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Numerical Investigations on Aerodynamic Characteristics of Savonius Wind Turbine

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ABSTRACT:
In This Paper Objective Is To Investigate The Aerodynamic Performance Of Savonius Wind Turbine. Wind Tunnel Investigation Was Carried Out To Find The Aerodynamic Characteristics Like, Drag Coefficient, Torque Coefficient, And Power Coefficient Of Three Blade Savonius Wind Turbine Rotor Models With And Without Overlap Ratio (Ratio Of Overlap Distance Between Two Adjacent Blades And Rotor Diameter ,Or = A/D) At Various Reynolds Numbers. Numerical Investigation Was Acarried Out To Find Those Aerodynamic Characteristics. For Numerical Investigation, Commercial Computational Fluid Dynamic (Cfd) Software Fluent Were Used. Afterwards Those Two Results Were Compared For Verification. The Results From The Experimental Part Of The Research Show A Significant Effect Of Overlap Ratio And Reynolds Number On The Improvement Of Aerodynamic Performance Of The Savonius Wind Turbine. At Higher Reynolds Number Turbine Model Without Overlap Ratio Gives Better Aerodynamic Coefficients And At Lower Reynolds Number Model With Moderate Overlap Ratio Gives Better Results.
Keywords: Wind Tunnel, Aerodynamic, Overlap Ratio, Reynolds Number

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I. INTRODUCTION

Renewable Energy Sources Include Wind Energy, Solar Energy, Tidal Energy, Geothermal Energy, And Biomass Energy. Wind Is Among The Most Popular Sources Of Alternative Energy Because It Is Pollution Free And Available Almost Any Time Of The Day, Especially In The Coastal Regions. As A Sustainable Energy Resource, Electrical Power Generation From The Wind Is Increasingly Important In National And International Energy Policy In Response To Climate Change. The Main Advantages Of Wind Energy Include Its Availability Year Round, No Green House Gases, And Domestic Availability. The Disadvantages Of Wind Energy Are High Installation Cost And The Necessity Of Strong Winds To Produce Electricity.

The Two Primary Types Of Wind Turbine Are The Horizontal Axis Wind Turbine (Hawt) And Vertical Axis Wind Turbine (Vawt). Hawts Include Both Upwind And Downwind Configurations, With Various Performance Enhancers, Such As Diffusers And Concentrators. Hawts Are The Most Popular Configuration Now Because They Have Higher Efficiency, But They Are Only Suitable For Places With Extremely Strong, Gusty Winds And Urban Areas [29]. In Contrast, Vawts Work Well In Places With Relatively Low Wind Strength, And Constant Winds [29]. Hawts Are Highly Developed And Used In All Large-Scale Wind Farms. Most Research On Vawt Design Was Carriedout As Long Ago As The Late 1970s And Early 1980s. Interest Dropped After Hawts Were Determined To Be More Efficient At Large Scale, And Very Little Research Probed Vawt Aerodynamics Or Sought To Resolve The Problem Of The Interaction Of Its Blade Structure With Unsteady Aerodynamic Loads. Their Technical Development Lags Significantly Behind That Of Hawts. However, Hawts Have Never Been Proven Fundamentally More Aerodynamically Efficient Than Vawts. Indeed, Vawts May Be More Appropriate Than Hawts On A Very Large Scale (10mw+) When The Alternating Gravitational Loading On A Hawt Blade Becomes Excessive. Vawts Have A Number Of Advantages Over Hawts. First, They Do Not Have To Constantly Yaw Into The Local Wind Direction. Second, Due To Their Relatively Lower Rotational Speed, They Are Typically Quieter. Third, The Cost Of Manufacturing Very Large Vawts Could Be Lower Due To Their Simple, Straight, Constant Section Blades As Compared To The Hawts' Complex, Three- Dimensional Blades And, For The Same Reason, They Could Be Easier To Manufacture. Finally, Vawts Are Mechanically Better Able To Withstand High Winds Because Their Stalling

Behavior Changes, Offering A Potential Safety Advantage During Gust Conditions. Vawts Include Both A Drag-Type Configuration, Such As The Savonius Rotor, And A Lift-Type Configuration, Such As The Darrieus Rotor.

II. LITERATURE REVIEW ON EXPERIMENTAL INVESTIGATION

Wind Turbine Aerodynamics Must Be Designed For Optimal Output To Exploit The Wind Energy In A Specific Location. This Problem Remains Both Challenging And Crucial. Much Research Has Been Conducted On Savonius Rotors With Two Semi-Cylindrical Blades And S-Shaped Rotors With Various Flow Parameters. Islam Et Al. [13] Investigated The Aerodynamic Forces Acting On A Stationary S-Shaped Rotor And Attempted To Predict Its Dynamic Performance. They Measured The Pressure Distribution Over The Surfaces Of The Blades And Found That Flow Separates Over The Front And Back Surfaces, And The Point Of Separation Depends On The Rotor Angle. They Also Found That The Net Torque Becomes Maximum At A Rotor Angle Of □ = 45□ And Negative While The Rotor Angle Is Between □ = 135□ And □ = 165□ .

Diaz Et Al. [5] Analyzed The Drag And Lift Coefficients Of A Savonius Wind Turbine To Quantify The Aerodynamic Performance Of The Rotor. They Found That Maximum Efficiency, In Terms Of Power Coefficient, Occurs At A Tip-Speed Ratio Of □ = 1, And The Drag Coefficient Decreases Sharply When The Tip-Speed Ratio Increases Or Decreases From This Value. They Also Found That The Most Important Region Of Savonius Rotor Operation Occurs At A Tip-Speed Ratio Around □ = 1, Where The Lift Coefficient Remains As A Constant 0.5.

Sawada Et Al. [33] Studied The Mechanism Of Rotation Of A Savonius Rotor With Two Semi- Cylindrical Blades And Found That A Rotor With Gap Ratio Of 0.21 Produces Positive Static Torque At All Angles. They Also Found That Lift Force Contributes Significantly To Dynamic Torque While The Rotor Angle Is Between □ = 240□ And □ = 330□ .

Aldoss And Obeidat [1] Used The Discrete Vortex Method To Analyze The Performance Of Two Savonius Rotors Running Side-By-Side At Different Separations. They Compared Their Computational Results On Torque And Power Coefficients With Their Experimental Results For Verification.

Fujisawa And Gotoh [8] Studied The Aerodynamic Performance Of A Savonius Rotor By Measuring The Pressure Distributions On The Blade Surfaces At Various Rotor Angles And Tip-Speed Ratios. They Found That The Pressure Distribution On The Rotating Rotor Differs Remarkably From Those On The Stationary Rotor, Especially On The Convex Side Of The Advancing Blade, Where A Low- Pressure Region Is Formed By The Moving-Wall Effect Of The Blade. Torque And Power Performance, Evaluated By Integrating The Pressure, Were In Close Agreement With Direct Torque Measurements.

Rahman Et Al. [26-28] Experimentally Studied Aerodynamic Characteristics, Such As The Torque And Drag Coefficients, Of A Three-Bladed Savonius Rotor Model By Measuring The Pressure Difference Between The Convex And Concave Surfaces Of Each Semi-Cylindrical Blade Of The Stationary Rotor At Different Rotor Angles And The Variation Of The Separation Point With The Increase Of Rotor Angle. They Used The Static Coefficients For Dynamic Prediction And Compared The Findings In Terms Of Power Coefficient For Different Tip-Speed Ratios With Experimental Results For The Two-Bladed Savonius Rotor.

Although The Starting Torque For Savonius Rotors Is High, It Is Not Uniform At All Rotor Angles. The Torque Characteristics Of An Ordinary Savonius Rotor Have Two Problems. First, They Vary Significantly At Different Rotor Angles, Causing The Rotor To Vibrate And Consequently Decrease Its Durability. Second, The Torque At The Rotor Angle Ranging From 135□ To 165□ And From 315□ To 345□ Is Negative Or Very Small, Which Hinders Its Use As A Starter [11]. To Decrease This Torque Variation And Improve Starting Characteristics, A New Type Of Savonius Rotor Was Designed And Fabricated By Hayshi Et Al. [12]. It Had Three Stages, With A 120□ Bucket Phase Shift Between Adjacent Stages. With This Design, Wind-Tunnel Tests Showed That Both Static And Dynamic Torque Variations In One Revolution Were Much Smoother Compared To An Ordinary One-Stage Rotor, Which Greatly Improved The Starting Characteristics. They Also Measured The Torque Characteristics Of The Rotors With Guide Vanes And Found That, On The Average The Guide Vanes Increased The Torque Coefficient In The Low Tip-Speed Ratio But Decreased It In The High Tip-Speed Ratio. They Concluded That Two- And Three-Stage Conventional Savonius Rotors Could Overcome The Problem Of Negative Torque. However, The Maximum Power Coefficient Decreases For This Kind Of Design With More Stages.

To Decrease The Variation Of Static Torque In Conventional Savonius Rotors With Rotor Angle Ranging From 0□ To 360□ , Kamoji And Kedare [15] Tested A Helical Rotor With A Twist Of 90□ . They Conducted Experiments In An Open-Jet Wind Tunnel At Gap Ratios Of 0.0, 0.05, And 0.08 To Study The Effect Of The Overlap Ratio And The Reynolds Numbers On Its Performance To Evaluate The Static Torque, The Dynamic Torque, And The Power Coefficients. They Compared Its Performance With And Without A Shaft Between The End Plates At Different Overlap Ratios. A Helical Rotor Without A Shaft Was Also Compared With The Performance Of The Conventional Savonius Rotor. They Found That All Helical Rotors Have A Positive Power Coefficient Of Static Torque For All Rotor Angles, But The Rotors With A Shaft Had A Lower Power Coefficient Than Those Without. The Power Coefficient Of The Rotor Without A Shaft With A Zero Overlap Ratio Was Marginally Less Than The Conventional Savonius Rotor. The Rotor Appeared To Be Sensitive To The Reynolds Number, But This Finding Must Be Confirmed By Rigorous Experiments.

III. LITERATURE REVIEW ON NUMERICAL INVESTIGATION

Benjanirat Et Al. [4] Numerically Investigated The Performance Of The Nrel Phase Vi Horizontal Axis Wind Turbine. They Used 3d Unsteady Navier-Stokes Solver And Their Solver Was Third Order Accurate In Space And Second Order Accurate In Time. They Also Used An Implicit Time Marching Scheme To Solve Their Numerical Simulation. They Varied Their Wind Speed From 7 M/S To 25 M/S And Studied Three Turbulence Models: Baldwind-Lomax Model, Spalart-Allmara One Equation Model And K-E Two Equation Model With And Without Wall Corrections. From The Investigation They Found That Torque Is Increased While The Wind Speed Changes From 7 M/S To 10 M/S. The Flow Was Largely Attached Over The Entire Blade Rotor. The Torque Is Decreased While The Wind Speed Changes From 10 M/S To 20 M/S Because Of Progressive Growth Of Separated Flow Region. The Flow Was Fully Separated Above Wind Speed 20 M/S. In Their Experiment, The Spalart-Allmara Model And The K-E Model Without Near Wall Correction Showed Good Prediction For The Low Speed Torque But Which Did Not Agree With Experimental Results. They Found That K-E Model With Near Wall Correction Was The Most Accurate Prediction.

Lida Et Al. [17] Performed A Numerical Simulation Of Vertical Axis Wind Turbine (Darrieus Wind Turbine) With Large Eddy Simulation (Les) Using The Sliding Mesh Technique. Their Wind Turbine Had Three Straight Airfoil Type (Naca0018) Wings. The Dimensions Of Their Design Were Diameter: 3600 Mm, Cord Length: 300 Mm And Span Wise Length: 240 Mm. To Solve The Large Separated Unsteady Flow, They Used Incompressible The Navier-Stokes Equation And For The Turbulence Sub Grid The Scale Model Was Used. They Divided Their Grid In Three Parts Of Rotational Grid, Stationary Grid And Buffer Grid. Their Mesh Was Coarse At The Buffer Region. They Applied Uniform Inlet Wind Speed 6 M/S At Inlet Boundary Condition And Zero Static Pressure At Outlet Boundary Condition. There Was No Slip Condition At Blades And Cylinder Surface And Symmetric Boundary Condition For Both Side Of Span Wise Direction. Their Tip Speed Ratio Was From 2 To 6. Their Large Eddy Simulated Results Were In Good Agreement With Conventional Momentum Theory. They Also Found The Effect Of Divergence Flow And Dynamic Stall Was Small At High Tip Speed Ratio And Becomes Large At Low Tip Speed Ratio. They Also Found That Power Coefficient Is Significantly Decrease In The High Tip Speed Ratio Region And Suggested Reduce Time Ratio.

Sargolzaei Et Al. [31] Simulated Savonius Wind Turbine Using Artificial Neural Networks (Anns) To Estimate Power Ratio And Torque. They Experimentally Investigated Seven Prototype Savonius Wind Turbine And Compared With Their Predicted Anns Results. Their Predicted Results Were In Good Agreement With Their Experimental Results. They Found That The Increase Of Wind Speed Causes Torque Increase. For All Their Models They Found Maximum Torque Was At 60^0 And Minimum Torque Was At 120^0 .

Altan Et Al. [2] Numerically Simulated Their Experimental Work Using Fluent 6.0 And Gambit 2.0. Their Model Was Two-Dimensional, And They Used A Standard K-E Turbulence Model. To Calculate Pressure And Velocity Distribution, They Used A Simple Analysis Algorithm. By Comparing The Numerical And Experimental Results, They Concluded That The Curtain Improved The Performance Of Savonius Wind Turbines.

IV. METHODOLOGY

Numerical Investigation Was Performed Using Commercial Software Gambit And Fluent. Gambit Was Used To Generate Mesh Of The Flow Domain Around The Three Blades Of The Turbine Models; These Mesh Files Were Then Exported In Fluent To Solve The Fluid Flow Field To Determine The Aerodynamics Coefficients Such As Torque And Power Coefficients. This Chapter Describes In Detail The Experimental Set Up Design And Development, Experimental Data Measurement Procedure, Design And Fabrication Of Three Rotor Models, Numerical Model Selection And Validation, And Numerical Technique To Solve Fluid Flow.

Savonius Rotor

The Three Bladed Savonius Rotor Model With No Overlap Between Adjacent Blades Was Designed And Fabricated. Top And Front, Model Of The Savonius Wind Turbine Are Shown In Figure 1(A), And1 (B). The Model Was Made Of Three Semi-Cylindrical Blades Of Diameter, D = 127 Mm, And Height, H = 300 Mm. The Turbine Model Was Made Of Acrylic. The Central Shaft Was Removed From The Turbine Model. The Blades Were 120 Apart From Each Other And The Overall Rotor Diameter Was D = 248 Mm For The Model .

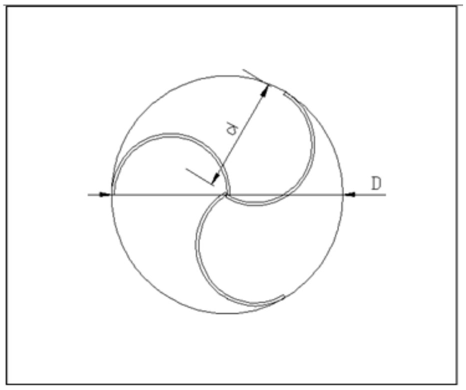

***Figure 1(A)*: Top View Of Model**

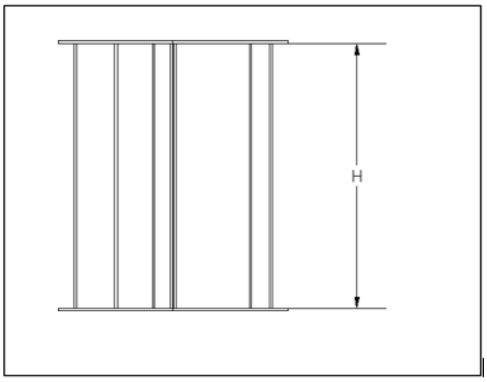

***Figure 1(B)*: Front View Of Model**

Mathematical Expressions

Rotor Area: $A = D.H$ [1]

Overlap Ratio: $OR = \frac{a}{D}$ [2]

Aspect Ratio: $AR = \frac{K}{d}$ [3]

Angular Velocity: $m = \frac{2nN}{60}$ [4]

Reynolds Number: $Re = \frac{VD}{u}$ [5]

Tip Speed Ratio: $h = \frac{mD}{2V}$ [6]

Torque Coefficient: $C_q = \frac{T}{\frac{1}{4}q Æ D V^2}$ [7]

Power Coefficient: $C_p = \frac{P}{\frac{1}{2}q Æ V^3} = \frac{Tm}{\frac{1}{2}q Æ V^3}$ [8]

V. RESULTS AND DISCUSSION

Pressure Contours At Three Different Reynolds Number

Pressure Contours Generated From Numerical Simulation Of Model 1 For Three Different Reynolds Number Are Shown In Figures 1 To 3. For All These Cases Higher Pressure Values Were Found At The Convex Side Of The First Blade Savonius Rotor Model. Negative Pressure Region Was Developed From Convex Side Of Blade 2 To Some Portion Of Convex Side Of Blade 3. This Negative Pressure Is Creating Pressure Difference Between Concave And Convex Surface That Eventually Rotates The Turbine Blades.

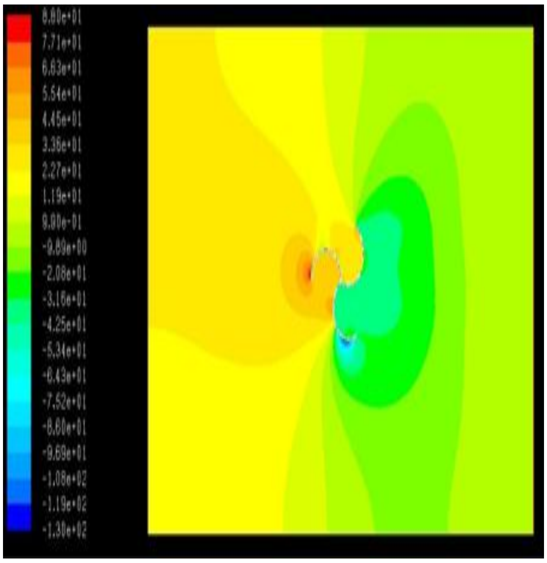

***Figure 1*: Pressure Contour Around Savonius Rotor Model 1 At Re = 1.61×10^5.**

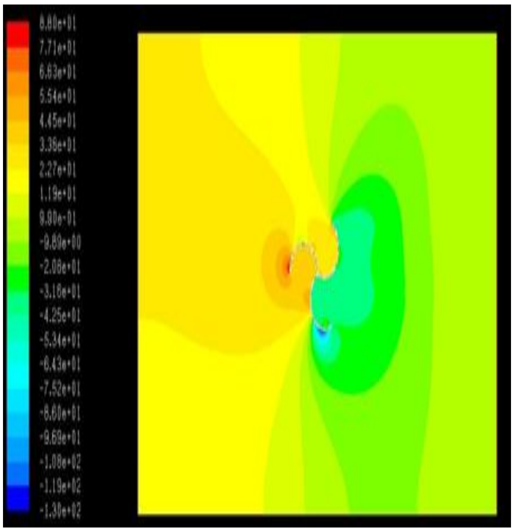

***Figure 2*: Pressure Contours Around Savonius Rotor Model 1 At Re = 1.37×10^5.**

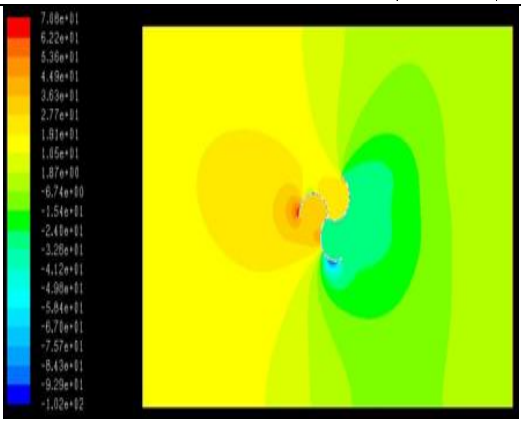

***Figure 3*: Pressure Contour Around Savonius Rotor Model 1 At Re = 1.22 $\times 10^5$.**

Velocity Contours For Three Models At Three Different Reynolds Number

Contours Of Velocity Magnitude For Savonius Rotor ***Model 1*** At Three Different Reynolds Number Are Shown In Figures 4.25 To 4.27. Patterns Of The Contours Are Almost Same For Different Reynolds Number Only Exception Is A Slight Variation In Velocity Magnitude. Once The Wind Strikes The Turbine Blades The Velocity Starts To Decrease At The Trailing Edge Of The Savonius Wind Turbine Model But After Some Distance Travel Stars To Regain The Velocity. Higher Velocity Region Was Created At The Top And Bottom Side Of The Wind Turbine Model.

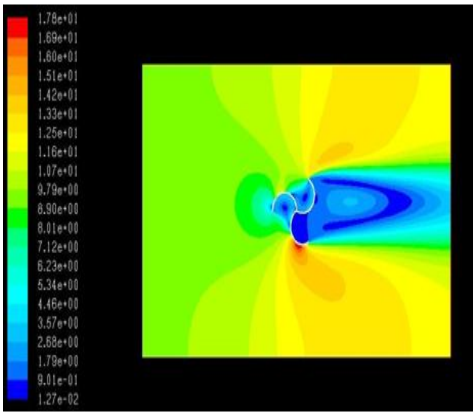

***Figure 4*: Velocity Contour Around Savonius Rotor Model 1 At Re = 1.61×10^5.**

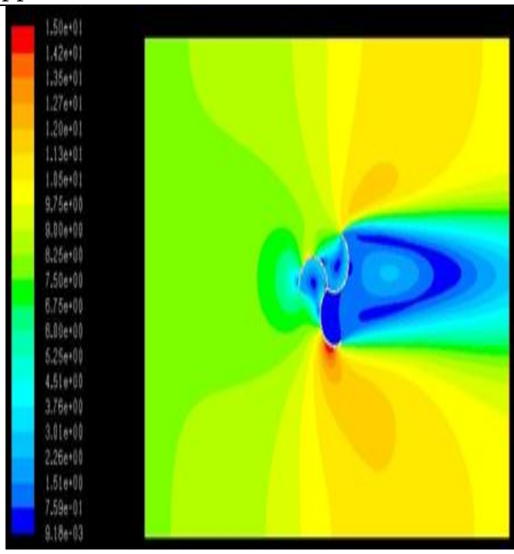

***Figure 5*: Velocity Contour Around Savonius Rotor Model 1 At Re = 1.37×10^5.**

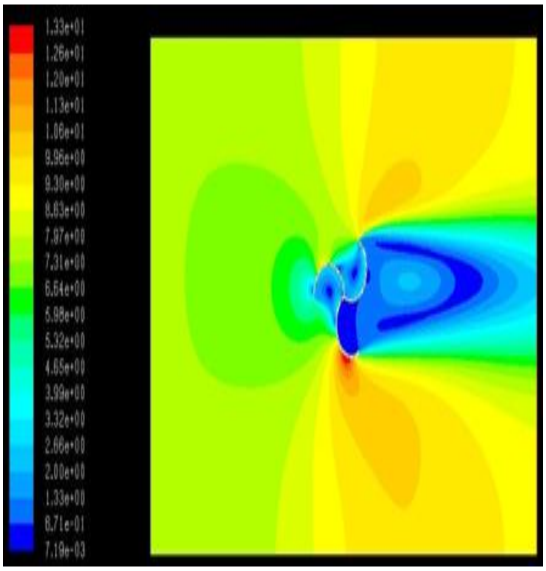

***Figure 6*: Velocity Contour Around Savonius Rotor Model 1 At Re = 1.22 $\times 10^5$.**

VI. COMPARISON OF NUMERICAL AND EXPERIMENTAL POWER COEFFICIENT

Figure 7 Shows The Comparison Of Numerically And Experimentally Calculated Power Coefficient (C_p) Of The Three Savonius Rotor Models With The Increase Of Tip Speed Ratio (Λ). Converged Solutions Of The Power Coefficient Values Were Considered At All Tip Speed Ratios For Numerical Results Whereas Power Coefficient At Four Rotor Positions 0°, 30°, 60° And 90° Were Considered For Experimental Values. Combined Blade Effect Was Considered For Both Experimental And Numerical Calculation. Figure 4.35 Shows That For Model 1 Experimental Power Coefficient At Rotor Position 0° Is Very Close To The Numerical Results. But The Deviation Is Huge For Rotor Position 60°. This May Be During Experiment There Was Disturbance From Environment Which Causes Sudden Power Increase And Also In Numerical Simulation The Boundary Effect Causes Lower Numerical Value.

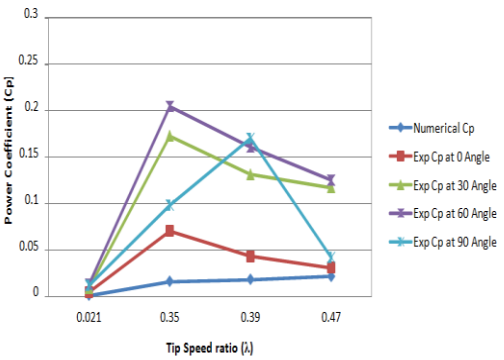

Figure 7: Power Coefficient (CP) versus Tip speed ratio (λ) for Model 1

I. CONCLUSION

Three Bladed Savonius Wind Turbine Scale Models With Different Overlap Ratioswere Designed And Fabricated For The Current Study. Aerodynamic Characteristics Of These Models Were Experimentally Investigated Using The Subsonic Wind Tunnel. Experimental Investigation Was Performed At Different Reynolds Numbers. Numerical Investigation Was Also Performed To Determine Torque And Power Coefficients Using Fluent.

i. For Model With Re = 1.22×10^5, Experimental Torque Coefficient (C_t) Shows Higher And Positive Values Compared To Other Reynolds Numbers. It Also Shows That Lower Reynolds Number Gave Better Torque Coefficient (C_t) Variation With The Increase Of The Angle Of Rotation For Each Model.

ii. For Model With Re = 1.22×105, Experimental Power Coefficient (Cp) Shows Higher And Positive Values Compared To Other Reynolds Numbers. Model 2 Shows The Better Experimental Power Coefficient (Cp) At Wind Speed 9.66 M/S And Wind Speed 8.23 M/S. But For Wind Speed 7.33 M/S Model 1 Shows The Better Power Coefficient (Cp).

iii. With The Increase Of Reynolds Number Numerical Torque Coefficient Increases.

iv. Power Coefficient Calculated From Numerical Method Shows That It Is Always Increasing With The Increase Of Tip Speed Ratio. For Model Numerical Power Coefficient Matches Well With The Corresponding Experimental Values At 0° Rotor Position.

REFERENCES

[1] Aldoss, T. K., Obeidat, K. M. (1987) Performance Analysis Of Two Savonius Rotors Running Side By Side Using The Discrete Vortex Method, Wind Engineering, 11, 79-88.

[2] Altan, B. D., Atilgan, M. (2008). An Experimental And Numerical Study On The Improvement Of The Performance Of Savonius Wind Rotor. Energy Conversion And Management, 3425-3432.

[3] Altan, B. D., Atilgan, M, Ozdamar, A. (2008). An Experimental Study On Improvement Of Savoniu Rotor

[4] Performance With Curtaining. Experimental Thermal And Fluid Science, 32, 1673-1678

[5] Benjanirat, S., Sankar, L., & Xu, G. (2003). Proceedings Of 41st Aerospace Sciences Meeting And Exhibit Evaluation Of Turbulence Models For The Prediction Of Wind Turbine Aerodynamics. Reno, Nevada.

[6] Diaz, F., Gavalda, J., Massons, J. (1991) Drag And Lift Coefficients Of The Savonius Wind Machine, Journal Of Wind Engineering. 15, 240-246. Fluent 6.3 User Guide

[7] Fujisawa , N. (1992). On Torque Mechanism Of Savonius Rotors. Journal Of Wind Engineering And Industrial Aerodynamics, 40, 227-292

[8] Fujisawa, N., Gotoh, F. (1994) Experimental Study On The Aerodynamic Performance Of A Savonius Rotor, Asme Journal Of Solar Energy Engineering, 116, 148 – 152.

[9] Gupta, R., Biswas, A., Sharma, K. K. (2008). Comparative Study Of A Three Bucket Savonius Rotor With A Combined Three Bucket Savonius –Three Bladed Darrieus Rotor. Rnewable Energy, 33, 1974-1981

[10] Hau, E. (2006) Wind Turbines: Fundamentals, Technologies, Applications,

Economics. Germany. Springer- Verlag Berlin Heidelberg.

[11] Hayashi, T., Li, Y., Hara, Y., Suzuki (2004) Proceedings Of European Wind Energy Conference And Exhibition, Wind Tunnel Test On A Three Stage Out Phase Savonius Rotor, London, England.

[12] Hayashi, T. , Li, Y., Hara, Y. (2005). Wind Tunnel Tests On A Different Phase Three Stage Savonius Rotor. Jsme International Journal, 48, 9-16.

[13] Islam, A. K. M. S., Islam, M. Q., Razzaque, M. M.,& Ashraf, R., (1995), Static Torque And Drag Characteristics Of An S-Shaped Savonius Rotor And Prediction Of Dynamic Characteristics, Wind Engineering, 19.

[14] Kamoji, M.A. , Kedare, S.B. , Prabhu, S.V. (2009). Performance Test Of Helical Savonius Rotors. Renewable Energy, 34, 521-529

[15] Kamoji, M. A., Kedare, S. B. (2007) Proceedings Of 5th Aiaa International Energy Conversion Engineering Conference. Wind Tunnel Tests On A Single Stage Helical Savonius Rotor.

[16] Launder, B. E. And Spalding, D. B.(1972) Lectures In Mathematical Models Of Turbulence. Academic Press.

[17] Lida, A., Kato, K. & Mizuno, A.(2007). Proceedings Of 16th Australasian Fluid Mechanics Conferences. Numerical Simulation Of Unsteady Flow And Aerodynamic Performance Of Vertical Axis Wind Turbine With Les. Gold Coast, Australia.

[18] Mcwilliam, M., Johnson, D.A. (2008). Velocity Measurement Of Flow AroundModel Vertical Axis Wind Turbines. International Journal Of Green Energy,5, 55-68.

[19] Menet, J.L., Bourabaa, N. (2004). Proceedings Of European Wind Energy Conference. Increase In The Savonius Rotor Efficiency Via A Parametric Investigation. London, Uk

[20] Menet, J.L., Valdes, L.C., Menart, B. (2001). A Comparative Calculation Of The Wind Turbines Capacities On A Basis Of The L-Σ Criterion, Renewable Energy, 22, 491-506.

[21] Newman, B. G. (1974). Proceedings Of Symposium On Wind Energy: Achievements And Potential. Measurements On A Savonius Rotor With A Variable Gap. Sherbrooke, Canada.

[22] Patankar, S. V., (1980) Numerical Heat Transfer And Fluid Flow, Hemisphere Publishing Corporation.

[23] Paraschivoiu, I. (2002). Wind Turbine Design: With Emphasis On Darrieus Concept. Montreal, Canada: Polytechnic International Press.

[24] Pike Research Llc (2009). Wind Energy Outlook For North America Wind Power Generation Capacity And Turbine Deployments: Market Analysis And Forecasts. Boulder, Co. : Beh, G. , Wheelock, C.

[25] Pinkerton, R. B. (1936). Calculated And Measured Pressure Distribution Over The Midspan Section Of The Naca 4412 Airfoil. Naca Report No 563. 365-380

[26] Rahman, M., Islam, M. Q., Islam, A.K.M.S. (1999) Proceeding Of The Third International Conference On Fluid Mechanics And Heat Transfer. Prediction Of Dynamic Characteristics Of A Three Bladed Savonius Rotor.

[27] Rahman, M. (1999) Torque And Drag Characteristics Of A Three Bladed Savonius Rotor, M. Sc. Thesis, Mech. Eng. Dept., Bangladesh University Of Eng. And Tech., Bangladesh.

[28] Rahman, M., Islam, M. Q., Islam, A.K.M.S. (1999) Proceeding Of The 2nd Int. Seminar On Renewable Energy For Poverty Alleviation, Ieb, Bangladesh, Aerodynamic Characteristics Of A Three Bladed Savonius Rotor.

[29] Riegler, H. (2003). Hawt Versus Vawt, Retrieved From

[30] Http://Www.Victordanilochkin.Org/Research/Turbine/Papers/Hawt%20ver Sus.Pdf

[31] Saha, U. K., Thotla, S., Maity, D. (2008). Optimum Design Configuration Of Savonius Rotor Through Wind Tunnel Experiment. Journal Of Wind Engineering And Industrial Aerodynamics. 96, 1359-1375.

[32] Sargolzaei, J., Kianifar, A. (2009). Modeling And Simulation Of Wind Turbine Savonius Rotor Using Artificial Neural Networks For Estimation Of The Power Ratio And Torque. Simulation Modeling Practice And Theory. 17, 1290-1298

[33] Savonius, S. J. (1931). The S Rotor And Its Application. Mechanical Engineering, 53, 333-338.

[34] Sawada, T., Nahamura, M., Kamada, S. (1986) Blade Force Measurement And Flow Visualization Of Savonius Rotors, Bulletin Of Jsme, 29, 2095-2100.

[35] Shepherd, D. G. (1990). Historical Development Of The Windmill. National Aeronautics And Space Administration Office Of Management.

[36] U. S. Department Of Energy (2008). 20% Wind Energy By 2030: Increasing Wind

Energy's Contribution To U.S. Electricity Supply. (Doe/Go-102008- 2567)

[37] Worldwatch Institute (2008). Renewables 2007: Global Status Report.

[38] Washington, Dc. : Martinot , E.

[39] Wulff, H. E., (1966). The Traditional Crafts Of Persia, Their Development,Technology And Influence On Eastern And Western Civilization.Mit Press. 284-289

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