ABSTRACT
A four-bladed, squirrel-cage, and scaled vertical kinetic turbine was designed, instrumented and tested in the water tunnel facilities at the University of Manitoba. With a solidity of 1.3 and NACA0021 blade profile, the turbine is classified as a high solidity model. Results were obtained for conditions during freewheeling at various Reynolds numbers. In this study, the freewheeling tip speed ratio, which relates the ratio of maximum blade speed to the free stream velocity at no load, was divided into three regions based on the Reynolds number. At low Reynolds numbers, the tip speed ratio was lower than unity and blades were in a stall condition. At the end of the first region, there was a sharp increase of the tip speed ratio so the second region has a tip speed ratio significantly higher than unity. In this region, the tip speed ratio increases almost linearly with Reynolds number. At high Reynolds numbers, the tip speed ratio is almost independent of Reynolds number in the third region. It should be noted that the transition between these three regions is a function of the blade profile and solidity. However, the three-region behavior is applicable to turbines with different profiles and solidities.

INTRODUCTION
Darrieus invented the H-shape, eggbeater, and squirrel-cage vertical turbines in the 1920s and patented them in 1931 [1]. The theory of horizontal turbines was then derived by Glauert in 1935 [2]. At the beginning of the twentieth century a wide range of investigations were conducted on the aerodynamics of airplane propellers. Because of higher theoretical efficiencies and the similarity between aerodynamics of horizontal turbines and airplane propellers, horizontal turbines were promoted instead of vertical turbines. Around 1960, two Canadian researchers reintroduced the Darrieus turbine [3]. Canadian government funded vertical wind turbine projects, and many grid connected systems were installed for demonstrations. Recently, vertical turbines are utilized to harness the kinetic energy from tides and river currents. Because the direction of rotation for vertical turbines is independent of the flow direction, these turbines are able to harness the energy contained in both flood and ebb tides in the absence of a yawing mechanism. Gearbox and power generating equipment of the vertical kinetic turbine can be placed above the water level, which simplifies the design and maintenance. Recently, a 5 and 25 kWe vertical turbines manufactured by New Energy Corporation were grid connected [4].

Freewheeling is the condition at which a turbine turns, but no power is harnessed. This may happen if the break system is off and the turbine is either disconnected from a load or the power electronics has not yet initiated grid connection and synchronization. During freewheeling conditions, flow current drives the turbine to the rotational speed at which the net generated power is zero. Without an external power source, a vertical turbine cannot turn faster than its freewheeling speed. In this study, a squirrel-cage vertical turbine is tested at
freewheeling conditions to assess the effect of the Reynolds number on the tip speed ratio of the turbine. These results help to understand the behavior of the turbine which is applicable in fatigue analysis, stress analysis, and instrumentation. Results are an important component when designing kinetic turbines and verifying if the turbine is functioning as designed during operations and to help quantify the energy required for self-starting.

HYDRODYNAMICS OF THE BLADE

Forces acting on a vertical turbine blade can be decomposed into the tangential force, \( F_T \), acting tangent to the rotational path, and the normal force, \( F_N \), acting perpendicularly. The tangential force generates torque about the axis of rotation and turns the turbine; however, the normal force generates no torque, but is an important parameter used for fatigue analysis. In Equation 1, \( T \) is the torque and \( r \) is the radius of the turbine. During freewheeling conditions, the net torque about the axis of rotation and the tangential force is zero.

\[
T = F_T \times r \tag{1}
\]

Equation 2 represents the tangential force in terms of the lift force, \( L \), the drag force, \( D \), and the angle of attack, \( \alpha \). The drag force is parallel and the lift force is perpendicular to the relative velocity. The angle of attack is the angle formed by the direction of the relative velocity and the chord line of the blade. Lift and drag forces are given by:

\[
F_T = L \sin(\alpha) - D \cos(\alpha) \tag{2}
\]

\[
L = 0.5 C_L \rho V_{rel}^2 c \tag{3}
\]

\[
D = 0.5 C_D \rho V_{rel}^2 c
\]

where \( \rho \) is the density of the flow, \( c \) is the chord length of the blade, \( V_{rel} \) is the relative flow velocity to the blade, and \( C_L \) and \( C_D \) are lift and drag coefficients, respectively. The lift and drag coefficients are functions of the blade’s profile shape, angle of attack, and Reynolds number. Therefore, for a known blade’s profile these coefficients are functions of the relative Reynolds number, \( \text{Re}_{rel} \) and angle of attack. The angle of attack and the Reynolds number vary during a rotation and are given by:

\[
\alpha = \tan^{-1}\left(\frac{\sin(\theta)}{\cos(\theta) + \lambda}\right) \tag{4}
\]

\[
\text{Re}_{rel} = \text{Re}\sqrt{1 + 2\lambda \cos(\theta) + \lambda^2} \tag{5}
\]

where \( \theta \) is the azimuth angle, as shown in Fig. 1, \( \text{Re} \) is the Reynolds number based on the free stream velocity, \( c \) is the chord length, and \( \lambda \) is the tip speed ratio which represents the ratio between the rotational speed and the free stream velocity, \( V_\infty \). The tip speed ratio and Reynolds number are given respectively by the following expressions:

\[
\lambda = \frac{\omega r}{V_\infty} \tag{6}
\]

\[
\text{Re} = \frac{c V_\infty}{\nu} \tag{7}
\]

where \( \nu \) is the kinematic viscosity of water, and \( \omega \) is the angular velocity of the blade.

According to Equation 4, when the tip speed ratio is greater than one, the angle of attack for a typical symmetric blade is zero at an azimuth angle of zero. It then increases to a maximum angle of attack and again reaches a zero value at a 180° azimuth angle. The same pattern but with a negative value is repeated for the second half of the rotation. If the blade passes the stall angle of attack at which point the flow is detached on a portion of the lifting surface, the lift coefficient decreases and the drag coefficient increases rapidly. In this condition, the torque decreases. At low tip speed ratios, the blade may overcome the stall angle of attack. The maximum angle of attack in a rotation occurs when:

\[
\theta_{a_{max}} = \cos^{-1}\left(\frac{-1}{\lambda}\right) \tag{8}
\]

and the maximum angle of attack is obtained from:

\[
\alpha_{max} = \tan^{-1}\left(\frac{1}{\sqrt{\lambda^2 - 1}}\right) \tag{9}
\]
At high tip speed ratios, the maximum angle of attack occurs near 90° azimuth angle. This location shifts to an azimuth angle of 180° when the tip speed ratio is closer to unity, as shown in Fig. 2. The maximum angle of attack increases as the tip speed ratio approaches unity (Fig. 3). Based on the solidity, profile shape, and Reynolds number, a typical vertical turbine operates at a tip speed ratio between 2 and 5. Therefore, except for the starting procedure at which the tip speed ratio requires to pass through unity, vertical turbines operate at a tip speed ratio higher than 2. Specifically, at the freewheeling condition, the tip speed ratio and rotational speed reach their maximum values which can be accessible without an external power source. So for a typical tip speed ratio of 4 or lower, according to Fig. 3, most of the blade profiles will have overcome their stall angle of attack. However, it should be noted that close to the actuating disk of the turbine, the free stream velocity is reduced and consequently the local tip speed ratio increases. On the other hand flow disturbances and downwash flows from other blades reduce the local angle of attack.

\[ S = \frac{Nc}{r} \]  

where \( N \) is the number of blades which is four in these experiments. Due to the stronger downwash that blades
experience from other blades in a high solidity turbine, the operating tip speed ratio is lower compared to that of a low solidity turbine.

The test section blockage ratio of a solid circular cylinder inside the water tunnel with a radius of 15 cm is 49%; however, in case of a vertical turbine, a portion of the flow can pass through the actuating disk of the turbine and thus reduce the blockage ratio. To assess the blockage ratio effect of the turbine, CFD code Fluent 6.3.26 was used to simulate a vertical turbine in the water tunnel and results were compared to that using the turbine in an open field. The torque difference between the two cases was found to be negligible. With the same method, Ferreira et al. [5] showed that the test section blockage ratio of 32%, calculated based on the diameter of a vertical wind turbine, does not affect wind tunnel test results of a vertical wind turbine.

The turbine torque and rotational speed are measured using a non-contact inline torque sensor. This sensor is able to measure rotational speeds lower than 300 rpm with an accuracy and nonlinearity of 0.25% of full scale. One end of the torque sensor is connected to the turbine shaft and the other end is unconstrained. Thus the torque sensor measures the freewheeling rotational speed. At no load, the torque supplied by the turbine is almost zero as any torque is dissipated via losses in the bearings and fluid friction.

Vertical turbines are often not self-starting and they may need an external power source to achieve freewheeling condition. To avoid this issue during experiments, the turbine is operated at the maximum water tunnel velocity, and then the velocity is reduced to its nominal value.

RESULTS

A freewheeling turbine was tested at various Reynolds numbers. Results show that the behavior of the turbine can be divided into three regions based on the tip speed ratio variation versus the Reynolds number, as shown in Fig. 5. At Reynolds numbers less than 19,400, the turbine operates at a tip speed ratio lower than unity. Therefore, during a rotation, blades overcome the stall angle of attack and get to a 180° angle of attack at which point the flow sweeps blades from the trailing edge toward the leading edge. Although in this region blades spend most of their rotation in a post stall condition, the turbine still turns and the tip speed ratio increases somewhat linearly with the Reynolds number.

When the Reynolds number increases beyond 19,400 but does not exceed 23,400, the tip speed ratio suddenly increases from 0.30 to 2.93. The turbine behaves in a transient mode and does not operate in a stable condition. In the second region starting at 2.93, the tip speed ratio increases with Reynolds number similar to the first region. In the last region, the Reynolds number does not significantly affect the tip speed ratio during freewheeling.
In the stall condition, the tip speed ratio is less than unity therefore the maximum angle of attack is 180°. In the second region the tip speed ratio is above unity so the maximum angle of attack does not overcome 90°. At the beginning of the second region where the Reynolds number is 23,400, the maximum angle of attack during freewheeling is 20°. When the Reynolds number increases, consequently the tip speed ratio increases, and the maximum angle of attack decreases. At a Reynolds number of 53,300, the maximum angle of attack that blades experience in a rotation is 16.4°. Based on the static wind tunnel results, at this relative Reynolds number the stall angle of attack is approximately 12°. Upstream velocity measurements taken with an acoustic Doppler velocity probe shows that the free stream velocity is reduced by approximately 10% near the vertical turbine actuating disk. Therefore, the local tip speed ratio is higher than theory and the maximum angle of attack is thus lower.

Table 1: Experimental testing conditions

<table>
<thead>
<tr>
<th>$V_\infty$(m/s)</th>
<th>$\omega$ (rad/s)</th>
<th>$\lambda$</th>
<th>$Re$</th>
<th>$Re_{rel,max}$</th>
<th>$Re_{rel,min}$</th>
<th>$\alpha_{max}$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.07</td>
<td>25.33</td>
<td>3.55</td>
<td>5.33e4</td>
<td>2.43e5</td>
<td>1.36e5</td>
<td>16.4</td>
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<td>3.56</td>
<td>5.08e4</td>
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<td>1.30e5</td>
<td>16.3</td>
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<td>0.95</td>
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<td>3.57</td>
<td>4.73e4</td>
<td>2.16e5</td>
<td>1.22e5</td>
<td>16.3</td>
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<tr>
<td>0.87</td>
<td>20.38</td>
<td>3.51</td>
<td>4.33e4</td>
<td>1.96e5</td>
<td>1.09e5</td>
<td>16.5</td>
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<tr>
<td>0.78</td>
<td>17.62</td>
<td>3.39</td>
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<td>1.70e5</td>
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<tr>
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<td>1.46e5</td>
<td>7.87e4</td>
<td>17.5</td>
</tr>
<tr>
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<td>3.13</td>
<td>2.89e4</td>
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<tr>
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<td>0.78</td>
<td>0.30</td>
<td>1.94e4</td>
<td>2.52e4</td>
<td>1.36e4</td>
<td>180</td>
</tr>
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<td>1.80e4</td>
<td>1.09e4</td>
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<tr>
<td>0.19</td>
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<td>0.06</td>
<td>9.46e3</td>
<td>9.99e3</td>
<td>8.94e3</td>
<td>180</td>
</tr>
</tbody>
</table>

CONCLUSION

Freewheeling vertical turbines have three operating zones based on Reynolds number. At low Reynolds numbers the tip speed ratio is lower than unity and the turbine operates in a stall condition. The blade's maximum angle of attack reaches 180° while the blade moves in the direction of the free stream flow. At a certain Reynolds number, the tip speed ratio increases above unity. Due to the unstable condition of the blades near a
tip speed ratio of one, a vertical turbine is not able to operate with stability near this tip speed ratio. When the freewheeling tip speed ratio is less than unity, operating the turbine at this Reynolds numbers is not practical. When the turbine overcomes the tip speed ratio of unity, the variation of the tip speed ratio versus the Reynolds number is linear until the maximum angle of attack as the rotation approaches the stall angle of attack of the blade. The tip speed ratio during freewheeling condition then remains constant.

NOMENCLATURE

- $c$: blade chord (m)
- $C_d$: drag coefficient (-)
- $C_l$: lift coefficient (-)
- $D$: drag force (N)
- $F_N$: normal force (N)
- $F_T$: tangential force (N)
- $L$: lift force (N)
- $N$: number of blades (-)
- $r$: radius (m)
- $S$: solidity (-)
- $V_\infty$: free stream velocity (m/s)
- $V_{rel}$: relative velocity (m/s)
- $\alpha$: blade angle of attack (deg)
- $\lambda$: tip speed ratio
- $\theta$: azimuth angle
- $\omega$: rotation velocity (rad/s)

REFERENCES