Rainwater- and air-driven 40mm bladeless electromagnetic energy harvester

Dan Zhao and Joe Khoo

Citation: [Appl. Phys. Lett.](#) **103**, 033904 (2013); doi: 10.1063/1.4813907

View online: <http://dx.doi.org/10.1063/1.4813907>

View Table of Contents: <http://apl.aip.org/resource/1/APPLAB/v103/i3>

Published by the [AIP Publishing LLC](#).

Additional information on Appl. Phys. Lett.

Journal Homepage: <http://apl.aip.org/>

Journal Information: http://apl.aip.org/about/about_the_journal

Top downloads: http://apl.aip.org/features/most_downloaded

Information for Authors: <http://apl.aip.org/authors>

ADVERTISEMENT

Rainwater- and air-driven 40 mm bladeless electromagnetic energy harvester

Dan Zhao^{a)} and Joe Khoo

Aerospace Engineering Division, College of Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore

(Received 17 May 2013; accepted 27 June 2013; published online 18 July 2013)

A 40 mm electromagnetic energy harvester driven by both rainwater and air is designed and experimentally tested. Its performance is first assessed by measuring the system response for 4 different levels of air flow excitations. It shows that about 0.5 W power is generated. Parametric analysis is then conducted in terms of the disc number, exhaust flow rates, and the inter-disc distance. Finally, it is used to harness energy from rainwater. It is found the harvester works much better than the air-driven one. And its energy conversion efficiency is reduced with increased disc diameter. The maximum electric current is 4.5 mA. © 2013 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4813907>]

With the development and wide application of small electronic devices, there is a need for the development of energy harvesters so that ambient energy can be converted into electrical energy to recharge batteries and to enable remote operation. Various devices and techniques have been developed to achieve this task. Typically, these techniques take advantage of magnetoelectric,¹ piezoelectric,²⁻⁴ thermoacoustic,⁵⁻⁹ thermoelectric,¹⁰ or optoelectric working principles. One of the interesting ideas is to harness the energy of rainfall and air flow. Small or microenergy harvesting systems driven by water or air¹¹⁻¹³ are becoming more and more popular due to the high power to weight ratio and reduced visual and ecological impacts in comparison with the large systems.

Conventional energy harvesters driven by air flow involve using large-diameter swept blades (>1 m).^{14,15} However, such bladed harvester cannot be used for water. However, bladeless energy harvesters can be used for both air and water. They are reliable as those bladed ones,¹⁶ especially in small size. As the working fluid is injected nearly tangentially to the bladeless systems with rotating discs, the injected fluid passes through the narrow gaps between the discs and approaches spirally towards the exhaust orifices located at the centre of each disc.¹⁷ The aero- or hydrodynamic viscous drag force generated due to the relative velocity between the disc and the flowing fluid causes the disc to rotate. The rotating discs are enclosed in a casing with a small radial and axial clearance. The bladeless system has many advantages: easy to manufacture and maintain, simple to design, low cost, and significantly reduced noise impact on environments. Furthermore, it can produce power from a variety of working media, like water or air. All these features indicate that the bladeless system can be used for the development of miniature energy harvesting system driven by rainfall and air flow. However, very few designs and applications can be found in literature.

In this work, a 40 mm bladeless electromagnetic¹⁸ energy harvester is designed and experimentally tested to explore a multi-function platform/system for energy harvesting from both rainfall and air flow. The energy harvesting

system involves using a number of co-rotating compact discs (CDs) as shown in Fig. 1(a). They are evenly spaced in the axial direction and attached to a central shaft, of which a magnet is attached, as shown in Fig. 1(b). The inter-disc distance can be varied from 0.3 mm to 5 mm.

The physics of the fluid flow through the discs helps to understand the bladeless system working principles: the viscous drag force between a compact disc and working fluid (water/air) acts in the direction of the relative velocity of the fluid. Assuming the fluid is injected at a velocity U through a stationary disc as shown in Fig. 2(a), the relative velocity of the disc is $-U$. The viscous drag force on the discs will act in the direction of the fluid flow, opposing the motion of the fluid. Since there is a relative velocity between the working fluid and the disc wall, a velocity gradient near the wall is present. It is responsible for the generation of shear stress,

$$\tau_w(r) = \mu \frac{\partial U_\theta(r, z)}{\partial z}, \quad (1)$$

and it gives rise to a torque on the disc wall Π , which can be calculated by integrating the elemental torque as

$$\Pi = \int_0^{2\pi} d\theta \int_{R_i}^{R_o} \tau_w(r) r^2 dr. \quad (2)$$

If the torque Π is greater than the frictional torque, the discs will start rotating. As the disc speed increases, the relative velocity of the fluid with respect to the disc decreases, until a steady state is reached when the disc rotates at a constant speed at which the frictional torque is balanced by the torque Π produced. This is what happens in the bladeless system driven by fluid flow. Fig. 2(b) illustrates the pressure contour of the disc wall estimated by solving the well-known Navier-Stokes equations⁸ in the cylindrical co-ordinates. It can be seen that as the fluid moves towards the center of the disc, its radial pressure decreases due to the gradual decrease of the flow area and increased radial velocity.

As the torque Π generated drives the discs to rotate, the shaft and the magnet attached at one end of the shaft will rotate too. The rotation of the magnet in a wound coil of copper gives rise to the electrical power being generated due to the magnetic flux change in the coil.¹⁸ The emf generated

^{a)}Electronic mail: zhaodan@ntu.edu.sg

FIG. 1. (a) Comparison of a 40 mm rotating disc with a 50 cent Singapore coin, (b) experimental setup of the 40 mm bladeless electromagnetic energy harvester driven by both rain-water and air.

$\mathcal{U}_N$ of N turns cooper wire loop is equal to the rate of change of the magnetic flux through the circuit surface S . Following the Maxwell-Faraday's law (Ref. 18) $-\nabla \times \mathbf{E} = \partial \mathbf{B} / \partial t$ and by using Stokes' theorem, $\mathcal{U}_N$ can be determined in integral form as

$$\begin{aligned} \mathcal{U}_N &= N \oint_{\mathcal{T}} \mathbf{E}_o \cdot d\mathbf{s} = N \iint_S (\nabla \times \mathbf{E}) \cdot \mathbf{n} dA \\ &= -N \frac{\partial}{\partial t} \iint_S \mathbf{B} \cdot \mathbf{n} dA, \end{aligned} \quad (3)$$

where $\mathcal{T}$ is a closed curve, S is the surface bounded by it, $\mathbf{E}$ is the electric field, and $\mathbf{B}$ is the magnetic field. Here we assume that emf generated from each turn of the coil is equal. The output electrical power $E_o = V_{\text{rms}}^2 / R_o = \mathcal{U}_N^2 / 2R_o$ can then estimated by

$$E_o = N^2 \frac{\left[\frac{\partial}{\partial t} \left(\iint_S \mathbf{B} \cdot \mathbf{n} dA \right) \right]_{\text{max}}^2}{2R_o}, \quad (4)$$

where R_o is copper wire resistance. It can be seen from Eqs. (3) and (4) that when N remains unchanged, the output voltage is proportional to the rate of change of the magnetic flux, i.e., $\mathcal{U}_N \propto \partial(\cdot)/\partial t$. However, the output power is proportional to the square of the rate of the magnetic flux, i.e., $E_o \propto (\partial(\cdot)/\partial t)^2$. To validate these theoretical prediction, the electrical power output from the 40 mm energy harvester is measured and shown in Fig. 3. Note that the electrical

power output E_o is measured by using Fluke digital multimeter. It can be seen that the output RMS (root mean square) voltage and power E_o are increased linearly and quadratically with increased revolutions per minute (RPM) of the discs, as measured by using AI3030 Tachometer. The maximum power output can reach to approximately 0.5 W at $\text{RPM} \approx 3300$.

A parametric analysis is then conducted to highlight the effect of the energy harvesting system parameters on its performance and to gain insight on its optimum design. The parameters involve the disc number, the distance between two neighboring discs, and the exhaust flow rate in terms of the orifice number. Fig. 4 illustrates the variation of the output electrical power with the system parameters. It can be seen from Fig. 4(a) that with the lowest flow rate, maximum power output occurs with 8 exhaust orifices. However, with the flow rate increased, the optimum orifice number is increased to 16. Similar trend is observed, when the disc number is increased as shown in Fig. 4(c). However, when the inter-disc distance is varied from 0.3 mm to 5.0 mm, the maximum power output occurs at 0.5 mm.

In order to explore the practical application of the miniature system, the bladeless harvester is experimentally tested by using rainwater collected and stored in a water tank with a volume of 20 litres. A soft PVC (Polyvinyl chloride) pipe with a diameter of 6.25 mm is used to connect the water tank

FIG. 2. (a) Schematic diagram of two neighboring discs, (b) pressure contour of air flow along the surface of a disc.

FIG. 3. Variation of output RMS voltage and power with revolutions per minute of the discs: (a) $\circ$ measured voltage—approximated voltage by using 1st order polynomial function $\bar{V}_{\text{rms}} = 2.453 \times 10^{-3}(\text{RPM}) - 0.1487$, (b) $\square$ measured power—approximated power by using 2nd order polynomial function $\bar{E}_o = 5.576 \times 10^{-8}(\text{RPM})^2 - 5.14 \times 10^{-5}(\text{RPM}) + 4.09 \times 10^{-2}$.

FIG. 4. Variation of output electrical power with system parameters (a) exhaust orifice number, (b) inter-disc distance, and (c) disc number, as air flow rate is set to 4 different values.

and a 40 mm bladeless harvester, as shown in Fig. 1. By placing the water tank at about 2 m away from the ground, a water flow is generated. The measured flow velocity is approximately 3.6 m/s, which is closed to the theoretical prediction by using Bernoulli equation¹⁹ as

$$\frac{\Delta p}{\rho_w g} + \Delta H = \frac{\Delta v^2}{2g} + \sum \epsilon_i \frac{\Delta v^2}{2g}, \quad (5)$$

where ρ_w is water density, g is the gravitational acceleration, $\Delta p \approx 0$ is the pressure difference assumed to be zero, $\Delta H = 1.96$ m is the height difference between the harvest and the water tank, Δv^2 is the kinetic energy difference between the inlet and outlet of the pipe. However, since the inlet velocity is zero (assumed stationary in the tank), Δv is the outlet velocity. $\sum \epsilon_i$ is the total head loss coefficient. And it consists of the entrance loss $\epsilon_1 = 0.8$, entrance elbow loss $\epsilon_2 = 0.3$, and friction loss ϵ_3 . The friction loss $\epsilon_3 = f(L/D)$ as indicated in Darcy-Weisbach energy loss equation depends on the pipe length L , diameter, D . Here, $f = 7.54 \times 10^{-3}$ is the friction factor determined from Moody diagram. By using these values, the estimated flow velocity is about 3.4 m/s. The corresponding Reynolds number is $Re = \rho_w \Delta v D / \mu_w = 1.9 \times 10^4$. And the inlet flow is turbulent. As the water flows in the bladeless system, electrical power is produced. Fig. 5 illustrates time evolution of the instantaneous measurement of the AC voltage, as measured by using Tektronix TDS1012B digital oscilloscope (100 MHz). It can be seen that a sinusoidal waveform of measured electromotive force (emf) is produced.

The electric power harnessed from the rainwater can be used for many purposes. For convenience, however, the energy harvester is coupled with a red light-emitting diode (LED) for demonstration, as shown in Fig. 6. The application indicates that the miniature energy harvester driven by rainwater provides a simple, low-cost but robust platform to harvest the mechanical energy of rainfall to generate electricity.

When the LED is replaced with a resistor, a closed-loop electrical circuit is built. Thus the current and output

FIG. 5. Measured emf from the 40 mm energy harvester driven by rainwater.

power of closed-loop electrical circuit are alternating ones as given as

$$I = \frac{U_c}{R_L}, \quad E_c = U_c I = \frac{U_c^2}{R_L}, \quad (6)$$

where R_L is the loading resistance of the resistor. Theoretically, when the resistor's resistance is equal to that of the copper wires, maximum power output is obtained. This is confirmed by our experimental measurement. The variation of measured output RMS voltage and power is shown in Fig. 7. It can be seen that the RMS voltage output is increased with increased resistance. However, the output power reaches the maximum value, when $R_o = 146 \Omega$, which is closed to the resistance of the copper wire. The corresponding maximum current is approximately 4.5 mA.

It is worth noting that the viscosity of the working fluid plays an important role on the performance of the harvester. In order to gain insight on the viscosity effect, the overall energy conversion efficiency η of the 40 mm rainwater-driven harvester is compared with the same-size air-driven one, while other parameters remain the same. Here η is defined as

$$\eta = \frac{E_c}{E_i} = \frac{U_c^2 / R_L}{\dot{m} v_i^2 / 2}, \quad (7)$$

FIG. 6. A red LED is powered by the 40 mm rainwater-driven energy harvester (enhanced online) [URL: <http://dx.doi.org/10.1063/1.4813907.1>].

FIG. 7. Measured electrical circuit voltage and power from the 40 mm rainwater-driven energy harvester with varying loading resistance, as $R_o = 146 \Omega$.

where E_i is the total input power (i.e. the kinetic energy), $\dot{m}$ is the mass flow rate of the water flow, and v_i is the velocity at the inlet of the harvester. Such overall efficiency (also known Brayton cycle thermal efficiency) is used to characterize a conventional miniature gas turbine.¹⁶ And it is shown that η is approximately 2%–3%. In addition, the component efficiency η' defined in terms of the power extracted divided by the maximum power available is typically used to characterize the “turbine” performance.¹⁶ It is experimentally shown that the measured maximum efficiency of a millimeter-size bladeless turbine $\eta'_{\max}$ is approximately 20%, which is lower than 22.03% of the present system performance.

Fig. 8(a) shows the variation of the overall energy conversion efficiency η with loading resistance R_L . It can be seen the harvester with 8 discs working more efficiently than that with 4 discs. Furthermore, the maximum energy efficiency occurs at $R_L \approx 146 \Omega$. Compared with the same-size air-driven one, the water-driven harvesters perform much better. This is due to the increased viscosity, i.e., $\mu_{\text{water}} \gg \mu_{\text{air}}$, as indicated in Eqs. (1) and (2). Fig. 8(b) illustrates the performances of three different diameter water-driven harvesters. It can be seen that the maximum energy conversion efficiency is decreased with increased disc diameter.

FIG. 8. (a) Variation of the overall energy conversion efficiency η with loading resistance R_L . (b) Maximum efficiency $\eta_{\max}$ varied with disc diameter.

In summary, a 40 mm bladeless energy harvester is designed and tested by applying fluid mechanics and electromagnetic theory. The system provides a simple platform on which to produce electric power via using a number of co-rotating discs. The present system can be used for both air and water flow. This is different from the conventional blade-involved²⁰ or piezoelectric-coupled systems.^{4,21} The harvester performance is first assessed by measuring the system response for 4 different levels of air flow excitations. It shows that about 0.5 W electrical power is generated. Parametric analysis of the harvester performance is conducted in terms of the disc number, exhaust flow rates, and the inter-disc distance. It is then used to harness energy from rainwater. The overall energy conversion efficiency of the rainwater-driven is found to be much higher than that of the same-size air-driven one due to the dramatically increased viscosity. Furthermore, the efficiency is shown to be decreased with increased disc diameter. To demonstrate its practical application, the electricity generated is used to power a red LED light. The maximum electric current is 4.5 mA. The present study reveals the potential of applying such miniature system for rainwater energy harvesting in countries with abundant rainfall, like Singapore.

This work was supported by the Ministry of Education, Singapore under Contract No. AcR-Tier1-R36/10-M5205012. I would like to thank Mr. C. G. Teo and Mr. T. F. Seow for their contribution in building the rig and helping on the experimental measurements.

- ¹P. Grasland-Mongrain, J. Mari, B. Gilles, J. Chapelon, and C. Lafon, *Appl. Phys. Lett.* **100**, 243502 (2012).
- ²H. Liu, S. Zhang, R. Kathiresan, and T. Kobayashi, *Appl. Phys. Lett.* **100**, 223905 (2012).
- ³C. A. K. Kwuimy, G. Litak, M. Borowiec, and C. Nataraj, *Appl. Phys. Lett.* **100**, 024103 (2012).
- ⁴D. Clair, A. Bibo, V. R. Sennakesavababu, M. F. Daqaq, and G. Li, *Appl. Phys. Lett.* **96**, 144103 (2010).
- ⁵C. Guthy, C. W. V. Neste, S. Mitra, S. Bhattacharjee, and T. Thundat, *Appl. Phys. Lett.* **100**, 203902 (2012).
- ⁶D. Zhao, *Energy Convers. Manage.* **66**, 87–97 (2013).
- ⁷J. Smoker, M. Nouh, O. Aldraihem, and A. Baz, *J. Appl. Phys.* **111**, 104901 (2012).
- ⁸D. Zhao and Y. Chew, *J. Appl. Phys.* **112**, 114507 (2012).
- ⁹D. Zhao and Z. Chow, *J. Sound Vib.* **332**, 3419–3437 (2013).
- ¹⁰R. Venkatasubramanian, E. Siivola, T. Colpitts, and B. O’Quinn, *Nature* **413**, 597 (2001).
- ¹¹D. Ozgener, *Energy Convers. Manage.* **47**, 1326–1337 (2006).
- ¹²J. D. K. Bishop and G. A. J. Amarutunga, *Energy Convers. Manage.* **49**, 1652–1661 (2008).
- ¹³L. Perkovic, P. Silva, M. Ban, N. Kranjcevic, and N. Duic, *Appl. Energy* **101**, 151–160 (2013).
- ¹⁴M. A. Sayed, H. A. Kandil, and A. Shaltot, *Energy Convers. Manage.* **64**, 541–550 (2012).
- ¹⁵J. Kumbemuss, C. Jian, J. Wang, H. X. Yang, and W. N. Fu, *Appl. Energy* **90**, 148–153 (2012).
- ¹⁶R. T. Deam, E. Lemma, B. Mace, and R. Collins, *J. Eng. Gas Turbines Power* **130**, 052301 (2008).
- ¹⁷N. Tesla, U.S. patent 1,061,206 (May 1913).
- ¹⁸R. P. Feynman, R. B. Leighton, and M. Sands, *The Feynman Lectures on Physics* (Addison Wesley Longman, Boston, 1970).
- ¹⁹B. R. Munson, D. F. Young, T. H. Okiishi, and W. W. Huebsch, *Fundamentals of Fluid Mechanics* (John Wiley, Hoboken, 2009).
- ²⁰J. A. Carta and D. Mentado, *Energy Convers. Manage.* **48**, 420–432 (2007).
- ²¹C. Boragno, R. Festa, and A. Mazzino, *Appl. Phys. Lett.* **100**, 253906 (2012).