating torque generated by some rotor designs on the drive train, and the difficulty of modelling the wind flow accurately and hence the challenges of analysing and designing the rotor prior to fabricating a prototype.

Despite some disadvantages, the VAWT concept is very attractive especially from point of view of application on a site where the wind direction is highly variable. It is also an advantage when the turbine is integrated into a building because it is inherently less steerable. These advantages favour the use of VAWT concept especially in urban, residential and industrial areas.

The main goal of the research described in this paper was to develop an innovative concept of the VAWT, which while maintaining the advantages mentioned above, would characterise by a high efficiency, comparable to Hats. It was also desirable, that the new turbine should have worked effectively in low-speed-wind conditions. It was assumed that the designed innovative VAWT would be equipped with typical, multi-blade rotor.

There are two crucial challenges when designing the VAWT. The first concerns the design of rotor, which in the case of VAWT works in specific conditions, with non-uniform velocity profile of air flowing through the rotor plane. The second fundamental problem refers to designing of the system which would be able to deflect effectively the horizontally blowing wind towards the plane of rotating, vertical-axis rotor. This problem is the main subject of the paper.

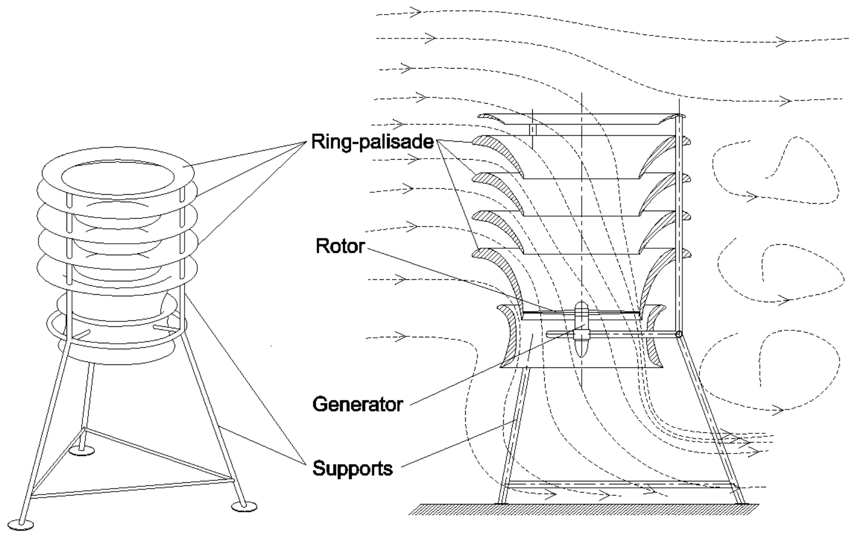

Fig. 1. General concept of the newly developed, innovative Vertical-Axis Wind Turbine

Based on results of research formerly conducted in Institute of Aviation, the general concept of the wind turbine, which would be able to fulfil mentioned above requirements was assumed as it was shown in Fig. 1. The wind turbine consists of:

– rotor with a vertical axis of rotation,
– electrical generator, driven by the rotor,
– ring-palisade casing, which task is to deflect wind stream so that it flows perpendicularly to the rotor plane,
– three vertical supports and abutments that hold together the structure of the turbine and attach it to the ground.

As it was mentioned above, the paper focuses on studies aimed at designing of the ring-palisade casing. The main goal was to design the innovative casing so as to improve significantly the efficiency of the VAWT while keeping typical advantages of such a concept of wind turbine.

Many different methods for designing and optimizing of the wind turbines have been described in the literature. Optimization is applied to aerodynamic components such as rotor blades, airfoils [5], turbine casing, mechanical issues [4] and noise generated by wind turbines [3]. Below is described the design and optimisation process of innovative wind turbine with the use of several unique engineering tools.

2. Design Methodology

The process of design and optimisation of the ring-palisade casing was conducted based on computational methods of Computer-Aided Design and Optimisation and Computational Fluid Dynamic. During this process, subsequent variants of the ring-palisade casing were designed using an appropriately adapted in-house-software package. Assumed design parameters described:
– number of the aerodynamic-shape rings,
– mutual positions of the rings,
– shapes of the rings.

By appropriately changing these parameters, sequential variants of the casing were obtained. Aerodynamic properties of designed variants of the innovative VAWT were evaluated using commercial URANS solver ANSYS FLUENT [8].

Two-dimensional cross-sections of the designed variants of the casing were developed using the in-house software:
– CODA4W – in-house code supporting airfoil design (see Fig. 2),
– INVDES – in-house code solving the Inverse-Airfoil-Design problem (see Fig. 3),
– CODA3D – in-house code supporting design of 3D aerodynamic objects.

Based on these codes, the preliminary aerodynamic design of the palisade-case rings was conducted in 2D case in respect to palisade of airfoils. This approach was based on observed similarities of pressure-coefficient distributions in 2D case and fully 3D case, with appropriately adjusted angle of attack in the 2D case. Based on cross-sections exported from the CODA4W code, the 3D CAD model of the VAWT chassis was developed using the code CODA3D. In the next step, the CAD model was used by the grid-generation software ICEM CFD to create 3D computational mesh, which example is shown in Fig. 4. The computational mesh was the input data for the ANSYS FLUENT code, which was applied to evaluate aerodynamic properties of sequential variants of the VAWT chassis.

In conducted CFD simulations of air flow around and inside the VAWT chassis, the following model of flow has been applied:
– unsteady,
– incompressible, constant air density = 1.225kg/m^3,
– URANS, model of turbulence: k-ω SST.

The assumed boundary conditions are explained in Fig. 4. The wall-type boundary conditions were set at material surfaces of palisade rings as well as on the lower surface modelling a ground. At the far-field boundary surfaces, the velocity-inlet and pressure-outlet boundary conditions were set.

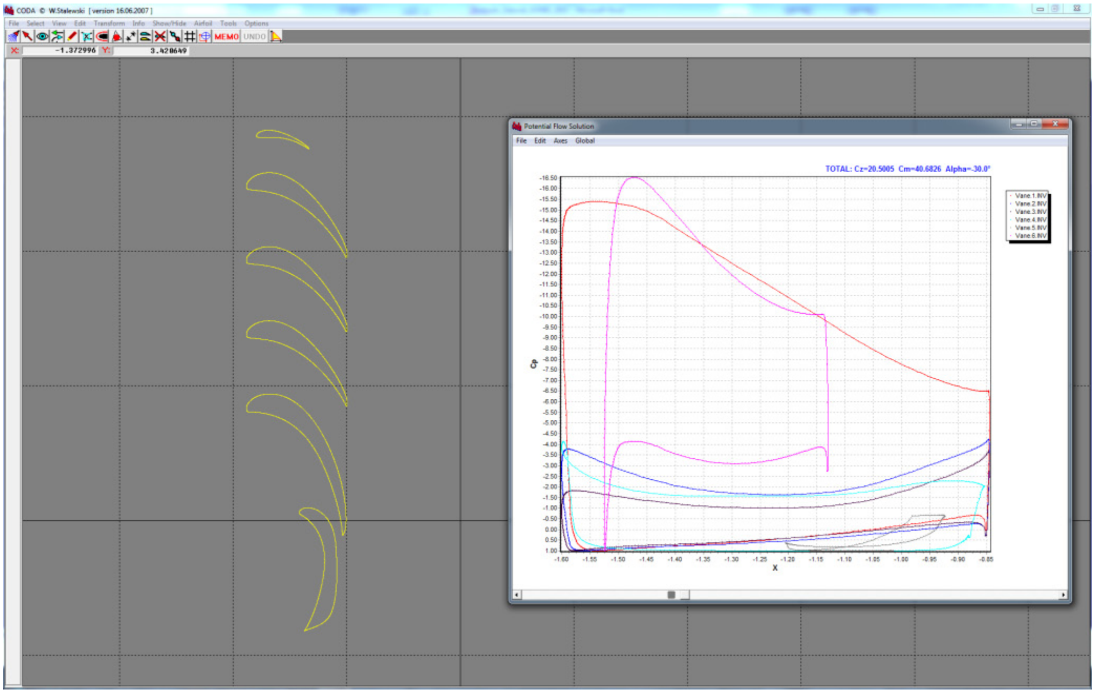

Fig. 2. Graphical User Interface of the software CODA4W, geometrical design and aerodynamic analyses of the palisade of airfoils

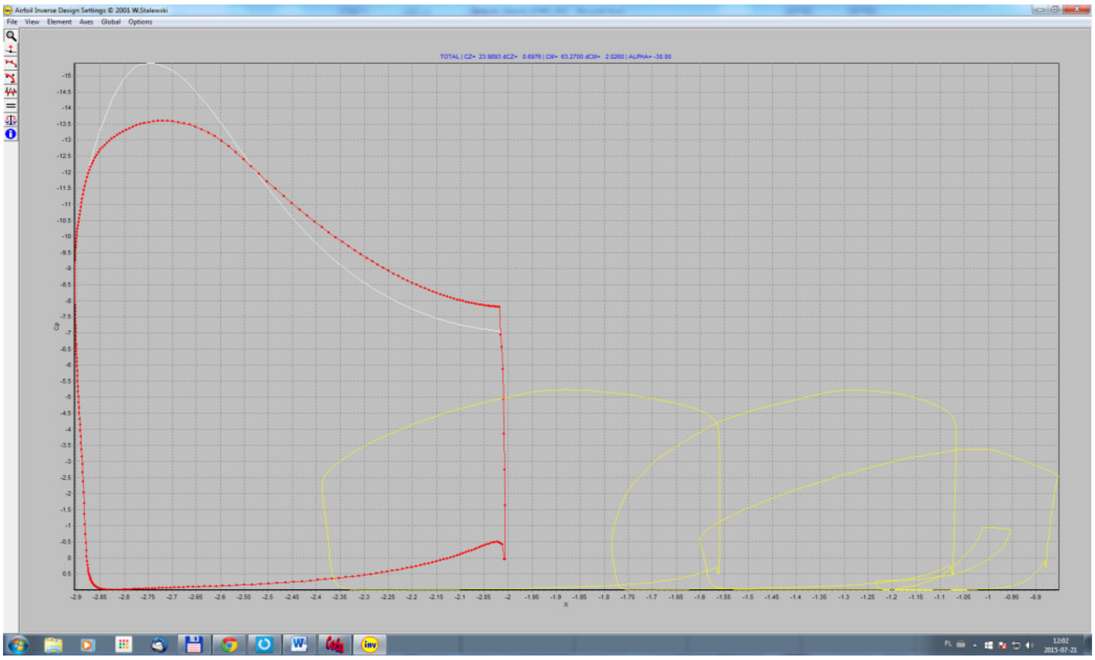

Fig. 3. Graphical User Interface of the software INVDES, aerodynamic design of the palisade of airfoils

3. Design and Optimisation of Innovative VAWT

The general concept of the proposed VAWT presented in Fig. , has been developed as a result of a long design-and-optimisation process. The starting point for this process was simple-design turbine, which casing consisted of three identical rings and diffuser forming the lower end of the turbine internal duct. CFD analyses showed specific behaviour of the turbine, manifested by large fluctuations and sudden drop of performance depending on several factors, including physical factors e.g. wind velocity, but also computational aspects such as assumed model of turbulence, quality of computational mesh, etc.

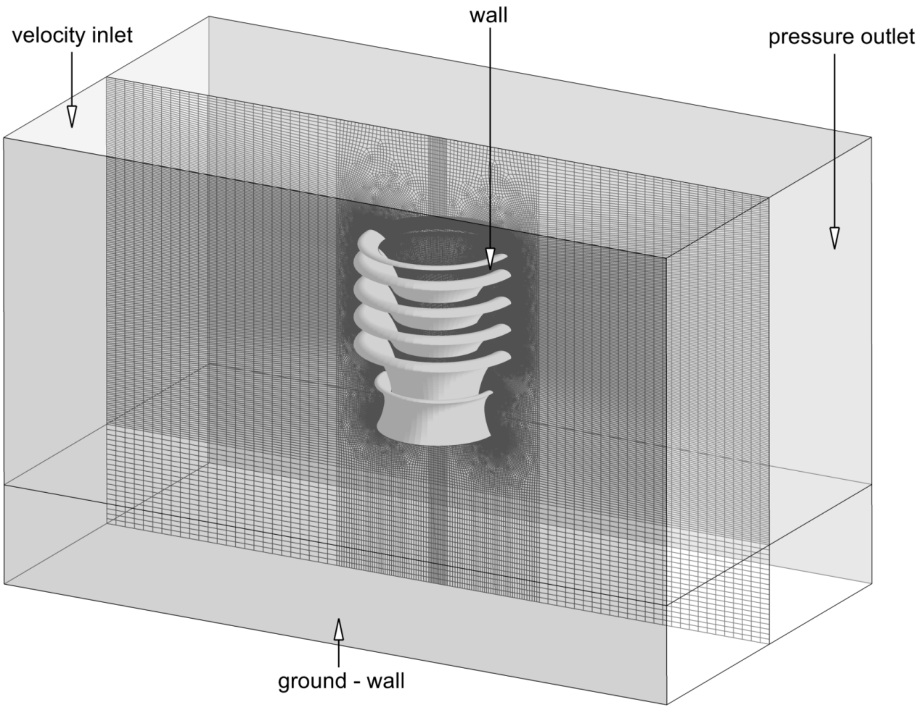

Fig. 4. Structure of computational mesh, applied boundary conditions

Thorough analyses indicated, that the main reason of observed flow instabilities could be strong flow separations, especially in two regions marked in Fig. 5. The first region include upper-inner surface of the topmost ring of the casing. The second strong flow separation occurs in windward part of the diffuser. The described flow separations cause instability, uncertainty and low performance of the turbine work, which is illustrated in Fig. 6, where average normal component of flow-velocity vector measured in the rotor rotation plane, has both the low value in respect to a wind velocity and large fluctuations.

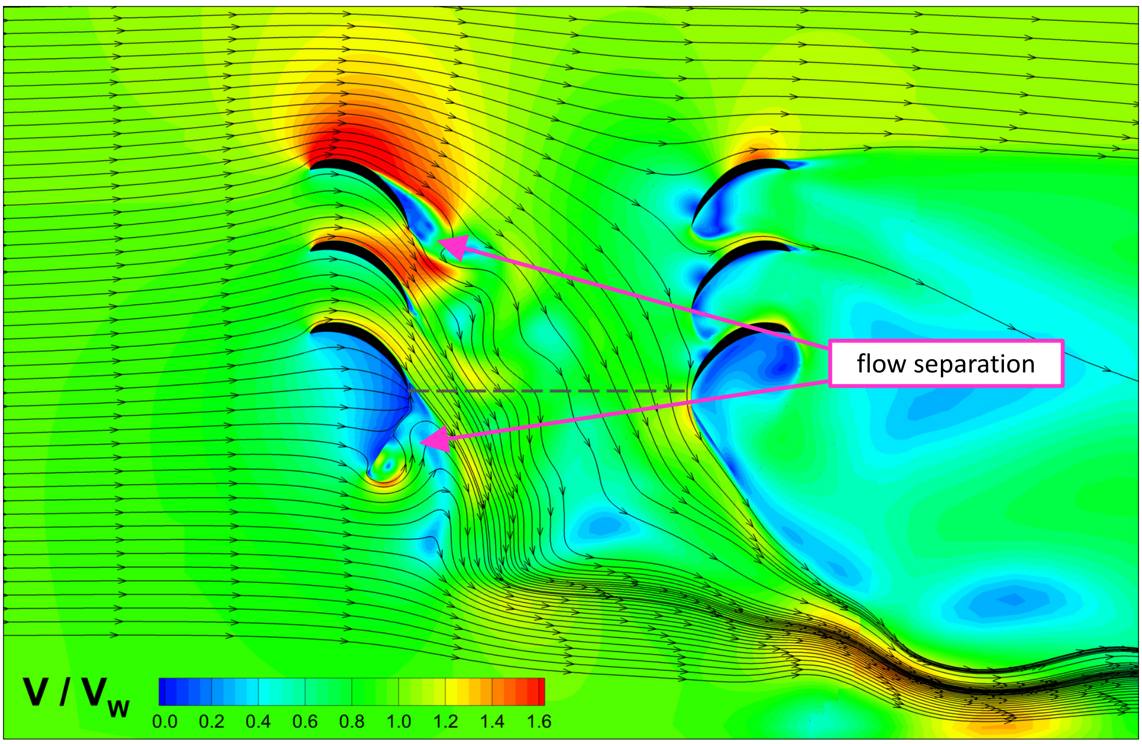

Fig. 5. Visualisation of air flow around the initial variant of designed wind turbine

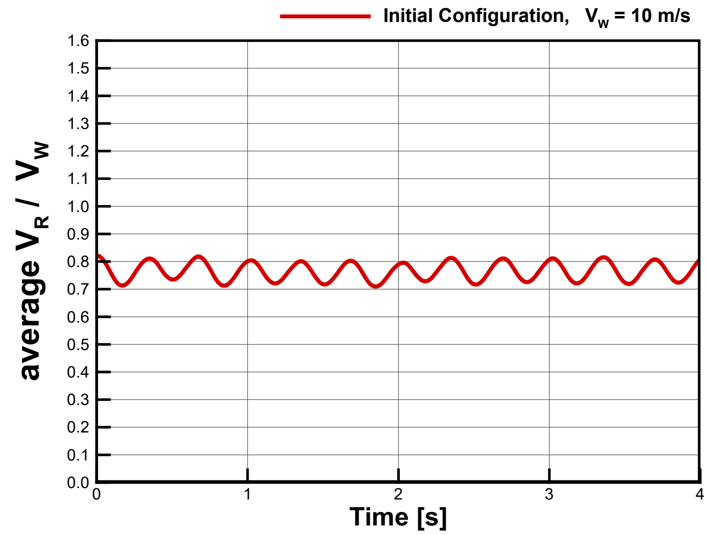

Fig. 6. Time-variable average normal component of flow-velocity vector, measured at the rotor-rotation plane (V_R) referenced to wind velocity (V_W) computed for initial configuration of the wind turbine, for wind velocity V_W = 10 m/s

Taking into account the mentioned above phenomena, the turbine-optimisation process was focused on significant reduction of effects of separation of flow on the casing rings. In the finally designed turbine, two main solutions (inventions) play main role when coping with the flow separation.

The first solution consists in application of additional, smaller ring placed above the topmost essential ring of the casing. This additional ring, if properly designed, successfully eliminates flow separation on the lying below the essential ring. The second solution is focused on alleviation of unfavourable effects of flow separation in windward part of the diffuser. In new design, the diffuser was replaced by additional ring, which shape and position was established as a result of thorough optimisation. Originally, the result of optimisation was the VAWT casing consisting of 6 rings. Such solution was characterised by the highest performance but also by largest dimensions of the wind-turbine structure. Further computational investigations showed that decrease of wind-turbine dimensions, achieved by removal of one or two essential rings, did not lead to drastic reduction of the performance. Therefore, finally, three variants of the new concept of VAWT were proposed as final result of the conducted design-and-optimisation process. These variants are presented in Fig. 7.

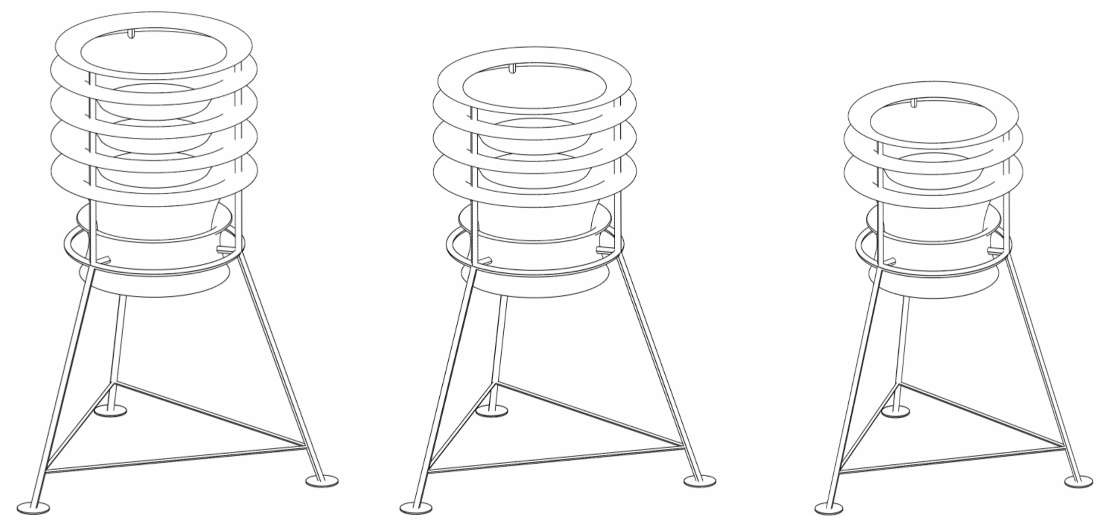

Fig. 7. 6-ring, 5-ring and 4-ring variants of finally designed and optimised wind turbine

Developed variants of innovative VAWT differ from each other by a number of essential rings forming the casing. In conducted investigations, the 6-ring, 5-ring and 4-ring configurations were taken into consideration, though configurations of higher number of rings are also possible to be designed. Based on results of CFD simulations, the evaluation of performance of the developed innovative VAWT has been conducted. Results of this evaluation are presented in Fig. 8, where the time-variable average normal component of flow-velocity vector, measured at the rotor-rotation plane (V_R) is analysed for two configurations: 6-ring and 4-ring and for two wind velocities: V_W = 10 m/s, 6 m/s. Fig. 8 shows that:

– 6-ring configuration is characterised by average V_R velocity higher than wind velocity V_W:
  – by approx. 47% for the wind velocity V_W = 10 m/s,
  – by approx. 45% for the wind velocity V_W = 6 m/s;
– 4-ring configuration is characterised by average V_R velocity higher than wind velocity V_W:
  – by approx. 33% for the wind velocity V_W = 10 m/s,
  – by approx. 32% for the wind velocity V_W = 6 m/s.

Additionally, for all investigated configurations, the fluctuations of the average V_R velocity are negligible. Fig. 9-12 present contours of local-velocity magnitude (V) referenced to the wind velocity (V_W), analysed in plane of symmetry of flow region, for four investigated configurations of the wind turbine. All the Figures visualise high acceleration of air flow reaching the plane of rotation of the rotor (marked in the drawings by dashed line).

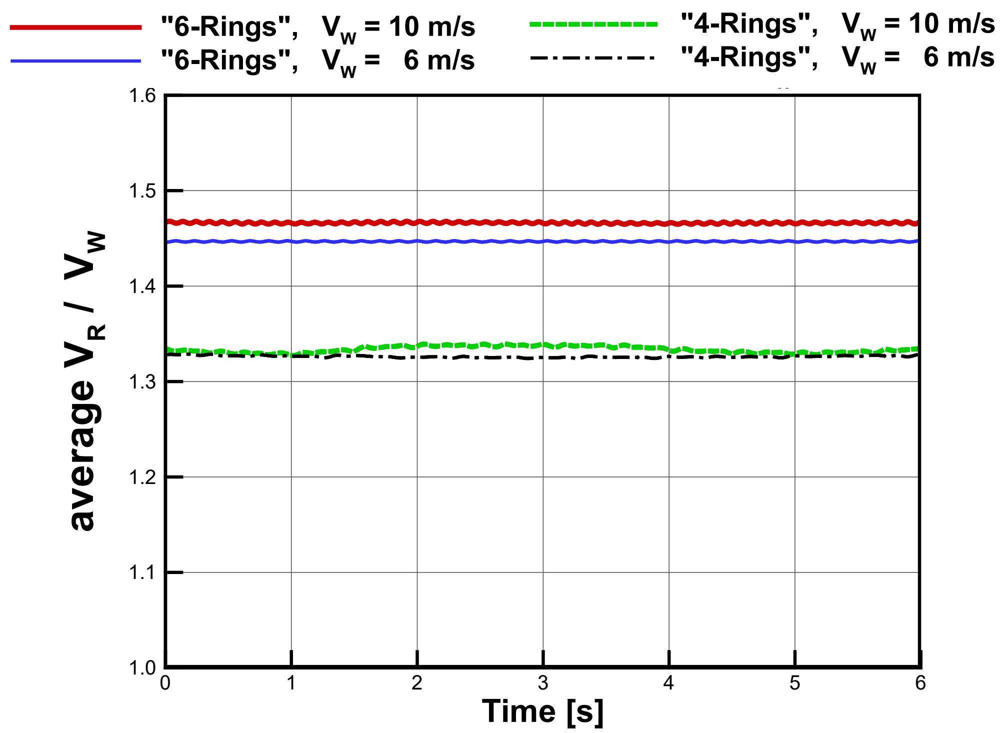

Fig. 8. Time-variable average normal component of flow-velocity vector, measured at the rotor-rotation plane (V_R) referenced to wind velocity (V_W) computed for 6-Ring and 4-Ring configuration of the wind turbine, for wind velocities V_W = 10 m/s, 6 m/s

Figure 13 presents distortion of normal component of flow-velocity vector (V_R) referenced to wind velocity (V_W), analysed in the rotor-rotation plane, for investigated configurations of the wind turbine. For the 6-ring configuration, the specific drop of V_R velocity is observed in leeward part of the rotor-rotation plane. This phenomenon is not present in the case of 4-ring configuration. Both the 6-ring and the 4-ring configuration are characterised by the drop (or higher distortion) of V_R velocity in central part of rotor-rotation plane. This phenomenon is in general favourable, because in real design, in this place the rotor hub is placed.

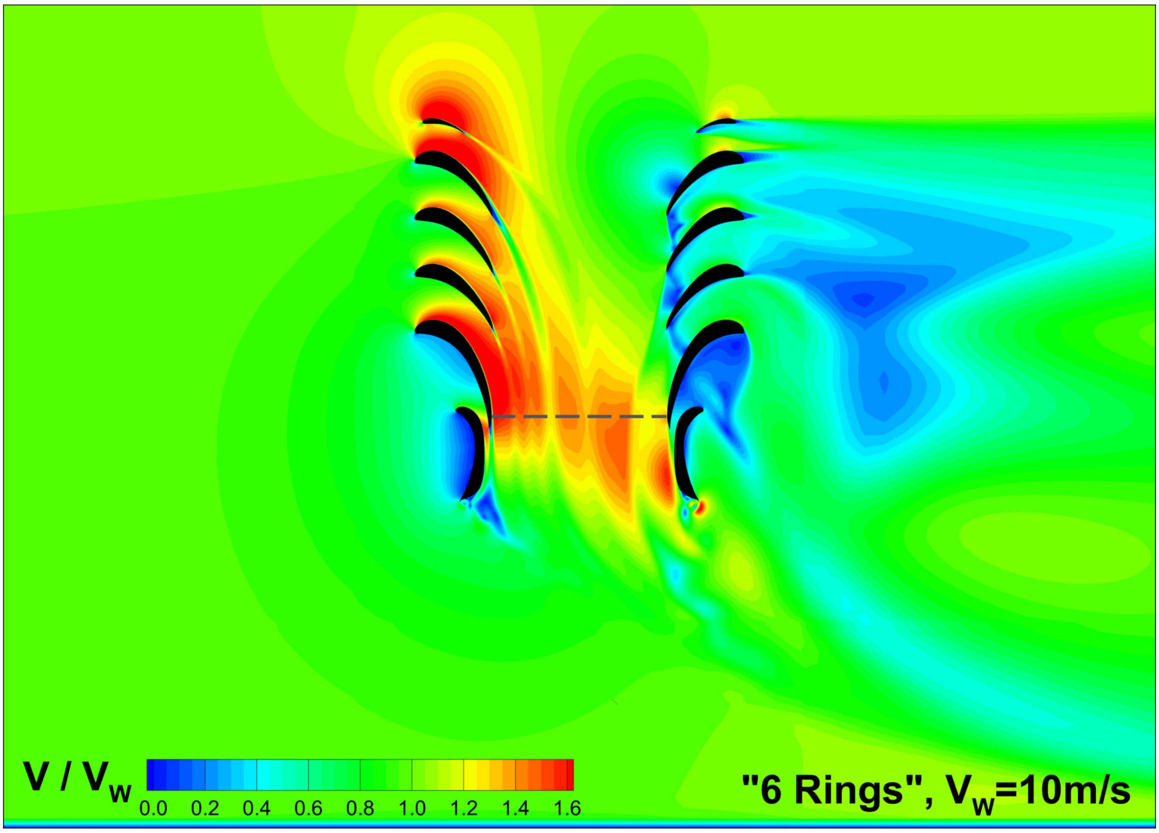

Fig. 9. Contours of local-velocity magnitude (V) referenced to wind velocity (V_W), analysed in plane of symmetry of flow region, 6-ring configuration, wind velocity V_W = 10 m/s

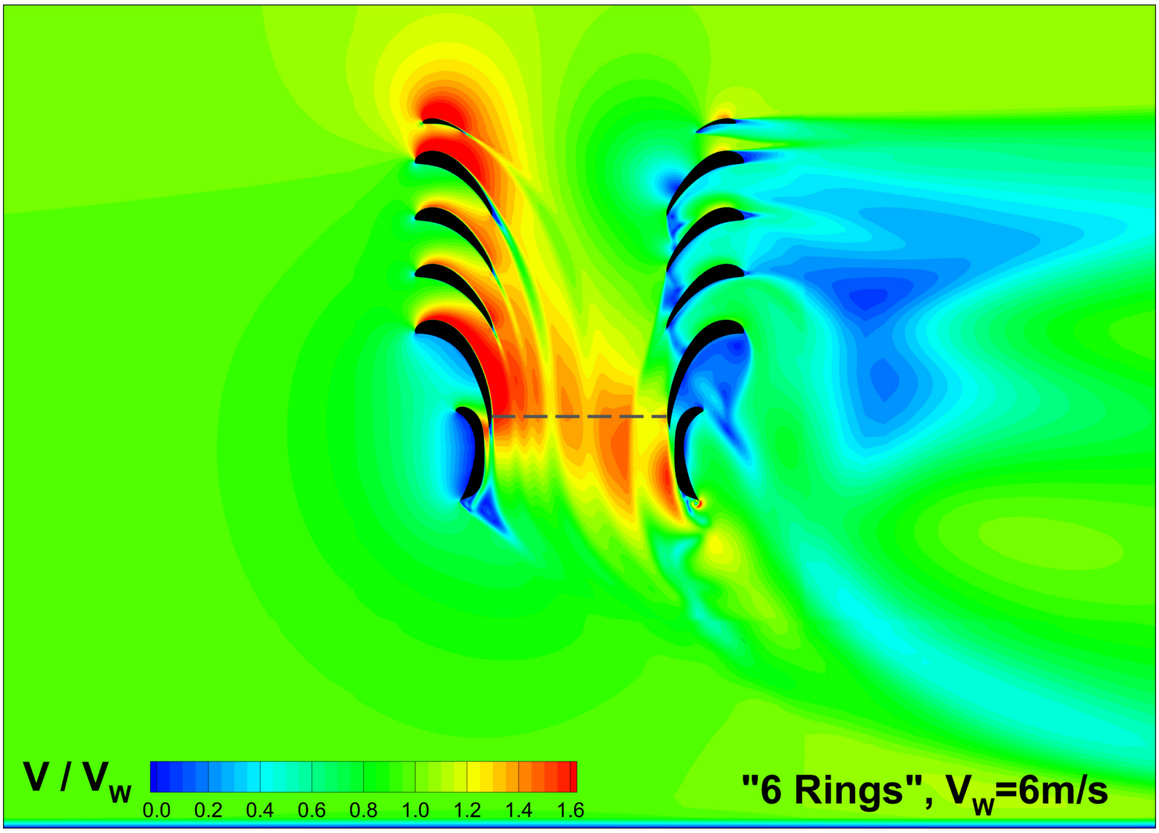

Fig. 10. Contours of local-velocity magnitude (V) referenced to wind velocity (V_W), analysed in plane of symmetry of flow region, 6-ring configuration, wind velocity V_W = 6 m/s

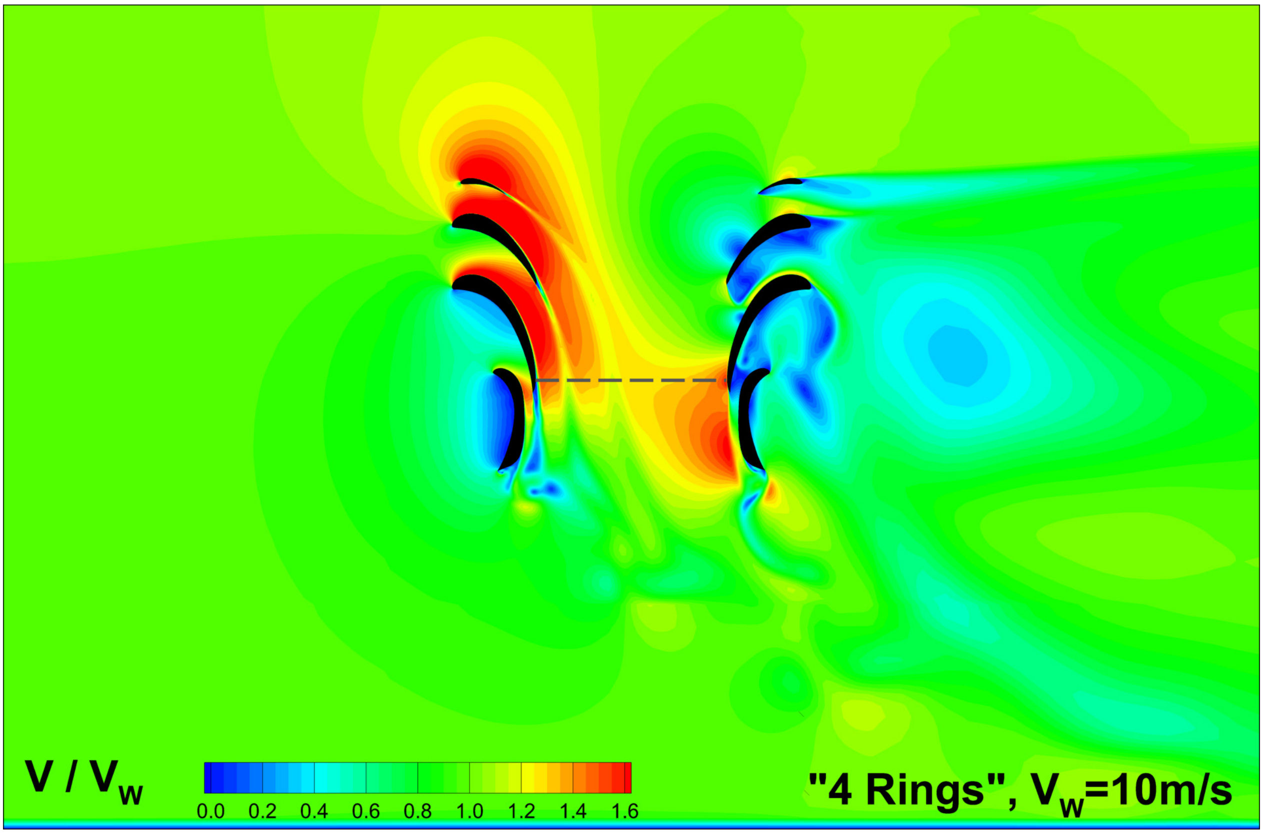

Fig. 11 Contours of local-velocity magnitude (V) referenced to wind velocity (V_W), analysed in plane of symmetry of flow region, 4-ring configuration, wind velocity V_W = 10 m/s

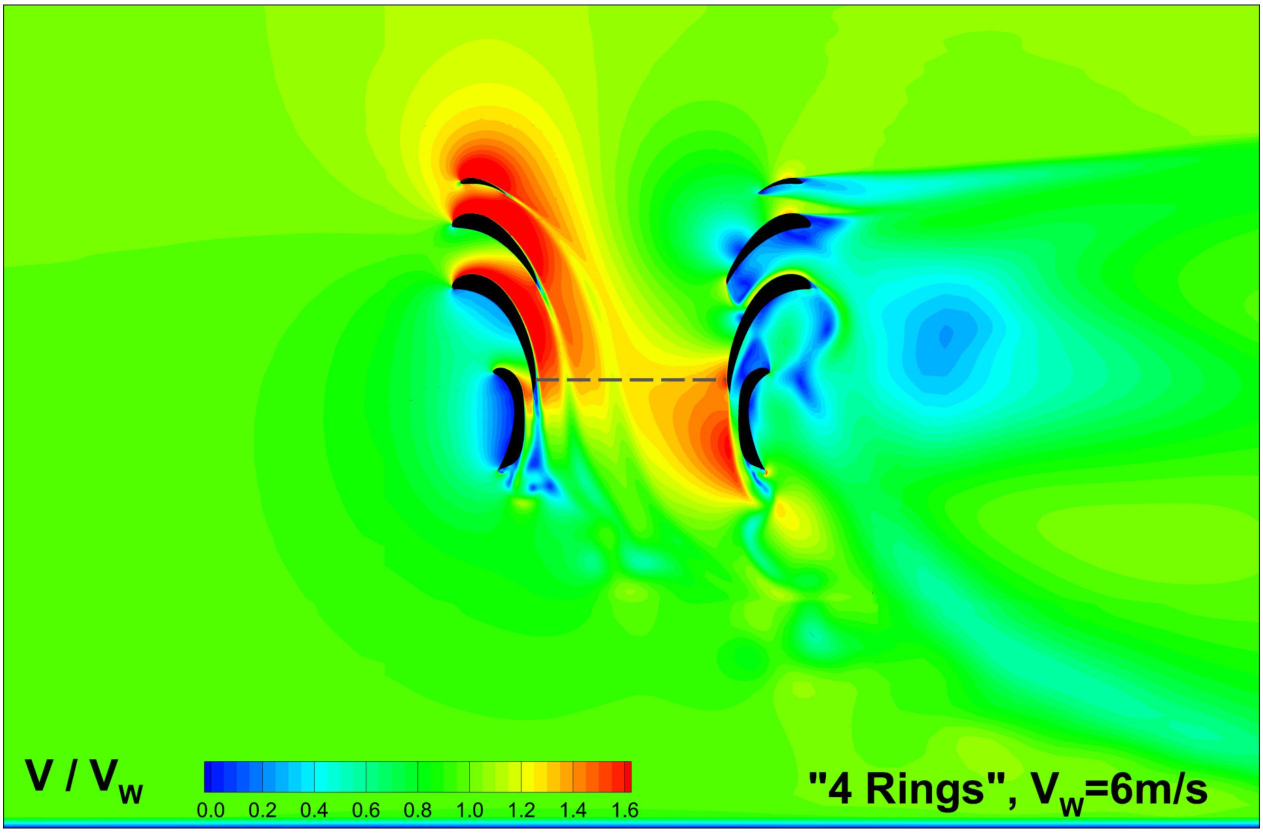

Fig. 12. Contours of local-velocity magnitude (V) referenced to wind velocity (V_W), analysed in plane of symmetry of flow region, 4-ring configuration, wind velocity V_W = 6 m/s

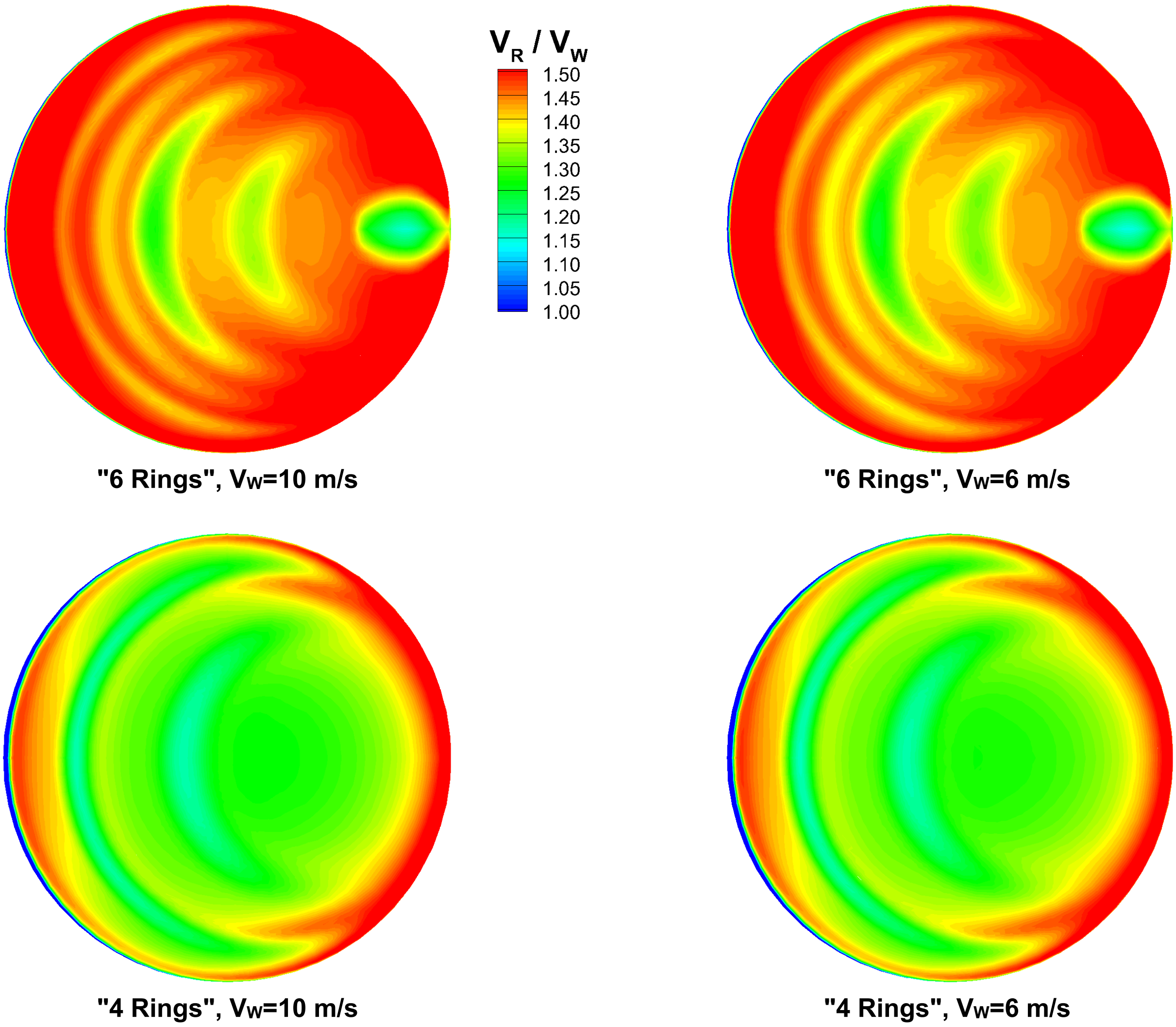

Fig. 13. Contours of average normal component of flow-velocity vector (V_R) referenced to wind velocity (V_W), analysed in the rotor-rotation plane for 6-ring and 4-ring configuration of the wind turbine for wind velocities V_W = 10 m/s, 6 m/s

Besides, of analysing of the average and distortion of normal component of flow velocity, also the analyses of total-pressure recovery and distortion in the rotor-rotation plane are very important. Such analyses may be done based on results presented in Fig. 14. Looking at the Figure it may be concluded that the total-pressure recovery and total-pressure distortion in the rotor-rotation plane are quite satisfactory. The only exception may concern the mentioned leeward area of the rotor-rotation plane. In this area, for the 6-ring configuration, the drop of total pressure is the largest. It is considered, that this drawback could be improved during a planned next stage of development of the presented wind turbine.

4. Summary and Conclusions

The new, innovative concept of Vertical-Axis Wind Turbine has been developed. The turbine consists of classic, bladed rotor of vertical rotation axis, electrical generator driven by the rotor, ring-palisade casing and three vertical supports and abutments that hold together the structure of the turbine and attach it to the ground.

The main objective of the research presented in the paper was to optimise the ring-palisade casing, which in final design consists of several ring vanes placed one on the other. The optimisation was focused on the optimal design of shapes of the rings and their mutual positions.

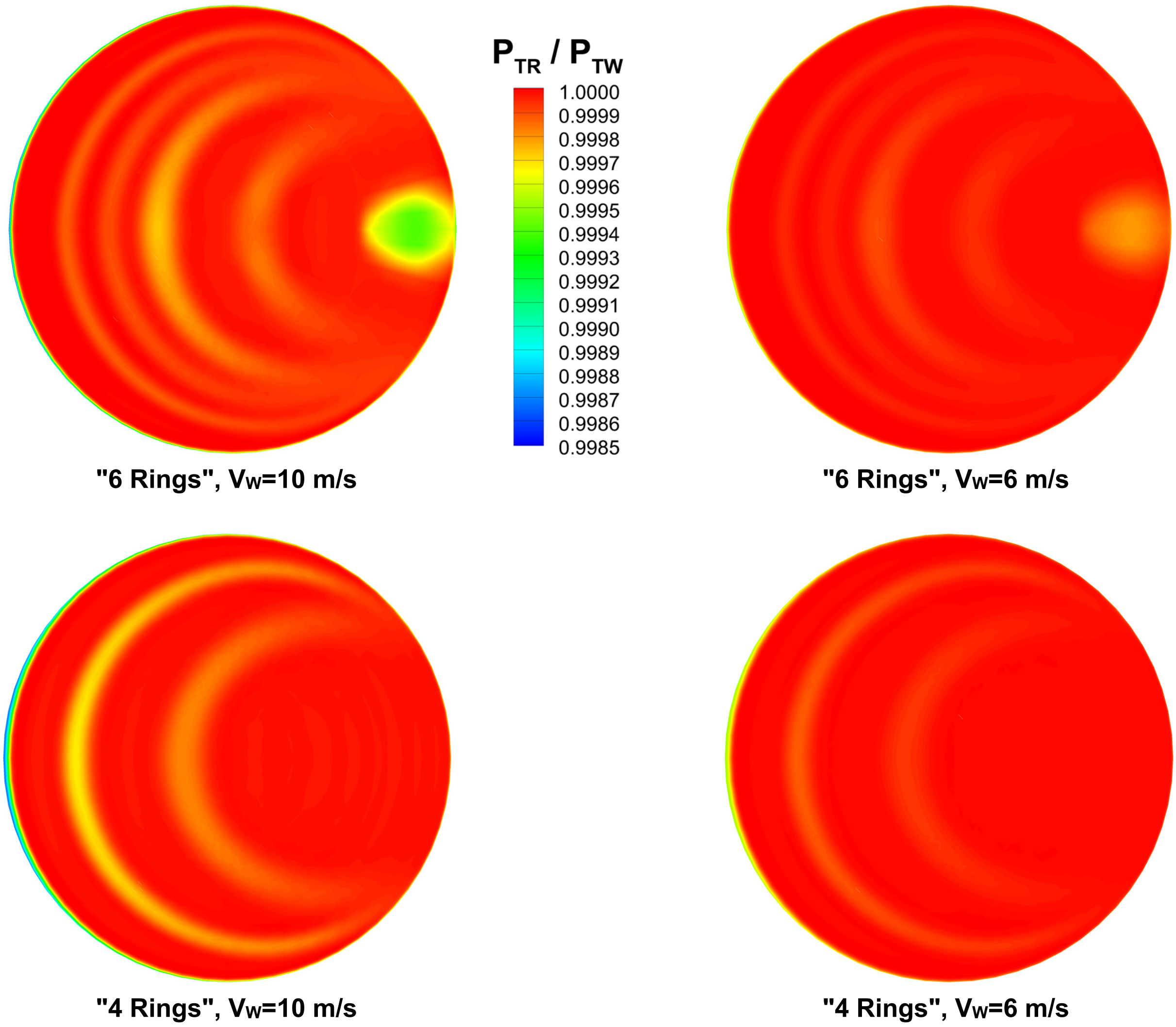

Fig. 14. Contours of total pressure, measured at the rotor-rotation plane (P_{RW}) referenced total pressure of undisturbed wind stream (P_{TW}), analysed in the rotor-rotation plane, for 6-Ring and 4-Ring configuration of the wind turbine, for wind velocities V_W = 10 m/s, 6 m/s

Several variants of the developed wind turbine have been proposed for potential practical implementations. They differ with each other by the number of essential rings forming the casing. In conducted investigations, the 6-ring, 5-ring and 4-ring configurations were taken into consideration, though configurations of higher number of rings are also possible to be designed.

The performance of sequential variants of the turbine was measured in terms of the ratio:

$$\text{average } V_R / V_W \,, \tag{1}$$

where V_R is the normal component of flow-velocity vector, measured at the rotor-rotation plane and V_W is the wind velocity. Based on conducted CFD simulations it may be concluded that:

– 6-ring configuration is characterised by average V_R velocity higher than wind velocity V_W:
  – by approx. 47% for the wind velocity V_W = 10 m/s,
  – by approx. 45% for the wind velocity V_W = 6 m/s.
– 4-ring configuration is characterised by average V_R velocity higher than wind velocity V_W:
  – by approx. 33% for the wind velocity V_W = 10 m/s,
  – by approx. 32% for the wind velocity V_W = 6 m/s.

Apart of the described concept of the wind turbine, the twin concepts, but characterized by deflecting wind stream vertically upwards, was developed too. Both of these concepts are the subject of pending patent [6, 7].

It is planned to continue the development of the presented concept of innovative wind turbine. Among others, the future research will focus on:

– redesigning of the casing rings so as to reduce or eliminate distortion of normal velocity and total pressure, observed in leeward part of the rotor-rotation plane for the 6-vane configuration,
– simplification of the wind-turbine design,
– designing and optimisation of the bladed rotor, dedicated for the developed casing.

Symbols

P_{TR} – total pressure, measured at the rotor-rotation plane,
P_{TW} – total pressure of undisturbed wind stream,
V – local-velocity magnitude,
V_R – normal component of flow-velocity vector, measured at the rotor-rotation plane,
V_W – wind velocity.

Acronyms and abbreviations

CAD – Computer Aided Design,
CFD – Computational Fluid Dynamics,
HAWT – Horizontal-Axis Wind Turbine,
URANS – Unsteady Reynolds-Averaged Navier Stokes (Equations),
VAWT – Vertical-Axis Wind Turbine.

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