Computational fluid dynamics on a newly developed Savonius rotor by adding sub-buckets for increase of the tip speed ratio to generate higher output power coefficient

Takanori MATSUI**, Tomohiro FUKUI* and Koji MORINISHI*
*Department of Mechanical Engineering, Kyoto Institute of Technology
Matsugasaki Goshokaido-cho, Saky-o-ku, Kyoto 606-8585, Japan
E-mail: fukui@kit.ac.jp
**Department of Master's Program of Mechanophysics, Kyoto Institute of Technology
Matsugasaki Goshokaido-cho, Saky-o-ku, Kyoto 606-8585, Japan

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Abstract
The output power coefficient of the Savonius rotor needs to be improved in attaining better practical applications. Up until now, to improve the output power coefficient, the newly developed Savonius rotor with semi-elliptical sub-buckets has been introduced. However, some of the parameters on the semi-elliptical bucket have not yet been properly determined. Therefore, the influence of the additional semi-elliptical bucket’s shape in the newly developed Savonius rotor on the output power coefficient was investigated. The flow around the rotor was simulated by using the regularized lattice Boltzmann method. The virtual flux method was used to describe the shape of the rotor on Cartesian grids, and the multi-block method was used for the local fine grids around the rotor. The rotational speed of the Savonius rotor was maintained as a constant, and its performance was evaluated by the output power and torque coefficients. As a result, the additional semi-elliptical bucket successfully generated a positive torque during the advancing bucket period. While, it did not generate a large negative torque during the returning bucket period owing to its position behind the main bucket in the wind flow direction. Through a cycle, the semi-elliptical bucket only generated a positive torque with the interaction of the main bucket. The output power coefficient of the newly developed Savonius rotor was improved when compared to that of the traditional or Bach-type ones. The maximum output power coefficient of the newly developed Savonius rotor was 50.7% higher than that of the traditional rotor and 16.9% higher than that of the Bach-type rotor.

Keywords: Savonius rotor, Torque coefficient, Additional semi-elliptical bucket, Tip speed ratio, Bach-type Savonius rotor, Vertical axis wind turbine

1. Introduction

Wind turbines are classified into horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) depending on the direction of the rotational axis to the wind direction (Tian et al., 2015). The propeller wind turbine, which is one of the HAWTs, is widely used due to its high output power coefficient (Akwa et al., 2012). Nowadays, installation of larger propeller rotors is spreading across suburbs, and offshore, to generate electricity. However, they have disadvantages, including loud noise generation, the risk of bird strike, maintenance difficulties, and a dependence on wind direction (Roy et al., 2013a). On the other hand, the Savonius rotor, which is one of the VAWTs, has many advantages, including less noise generation, simplicity of structure, compact size, and independence of wind direction (Shigetomi et al., 2011; Tian et al., 2015). Owing to these advantages, the Savonius rotor is widely used in urban areas, where the wind direction is unsteady. However, its output power coefficient is still poor compared with that of other rotors. The maximum output power coefficient of the Savonius rotor is less than half of that of the propeller one (Ushiyama, 2002). Therefore, the output power coefficient of the Savonius rotor needs to be improved for better practical applications. The reason for the low output power coefficient is partly due to its fluctuations during one cycle, i.e., when one bucket generates a positive torque, the other bucket simultaneously generates a negative torque (Tian et
al., 2015; Roy et al., 2016). Since the two buckets are symmetrical with respect to the rotational axis, the net torque of the buckets is always offset against each other, and the output power coefficient becomes lower.

Ushiyama et al. (1986) investigated the influence of the rotor aspect ratio, overlap and gap ratio between the rotor buckets, profile of the bucket, number of buckets, and end plate on the output power coefficient. Roy et al. (2013b) found that an overlap ratio of 20% is the most effective. Mohamed et al. (2010) found that a bucket installed in front of the Savonius rotor can improve the output power coefficient by about 27.3% by reducing the inflow rate to the returning bucket. El-Askary et al. (2015) improved the output power coefficient by controlling the wind direction and, consequently, by increasing the inflow rate to the advancing bucket and decreasing it to the returning bucket. The improvement of the output power coefficient with installation of obstacles or controlling walls, depends on the wind direction. Moreover, installation of these buckets requires a larger space around the rotor compared with the traditional rotor. Therefore, modifying the bucket shape may be regarded as the most effective method by which to improve the output power coefficient while still maintaining independence of the wind direction.

Many researchers have investigated the effect of the modified main bucket shape. For example, Zhang et al. (2017) modified the traditional Savonius rotor and found that the output power coefficient of this rotor improved by about 6% when compared with the traditional one. Al-Faruk et al. (2016) investigated the effect of the arc angle for the cylinder bucket and found that the bucket with the arc angle of 195° improved the output power coefficient by about 29% compared with one with an arc angle of 180°. Meanwhile, Roy et al. (2016) developed a design modification, and the output power coefficient of their rotor improved by about 32.1% when compared with the traditional one. According to these reports referring to modification of the bucket shape, the net torque generated by the buckets is always offset against each other. In addition, the output power coefficient fluctuates substantially during a cycle.

The fluctuation of the torque coefficient of the rotor can be suppressed when the generation of the negative torque is reduced at the returning bucket period. Moreover, the output power coefficient of the rotor is also expected to be improved. Thus, suppressing the generation of the negative torque at the returning bucket period may be the key to improve the average output power coefficient. In the previous research, researchers have investigated the influence of number of buckets or tiers of the rotors to suppress the fluctuation of the torque (Ushiyama et al., 1986; Roy et al., 2013d; Kamoji et al., 2008). The three-bucketed rotor has a greater starting static torque compared with the two-bucketed rotor (Sheldahl et al., 1978). However, the two-bucketed rotor has shown a better performance during a cycle. Multi-tiered set of the rotor has shown high starting ability. Experimental investigation with multi-tiered set has shown a reduction of power and dynamic torque compared to a rotor with the same aspect ratio, which is defined as the height of the rotor relative to the diameter of the rotor (Kamoji et al., 2008). According to these reports, to increase the number of buckets or multi-tiered set of the rotors appears to give a better starting torque. However, the maximum output power coefficient of these rotors decreases compared with that of the traditional one.

The reason for low efficiency of the Savonius rotor is partly due to high negative torque during the returning bucket period. As we mentioned, installation of the obstacles around the rotor can reduce the negative torque during the returning bucket period. So, we have proposed a newly developed Savonius rotor with additional semi-elliptical sub buckets that generate a positive torque during a cycle due to interactions with the main bucket (Matsui et al., 2019). The influence of the moment arm length of the semi-elliptical bucket was only investigated while elliptical bucket shape itself was fixed. It was found that the additional semi-elliptical bucket generated a positive torque and did not generate a large negative torque, depending on the length of the moment arm of the semi-elliptical bucket. As a result, the output power coefficient of the newly developed Savonius rotor was improved when compared with that of the traditional one. However, we have not investigated the effect of the semi-elliptical bucket’s shape on its performance. Thus, there may remain room for improvement of the output power coefficient by modifying the semi-elliptical bucket’s parameters, which therefore needs further study. In this research, the semi-elliptical bucket shape of the newly developed Savonius rotor is modified to improve the output power coefficient.

**Nomenclature**

- \( f_e \): distribution function
- \( f_{e\text{eq}} \): equilibrium distribution function
- \( f_{e\text{neq}} \): non-equilibrium distribution function
- \( e_v \): discrete velocity vector
- \( \delta t \): time step size
- \( \rho \): density
- \( p \): pressure
- \( u \): velocity vector
2. Numerical methods

In this study, two-dimensional simulation was carried out to reduce computational cost. Though two-dimensional simulations may fail to consider the three-dimensional effect, previous studies have shown that two-dimensional give acceptable results for Savonius rotor (Tian et al., 2015; Zhang et al., 2017). The regularized lattice Boltzmann method (RLBM) for the D2Q9 lattice speed model was used as a governing equation (Izham et al., 2011; Morinishi et al., 2016). Instead of solving the Navier–Stokes equations directly, a fluid density on a lattice is simulated with streaming and collision processes in lattice Boltzmann method (LBM) (Tsutahara, 2018). The RLBM is designed to reduce memory usage and to simulate flow at high Reynolds numbers without compromising accuracy. Fig. 1 shows the graphical representation of the lattice speed model (D2Q9 lattice speed model). The particles propagate to nine surrounding points. The virtual flux method (Tanno et al., 2006; Morinishi et al., 2012) was used to describe the shape of the rotor on a Cartesian grid. The multi-block method (Yu et al., 2002) was used for the locally fine grids around the Savonius rotor. This simulation program was written by using Fortran 90.

![Graphical representation of the lattice speed model (D2Q9 lattice speed model).](image)

2.1 Regularized lattice Boltzmann method

We use the RLBM (Izham et al., 2011; Morinishi et al., 2016) as the governing equation. The distribution function represents the distribution of the mass of fluid particles per unit volume. The distribution function \( f_\alpha \) for the lattice Boltzmann equation can be written as Eq. (1).

\[
f_\alpha = w_\alpha \left( a_0 + b_i e_{\alpha i} + c_{ij} e_{\alpha i} e_{\alpha j} + \cdots \right).
\]

(1)

When the distribution function is used up to the second order moments, it is equivalent to the approximation of the incompressible Navier–Stokes equation. Thus, the distribution function \( f_\alpha \) becomes
velocity to propagate toward nine surrounding points for the D2Q9 lattice speed model.

The weight coefficient $w_\alpha$ and particle velocity $e_\alpha$ are given as Eqs. (3), (4). The particle velocity represents the velocity to propagate toward nine surrounding points for the D2Q9 lattice speed model.

$$f_\alpha \approx w_\alpha (a_0 + b_i e_{ai} + c_{ij} e_{ai} e_{aj}).$$

The weight coefficient $w_\alpha$ and particle velocity $e_\alpha$ are given as Eqs. (3), (4). The particle velocity represents the velocity to propagate toward nine surrounding points for the D2Q9 lattice speed model.

$$w_\alpha = \begin{cases} 4/9 & (\alpha = 0) \\ 1/9 & (\alpha = 1\sim 4), \\ 1/36 & (\alpha = 5\sim 8) \end{cases}$$

$$e_\alpha = \begin{cases} (0, 0) & (\alpha = 0), \\ \sqrt{2}c \left( \cos \frac{(\alpha-1)\pi}{2}, \sin \frac{(\alpha-1)\pi}{2} \right) & (\alpha = 1\sim 4), \\ \sqrt{2}c \left( \cos \frac{(2\alpha-9)\pi}{4}, \sin \frac{(2\alpha-9)\pi}{4} \right) & (\alpha = 5\sim 8) \end{cases}$$

The density $\rho$, momentum $\rho u_i$, and the non-equilibrium tensor $\Pi_{ij}^{\text{neq}}$ are given as

$$\sum_\alpha f_\alpha = \rho,$$

$$\sum_\alpha f_\alpha e_{ai} = \rho u_i,$$

$$\sum_\alpha e_{ai} e_{aj} f_\alpha = \frac{c^2}{3} \rho \delta_{ij} - \rho u_i u_j = \Pi_{ij}^{\text{neq}}.$$ 

Using Eqs. (5), (6), and (7), $a_0$, $b_i$, and $c_{ij}$ can be represented by $\rho$, $u$, $\Pi_{ij}^{\text{eq}}$. Then Eq. (2) becomes Eq. (8).

$$f_\alpha = w_\alpha \rho \left( 1 + \frac{3(e_{ai}u_i)}{c^2} + \frac{9(e_{ai}u_j)^2}{2c^4} - \frac{3(u_i u_j)}{2c^2} \right) + \frac{9w_\alpha}{2c^2} \left( \frac{e_{ai} e_{aj}}{c^2} - \frac{1}{3} \delta_{ij} \right) \Pi_{ij}^{\text{eq}}.$$ 

The equilibrium distribution function $f_\alpha^{\text{eq}}$, and the non-equilibrium part of the distribution function $f_\alpha^{\text{neq}}$ are defined by Eqs. (9), (10).

$$f_\alpha^{\text{eq}} = w_\alpha \rho \left( 1 + \frac{3(e_{ai}u_i)}{c^2} + \frac{9(e_{ai}u_j)^2}{2c^4} - \frac{3(u_i u_j)}{2c^2} \right),$$

$$f_\alpha^{\text{neq}} = \frac{9w_\alpha}{2c^2} \left( \frac{e_{ai} e_{aj}}{c^2} - \frac{1}{3} \delta_{ij} \right) \Pi_{ij}^{\text{neq}}.$$ 

From Eqs. (9), and (10), Eq. (8) becomes

$$f_\alpha = f_\alpha^{\text{eq}} + f_\alpha^{\text{neq}}.$$ 

The time evolution of the distribution function is given as

$$f_\alpha(t + \delta t, \mathbf{x} + \mathbf{e}_\alpha \delta t) = f_\alpha^{\text{eq}}(t, \mathbf{x}) + \left( 1 - \frac{1}{r} \right) f_\alpha^{\text{neq}}(t, \mathbf{x}).$$ 

In the formulation for incompressible flow, distribution functions of pressure is introduced as (He et al., 1997)

$$p_\alpha = c_s^2 f_\alpha.$$ 

Thus, this formulation was applied to Eqs. (5), (6), and (7), the pressure $p$, velocity $u_i$, and the non-equilibrium stress tensor $\Pi_{ij}^{\text{neq}}$ are given as
\[
\sum_a p_a = p, \quad (14)
\]
\[
\frac{1}{\rho_0 c_s^2} \sum_a p_a e_{ai} = u_i, \quad (15)
\]
\[
\frac{1}{c_s^2} \left( \sum_a e_{ai} e_{aj} p_a - \frac{c^2}{3} p \delta_{ij} - \frac{c^2}{3} \rho_0 u_i u_j \right) = \Pi_{ij}^{neq}. \quad (16)
\]

The evolution becomes
\[
p_a(t + \delta t, \mathbf{x} + \mathbf{e}_a \delta t) = p_a^{eq}(t, \mathbf{x}) + \left(1 - \frac{1}{\tau}\right) p_a^{neq}(t, \mathbf{x}). \quad (17)
\]

### 2.2 Virtual flux method

The virtual flux method (Tanno et al., 2006; Morinishi et al., 2012) is used in a Cartesian grid to describe arbitrary objects with a curved boundary. The fluids around the objects can be calculated regardless of either the inside or the outside of the object using this method. In addition, this method can describe the pressure field around an object more sharply when compared with the other immersed boundary methods for the same grid resolution. Thus far, this method has been implemented successfully in many applications, including blood flow simulation, by the Navier–Stokes equations (Fukui et al., 2017) and suspension rheology by the regularized lattice Boltzmann equation (Fukui et al., 2018). Figure 2 shows the schematic view of the virtual boundary points. The virtual boundary points are the intersections of the surface of the object with the grid lines or the surface with the diagonal of the grid point.

A non-slip boundary condition was applied at a virtual boundary points. The velocity at a virtual boundary points \(\mathbf{u}_{vb}\) is evaluated by Eq. (18).

\[
\mathbf{u}_{vb} = \mathbf{u}_{wall}, \quad (18)
\]

where the velocity of the virtual boundary wall is \(\mathbf{u}_{wall}\). The pressure gradient in the normal direction of the virtual boundary wall is equal to 0. This condition is given as Eq. (19), where \(\mathbf{n}\) is the normal vector on the virtual boundary wall:

\[
\frac{\partial p_{vb}}{\partial \mathbf{n}} = 0. \quad (19)
\]
taken as 0.3% to the diameter of the rotor (Roy et al., 2015b). Therefore, we assume the effect of thickness of the bucket is minor. In this study, we set thickness of the bucket is 0 like shell elements. Here, the line $CD$ is divided by the virtual boundary. The line $CD$ then is divided into two fluids by the virtual boundary point $vb$ as the ratio of $a$ to $b$ ($a + b = 1$). The distribution function of particle velocity $c(-1, 0)$ at the grid point $C(i, j)$ propagates from the distribution function at the grid point $D(i+1, j)$. However, the particle at grid point D is unable to travel across the virtual surface toward grid point C. Therefore, a virtual distribution function at the point D is estimated from the virtual wall surface. The velocity $u_{vb}$ is $u_{vb} = u_{wall}$ by the non-slip condition.

Figure 4 shows the schematic view of extrapolation of the pressure on the virtual wall. The pressure on the virtual boundary $p_{vb}$ is given as Eq. (20) applying the second order finite difference approximation to Eq. (19) with the second order precision, where $p_S$ and $p_T$ are the pressures at the point S and point T, respectively. The pressures $p_S$ and $p_T$ are interpolated from those of the surrounding grid points. In this research, $h_1$, $h_2$ are defined as $h_1 = \sqrt{2}$ and $h_2 = 2\sqrt{2}$ so that the surrounding points around the points S and T avoid including the point in the concave side.

$$p_{vb} = \frac{h_2^2 p_S - h_1^2 p_T}{h_2^2 - h_1^2}. \quad (20)$$

The equilibrium distribution function at the point $vb$ $p_{a,vb}^{eq}$ is calculated from the velocity $u_{vb}$ and the pressure $p_{vb}$. The virtual equilibrium distribution function $p_{a,D}^{eq}$ at the grid point D can be interpolated as Eq. (21). In the case of $a < 0.5$, instead of Eq. (21), Eq. (22) is used for numerical stability:

$$p_{a,D}^{eq} = \frac{a + b}{a} p_{a,vb}^{eq} - \frac{b}{a} p_{a,C}^{eq} \quad (a \geq 0.5), \quad (21)$$
In addition, the virtual non-equilibrium distribution function \( p_{\text{neq}}^{a,D} \) is calculated as Eq. (23):

\[
p_{\text{neq}}^{a,D} = p_{a,C} - p_{a,D}.
\]

Thus, the distribution function in the next step is obtained from Eq. (24) by the virtual non-equilibrium part of the distribution function \( p_{\text{neq}}^{a,D} \) and the virtual equilibrium distribution function \( p_{\text{eq}}^{a,D} \):

\[
p_a(t + \delta t, \mathbf{x}_c) = p_{\text{eq}}^{a,D} + \left(1 - \frac{1}{t}\right)p_{\text{neq}}^{a,D}.
\]

### 2.3 Setups and verification

In this research, the flow around the traditional, Bach-type, and newly developed Savonius rotors was simulated and evaluated with respect to the difference of bucket shape on the output power and torque coefficients. Figure 5 shows schematic views of the (a) Traditional, (b) Bach-type, and (c) Newly developed Savonius rotors, respectively. Moreover, Fig. 5(d) shows schematic view of the definition of the rotational angle as a sample of the Traditional rotor. As shown in Fig. 5(a), \( D \) is the diameter of the rotor circle which is drawn with broken lines (\( D = 1024 \) cells), \( L \) is the diameter of the bucket, and \( e \) is the overlap distance, which is set to 0.2L. As shown in Fig. 5(b), the bucket consists of straight and circular buckets with reference to Roy’s (2013c, 2015a) and Kamoji’s (2009) bucket shape. As shown in Fig. 5(c), red and blue lines indicate the main and semi-elliptical buckets, respectively. The shape of the main bucket refers to the Bach-type bucket, and the additional bucket is semi-elliptical. This semi-elliptical bucket is installed to receive flows effectively when the output power coefficient of the main rotor is minimum. The parameters of the elliptical bucket \( a \) and \( b \) are the semi short-axis and long-axis length, respectively. The main bucket’s shape and position depend on the circular radius parameter \( r \). Here, the radius of the circular bucket is determined to inscribe the circle of the rotor. The diameter of the rotors as the characteristic length is the same in all shapes. So, parameter \( r \) can be calculated as Eq. (25).

\[
r = \frac{D}{2} \frac{1}{\sqrt{(1 - \frac{1}{2} \cdot 0.18 \cdot L)^2 + \left(\frac{1}{2}\right)^2 + 1}} \approx D / 3.88.
\]

![Fig. 5](image)

**Fig. 5** Schematic view of Savonius rotors when the rotational angle \( \theta = 0^\circ \) (ia), (b), and (c)).

Definition of the rotational angle is shown in (d).

Up until now, we have investigated the effect of the moment arm length (parameter \( s \)) of the semi-elliptical bucket with \( a = 0.2r \) and \( b = 0.3r \) (Matsui et al., 2019). As a result of this previous research, we found that the newly developed Savonius rotor when the moment arm length of the semi-elliptical bucket is around \( s = 1.3r \), generates maximum output power coefficient. Thus, in this study, the moment arm length is fixed as \( s = 1.3r \). Following this, the long-axis length of the semi-elliptical bucket of the newly developed Savonius rotor was increased from \( b = 0.3r \) to \( b = 0.45r \) to generate more torque by the semi-elliptical bucket. Moreover, parameter \( a \) is a variable as \( a = 0.00r, 0.15r, 0.30r, 0.45r \) to investigate the effect of the semi-elliptical bucket’s short-axis length. Table 1 summarizes the rotor type and parameters for the simulation. In the comparison with the torque coefficient in the next session, case 5 is discussed with case 1, which was improved in the previous research (Matsui et al., 2019). The rotors rotate counterclockwise. Rotational angle \( \theta \) is the azimuth angle of the bucket defined as the angle between the flow direction and the line from...
the bucket tip to the rotation center. For example, the rotational angle of each rotor is represented \( \theta = 0^\circ \) at the position of each rotor in Fig. 5(a), (b), and (c). The bucket is referred to as an advancing bucket when the bucket is positioned at \( 0^\circ < \theta \leq 180^\circ \); otherwise, it is referred to as a returning bucket.

Table 1  Rotor type for the simulation.

| Case | Rotor type and parameters |
|------|---------------------------|
| 1    | \( a = 0.20r, b = 0.30r \) (Matsui et al., 2019) |
| 2    | Newly developed rotor \( a = 0.00r, b = 0.45r \) |
| 3    | \( a = 0.15r, b = 0.45r \) |
| 4    | \( a = 0.30r, b = 0.45r \) |
| 5    | \( a = 0.45r, b = 0.45r \) |
| 6    | Traditional rotor |
| 7    | Bach-type rotor |

Figure 6 shows a schematic view of a multi-block model for the simulation. As shown in the same figure, the computational domain was \( 30D \times 30D \) using the multi-block method, and the coordinate of the center of the rotor was \( (10D, 15D) \). The traditional Savonius rotor (Fig. 5(a)) is shown in Fig. 6 as an example. The convective flow condition (Tsutahara et al., 2006) is given at the right side of the computational domain. The velocity and the pressure gradients are both equal to 0 at the other side of the computational domain. The Reynolds number \( Re \) based on the characteristic length of the diameter of the Savonius rotor is 1,000. The grid independence study is described in the next paragraph. Rotational speed was set as constant in order to satisfy the following tip speed ratio \( \lambda = 0.5, 0.625, 0.75, 0.875, 1.0, 1.125 \); and the simulation was conducted for a 10th cycle in order to eliminate the influence of the initial condition. The torque coefficient was obtained by an ensemble of average processing between the fifth and tenth cycles. The torque coefficient, output power coefficient, and tip speed ratio are defined in Eq. (26), Eq. (27), and Eq. (28), respectively. The torque coefficient, output power coefficient, and tip speed ratio are calculated using \( R = D/2 \) in all rotors, where \( D \) is the diameter of the rotor as the characteristic length.

\[
C_Q = \frac{q}{\frac{1}{2} \rho U^2 RA},
\]  

Eq. (26)
A verification study was conducted for Reynolds number $Re = 500$ and tip speed ratio $\lambda = 0.8$. An independence study of a number of grids for characteristic length was tested by assessing the torque of the traditional Savonius rotor. This test was conducted with three different numbers of grids for characteristic length ($D = 640, 960, 1280$ cells). Figure 7 shows the ensemble average torque coefficient diagram between the fifth and tenth cycles. Table 2 shows the results of the averaged torque coefficient. The average torque coefficient has a good consistency for different numbers of grids for characteristic length ($D = 640, 960, 1280$ cells). Accordingly, a number of grids for characteristic length with $D = 640$ could be sufficient for $Re = 500$. The number of grids required for the characteristic length is proportional to $Re^{1/2}$ times by the boundary layer thickness theory (Fujii, 1994). Based on this theory, the number of grids for characteristic length with $Re = 1000$ can be estimated to be about $D = 905$. Hence, the number of grids for characteristic length in this research is set to $D = 1024$. Table 3 shows the number of cells at each block when the number of cells per characteristic length is 1024.

\[
C_P = \frac{Q \cdot \omega}{\frac{1}{2} \rho U^2 A} = C_Q \cdot \lambda, \quad (27)
\]

\[
\lambda = \frac{R \omega}{U}, \quad (28)
\]
3. Results and discussion

In this section, the effect of the newly developed Savonius rotor’s semi-elliptical bucket shape is discussed using torque coefficient, pressure coefficient, and velocity vector diagrams. Furthermore, the performance of the newly developed Savonius rotor is also analyzed compared with traditional and Bach-type Savonius rotors in terms of the output power coefficient at different tip speed ratios.

Figure 8 shows the comparison of the torque coefficient of each set of main and semi-elliptical buckets at different rotor angles for tip speed ratio $\lambda = 0.875$. The corresponding position of each bucket set is schematically drawn with bold lines in Fig. 8. The present result of the torque coefficient whose maximum value is around $\theta = 60^\circ$ and minimum value is around $\theta = 270^\circ$ is consistent well with that of other studies (Tian et al., 2015; Zhang et al., 2017; Roy et al., 2016). Figure 7 shows that the generating torque coefficient of case 5 (in red) is larger than that of case 1 (in black) between $\theta = 30^\circ$ and $\theta = 180^\circ$. On the other hand, the generating torque coefficient of case 5 (in red) is smaller than that of case 1 between $\theta = 300^\circ$ and $\theta = 360^\circ$. These differences are discussed using the torque coefficient diagram of each main and semi-elliptical bucket.

Figure 9(a) shows the torque coefficient of the main bucket at different rotor angles for tip speed ratio $\lambda = 0.875$. This corresponding main bucket is shown by the bold lines on the schematic view of the newly developed Savonius rotor in Fig. 9(a). Figure 9(b) shows the torque coefficient of the semi-elliptical bucket at different rotor angles for tip speed ratio $\lambda = 0.875$. Figure 9(b) also shows this semi-elliptical bucket, indicated by the bold lines on the schematic view of the newly developed Savonius rotor. As shown in Fig. 9(a), the main bucket in case 1 generated larger torque than that in case 5 between $\theta = 0^\circ$ and $\theta = 60^\circ$. Figure 10 shows the pressure coefficient distribution at $\theta = 30^\circ$, where the difference in torque coefficient of the main bucket is large in Fig. 9(a). As shown in Fig. 10, the acting pressure on the concave side of the advancing main bucket in case 1 is higher than that in case 5. Moreover, fluid flows into the gap between the tip of the concave side of the advancing main bucket and the convex side of the semi-elliptical bucket (blue arrow in Fig. 10). This gap in case 1 is larger than that in case 5, so the main bucket in case 1 generated large torque compared with that in case 5. On the other hand, the gap between the advancing main and semi-elliptical buckets in case 5 is small because the receiving area of the semi-elliptical bucket in the wind flow direction in case 5 is large. Thus, the main bucket in case 5 generated smaller torque than that in case 1 due to restricting flows into the main bucket. It is important for the gap between the advancing main and semi-elliptical buckets to generate torque by the
main bucket between $\theta = 0^\circ$ and $\theta = 60^\circ$.

In Fig. 9(b), the generating torque coefficient of the semi-elliptical bucket in case 5 is larger than that in case 1 between $\theta = 30^\circ$ and $\theta = 180^\circ$. Moreover, the semi-elliptical bucket of both cases generated maximum torque at $\theta = 120^\circ$. Figure 11 shows the pressure coefficient distribution at $\theta = 120^\circ$, where the difference in torque coefficient of the semi-elliptical bucket is large, as shown in Fig. 9(b). The semi-elliptical bucket in both cases 1 and 5 generated maximum torque at $\theta = 120^\circ$ because the receiving area of the semi-elliptical bucket is the largest. Moreover, the semi-elliptical bucket in case 5 generated larger torque than that in case 1 in Fig. 9(b). This is because the receiving

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**Fig. 9** Comparison of the torque coefficient of each bucket for different parameters $a$ and $b$ of a newly developed Savonius rotor at tip speed ratio $\lambda = 0.875$.

**Fig. 10** Pressure coefficient distributions around a newly developed Savonius rotors at $\theta = 30^\circ$ (for thick white buckets) for tip speed ratio $\lambda = 0.875$. 

In Fig. 9(b), the generating torque coefficient of the semi-elliptical bucket in case 5 is larger than that in case 1 between $\theta = 30^\circ$ and $\theta = 180^\circ$. Moreover, the semi-elliptical bucket of both cases generated maximum torque at $\theta = 120^\circ$. Figure 11 shows the pressure coefficient distribution at $\theta = 120^\circ$, where the difference in torque coefficient of the semi-elliptical bucket is large, as shown in Fig. 9(b). The semi-elliptical bucket in both cases 1 and 5 generated maximum torque at $\theta = 120^\circ$ because the receiving area of the semi-elliptical bucket is the largest. Moreover, the semi-elliptical bucket in case 5 generated larger torque than that in case 1 in Fig. 9(b). This is because the receiving
area and the camber of the semi-elliptical bucket in case 5 are larger than those of case 1. Also, the acting pressure on the concave side of the semi-elliptical bucket in cases 1 and 5 are similar. On the other hand, the acting pressure on the convex side of the semi-elliptical bucket in case 5 is lower than that in case 1 as shown in Fig. 11. Thus, the difference of the pressure between concave and convex sides of the semi-elliptical bucket in case 5 is larger than that in case 1. For this reason, the generation of the torque coefficient of the semi-elliptical bucket in case 5 is larger than that in case 1.

As shown in Fig. 9(a), the main bucket in case 5 generated almost the same or larger torque than that in case 1 between $\theta = 60^\circ$ and $\theta = 120^\circ$. Figure 12 shows the velocity vector distributions at $\theta = 120^\circ$. As shown in Fig. 12, fluid flows along the straight part of the returning main bucket (thin buckets in Fig. 12) and into the advancing semi-elliptical and main buckets (thick buckets). The fluid flow in the gap between the advancing semi-elliptical bucket and the returning main bucket in case 5 is stronger than that in case 1. This strong flow into the main bucket in case 5 occurred due to the narrow gap between the advancing semi-elliptical bucket and the returning main bucket. Although, the fluid flowing into the main bucket was restricted by the semi-elliptical bucket, the main bucket in case 5 generated a positive torque.

As shown in Fig. 9(b), the generation of a negative torque by the semi-elliptical bucket in case 5 was larger than that in case 1 during the returning bucket period ($180^\circ < \theta \leq 360^\circ$). Figure 13 shows the pressure coefficient distribution at $\theta = 330^\circ$, where the difference in torque coefficient of the semi-elliptical bucket was large in Fig. 9(b).
Figure 13(b) shows that the acting pressure on the convex side of the semi-elliptical bucket in case 5 was high. This is because the fluids in case 5, which did not collide with the convex side of the returning main bucket, collided with the convex side of the returning semi-elliptical bucket. Furthermore, the returning semi-elliptical bucket in case 5 generated a large negative torque, whereas the returning semi-elliptical bucket in case 1 did not generate a large negative torque when compared with that in case 5. This is because its position is located behind the returning main bucket in the wind flow direction. Moreover, the shape of the semi-elliptical bucket in case 1 is smaller than that in case 5. The position of the semi-elliptical bucket is important in suppressing the generation of the negative torque during the returning bucket period. The semi-elliptical bucket should be located in the position that is hidden by the main bucket in the flow direction during the returning bucket period to be able to reduce the negative torque generation of the semi-elliptical bucket.

In summary, the semi-elliptical bucket generates a positive torque during the advancing bucket period. However, it does not generate a large negative torque during the returning bucket period because the main bucket works as an obstacle plate for the semi-elliptical bucket. Through a cycle, the semi-elliptical bucket generates almost a positive torque due to interactions with the main bucket.

Figure 14 shows the comparison of the average output power coefficients of the traditional, the Bach-type, and the newly developed Savonius rotors at different tip speed ratios. These approximate curves were obtained by the least squares method. In this study, we conducted flow simulation for Reynolds number \( Re = 1,000 \), which is lower than those of other researchers in order to reduce computational cost. However, the present results of averaged output power coefficient of the traditional Savonius rotor are qualitatively in agreement with other results (Zhang et al., 2017; Tian et al., 2015; Jaohindy et al., 2014; Roy et al., 2015a, 2016). For example, the maximum output power coefficient decrease when the Reynolds number decreases. Moreover, the range of the tip speed ratio that generates the maximum output power coefficients is \( \lambda = 0.65 – 0.73 \) (Roy et al., 2013d, 2015a). In the experimental study at \( Re = 6.0 \times 10^4 – 1.2 \times 10^5 \), the range of the tip speed ratio that generates the maximum output power coefficient of the traditional rotor is \( \lambda = 0.66 – 0.73 \). Furthermore, that of the Bach-type rotor is \( \lambda = 0.75 – 0.80 \) (Roy et al., 2015a). In this present study, the tip speed ratios that generate the maximum output power coefficient of the traditional and the Bach-type rotor are \( \lambda = 0.62 \) and 0.76, respectively. So, the tendency of the result is in good agreement with the experimental results. Moreover, the maximum output power coefficient of the Bach-type rotor is higher by 22.8% – 30.4% than that of the traditional one at \( Re = 6.0 \times 10^4 – 1.2 \times 10^5 \) (Roy et al., 2015a). In this study, the maximum output power coefficient of the Bach-type rotor is higher by 28.9% than that of the traditional one. So, it may be acceptable to consider output power coefficient with a flow condition for Reynolds number \( Re = 1,000 \). Table 4 highlights the maximum average output power coefficients of the traditional, the Bach-type, and the newly developed Savonius rotors. The torque generation of the

![Pressure coefficient distributions around a newly developed Savonius rotors at \( \theta = 330^\circ \) (for thick white buckets) at tip speed ratio \( \lambda = 0.875 \).](image-url)
newly developed Savonius rotor with the increasing long-axis length of the semi-elliptical bucket \((b = 0.45r)\) go up as the parameter \(a\) of the semi-elliptical bucket increases as shown in Fig. 14. The newly developed Savonius rotor of case 5 \((a = 0.45r, b = 0.45r)\) generated maximum output power coefficient as in Fig. 14. Moreover, the newly developed Savonius rotor of case 5 \((a = 0.45r, b = 0.45r)\) was improved when compared with the previous one of case 1 \((a = 0.20r, b = 0.30r)\) (Matsui et al., 2019). Table 4 shows that the output power coefficient of the newly developed Savonius rotor of case 5 \((a = 0.45r, b = 0.45r)\) was improved, compared with traditional Savonius rotor, by 50.7%. Moreover, this rotor was improved, compared with the Bach-type Savonius rotor, by 16.9%. Many researchers have found that the Bach-type Savonius rotor was improved when compared to the traditional Savonius rotor (Roy et al., 2013c, 2015a and Kamoji et al., 2009). Thus, the newly developed Savonius rotor is superior to the Bach-type and the traditional Savonius rotors. Tip speed ratios at generating maximum output power coefficient of the newly developed Savonius rotors increased compared with those of the traditional and Bach-type Savonius rotors. The semi-elliptical buckets, generating almost positive torque through a cycle, contributed to these increase.

The installation of the obstacle plates out of the rotor is an easy method by which to improve the performance of the output power coefficient of the rotor. However, this approach brings dependence on the wind direction; therefore,

![Fig. 14](image.png)

**Fig. 14** Comparison of the average output power coefficient of traditional, Bach-type, and newly developed Savonius rotors at different tip speed ratio.

| Case | Rotor type and parameters | Maximum output power coefficient | Difference Traditional rotor | Difference Bach-type rotor |
|------|---------------------------|----------------------------------|-----------------------------|---------------------------|
| 1    | \(a = 0.20r, b = 0.30r\)  | 0.133 (\(\lambda = 0.794\))     | 27.4%                       | -1.1%                     |
| 2    | Newly developed rotor     | \(a = 0.00r, b = 0.45r\)        | 0.117 (\(\lambda = 0.793\)) | 12.5% -12.7%              |
| 3    | \(a = 0.15r, b = 0.45r\)  | 0.134 (\(\lambda = 0.781\))     | 28.4%                       | -0.4%                     |
| 4    | \(a = 0.30r, b = 0.45r\)  | 0.146 (\(\lambda = 0.819\))     | 40.0%                       | 8.6%                      |
| 5    | \(a = 0.45r, b = 0.45r\)  | 0.157 (\(\lambda = 0.816\))     | 50.7%                       | 16.9%                     |
| 6    | Traditional rotor         | 0.104 (\(\lambda = 0.620\))     | -                           | -22.4%                    |
| 7    | Bach-type rotor           | 0.134 (\(\lambda = 0.758\))     | 28.9%                       | -                         |

Table 4 Maximum averaged output power coefficient of traditional, Bach-type, and newly developed Savonius rotors.
some functions should be added such as wind direction control. Independence of wind direction of the Savonius rotor is a strong point compared with other wind turbines. Thus, the newly developed Savonius rotor is effective in improving the output power coefficient and maintaining its independence of the wind direction. This improvement is attributed to the semi-elliptical bucket, which generates almost positive torque during a cycle due to interactions with the main bucket.

4. Conclusions and future work

In this paper, flow around the newly developed Savonius rotor with added semi-elliptical buckets was simulated to investigate the effect of the semi-elliptical bucket’s shape. The output power coefficient of the newly developed Savonius rotor was compared with those of the traditional and the Bach-type Savonius rotors. Based on the results in this paper, the following conclusions have been drawn.

(1) The additional semi-elliptical bucket generates a positive torque in the range of the advancing bucket and does not generate a large negative torque in the range of the returning bucket. Thus, the semi-elliptical bucket contributes to the improvement of the output power coefficient, without generating a large negative torque during a cycle.

(2) The output power coefficient of the newly developed Savonius rotor is improved when compared with that of the traditional one by 50.7% and the Bach-type by 16.9%, respectively.

(3) Tip speed ratio at the generation of maximum output power coefficient of the newly developed Savonius rotors is also increased when compared with those of the traditional and Bach-type Savonius rotor because only positive torque generation by the semi-elliptical bucket through a cycle is present. The newly developed Savonius rotor generates large torque at the high tip speed ratio.

It should be noted that in this research, the moment of inertia of the newly developed Savonius rotor (parameters $a = 0.45r$, $b = 0.45r$) is less than that of the traditional Savonius rotor by about 20%. However, the total bucket length of the newly developed Savonius rotor (parameters $a = 0.45r$, $b = 0.45r$) is longer than that of the traditional Savonius rotor by about 18%. Thus, this proposed newly developed Savonius rotor would be optimized by reducing the bucket length to be the same as that of the traditional one to keep the weight of the traditional Savonius rotor the same.

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