DESIGN AND ANALYSIS OF WIND ACCELERATING AND GUIDING ROTOR HOUSE FOR A VERTICAL AXIS WIND TURBINE

Abdul Latif Manganhar*, Saleem Raza Samo**, Muhammad Ramzan Luhur*** and Altaf Hussain Rajpar****

ABSTRACT

The intermittent behavior and low wind speed (at sites) are major barriers to wind energy effective harness. Several efforts have been made to overcome these shortcomings; however, ducting or funneling of rotors has been proposed as good technique to achieve improvement over these deficiencies. Latter approach not only improves efficiency, but covers environmental concerns of wind power generators also. For the sites where wind speed is very low and turbulent, vertical axis wind turbines (VAWTs) remained the better choice. In this study wind accelerating and guiding rotor house (WAG-RH) is introduced to enhance the working range of a VAWT in low wind speed with improved efficiency. The WAG-RH collects the free stream wind parcel, directs and accelerates it towards the useful space left for VAWT to avoid the negative torque and generate more positive torque. In present study, multiple WAG-RH design concepts have been investigated, and favorable results have been achieved in terms of increase in velocity. Nevertheless, final configuration RH(4,45) gives the better performance over all proposed WAG-RH configurations. The numerical simulations are performed using design software Gambit and CFD software ANSYS Fluent 14.5 and compared with experimental results. The comparison of both approaches show good agreement.

Keywords: Ducting; vertical axis wind turbine; wind acceleration; rotor efficiency; ANSYS Fluent

1. INTRODUCTION

The power output of a wind turbine is proportional to cube of the wind speed that impinges on the rotor blades. Any technique, which can increase the upstream wind speed to the turbine, even by a small amount, can largely improve the power output of turbine. Converging diverging ducts have been used to increase the upstream wind speed striking the turbine to improve its power output [1-3]. Ducting of wind turbine rotors have been done mainly for three reasons. First, to improve the power of low-speed wind and enhance working range of wind power generators; second, to improve the efficiency of wind rotors through effective working of incoming wind; and third, to avoid the environmental effects of wind energy as reported in [4,7]. The maximum theoretical efficiency, a conventional wind turbine may extract, is 59.3% of the power available in a stream tube of wind with an area equal to the swept area of the rotor, known as Betz limit (Betz 1966). It has been reported by several researchers that improvement in efficiency beyond the Betz limit can also be achieved by placing a turbine inside a shroud [8-14]. The ducting of vertical axis wind turbine (VAWT) was first introduced by Webster [15] for a building integrated VAWT. In this concept wind enters horizontally and leaves the duct vertically after transferring its energy to vertical rotor. This approach was proved effective and robust in operation by [16]. In 2008, Hau and Cheng [17] developed a bucket-shaped duct for an in-house VAWT and reported 80% increase in rotor efficiency compared to its bare working efficiency.

Carcangiu and Montisci [18] introduced a roof top system suitable for wind power generation in urban areas and reported that the system can fulfill the energy demand of a common building. Corscadden [19] proposed an idea to investigate the improvement over potential performance possible with strategic placement of VAWT in the built environment.

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In order to avoid the negative torque produced by VAWT, wind deflectors, curtains and concentrators have been introduced. A concentrator nozzle attached at rotor inlet can direct (wind flow only to the concave side of blade) and increase the wind speed at rotor inlet, leading to improved power coefficient of VAWT [20,21]. A wind-solar hybrid renewable energy harvester was introduced by Tong et al. [22], which overcomes the inferior aspect of low wind speed by guiding and increasing the speed of free-stream wind through fixed or yaw-able power-augmentation-guide-vane (PAGV) before approaching the wind turbine. Latter system was again verified by placing a Sistan wind turbine inside the PAGV and improved performance of rotor has been reported [6]. Nevertheless, both the concentrator nozzle and the PAGV concepts, eliminate the possibility of VAWT to receive wind from any direction and require yaw mechanism.

To overcome this deficiency, a rotor house design based on wind accelerating technique was proposed by Manganhar et al. [23], which can receive wind from all the directions, besides accelerating and concentrating the wind in the proposed rotor zone. Additionally, the proposed design can accommodate a solar air heater on upper surface of the house, which can further accelerate the wind inside the structure beside the use for space heating in winter. At the same time, Chong et al. [24] also introduced a shrouded wind-solar hybrid renewable energy and rain water harvester with an omni-directional-guide-vane (ODGV) for urban high-rise application, where authors claimed that ODGV guides the flow to an optimum flow angle before it interacts with the rotor blades. However, neither the flow angle nor the other design parameters are optimized as it is claimed. Authors only analyzed one design configuration for three wind directions.

The recent development of the technology sector of micro vertical wind systems is inclined to improve the performance of technology and versatility of its use. This can be achieved through the integration of new technologies such as magnetic levitation rotors to reduce friction, and the new Invelox turbine which relies on a wind acceleration duct immediately before the turbine itself and the funnel-shaped structure with multiple openings to catch breezes from any direction [24a].

In this work emphasis has been given to increase the wind speed by developing a novel wind accelerating and guiding rotor house(WAG-RH) system. The proposed WAG-RH is a simple and an economical design that can collect, guide, accelerate and concentrate free stream wind parcel of an area nearly equal to the projected area of the rotor house before interacting the rotor blades inside the house. The present design compared to complex design (with eight tapered walls and concave top surface) introduced by Chong et al. [24], uses four uniform walls and a flat top surface. The performance parameters of WAG-RH have been optimized by testing multiple-RH design configurations with four wall geometries using numerical simulations. Numerical methods compared to experimental methods are less expensive and less time consuming for testing of such systems[24b]. The final WAG-RH design gives good improvement over in-coming wind speed and guides it to pass through most useful location in the rotor zone. The simulated results have been compared with the experimental results and show good agreement.

The paper is structured in such a way that Section 2 describes the design parameters and the methods applied. Section 3 presents the results and discussions, and final Section 4 concludes the outcome of the work.

2. MATERIALS AND METHODS

The WAG-RH is a house for a VAWT, which improves the performance of a conventional vertical rotor. The geometrical features of the proposed WAG-RH design are shown in Fig.1, where D is the diameter of the rotor house and d the diameter of the rotor zone. The dimension H represents the height of the vertical wall and B its length.

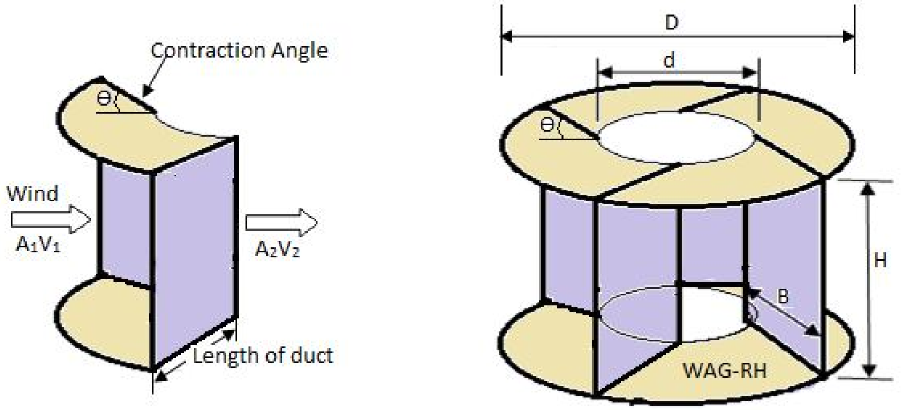


Fig. 1 Geometrical features of WAG-RH

The rotor house has four vertical walls, which constitute four converging channels towards the rotor zone. The parameters A_1V_1 describe the flow at inlet and A_2V_2 the flow at outlet of the channel, where A_1 and A_2 are the areas, and V_1 and V_2 the velocities at inlet and outlet of the channel, respectively. The convergence of each channel depends on the tilt angle (contraction angle) and the length of the channel wall. Both the contraction angle and the length of the channel, change the contraction ratio (A_1/A_2) of the channel, which cause variation in the velocity. The higher the contraction ratio, the higher the increase in velocity. The length of the channel also changes the diameter of the rotor house leading to change in the diameter ratio (D/d).

The initial design specifications (used for experimental analysis) for the walls were taken as 0.3 m length and 0.3 m height. Each wall was tilted at contraction angle of 45^o in clockwise direction about its origin at the circumference of circular rotor zone. This configuration gives the diameter ratio of 4 with 0.2 m diameter of the rotor zone.

2.1 SIMULATION OF WAG-RH GEOMETRY

The numerical simulations are performed by several experts such as [24-26] using CFD as an essential tool for analyzing wide-range of wind flows for the structures such as proposed in present study. The Navier-Stokes equations have been considered as the model equations for all CFD problems, which formulate the principles of conservation of mass, energy and momentum in the form of partial differential equations. In this study two-dimensional steady state Reynolds Averaged Navier-Stokes (RANS) equations are used as governing equations, which are solved through CFD educational version of ANSYS fluent 14.5. The RANS method is one of the most popular methods used by the CFD community [27] to solve the complex type flow problems.

The selection of a turbulence model in any CFD code is highly dependent on the nature of the flow considered [28]. The change in nature of flow, changes its mathematical nature that can directly or indirectly affect the computational resources, time and accuracy of results. For the present study SST k-ω turbulence model was selected, which is successfully applied by Chong et al. [24,6] and Shahizare et al. [28a] for such structures as adopted in these simulations. The SST k-ω model carries the combination of k-ω turbulence model (robust for near wall region) and the k-ε model (suitable for away from walls) [27]. Further, SST k-ω model behaves well in adverse pressure gradients and separating flow also [29]. Table 1 below contains the setup conditions used for present ANSYS Fluent computations.

Table 1 ANSYS Fluent Solver Setup Conditions

Solver type	: Pressure-based
Velocity formulation	: Absolute
Time	: Steady
Gravity	: -9.81 m/s^{2} in Y
Models	: Viscous SST k-ω
Material	: Air
Scheme	: Simple
Gradient	: Least squares cell
Pressure	: Standard
Momentum	: Second-order upwind
Turbulent kinetic energy	: First-order upwind
Specific dissipation rate	: First-order upwind

2.2 WAG-RH PERFORMANCE ANALYSIS

2.2.1 PERFORMANCE PARAMETERS AND CONFIGURATION CODES

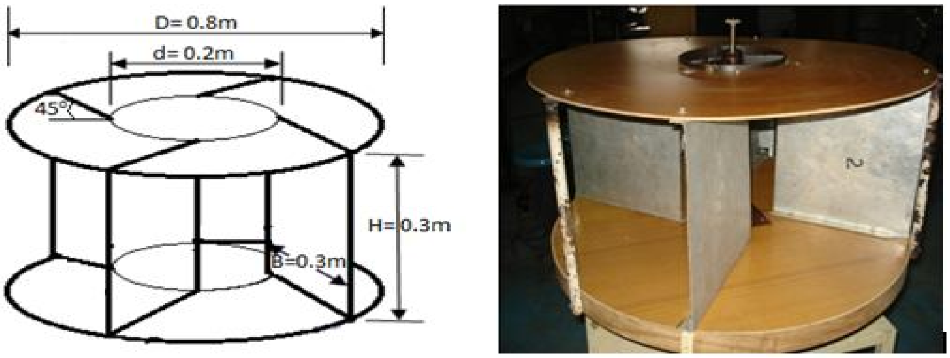
From Fig. 1 it is obvious that the performance parameters of WAG-RH to be optimized can be:

- Contraction angle (Θ)
- The ratio between house and rotor zone diameters (D/d)
- Angle of incidence (Φ)
- Wind velocity (V)

With change in the above parameters, various rotor house design configurations can be developed. For the identification of the configurations, a coding system has been introduced based on RH(D/d,Θ), where RH represents the rotor house. In the investigation, three variations to each parameter were found enough to understand the effect on the performance of the WAG-RH. For these variations, the values for diameter ratios and contraction angles were taken as D/d=4,3,2 and Θ=45^{o},40^{o},30^{o}. Based on this, nine RH configurations were developed and simulated, which are RH(4,30), RH(4,40), RH(4,45), RH(3,30), RH(3,40), RH(3,45), RH(2,30), RH(2,40), and RH(2,45).

2.2.2 MANUFACTURING OF WAG-RH AND EXPERIMENTAL SETUP

The WAG-RH geometry was finalized through numerical simulations carried out for nine configurations described in Section 2.2.1. The geometrical configuration RH(4,45) as shown in Fig. 2(a) delivered better results than all other configurations. In final design, the diameter of the WAG-RH D=0.8 m, diameter of the rotor zone D=0.2 m, height and length of the vertical walls are H=0.3 m and B=0.3 m, respectively, tilted at contraction angel of 45^{o}. Based on these dimensions, the experimental model was manufactured as shown in Fig. 2(b) at mechanical engineering workshop of Quaid-e-Awam University of Engineering, Sciences and Technology (QUEST), Nawabshah, Pakistan.



(a) (b)

Fig. 2 (a) Optimized WAG-RH geometry and (b) manufactured model

The performance of WAG-RH experimental model in terms of wind speed amplification was studied by using subsonic open type wind tunnel of the QUEST shown in Fig. 3 and compared with numerically simulated performance. The WAG-RH was placed in front of the wind tunnel opening having dimensions of 0.5 m x 0.5 m. The measurements were performed at different inlet velocities, V_{in} =(1,3,5,7,9) m/s.

(a) (b)

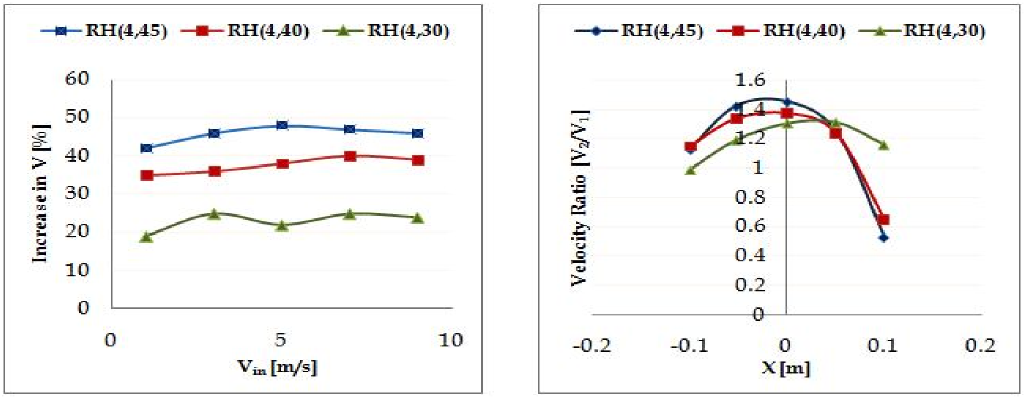
Fig. 3 (a) Experimental setup and (b) experimental layout showing five important locations in the rotor zone in stream-wise direction where measurements were taken.

The velocity variations were measured at five fixed points in the stream-wise direction in the rotor zone, as shown in Fig. 3(b). The wind speed measurements were performed using TES-1340 Hot-Wire Anemometer having accuracy of ±3% of reading ±1%FS.

3. RESULTS AND DISCUSSIONS

3.1. EFFECT OF CONTRACTION ANGLE

Here, performance of each RH configuration is analyzed in terms of velocity variation along the stream-wise direction in the rotor zone. The configuration RH(4,30) contributes 20-25% increase in velocity for five selected inlet velocities as described in Section 2.2.2. Similarly, RH(4,40) gives 33-35% and RH(4,45) 41- 49% for the same inlet velocities as shown in Fig. 4(a).



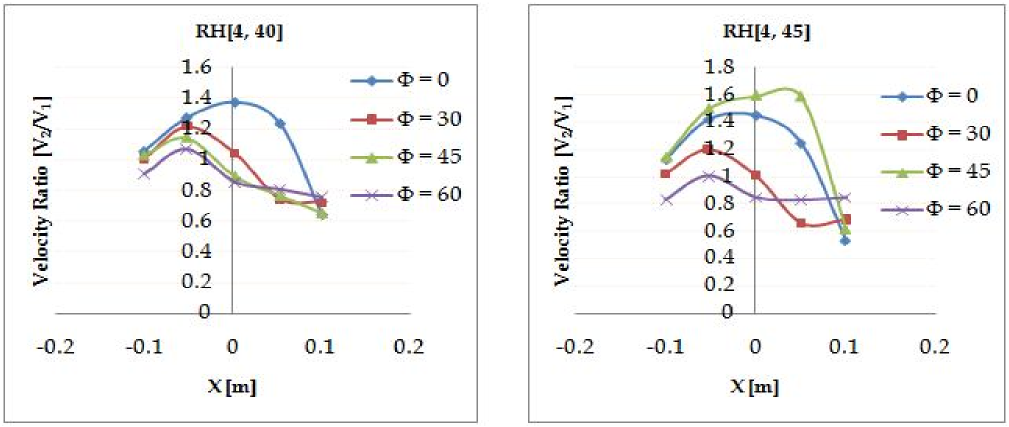
(a) (b)

Fig. 4 Performance comparison of three RH configurations in terms of. (a) Increase in inlet velocity for five different velocities and (b) velocity ratio at 5 m/s inlet velocity for five fixed points in the rotor zone in stream-wise direction

The comparison of velocities shows that the configuration RH(4,45) gives better performance in terms of velocity amplification than other two configurations. Fig. 4(b) presents the comparison of velocity ratio (V_2/V_1) for three RH configurations at inlet velocity of 5 m/s at five fixed points in the rotor zone in stream-wise direction. The results reflect 1.5 times increase in inlet velocity in case of RH(4,45), which is 14% greater than the increase contributed by RH(4,40) and 20% greater than the increase achieved with RH(4,30).

3.2 EFFECT OF WIND DIRECTION

It is clear from discussion in 3.1 that the performance of configurations RH(4,45) and RH(4,40) based on effects of contraction angle are better and close to each other. The performance of RH(4,30) is not up to the mark as compared to other two configurations; therefore, the investigation of wind direction effect can be limited to RH(4,45) and RH(4,40). The effect of wind direction on the performance of latter RH configurations is analyzed by changing the angle of incidence, as shown in Fig. 5.



(a) (b)

Fig. 5 Performance comparison of two RH configurations in terms of velocity ratio contribution

The Fig. 5 indicates the change in velocity ratio in the rotor zone in stream-wise direction for RH(4,40) and RH(4,45) at inlet velocity of 5 m/s for angles of incidence $\Phi=0^o,30^o,45^o,60^o$. According to Fig. 5(a), RH(4,40) configuration contributes maximum 1.38 times increase in inlet velocity at 0^o and less or equal to 1.25 times for rest of angles of incidence. Looking at Fig. 5(b), it has been observed that RH(4,45) gives high velocity ratios at 0^o and 45^o, which are 1.5 times and 1.6 times increase in inlet velocity, respectively. The optimum values of velocity ratio at different angles of incidence for both configurations are summarized in Table 2.

Table 2. Optimum values of velocity ratio

RH Configurations	Angle of incidence (Φ)			
	0^o	30^o	45^o	60^o
RH(4,40)	1.38	1.2	1.2	1.15
RH(4,45)	1.5	1.25	1.6	1.12

3.3 EFFECT OF DIAMETER RATIO

The analysis of Sections 3.1.1 and 3.1.2 attributed that the configuration RH(4,45) gives better performance than the other configurations. Thus, further investigation are performed only for remaining configurations of this design such as RH(2,45) and RH(3,45) to optimize the diameter ratio. For this purpose, simulations are performed for these three configurations and results are shown in Fig. 6.

The fig. 6 demonstrates the contours of velocity magnitude developed for RH(2,45), RH(3,45) and RH(4,45) configurations at V_{in} =5 m/s and $\Phi=0^o$. It clearly indicates that each design configuration collects the free stream wind parcel of an area approximately equal to the projected area of that design configuration, concentrates and accelerates it in the rotor zone. It is also obvious that the walls divert and guide the flow to pass through half of the rotor zone, which could be beneficial to minimize the generation of negative torque and generate more positive torque when the rotor will operate in this zone. Further, in comparison to RH(2,45) and RH(3,45) configurations, more stream-lined and concentrated flow pattern has been observed for RH(4,45) in the rotor zone.

In order to better understand the contour results, graphical representation of the flow patterns are presented in Fig. 7. The figure indicates that with the increase in diameter ratio (D/d), there is increase in velocity ratio inside the rotor zone.

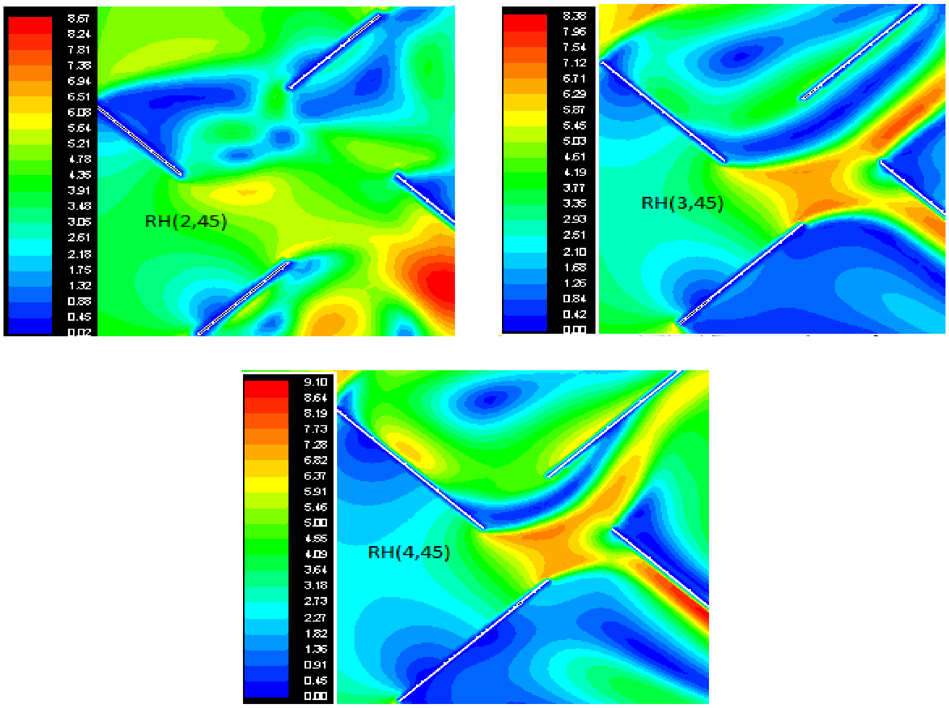


Fig. 6 Contour plots colored by velocity magnitude showing the flow pattern for three RH configurations based on diameter ratio

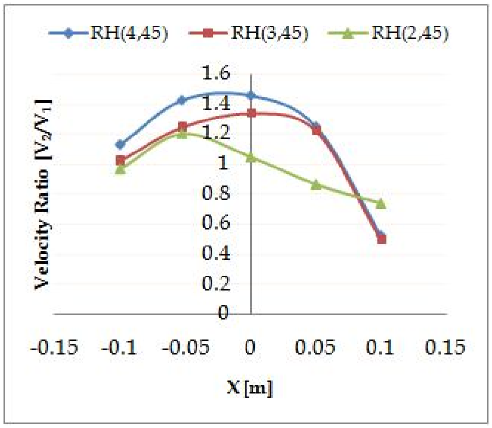
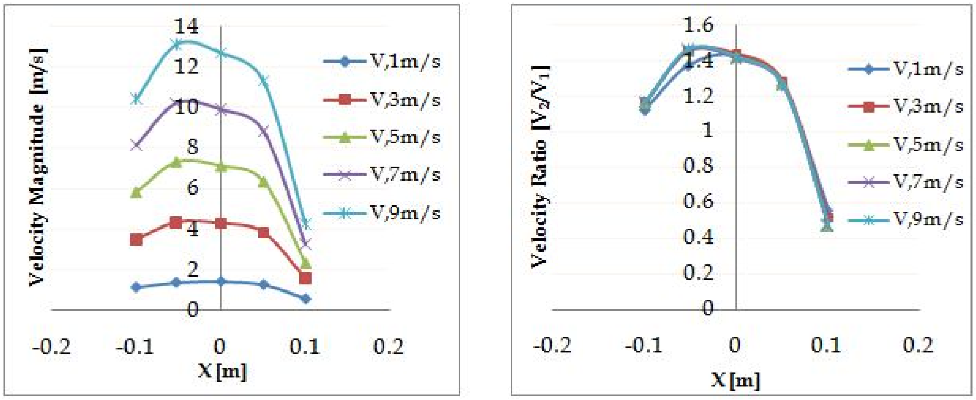


Fig.7 Performance comparison of three RH configurations based on diameter ratio

3.4 EFFECT OF WIND VELOCITY

In this section, the performance of optimal configuration RH(4,45) has been verified in the context of wind velocities V_{in}=(1,3,5,7,9) m/s at $\Phi=0^o$ as mentioned in Section 2.2.2. The variations in wind velocity magnitude and velocity ratio in the rotor zone in stream-wise direction are shown in Fig. 8.



(a) (b)

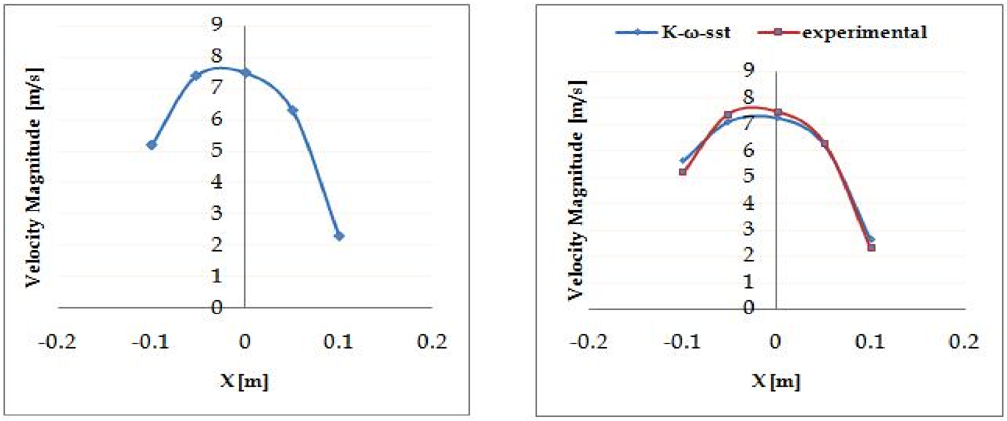
Fig. 8 Contribution of RH(4,45) for change in velocity magnitude and velocity ratio at different inlet velocities in the rotor zone

The Fig. 8(a) demonstrates that with the increase in inlet velocity, the velocity magnitude in the rotor zone increases significantly. For the quantification of change in velocity magnitude, velocity ratio is estimated as given in Fig. 8(b). The figure indicates that for all inlet velocities, there is nearly 1.5 times increase in inlet velocity in the rotor zone.

3.5 EXPERIMENTAL RESULTS

The performance investigation of manufactured model for RH(4,45) configuration was conducted experimentally as described in Section 2.2.2. The results are shown in Fig. 9, which describes the change in velocity magnitude in the rotor zone in stream-wise direction at V_{in}=5 m/s and $\Phi=0^o$.

According to observations, the inlet velocity magnitude of 5 m/s increases to 7.7 m/s in the rotor zone (see Fig. 9(a)), which in terms of velocity ratio, is 1.54 times increase in the inlet velocity. Further, in Fig. 9(b), experimental and numerical results are compared for identical conditions, and show good level of agreement.



(a) (b)

Fig. 9 Performance of RH(4,45) configuration (a) Experimental results and (b) comparison of experimental and numerical results.

4. CONCLUSION

A wind accelerating and guiding rotor house (WAG-RH) has been developed to enhance the speed and working range of a conventional VAWT at low wind speed with improved efficiency. The WAG-RH collects the free stream wind parcel of an area nearly equal to the projected area of the rotor house, and directs and accelerates it towards the useful space left for VAWT to avoid negative torque and generate more positive torque.

Multiple WAG-RH design concepts have been investigated and favorable results have been observed in terms of increase in velocity. Nevertheless, final configuration RH(4,45) contributes better performance as compared to other proposed configurations. The optimized configuration RH(4,45) for any channel with any velocity at angles of incidence $\Phi=0^o$ and 45^o gives nearly 1.5 and 1.6 times increase in inlet velocity, respectively, in the rotor house. The increase in diameter ratio of WAG-RH(4,45) higher than 4 can further increase the performance, but the system may not be economical. The comparison of experimental and numerical results for identical conditions reflects good agreement.

The future aim is to investigate the performance of conventional VAWT in the designed WAG-RH as well as to integrate the rotor house with a solar air heating system that may further improve the performance of rotor, which is work in progress. The solar heater can also be used for space heating in winter.

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