



## ENERGY HARVESTING FROM BISTABILITY PHENOMENON ON CIRCULAR CYLINDERS

**Patrick Batista Habowski**

**Alexandre Vagtinski de Paula**

Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Engenharia Mecânica (PROMEC), Rua Sarmento Leite, 425, Porto Alegre, CEP 90050-170, Brazil

[patrick.habowski@ufrgs.br](mailto:patrick.habowski@ufrgs.br) (P.B. Habowski), [depaula@ufrgs.br](mailto:depaula@ufrgs.br) (A.V. de Paula)

**Sérgio Viçosa Möller**

Universidade Federal do Rio Grande do Sul, Programa de Pós-Graduação em Engenharia Mecânica (PROMEC), Rua Sarmento Leite, 425, Porto Alegre, CEP 90050-170, Brazil

[symoller@ufrgs.br](mailto:symoller@ufrgs.br)

**Abstract.** *An experimental study for a configuration with two circular cylinders in an aerodynamic flow channel is presented. The main objective is to explore the ability of the cylinders to produce power in small scales, known as energy harvesting, using the bistability phenomenon as the initiator mechanism. A setup with a circular table and two circular cylinders were assembled inside the flow channel, and an electric circuit with a generator was coupled outside. The rotational velocity and instantaneous power generation of the setup were measured. Two distinct configurations using aerodynamic devices were proposed. A Savonius turbine was also tested, imposing the same methodology applied for the circular cylinders. Results showed that the cylinders' setup was able to produce small quantities of power using the aerodynamic devices, generating appreciable amounts of energy compared to the amount generated by the Savonius turbine, a device for large-scale generation.*

**Keywords:** *Aerodynamic Flow Channel, Bistability, Circular Cylinders, Energy Harvesting, Turbulent Flow.*

### 1. INTRODUCTION

Circular cylinders are simple structures employed in engineering: bridges, heat exchangers, chimneys, pipelines, transmission lines, and nuclear reactors are some examples. In the literature, the flow past cylinders is a topic explored by many authors through the last decades (Zdravkovich, 1987; Blevins, 1990; Sumner, 2010; Zhou and Alam, 2016; Habowski et al., 2020; Neumeister et al., 2021). Also, complex structures can be simplified to circular cylinders in order to explore a particular phenomenon and then be expanded to complex studies. Meanwhile, the flow past cylinders is complex and irregular, having no complete analytical model (Endres and Möller, 2001).

There is no doubt that flow around two or more cylinders is more complex than in a single cylinder. This fact is due to the interaction between the cylinders, the wake, and the shear layers (Alam and Meyer, 2011). Configurations with two cylinders can be arranged placing the cylinders side-by-side, staggered, tandem, or, in the case of more than two cylinders, tube arrays (Olinto et al., 2009; De Paula et al., 2012). Kim and Durbin (1988) presented a study with side-by-side cylinders where the authors reported the flow reducing its mean value along time in the cases in which the distance between the cylinders was reduced. This fact is linked to the asymmetry of the wakes, generated by a phenomenon known with more details currently: the bistability. Even though several authors developed studies involving this phenomenon, its understanding is a topic still very explored and discussed.

Bistable is the concept used to describe a phenomenon that presents distinct behaviors in a stable state for the same imposed conditions. The behavior of flows on specific configurations with two circular cylinders placed side-by-side are called bistable flow, once for these configurations, the flow presents two levels of average velocities under the same imposed conditions. For side-by-side cylinders, the bistable flow is reported for  $p/d$  ratio 1.1 – 2.5 (Alam et al., 2003; Alam and Sakamoto, 2005; Sumner, 2010), presents a chaotic behavior and do not depends on the Reynolds number or misalignments (De Paula and Möller, 2018).

In our laboratory, the topic of bistability has been explored in the last two decades. Olinto et al. (2009) presented a study in the first rows of tube banks using hot wire anemometry and flow visualizations in a water channel. The author reported flow instabilities after the second row of the tube bank that propagated to the interior of the bank. De Paula et al. (2012, 2013) presented results for triangular arrangements in tube banks. The author observed the bistability phenomenon for the case with one cylinder upstream and two cylinders downstream, but for the opposite configuration with two cylinders upstream and one cylinder downstream the bistability phenomenon was not detected. In addition, these two configurations presented distinct shedding frequencies. De Paula and Möller (2013) investigated the flow modes presented

in the bistability phenomenon on two circular cylinders. Main conclusions using a finite mixture model suggested no evident correlation between the flow mode changes and the time. Also, the presence of more than two flow modes was observed.

More recently, Ost et al. (2019) presented the performance of Hilbert-Huang Transform as a tool of analysis of turbulent flows, applied to the case of a single cylinder. The authors obtained satisfactory results for separated short periods using this methodology. Habowski et al. (2019, 2020) presented a study with two circular cylinders placed at several angular positions to the flow, from side-by-side ( $0^\circ$ ) to tandem position ( $90^\circ$ ). The main contributions of this work were the description about the characteristics of the wake downstream of the cylinders with flow visualization for the several proposed static positions. In addition, the authors were able to describe an equation relating the angular position of the cylinder's setup and the wake angle formed downstream the cylinders.

These works were followed by the work of Neumeister et al. (2021) who studied FIV for single and pairs of cylinders side-by-side and tandem placed. For single cylinders, the authors reported that the highest amplitudes of vibration were associated with the vibration modes of the cylinder. The case of side-by-side cylinders presented vibration amplitude similar to the single cylinder. The main conclusion was obtained in the case of the cylinders tandem placed, which presented a sudden increase in the vibration amplitude due to the fixed cylinder upstream.

Studies involving a setup with two cylinders initially placed side-by-side with the freedom to rotate showed that the bistability phenomenon is able to unbalance this setup, leading to a rotational movement of the setup (Varela et al., 2018).

According to Priya and Inman (2009), energy generation is a peculiar concern for remote places, such as deserts and isolated islands, once the energy distribution to these places is very expensive. To solve this problem, wireless systems are very interesting, since the costs of energy distribution no longer exist. However, supply big demand for energy is still a challenge. Wireless systems are devices linked to the idea of energy harvesting.

The concept of energy harvesting is to use unused or wasted power to generate energy (Priya, 2007), using immediately or storing in batteries. Examples of unused power are human activity, motion, vibration, wind, solar power, electromagnetic and pressure gradients (Scarselli et al., 2016), which may be converted into electrical energy by simple electronic systems. Energy harvesting has been investigated in the last decades since self-powered microsystems to bigger and more complex systems (Anton and Sodano, 2007; Beeby et al., 2006; Yang et al., 2014). The concept of power harvesting works towards developing self-powered devices that do not require replaceable power supplies, like the already mentioned wireless systems.

Considering that, this work aims to generate small quantities of electrical power exploring the ability of two circular cylinders in specific arrangements. To evaluate the ability of power generation, the bistability phenomenon was used as the initiator mechanism, and two configurations employing aerodynamic devices were proposed.

## 2. EXPERIMENTAL PROCEDURE

### 2.1 Aerodynamic channel

This study was performed in one of the aerodynamic channels of the Fluid Mechanics Laboratory of UFRGS, using air as the working fluid. The channel is a 2.29 meters long rectangular section of  $193 \times 146$  mm (width  $\times$  height), made of acrylic glass, due to its smoothness and transparency. The air from the surroundings is blown to the flow channel by a centrifugal blower with 0.75 kW, and then passes through a diffuser, two honeycombs, and two screens, reducing the turbulent intensity to about 1% of the streamflow in the cross-section. Figure 1 presents a detailed view of the aerodynamic flow channel. After passing through the screens, the air goes to the test section where cylinders and measuring equipment are placed. Also, a section with a Pitot tube, pressure static tap, and a thermometer is located before the test section to measure the streamflow.

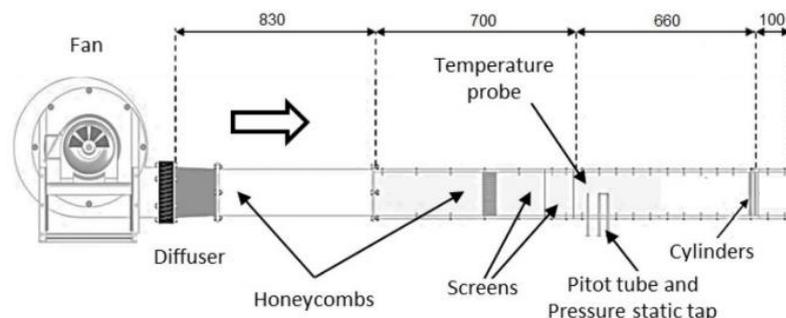


Figure 1. Detailed view of the aerodynamic channel.

The cylinders used in the experiments are two rigid smooth circular cylinders with 25.1 mm of diameter, made of commercial PVC. A circular table 3D printed with a centralized pin was employed to support the cylinders inside the test

section, as shown in Figure 2. This circular table was assembled on low wear bearings fixed on the upper and lower channel walls. Therefore, the damping in the system was not accounted in the present study. The distance between the cylinders is 6.5 mm, so that the  $P/D$ -ratio of the cylinder set was 1.26, being  $P$  the pitch, the distance between cylinders' center.

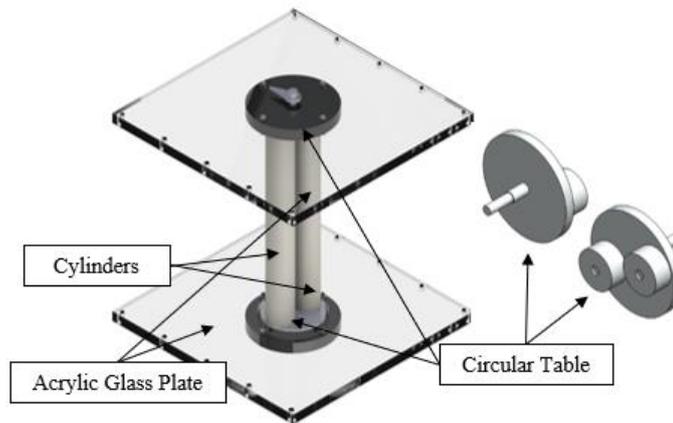


Figure 2. Details about the cylinder setup and its assembly in the test section.

To explore the ability of the setup to generate power, two configurations with aerodynamic devices were proposed, in addition to the initial configuration with only the cylinders' setup set in the test section. These two proposed configurations, presented in Figure 3, has the objective to accelerate the flow close to the cylinders to increase the rotational velocity of the setup and, as consequence, generate more power. The freestream velocity adopted in this study was 12.6 m/s, generating a Reynolds number of  $20.9 \times 10^3$ , computed for the cylinder diameter.

In the first proposed configuration, shown in Figure 3a, was placed a throat device, similar to a quarter of a circle, tangent to the walls and upstream to the cylinders' setup. The second configuration, shown in Figure 3b, has a third cylinder placed on the side of the cylinders' setup, creating a  $p/d$ -ratio of 1.26, the same as the cylinders in the circular table. Considering the devices inserted inside the aerodynamic channel, the blockage ratio is 38 – 51% and 26 – 39% in the first and second proposed configurations, respectively, depending on the instantaneous position of the cylinders' setup.

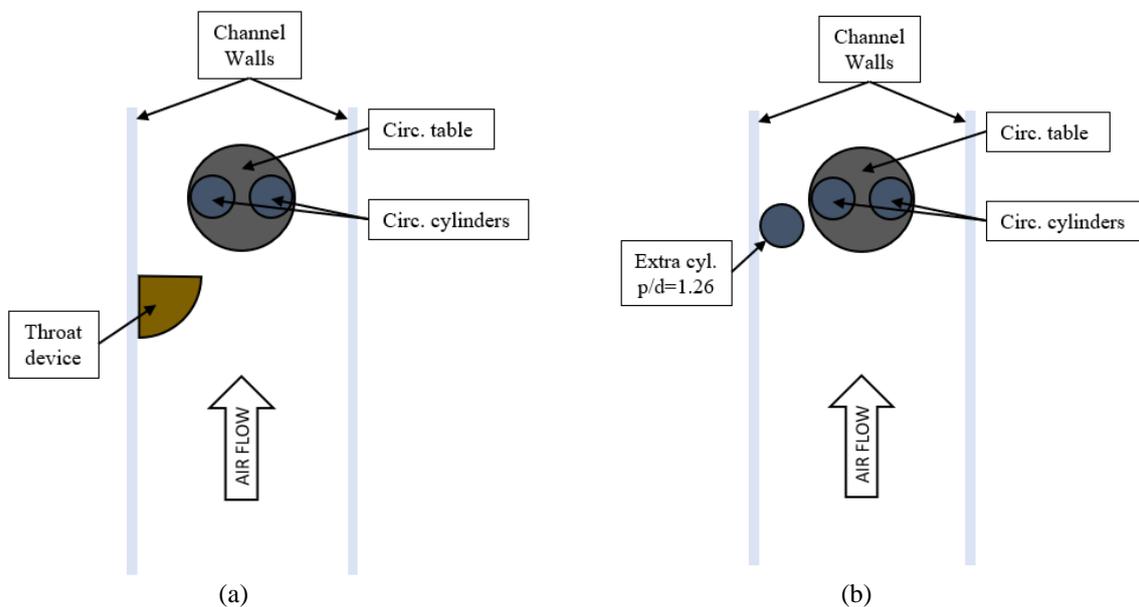


Figure 3. Proposed configurations with aerodynamic devices to increase the power generation: (a) throat device and (b) extra cylinder, positioned with  $p/d$ -ratio = 1.26.

To determine the amount of instantaneous power generated by the cylinders' setup, an electric circuit with variable resistance was mounted. The instantaneous power generation ( $P$ ) is defined by Eq. (1), where  $I$  is the electric current and  $U_e$  is the electric voltage. The less is the equivalent resistance in the electric circuit, the more is the power generated by the cylinders setup up to the system loss significant rotational velocity. When this point is achieved, the system starts to generate less power in comparison to the previously tested resistance.

$$P = I \cdot U_e \tag{1}$$

The electrical circuit employed to measure the amount of power generated consists of a stepper motor, used as a generator, two digital multimeters, used to measure the values of electric current and voltage at the same time, resistors, and a digital tachometer, employed to measure the rotational velocity. The experiment consisted of coupling the generator in the assembly with the cylinders, turn on the blower with the generator off and when the rotational velocity was stabilized, turn on the generator.

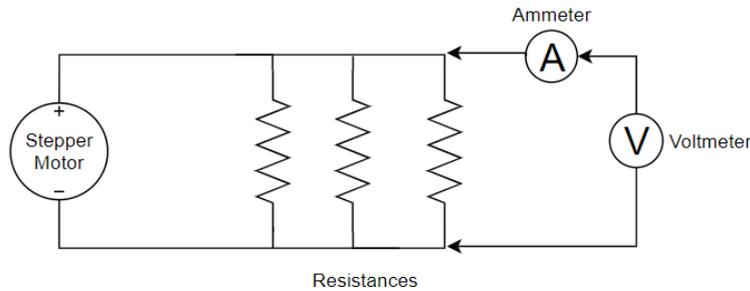


Figure 4. Electric system details to measure the amount of instantaneous power generated.

To modify the electric resistance in the system, 11 resistors were mounted in parallel, being added one resistor at each time, reducing the equivalent resistance. Thus, 11 cases were tested with different resistances, as shown in Table 1. The “Case 0” represents the system turned on unplugged from the electrical system, where the maximum rotational velocity is achieved.

Table 1. Explored cases in the electric circuit.

Case	Equivalent Res. ( $\Omega$ )	Case	Equivalent Res. ( $\Omega$ )
0	-	6	9.7
1	58	7	8.3
2	29	8	7.3
3	19.3	9	6.4
4	14.5	10	5.8
5	11.6	11	5.3

Considering the novelty of the energy harvesting exploration in circular cylinders through the bistability phenomenon, the results obtained from the proposed configuration and cases were compared with a Savonius turbine. The same cases presented in Table 1 were tested. The Savonius turbine employed was a 3D printed part assembled in the flow channel with low wear bearings and without aerodynamical devices, as presented in Figure 5.

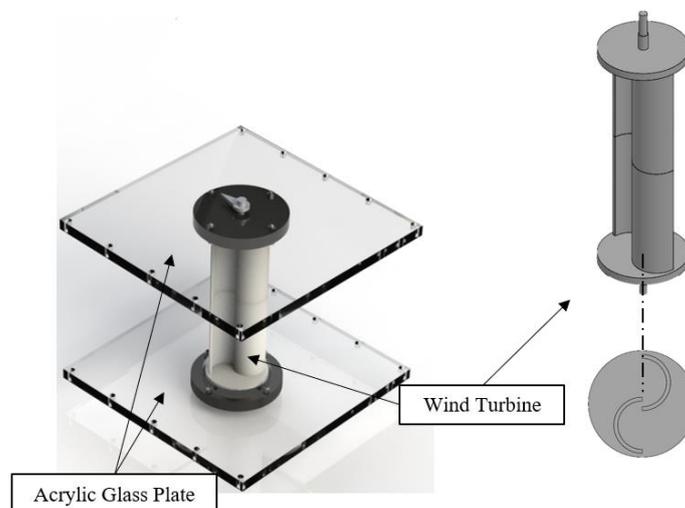


Figure 5. Savonius turbine employed in the present study to compare the results with energy harvesting in circular cylinders.

Due to its shape, the blockage ratio of the turbine is 10.9 – 26%, depending on its instantaneous position. Thus, the comparison of the results of power generation in circular cylinders and Savonius turbine can evaluate the applicability of the proposed configurations.

### 3. RESULTS

The results of the instantaneous power generation and rotational velocity for each case and the two proposed configurations are presented in Figure 6. When the cylinders' setup was placed inside the test channel without aerodynamic devices and the blower was turned on, the cylinders' setup remained in the rest position.

The first proposed configuration, shown in Figure 6a, was assembled and the blower was turned on. Starting unplugged the electric system (Case 0 from Table 1), this configuration achieved a maximum rotational velocity of 2330 rpm. Thus, each case was tested and a maximum power of 67.59 mW was generated in Case 8, where the equivalent resistance is 7.3 Ω. In the second proposed configuration (Figure 6b), the same procedure was developed. The maximum rotational velocity achieved by the setup in the Case 0 was 1000 rpm. In case 10, with an equivalent resistance of 5.8 Ω, the maximum instantaneous power generation of 10.07 mW was obtained.

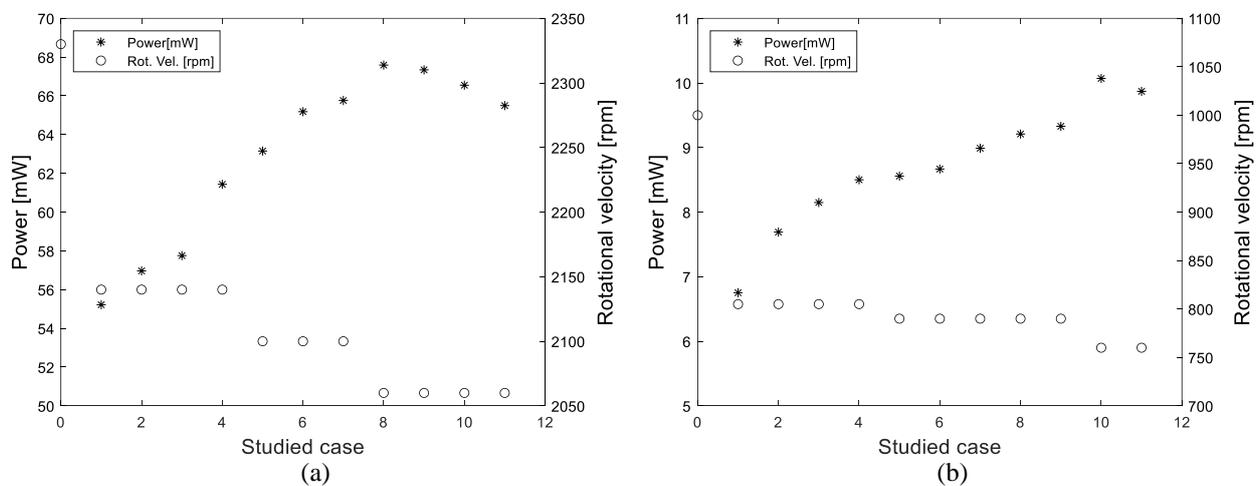


Figure 6. Results for instantaneous power generation and rotational velocity of the circular cylinders' setup, using (a) throat device and (b) the extra cylinder.

Through the results presented in Figure 6, the configuration with the throat device (Figure 6a) generated 6.7 times more power than the configuration with the extra cylinder (Figure 6b). One reason for that is the higher blockage ratio generated by the throat device. In addition, the design of this device, similar to a quarter of a circle, accelerates the flow more than just a circular cylinder.

The results for instantaneous power generation and rotational velocity for the Savonius turbine experiment are presented in Figure 7. For the turbine's experiment, the throat device and extra cylinder were not used. The same free stream velocity and the cases from Table 1 were imposed. Since the Savonius turbine is a device designed to generate energy on large scales, it was expected higher power generation by the turbine, and also higher values for the rotational velocities. The maximum rotational velocity achieved by the turbine was 3800 rpm in Case 0, and the maximum value of instantaneous power generation of 115.6 mW was achieved in Case 10, where the equivalent resistance is 5.8 Ω.

Comparing all the results obtained in the experiments in the present work, Table 2 was generated. The circular cylinders with the throat device and the extra cylinder were able to produce 58.4 and 8.71% of the Savonius turbine power generation, respectively, with the same stream velocity imposed. The amount of power generated can be considered useful for energy harvesting applications.

Table 2. Main results of the performed experiments in this study.

Experiment	Aerodynamic device	Max. rotational vel. [rpm]	Max. power gen. [mW]
Circ. cylinders	Without	-	-
Circ. cylinders	Throat device	2330	67.59
Circ. cylinders	Extra cylinder	1000	10.07
Savonius turbine	Without	3800	115.60

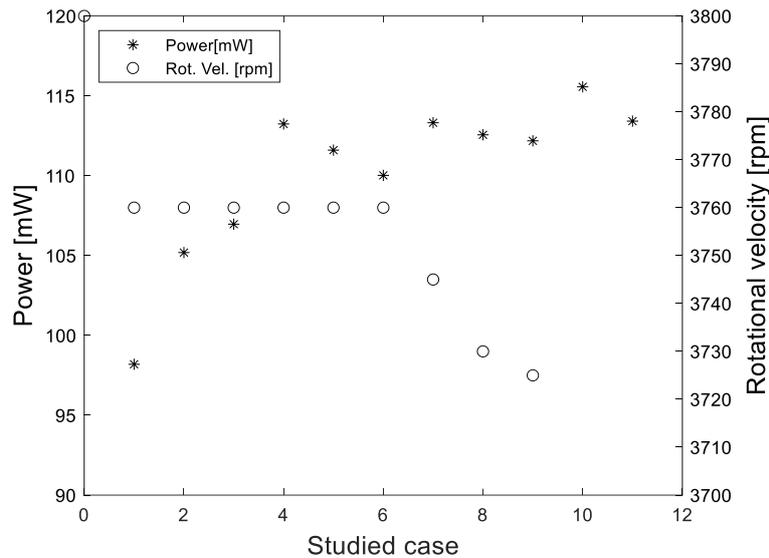


Figure 7. Results for instantaneous power generation and rotational velocity of the Savonius turbine.

#### 4. FINAL REMARKS

This article presented an experimental study of the ability of a setup with two circular cylinders to produce energy in small quantities, called as energy harvesting, through the presence of the bistability phenomenon. The experiments were performed in an aerodynamic channel using air as work fluid. The setup with two circular cylinders was assembled inside the flow channel and two configurations using aerodynamic devices were proposed. An electric circuit with a generator, variable resistance, and two digital multimeters was mounted to measure the values of electric current and voltage to compute the instantaneous power generated. In addition, the same procedure was performed on a Savonius turbine to compare the results.

Results for the cylinders' setup without aerodynamic devices were unable to start the rotational movement and, consequently, was not able to produce energy. Thus, the aerodynamic devices were inserted, and the cylinders' setup was able to produce small quantities of energy. For the presence of the throat device, which increased the blockage ratio to 38 – 51%, the maximum instantaneous power produced was 67.59 mW and the maximum rotational velocity was 2330 rpm. After this, the extra cylinder was assembled inside the flow channel, increasing the blockage ratio to 26 – 39%, and generated a maximum instantaneous power of 10.07 mW and a maximum rotational velocity of 1000 rpm. Finally, the same procedure was adopted in the experiment with the Savonius turbine, without aerodynamic devices, generating maximum instantaneous power of 115.6 mW and maximum rotational velocity of 3800 rpm.

Since the Savonius is a device properly designed to generate energy, it was expected that the turbine would generate more power than the cylinders' setup proposed in this article. Using the same stream velocity, the cylinders' setup with throat device and extra cylinder generated 58.47 and 8.71 %, respectively, of the power generated by the Savonius turbine without aerodynamic devices.

Considering the results presented in this article, it can be concluded that a setup with two circular cylinders with  $p/d = 1.26$  is able to perform energy harvesting since the bistability allows the rotational movement of the setup. Future studies with a more accurate electric circuit and a proper generator will be carried out.

#### 5. ACKNOWLEDGEMENTS

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## 7. RESPONSIBILITY NOTICE

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