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Energy Harvesting Using Piezoelectric-Film Transducers Excited by Vortex-Induced Vibrations Behind Bluff Bodies for Off-Grid Applications

Alper BURGAÇ[1, *]

[1] *Adana Alparslan Türkeş Science and Technology University, Engineering Faculty, Department of Energy Systems Engineering, Sarıçam, 01250, Adana, Türkiye*

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* *Corresponding Author*
e-mail: aburgac@atu.edu.tr

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ORCID Numbers in author order:
0000-0002-0238-164X

ABSTRACT

Piezoelectric energy harvesting is crucial for providing power to systems where conventional power sources are unavailable. In this study, a novel wake-driven energy harvesting concept is proposed by exploiting vortex-induced vibrations generated downstream of semi-circular bluff body cylinders using piezoelectric film transducers. Flow visualization experiments are conducted to characterize the wake topology behind the bluff bodies. Bluff bodies with various length-to-diameter ratios are systematically investigated to examine the influence of geometric parameters on wake dynamics Based on the flow visualization results, piezoelectric film transducers are positioned at various streamwise distances and mounting orientations to evaluate their interaction with the unsteady wake of these various bluff bodies. Energy harvesting experiments for all configurations are performed by connecting the transducers to an input capacitor. The time-dependent charging behaviour is recorded to assess the energy output of each configuration. The models showing the best results are connected to the output capacitor, and their charging performance is measured. The experimental results demonstrate that optimized configurations yield average output capacitor voltages of 2.41 V and 2.84 V for different orientation and distances. The findings reveal a strong correlation between flow topology and energy generation. Moreover, both bluff body geometry and the spatial placement and orientation of the piezoelectric transducers play a critical role in maximizing energy output. This study highlights the potential of this approach for enabling self-sufficient energy generation in remote areas with promising applications in low-power off-grid systems.

Şebeke Dışı Uygulamalar İçin Küt Cisimlerin Arkasındaki Girdap Kaynaklı Titreşimlerle Uyarılan Piezoelektrik Film Transdüserleri Kullanılarak Enerji Hasadı

MAKALE BİLGİSİ

Anahtar Kelimeler*:*
Enerji hasadı
Piezoelektrik malzeme
Yenilenebilir enerji
Girdap kaynaklı titreşim

ÖZET

Piezoelektrik enerji hasadı, geleneksel güç kaynaklarının bulunmadığı sistemlere güç sağlamak için çok önemlidir. Bu çalışmada, piezoelektrik film transdüserleri kullanılarak yarı dairesel küt gövdeli silindirlerin aşağısında oluşan girdap kaynaklı titreşimlerden yararlanılarak yeni bir akış yönüne dayalı enerji hasadı konsepti önerilmiştir. Küt gövdelerin arkasındaki akış topolojisini karakterize etmek için akış görselleştirme deneyleri yapılmıştır. Geometrik parametrelerin akış dinamikleri üzerindeki etkisini incelemek için çeşitli uzunluk-çap oranlarına sahip küt gövdeler sistematik olarak incelenmiştir. Akış görselleştirme sonuçlarına dayanarak, piezoelektrik film transdüserleri, bu çeşitli küt gövdelerin kararsız akışıyla etkileşimlerini değerlendirmek için çeşitli akış yönü mesafelerinde ve montaj yönlerinde konumlandırılmıştır. Tüm konfigürasyonlar için enerji hasadı deneyleri, transdüserlerin bir giriş kapasitörüne bağlanmasıyla gerçekleştirilmiştir. Her konfigürasyonun enerji çıkışını değerlendirmek için zamana bağlı şarj davranışı kaydedilmiştir. En iyi sonuçları gösteren modeller çıkış kapasitörüne bağlanmış ve şarj performansları ölçülmüştür. Deneysel sonuçlar, optimize edilmiş konfigürasyonların farklı yönelim ve mesafeler için ortalama çıkış kapasitör voltajlarının sırasıyla 2,41 V ve 2,84 V olduğunu göstermektedir. Bulgular, akış topolojisi ile enerji üretimi arasında güçlü bir korelasyon olduğunu ortaya koymaktadır. Dahası, hem küt cisim geometrisi hem de piezoelektrik dönüştürücülerin uzamsal yerleşimi ve yönelimi, enerji çıkışını en üst düzeye çıkarmada kritik bir rol oynamaktadır. Bu çalışma, bu yaklaşımın uzak bölgelerde kendi kendine yeten enerji üretimine olanak sağlama potansiyelini ve düşük güçlü şebeke dışı sistemlerde umut vadeden uygulamalarını vurgulamaktadır.

NOMENCLATURE

D	Diameter (cm)
L	Length (cm)
L/D	Length to diameter ratio
Re	Reynolds number
SAE	Society of Automotive Engineers
TiO_2	Titanium dioxide
VIV	Vortex induced vibration
V	Voltage (volt)

INTRODUCTION

The increasing global demand for energy and environmental concerns have intensified researchers' focus on sustainable and environmentally friendly energy sources. It is widely acknowledged that fossil fuel reserves are finite and are depleting at an accelerating rate. Additionally, primary environmental challenges, such as rising global warming and expanding carbon footprints, further exacerbate these issues. These concerns have prompted researchers to explore alternative renewable energy sources that are both environmentally sustainable and capable of meeting future energy demands. Among the most prominent renewable energy sources are wind energy, wave energy, and solar energy (Ang et al., 2022). While energy harvesting from these sources is well-established, particularly for large-scale applications, the overall efficiency of these systems tends to decline as the system scale decreases, primarily due to inherent physical limitations (Le Scornec et al., 2022). Energy harvesting from renewable sources on a small scale has emerged as a prominent research area, aiming to transform these sources into usable energy forms (Bhatt et al., 2024). Among various renewable energy production techniques, the utilization of piezoelectric transducers has gained significant attention, particularly for small-scale applications (Toprak and Tigli, 2014). Flow-induced vibration-based energy harvesters utilizing piezoelectric materials represent a cutting-edge technology for generating renewable electrical power from fluid flows, providing electrical energy for small-scale applications, especially in remote locations such as wireless sensor networks, which often require long-term, maintenance-free operation due to the high costs associated with access and maintenance (Mazharmanesh et al., 2022; Stamatellou and Kalfas, 2018).

The piezoelectric effect was first discovered by Pierre and Jacques Curie in 1880, revealing its potential for use as both a sensor and a micro-generator (Maghsoudi et al., 2019). This phenomenon, referred to as the "piezoelectric effect," describes the ability of certain materials to generate an electric charge in response to applied mechanical stress. Notably, the process is reversible; the application of an external electric charge to piezoelectric materials induces mechanical stress within the material, with the direction of the resulting stress being opposite to that of the applied electric charge (Pan et al., 2024). This underpins the fundamental mechanism by which mechanical energy is converted into electrical energy using piezoelectric materials. Piezoelectric energy harvesting represents a relatively straightforward method of converting mechanical energy into electrical power, particularly from vibrational sources (Chen and Li, 2024). The utilization of piezoelectric energy harvesters for energy harvesting from fluid flows via vortex-induced vibrations has become a focal point of research in this domain.

Piezoelectric energy harvesters have been extensively developed to enable small-scale energy conversion, particularly by transforming ambient vibrational and fluid energy into usable electrical energy (Zou et al., 2017). Among these, fluid energy has increasingly gained attention as a viable and renewable source for energy harvesting applications (Akaydin et al., 2012).

Traditionally, large-scale fluid energy conversion has been achieved through the deployment of wind turbines in wind energy systems and tidal or wave energy converters, such as tidal surging devices, in marine environments. However, the high initial capital costs and ongoing maintenance requirements of these conventional systems often pose significant barriers to their implementation in small-scale or distributed energy applications (Kim et al., 2022). In wind energy systems, harvesters are commonly deployed in arrays arranged in field-like patterns to capture energy efficiently from the fluid flow. In wave energy applications, surging converters are used to harness the mechanical energy of moving water. Despite their effectiveness at large scales, both types of systems involve substantial infrastructure and operational costs, making them less practical for low-power or distributed energy needs (Alnasir and Kazerani, 2016). Piezoelectric materials provide an alternative approach by converting fluid-induced vibrations into electrical energy using compact, lightweight, and scalable devices. These systems offer lower initial costs and minimal maintenance requirements, making them well-suited for small-scale energy harvesting, particularly in environments where traditional fluid energy systems are economically unfeasible. A comprehensive analysis of vibration-based piezoelectric energy harvesting systems has been conducted, wherein the characteristics of various widely used piezoelectric materials are systematically summarized and compared. Additionally, the role of compliant mechanisms in enhancing the performance of these systems has been explored in detail (Liang et al., 2021).

Frequent battery replacements in battery-operated systems can lead to various issues, including system malfunctions. Piezoelectric energy harvesting systems mitigate these disruptions by utilizing an energy conversion mechanism, such as a DC-DC buck converter, and storing the harvested energy. This system eliminates the need for continuous battery replacements, thereby enhancing the system's operational lifespan. Extensive research has been conducted on piezoelectric energy harvesting systems, demonstrating that the electrical energy generated through these systems is highly efficient (Stamatellou and Kalfas, 2018; Talaat et al.,2019).

Vortex-induced vibrations (VIV) are widely recognized for causing significant damage to structures in fields such as aerospace, civil, mechanical, marine, offshore, and nuclear engineering. However, with recent advancements in scientific research, it has become possible to harness this phenomenon, traditionally associated with destructive effects, as a viable source of usable energy. The literature presents many different applications involving energy production by bluff bodies with VIV. In some studies, bluff bodies are used as a tip mass to initiate galloping, thus improving energy harvesting efficiency. Additionally, they serve to synchronize the vortex shedding frequency with the natural frequency of the energy harvester and promote resonance in the transverse direction (Wang et al., 2020; Li et al., 2023). The use of fluttering phenomena is another method for energy harvesting through flow-induced vibration (Zakaria et al., 2015). However, it must be considered that it is quite difficult both to harvest a significant amount of energy (Dai et al., 2014) and to prevent damage to a galloping or fluttering energy collector due to the very large vibration amplitude if the flow rate is not well controlled (Zhang et al., 2021).

By strategically placing piezoelectric devices in the wake regions of bluff bodies, which are typically prone to vortex-induced oscillations, researchers have been able to harness the mechanical energy produced by these vibrations (Naqvi et al., 2022; Hu et al., 2018; Hamlehdar et al., 2019). In particular, the wake of a bluff body, characterized by alternating vortices, provides an ideal environment for the conversion of flow energy into mechanical motion. In the literature, the flow dynamics around bluff bodies and the associated vortex shedding process have been extensively studied. The semi-circular cylinder is one of the most extensively studied and widely recognized bluff bodies in the literature, frequently used to investigate vortex shedding phenomena and wake flow topology due to its distinct flow separation characteristics compared to circular cylinders (Matheswaran and Miller, 2024). One of the critical factors influencing wake formation is the geometric configuration of the bluff body. Upon examining the wake regions behind bodies of different geometries, it is evident that various shapes significantly impact aerodynamic parameters such as vortex shedding frequency, vortex strength, wake length, and wake width. These effects are not solely dependent on the geometry but are also significantly influenced by the Reynolds number. Chen and Li investigated the response and energy harvesting performance of a semi-circular cylinder under both low- and high-Reynolds number conditions (Chen and Li, 2024). Matsumoto provides a comprehensive analysis of the various vortex generation mechanisms and the corresponding response characteristics of bluff bodies (Matsumoto, 1999). Mehmood et al. conducted a numerical investigation into the concept of energy harvesting from a circular cylinder subjected to VIV (Mehmood et al., 2013). An extensive review thoroughly examined the wake region formed behind bluff bodies, detailing the wake characteristics for different bluff body geometries across various Reynolds numbers (Derakhshandeh and Alam, 2019). It has been observed that the flow regime around a circular cylinder is highly dependent on the Reynolds number (Achenbach and Heinecke, 1981). Additionally, Zhang et al. investigated the influence of Reynolds number on piezoelectric energy harvesting from VIV of a circular cylinder (Zhang et al., 2021). The wake characteristics of different cross-sections of bluff bodies are also examined (Zhang et al., 2017). Moreover, the impact of oscillation frequency on the dynamics and energy harvesting performance of piezoelectric flags has been analysed (Mazharmanesh et al., 2022). It is well established that any alteration in the flow profile will affect the vibration formation of piezoelectric transducers and consequently the electrical output. Therefore, it is essential to study the effects of variations in the incoming flow conditions and bluff body size on the energy harvesting performance of piezoelectric materials. As seen in the literature review, wake regions behind bluff bodies with different geometries have been examined in a similar manner (Zhang et al., 2021; Weinstein et al., 2012; Mehdipour et al., 2022). Within the scope of this study, a semi-circular cylinder was chosen as the bluff body. While the examination of vortex structures in the wake region formed behind the semi-circular cylinder is carried out, a practical energy production solution is also presented using these structures. Therefore, the semi-circular cylinder was selected as the bluff body for this study.

In the current study, the potential for energy generation through the integration of piezoelectric materials within the vortex region formed behind a bluff body is explored. The literature indicates that efficient energy harvesting based on VIV generally requires the application of active control mechanisms. However, this study aims to develop a mobile model that does not rely on active control. This model was specifically designed as a passive system that functions by leveraging the detailed characterization of the flow topology in the wake region of the bluff body, thereby eliminating the need for active control strategies. While it is well understood that higher energy output could be achieved through active control, the objective here was to design a robust system capable of adapting to various fluid environments and generating low-power communication signals with improved reliability. To achieve this, the flow topology behind a semi-circular cylinder was thoroughly analysed. Based on this analysis, a module was developed in which a semi-circular cylinder bluff body was embedded inside a square cylinder. All necessary investigations were conducted within this configuration to understand the fluid-structure interaction and assess its energy harvesting potential. Following the flow topology analysis, a commonly used piezoelectric film transducer was selected. The transducer was placed at positions determined to be optimal according to the observed flow characteristics. Its energy harvesting performance was then evaluated by analysing the electrical output under different spatial placements and angular orientations.

This study aims to investigate the feasibility of energy generation by utilizing piezoelectric materials to harvest energy from vortex shedding in the wake region behind a bluff body. The main objectives of this study are:

- To elucidate the determination of vortex fields that will form behind bluff bodies with different geometric parameters by conducting a surface oil flow visualization experiment.
- To develop a practical and portable energy harvesting solution for off-grid locations, thereby contributing to the advancement of sustainable energy technologies in areas lacking reliable access to electrical grids.

In this paper, the flow topology behind a bluff body is investigated. Afterwards, piezoelectric material is placed into the wake region behind the bluff body, and energy production utilizing VIV is performed. In Section 2, the experimental setup used in the study is described. In Section 3, the details of the flow topology and experimental results are presented. In Section 4, the experimental results are discussed. Finally, in Section 5, the work performed and presented in this paper is concluded.

EXPERIMENTAL SETUP

In this study, the flow visualization and energy harvesting experiments were conducted in an open-suction type low-speed wind tunnel with a test cross-section size of 400 mm × 400 mm × 1000 mm, as shown in Figure 1. The turbulence intensity of the wind tunnel was less than 1% for the test velocity. The test velocity was controlled using a frequency inverter, and the free-stream velocity in the test section was measured with a pitot-static tube positioned perpendicular to the flow.

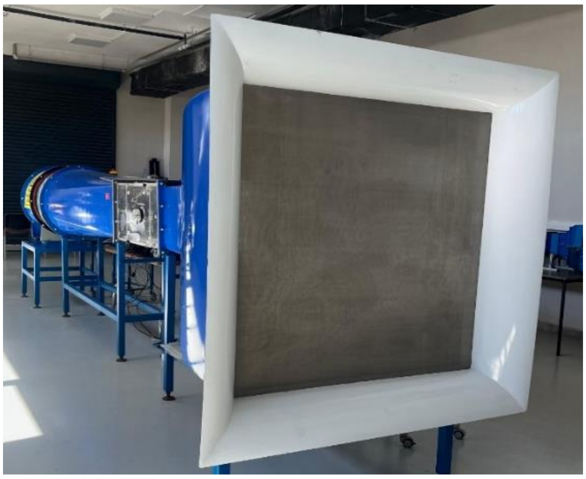


Figure 1. The open suction type wind tunnel.

The semi-circular cylinder test models were fabricated from SLA resin using a bottom-up printing technique with the help of an "ANYCUBIC Mono X6 KS" 3D printer and an "ANYCUBIC Wash & Cure 3 Plus" machine, as shown in Figure 2. The main purpose of using this manufacturing method was to ensure that the model surfaces were produced with higher smoothness and precision.

Figure 2. Anycubic Wash&Cure and SLA Printer

The semi-circular cylinder test models were designed with diameters of 2, 3, and 4 cm and L/D ratio variations of 0.5, 1, 2, and 3. Mair and Stansby stated that the L/D ratio is an important parameter influencing the vortex shedding phenomenon (Mair and Stansby, 1975). Furthermore, Griffin explicitly demonstrated that the L/D ratio significantly affects vortex cell patterns and vortex shedding behaviour (Griffin, 1985). Considering these findings, different L/D ratios were selected in the present study to examine the formation and intensity of vortices in the context of electricity generation via piezoelectric methods. Additionally, Kumar et al. established that the vortex shedding frequency of a semi-circular cylinder increases with rising Reynolds numbers (Re) (Kumar et al., 2016). In this study, the experiments were performed at a free-stream velocity of 20 m/s. These findings highlight that, alongside the length (L) to diameter (D) ratio (L/D), Reynolds number is also a crucial parameter in electricity generation using piezoelectric materials. The corresponding Reynolds numbers for the investigated bluff body configurations range from 1.3×10^4 to 2.6×10^4, which lies within the 10^3–10^5 regime. In this regime, the drag coefficient of bluff bodies remains relatively insensitive to Reynolds number, and the wake flow exhibits fully turbulent characteristics (Çengel and Cimbala, 2010). Consequently, variations in vortex shedding frequency and intensity are primarily governed by bluff body geometry. The research parameters related to the piezoelectric material's electricity generation performance are summarized in Table 1.

Table 1. The research parameters about semi-circular cylinder test models

Parameters	***Value***	***Unit***
Diameter	2,3,4	cm
L/D Ratio	0.5, 1, 2, 3	-
Distances	1, 3.5	D
Re	Between 13×10^3 and 26×10^3	-

The schematic representation of the wind tunnel test section is shown in Figure 3. The test models were placed at a minimum distance of 5D downstream from the front end of the plate to ensure a fully developed velocity profile on the two-dimensional plate, as described in (Shahmohamadi and Rashidi, 2017). The bottom plate was chamfered with an angle of 30° at the front end. The wall effect on the test models was assumed to be eliminated. The chamfered bottom plate was designed sufficiently large to facilitate clear observation of surface flow topologies (Ramamurthy and Lee, 1973).

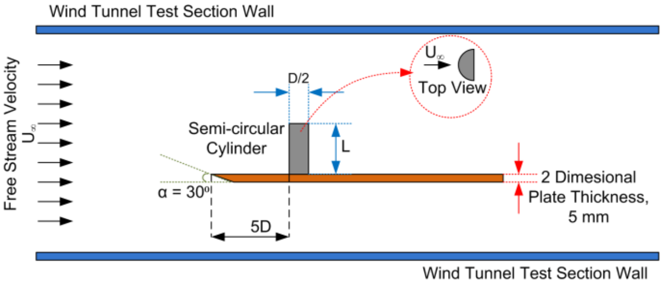


Figure 3. Schematic representation of the wind tunnel test section

Surface oil flow visualization experiments were performed using a mixture of titanium dioxide (TiO_2) powder, oleic acid, and SAE 20 engine oil in a 1:5:7 ratio, following previously reported studies (Kurt and Akbıyık, 2026; Kaya and Akbıyık, 2025). The components were blended in a beaker for 15 minutes using a standard mixing procedure to ensure homogeneity. The prepared mixture was then applied to both the model and flat plate surfaces with a brush. The flow structures were allowed to develop under exposure to the free-stream flow for 20 minutes, after which the resulting patterns were recorded instantaneously for analysis. This procedure enabled the visualization of wake vortices and surface flow features around the bluff body configurations studied in the present work.

The second phase of the experimental study involved energy generation using piezoelectric materials. In the experiments, TE Connectivity DT series piezoelectric films with lead attachments were used. The main reason for choosing this type of piezoelectric material was that films can stretch more than disks. The properties of the piezoelectric material are listed in Table 2.

Table 2. Parameters of piezoelectric material

Parameter	***Value***	***Units***
Dimensions	41 x 16 x 40	(mm) x (mm) x (μm)
Operation Temperature	0 to 70	°C
Storage Temperature	-40 to 70	°C
Output Voltage:	0.01 to 100 (depending on Force and Circuit Impedance)	V

The piezoelectric film energy harvesters were placed in a prototype model referred to as the energy generating case. The mounting points of the piezoelectric energy harvesters in the generator case were determined based on flow visualization results presented in Table 3 at following section. To maximize efficiency from vortices detaching from the model surface, the mounting positions of the piezoelectric material were selected along the free-stream direction at both 1D and 3.5D distances considering vortex cores. A design was implemented to place the piezoelectric films in the test area of the tunnel to harvest energy at the test site and to ensure portability, which is one of the main objectives of this study. This study not only focuses on the electrical power generation capability of a piezoelectric harvester placed in the wake of a bluff body but also aims to test the system in a more mobile and modular configuration. The objective is to evaluate how such a mobile system behaves under various flow conditions and to determine its potential for energy production in diverse environments. Although environmental conditions significantly influence fluid flow behaviour, it is well established in fluid mechanics that these effects can be nondimensionalized using the Reynolds number. This dimensionless parameter enables flow characteristics to be generalized across different scales and working fluids. By utilizing this principle, the developed system is expected to provide robust and scalable results even when tested in different media, such as air or water, or in different experimental setups like wind tunnels or water channels (McTavish et al., 2013). This allows for reliable prediction of system performance independent of the specific fluid environment, provided the Reynolds number is preserved. Since the D term varies for each model, the adapters where the piezoelectric films are mounted were produced separately for each case. The 1D and 3.5D positions for the piezoelectric films were determined individually. The front and side views of the test section are presented in Figure 4. The inner section of the model where the semi-circular cylinder and piezoelectric films were placed measures 10 cm × 10 cm.

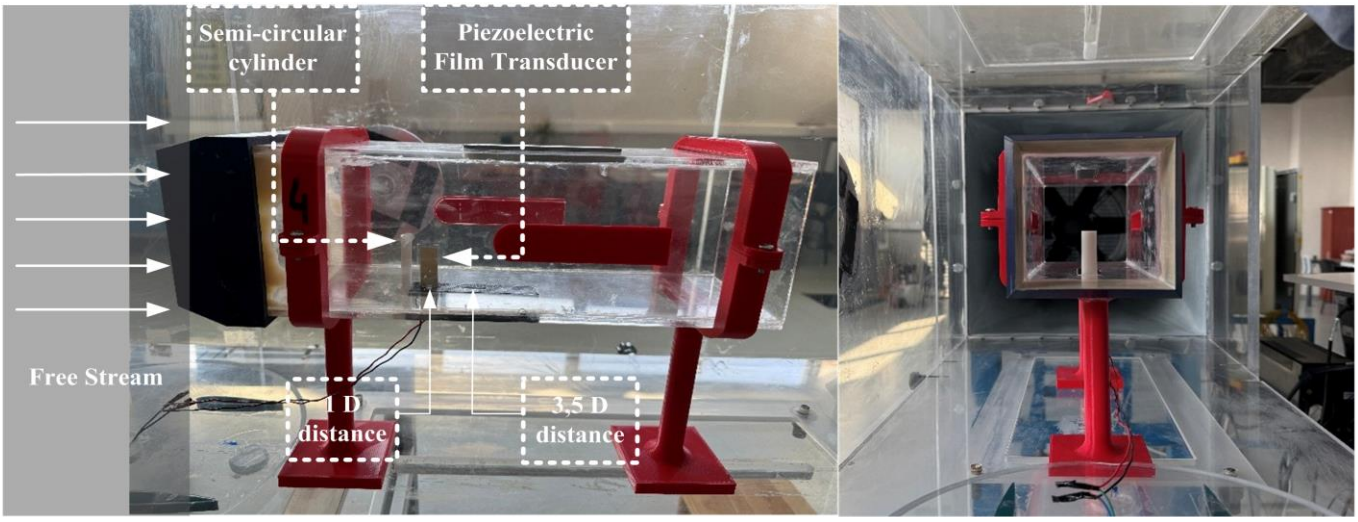


Figure 4. Front and side views of the test section

Additionally, the adapters were designed in various configurations to allow vertical and horizontal placement of the piezoelectric films at 1D distance and 3.5D distances. The schematic representation of the mounting orientation is given in Figure 5.

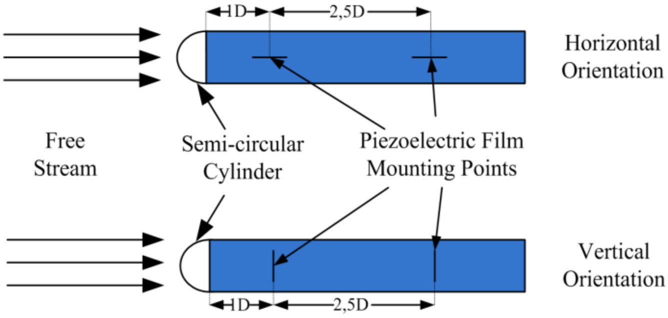


Figure 5. Top view of mounting orientation of the piezoelectric film transducer (schematic)

The energy produced by the piezoelectric film varies depending on experimental conditions. To determine this, the Energy harvester breakout module LTC3588-1 was used. This module, which commonly used for low-scale power harvesting operations, includes a full- wave bridge rectifier and a high-efficiency buck converter to provide an effective energy harvesting solution. The schematic representation of the voltage rectifier circuit and related electrical connections is shown in Figure 6. At the inlet side of the board, a 1 µF capacitor was connected, while at the outlet, a 47 µF capacitor and a parallel resistor were connected. The capacitor value was chosen to allow stable charging behaviour without saturation within the experimental time scales. This low-loss full-wave bridge rectifying board also stores charge in the input capacitor until a lockout voltage is reached. After reaching the lockout voltage, it transfers the stored charge to the output capacitor.

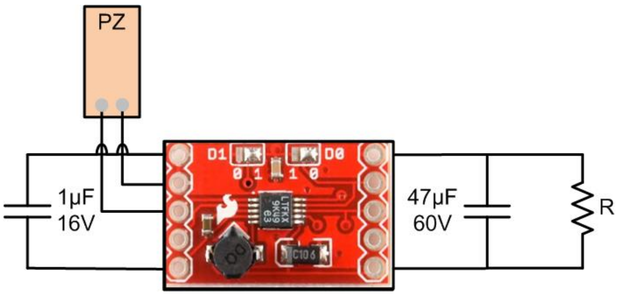


Figure 6. Voltage rectifier circuit and related electrical connections.

In the experiments, voltage and current measurements were taken using the GW Instek DAQ-9600 Data Acquisition System combined with the DAQ-901 20+2 Channels Universal Multiplexer. The complete experimental setup, including the open suction type wind tunnel, test section with piezoelectric materials, the newly designed module, data acquisition components, and the computer, is presented in Figure 7.

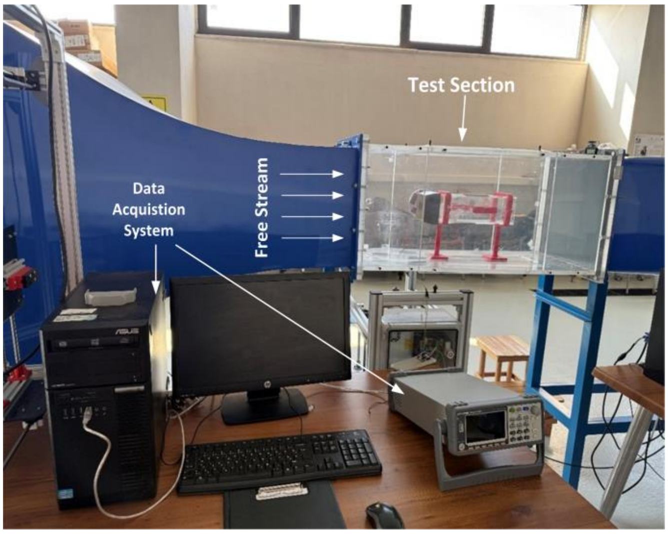


Figure 7. The experimental setup with all components

EXPERIMENTAL SETUP

Flow Visualization Experiment Results

The results of this study are presented in multiple sections. The first section provides a detailed examination of the flow topology behind a semi-circular cylinder. Wake structures at various model scales are comprehensively analysed and illustrated. It is well documented in the literature that the wake region behind bluff bodies is highly dependent on the Reynolds number, which governs the transition between laminar and turbulent regimes, as well as the formation and interaction of vortices (Norberg, 1994; Williamson,1996). In this study, the investigation of the flow topology around the selected bluff body, the presence and positions of the primary and secondary vortex regions were clearly identified in relation to the wake geometry. These vortex regions align with known vortex shedding patterns observed in similar bluff body configurations. Based on this characterization, a specific free-stream velocity was selected for further analysis. This velocity corresponds to a Reynolds number representative of natural outdoor environments, such as mountainous terrain, and is compatible with laboratory-scale water or wind tunnel conditions. By matching Reynolds numbers across different media, the results obtained under experimental conditions can confidently be extended to real-world applications. Consequently, the selected flow speed was investigated in greater detail to ensure that the energy harvesting behaviour observed in controlled environments remains valid and robust in practical scenarios.

Figure 8 presents the ground plate and experimental model, both coated with TiO_2, alongside the flow structures around the model. At the leading edge, boundary layer separation is observed as the flow interacts with the model surface, leading to the distinct formation of a horseshoe vortex structure. A stagnation line forms along the model length due to flow contact with the surface. Examination of the flow around the semi-circular cylinder reveals boundary layer separation occurring after approximately 80 degrees, consistent with prior literature (Akbıyık and Akansu, 2021). The Kármán vortex street is distinctly visualized using TiO_2, with clearly formed vortex cores at the rear of the model. Free flow separates from the model surface and reattaches to the upper surface, creating a reattachment region. Following this zone, the flow again detaches from the upper surface. This detailed presentation of flow topologies directly informs the optimal positioning of piezoelectric materials in this study, thereby influencing their energy generation potential. Flow visualization results for different L/D ratios and diameters are summarized in Table 3. As shown in Table 3, for D = 2, 3, and 4 at the smallest L/D ratio, distinct vortex pair structures are clearly observed to form immediately downstream of the bluff body, primarily near the trailing-edge region. When L/D = 1 for all investigated models, the centers of these vortex pairs are observed to shift downstream in the direction of the free-stream velocity, with noticeable separation between the individual vortex cores. In addition, vortices originating from the free-end (top section) of the bluff body play a dominant role in the wake structure when L/D = 0.5, suppressing the lateral vortices shed from the side surfaces and pushing them toward the trailing edge. As L/D increases to 1, the free-end vortices are observed to form further downstream, reducing their backward influence on the vortices shed from the side surfaces. For L/D = 2, the influence of free-end vortices diminishes further, and the vortex pairs shed from the side surfaces begin to merge along the centreline of the wake. At L/D = 3, these merged vortex structures extend downstream in the direction of the free-stream velocity. Considering both the vortex pairs and the vortices shed from the free end, the resulting changes in wake topology are found to play an important role in the energy harvesting performance of the piezoelectric transducer.

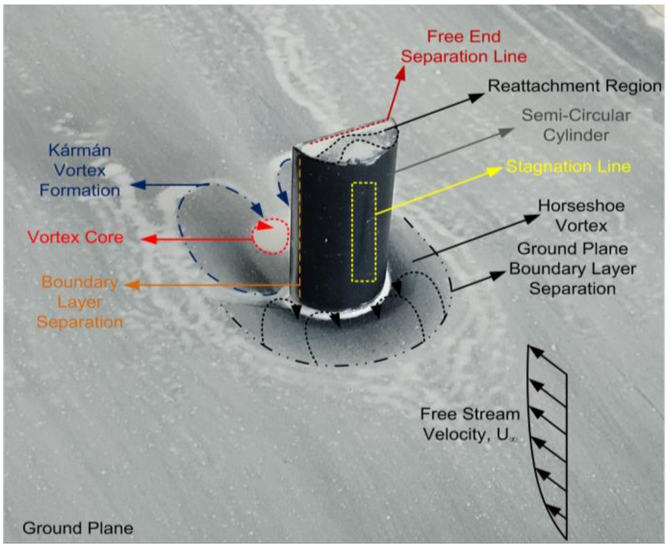
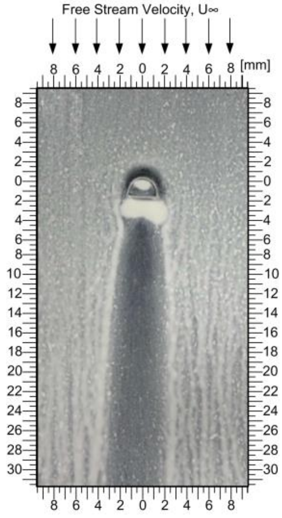
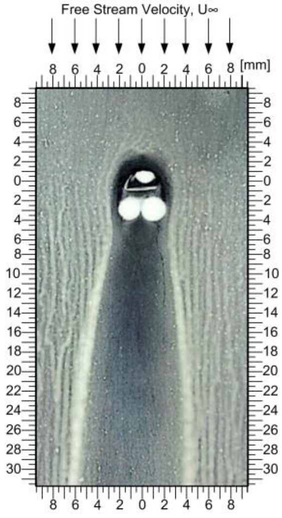
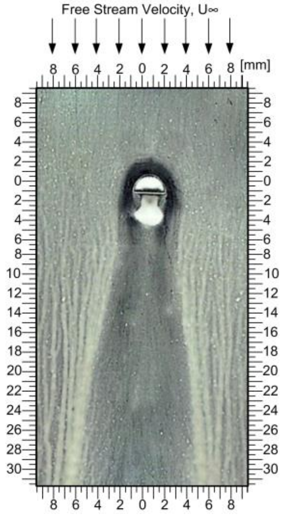
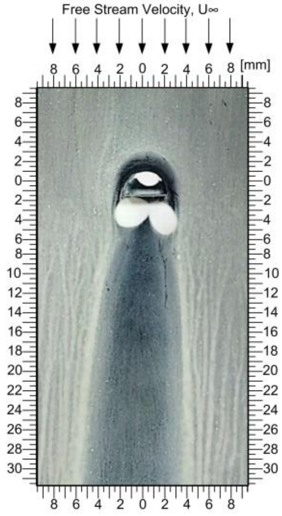
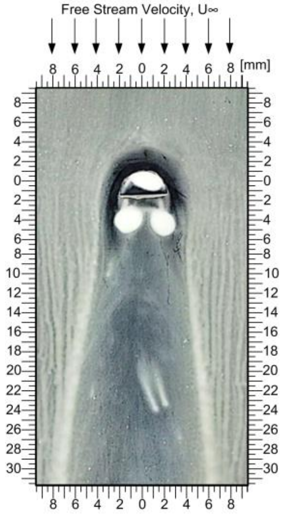
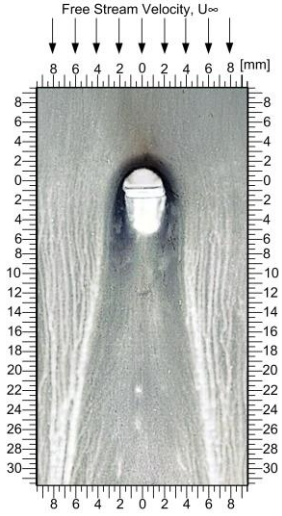


Figure 8. Detailed representation of the flow topology on the experimental model

The top-view flow visualization results, conducted according to the experimental matrix, are presented in Table 3. As clearly observed from the flow visualization results, the turbulent wake region downstream of the bluff body is not solely generated by lateral vortex shedding but also includes vortical structures originating from the free-end of the bluff body. Consequently, the wake region extends beyond the immediate lateral shedding zone and occupies a relatively broad downstream area. The flow topology described in Figure 8 is summarized for each experimental model. Analysis indicates that vortex cores typically form at approximately 1D and 3.5D distances behind the model. Accordingly, the piezoelectric materials were positioned at these distances, aligned with the central axis of the experimental setup.

Table 3. Flow visualization results at different diameter and L/D ratios

	L/D=0.5	***L/D=1***	***L/D=2***	***L/D=3***
D=2				
D=3				
D=4				

Energy Production Experiment Results

Subsequently, the power generation capability of the piezoelectric-film transducers was evaluated. Energy generation tests were conducted for each configuration, with data recorded via a data logger and processed on a PC. Figures 9 through 12 illustrate the charge stored in the inlet capacitor over 60 seconds for varying placement distances and horizontal-vertical configurations across different L/D ratios.

Figure 9 presents voltage outputs for horizontally placed piezoelectric films at a distance of D behind semi-circular cylinders of various diameters. Results indicate that the piezoelectric-film transducers generate more energy from the vortex behind the L/D=2 model in this configuration. Notably, the 3cm diameter models, horizontally oriented at D distance with L/D=2 exhibits a sawtooth voltage profile, reaching a threshold value that triggers charging of the output capacitor. The observed zigzag voltage pattern arises from this charging behavior in the input capacitor. For other models, the system was unable to sufficiently charge the input capacitor to reach this threshold. This discrepancy likely stems from variations in flow separation effectiveness behind the bluff body and at its top end. Moreover, vortices shedding behind the bluff body are influenced not only by free-stream velocity but also by the diameter of the bluff body. The data suggests that both diameter and length affect vortex shedding effectiveness for energy generation, while the transducer orientation (vertical or horizontal) also plays a significant role. Generally, increasing model size correlates with higher energy output due to more pronounced vortex formation.

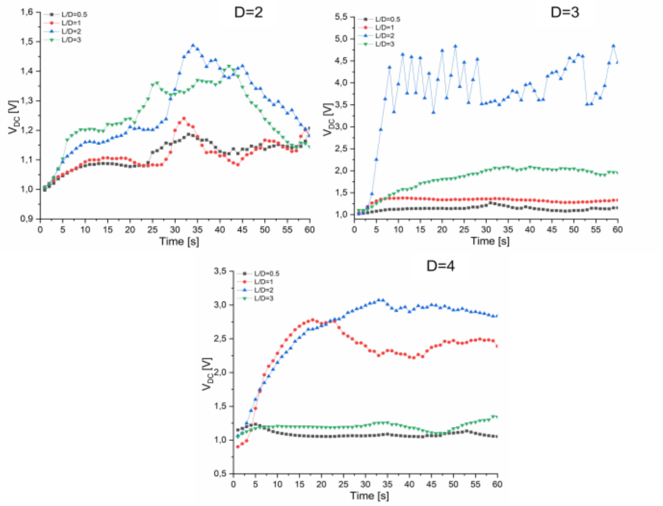


Figure 9. Voltage outputs of horizontally placed piezoelectric film at a distance of D behind various diameters of semi-circular cylinder

Figure 10 illustrates voltage outputs for horizontally placed piezoelectric films at a distance of 3.5D behind various cylinder diameters. As model size increases, energy production within this configuration likewise improves. Although transducers in this setup do not generate sufficient energy to surpass the input capacitor's threshold and transfer charge to the output capacitor, increasing the distance behind the model enhances vortex effectiveness on the transducers compared to the D distance. This phenomenon is attributable to flow reattachment and subsequent separation occurring downstream of the upper model surface, as depicted in Figure 8, facilitating more efficient energy harvesting.

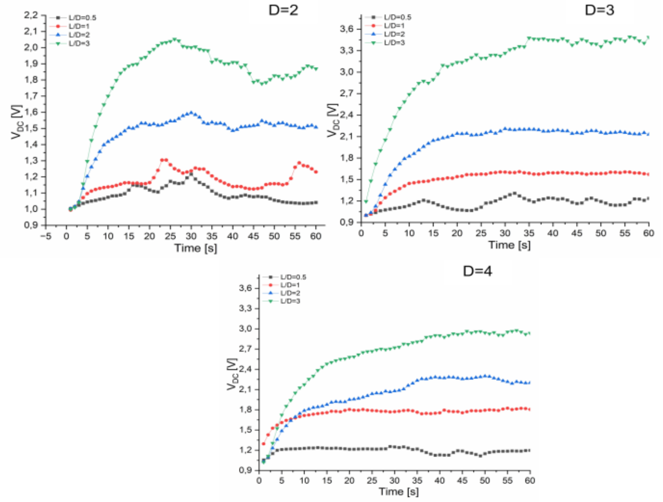


Figure 10. Voltage outputs of horizontally placed piezoelectric film at a distance of 3,5D behind various diameters of semi-circular cylinder

Figure 11 shows energy harvesting results for vertically placed piezoelectric films located at distance D behind the models. As observed in other configurations, vortex shedding activity correlates with bluff body diameter. Additionally, for the 4cm diameter model, vertically oriented at D distance, the influence of model height on energy production is pronounced, especially when comparing the shortest and longest models. The separated flow at the bluff body's upper end aligns with the energy generation behavior of vertically oriented piezoelectric films placed 1D downstream. This is because flow over the bluff body's upper surface contributes directly to the mechanical excitation of the transducer, enhancing energy generation in both short and long models.

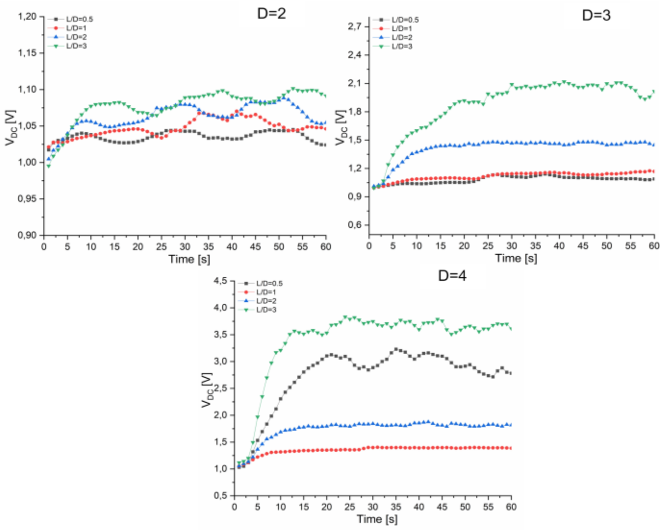


Figure 11. Voltage outputs of vertically placed piezoelectric film at a distance of D behind various diameters of semi-circular cylinder

Figure 12 presents results for vertically placed piezoelectric films at 3.5D behind the models. Increasing model diameter improves energy harvesting performance, with the 4 cm diameter model, vertically oriented at 3.5D distance successfully charging the output capacitor. At the piezoelectric film's location, vortex size grows toward the rear, and flow separation at the bluff body's upper end exerts an influential effect. The selected transducer placement efficiently harnesses vortex strength as indicated in Table 3. Remarkably, this energy generation occurs without any relative motion between the piezoelectric film and the bluff body, highlighting the significance of frequency matching between vortex shedding and piezoelectric film dynamics, which amplifies energy output.

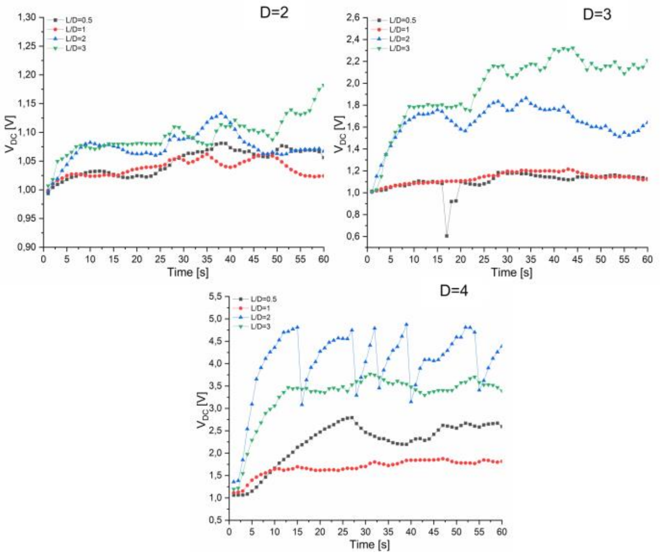


Figure 12. Voltage outputs of vertically placed piezoelectric film at a distance of 3.5D behind various diameters of semi-circular cylinder

Figure 13 presents the voltage levels measured at the output capacitor for the evaluated model configurations, with data collected continuously over a 600-second interval. Among the tested setups, two configurations successfully reached the voltage threshold required to charge the output capacitor. Notably, the model which has diameter of 4 cm and L/D=2, vertically mounted at 3.5D exhibited superior performance, producing an average voltage approximately 15% higher than the other test model which has diameter of 3cm and L/D=2, horizontally mounted at D distance. The measured values are 2.84 V and 2.41 V, respectively.

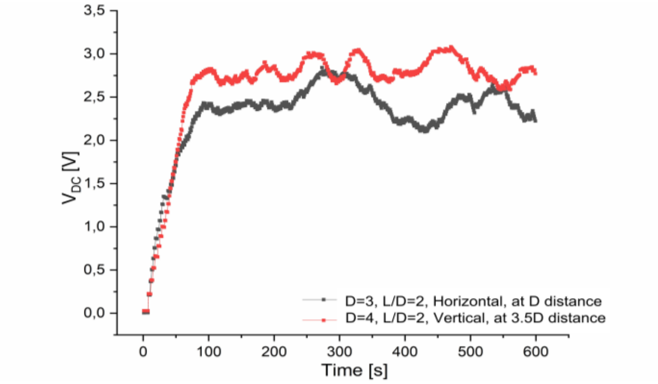


Figure 13. The voltage levels of output capacitor in the setup with the best performance among all modifications at the given orientation

The results clearly indicate that while all investigated parameters, including bluff body diameter, L/D ratio, and transducer orientation, have an influence on the energy harvesting performance, the most critical factor is the compatibility between the wake dynamics and the piezoelectric transducer. Configurations in which the wake-induced excitations are well matched with the mechanical response of the transducer yield the highest energy output, highlighting the importance of optimizing the interaction between the flow structures and the transducer placement and orientation. These results clearly demonstrate that the vortices formed in the wake of the bluff bodies significantly influence the energy harvesting capability across all tested configurations. Furthermore, the findings reveal that the efficiency of energy generation is intrinsically tied to the excitation of harmonic motion within the piezoelectric film transducers. This highlights the critical relationship between the fluid dynamic behaviour and the mechanical response of the transducers, underscoring the importance of careful design considerations in maximizing piezoelectric energy harvesting performance.

CONCLUSION

In this study, the potential for electrical energy generation through piezoelectric-film transducers has been investigated by examining the effects of vortex structures formed in the wake of semi-circular cylindrical bluff bodies. The study was conducted in two main stages. First, the flow topology behind 12 different bluff body configurations was visualized using TiO_2 flow visualization techniques in a low-speed wind tunnel at a free-stream velocity of 20 m/s. In the second phase, energy generation was evaluated across 48 distinct model configurations, and the voltage output over time was recorded and analysed.

The experimental results reveal that successful energy harvesting is strongly dependent not only on bluff body geometry, but also on the spatial configuration and orientation of the piezoelectric-film transducers. Among all configurations, two specific setups succeeded in generating sufficient energy to charge the output capacitor. For these cases, output voltage levels were monitored over a 600-second duration, and the results demonstrated a clear relationship between energy output and both the vortex dynamics and the mechanical response of the piezoelectric film.

The key findings of the study can be summarized as follows:

- The size of the bluff body directly affects the strength and structure of the vortex street, which in turn significantly influences the energy generation potential of the system.
- In addition to the classical Kármán vortex street, the flow reattachment and separation from the upper side of the bluff body was found to contribute notably to vortex-induced excitation of the transducers.
- The performance of the piezoelectric-film transducers is highly dependent on the harmonic motion induced by the incoming flow, which emphasizes the critical role of flow-transducer interaction.
- Even at identical L/D ratios, transducers placed behind larger diameter bluff bodies (D=4 cm and D=3 cm) yielded significantly different average voltage levels (2.84 V and 2.41 V, respectively), highlighting the influence of both bluff body size and transducer placement (D/3.5D) and orientation (horizontal/vertical) on energy harvesting efficiency.

This work contributes to the growing body of literature focused on low-power energy harvesting from unsteady flows and offers a practical design methodology for maximizing energy output through careful geometrical and aerodynamic tuning. While previous studies have emphasized the role of Reynolds number and bluff body geometry in vortex shedding (Achenbach and Heinecke, 1981; Zhang et al., 2017), this study advances that understanding by demonstrating how specific flow features can be coupled with transducer positioning to enhance energy capture.

Overall, the presented system offers a promising solution for powering low-energy devices in off-grid or remote environments where conventional power sources are unavailable. The mobility, modularity, and simplicity of the design make it a strong candidate for applications in defence, environmental monitoring, and autonomous sensing systems. The findings underline that effective energy harvesting from naturally occurring fluid flows is not only feasible, but also scalable, as long as the governing aerodynamic principles are maintained. Also, future studies will focus on incorporating statistical design of experiments and optimization-based frameworks to quantitatively assess the influence of governing parameters on energy harvesting performance.

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