Energy 74 (2014) 99–108

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance of small-scale bladeless electromagnetic energy harvesters driven by water or air

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ARTICLE INFO

Article history:
Received 8 September 2013
Received in revised form
20 March 2014
Accepted 2 April 2014
Available online 26 April 2014

Keywords:
Electromagnetic
Bladeless harvester
Energy harvesting
Hydropower
Rainwater

ABSTRACT

In this work, three different-diameter energy harvesters driven by turbulent air flow and rainwater are designed. Experiments are conducted first on the air-driven harvesters to gain insight on the energy conversion process. Unlike conventional blade-involved systems, the present setup involves using a number of co-rotating compact discs. They are closely spaced and attached to a central shaft, on which a magnet is attached. As the air flow excitations are set to 4 different levels, the harvester performances are measured in both open- and closed-loop electrical circuits. The results show that approximately 0.3 W electricity is produced. Parametric analysis is then conducted to highlight the effect of the system parameters, such as disc diameter, number, exhaust flow rates and inter-disc distance on its performance and to gain insight on its optimum design. Numerical simulations are then conducted to understand the flow physics. Finally, a 40 mm harvester is used to harness energy from rainwater. Compared with the same size air-driven harvester, the rainwater-driven one is working more efficiently in terms of the overall energy conversion efficiency. The maximum electric current is about 4.5 mA. A practical demonstration is then conducted by using the electricity generated to power a red light-emitting diode (LED).

1. Introduction

Currently, there is a need for the development of energy harvesters so that ambient energy can be converted into electricity to meet the increased energy demand arising from the development and wide application of electronic devices. Various energy harvesting techniques have been developed to achieve this task. Typically, these techniques take advantage of thermoacoustic [1–9], magnetoelectric [10], piezoelectric [11,12], thermoelectric [13,14] or optoelectric working principles. One of the interesting ideas is to harness the mechanical energy of rainwater or air flow [15,16].

The technology to harvest wind energy or hydropower [15,16] is well-developed by using wind or water turbines. Some of the turbines such as impulse water turbines convert the kinetic energy by rotating large-diameter blades (with unit in meter). Wind energy and hydropower utilization systems as reliable energy sources have become major power generation industries in the last two decades. The energy generated from those systems has increased dramatically. Since the performance of wind/water turbines depends strongly on the hydrodynamic characteristics of runner blades [15], the optimum design of the blade profiles and angle of attack need to be determined. The performance of different blade profiles at different wind speeds and angles of attack was investigated by using finite volume computational method [17] to solve Reynolds-averaged Navier–Stokes equations.

Wind farm and hydropower advocate favor developments in the context global warming abatement. However the direct or indirect effects on wildlife (aquatic life), or the local concerns of visual intrusion are not addressed. In addition, aero- or hydrodynamic noise is of a real annoying issue for large wind or water harvester. The effects on the wild/aquatic life, and the 'sensed visual or noise impact' may contribute to the social opposition to large wind/water harvesters. Thus 'small' or 'micro' harvesters [18,19] 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 harvesting systems.

Conventional air- or water-driven energy harvesters involve using large-diameter blades (>1 m) [20]. However, bladeless energy harvesters [21–28] might be as efficient and reliable as those bladed ones. The working fluid is injected nearly tangentially to the bladeless systems with rotating discs. The injected fluid passes

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http://dx.doi.org/10.1016/j.energy.2014.04.004
0360-5442/

through the narrow gaps between the discs and approaches spirally towards the exhaust orifices located at the center of each disc [27]. The 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 [28,29]: easy and cheap to manufacture and maintain, low cost, and significantly reduced noise impact on environments. It can produce power from a variety of working media, like water or air, or mixed fluids. All these features indicate that the bladeless system can be used for the development of a miniature energy harvesting system.

Like many other tropical countries, Singapore receives abundant rainfall throughout the year. The average annual rainfall of Singapore is about 2400 mm. Such rainfall is a source of 'green' energy, which has great potential to be harnessed, especially for rainwater collection systems applied in Singapore. In this work, small-scale energy harvesters driven by air or water are designed. Experimental tests of air-driven harvesters are first conducted to gain insights on its working principles. Three different diameter harvesters are studied, as the inlet volume flow rate is set to 4 different values. This is described in Sect. 2.1. The working principles and numerical simulations are discussed in Sect. 2.2. The harnessed electrical power can be measured in open- or closed-loop electrical circuit configuration, as discussed in Sect. 2.3. In addition, four design parameters are identified. In Sect. 3, experimental results are shown and discussed. Finally, in Sect. 4, the potential of applying such miniature bladeless system for harvesting energy from rainwater is experimentally investigated. Comparison is then made between the rainwater-driven harvester and the same-size air-driven one.

2. Description of experiments

2.1. Experimental setup

A bladeless electromagnetic energy harvester driven by turbulent air flow is designed and experimentally tested first, with the overall aim of exploring an alternative system for harvesting the mechanical energy of rainwater flow. The energy harvesting system (see Fig. 1(a)) involves using a number of co-rotating CDs (compact discs), as shown in Fig. 1(b). They are evenly spaced in the axial direction and attached to a central shaft, on which a magnet is attached. The inter-disc distance can be varied from 0.2 mm to 3.5 mm. In addition, three harvesters with different disc diameters are built: 120 mm, 80 mm and 40 mm. The smallest disc is chosen to be 40 mm so that the disc diameters of the three harvesters are changed with a constant step size of 40 mm.

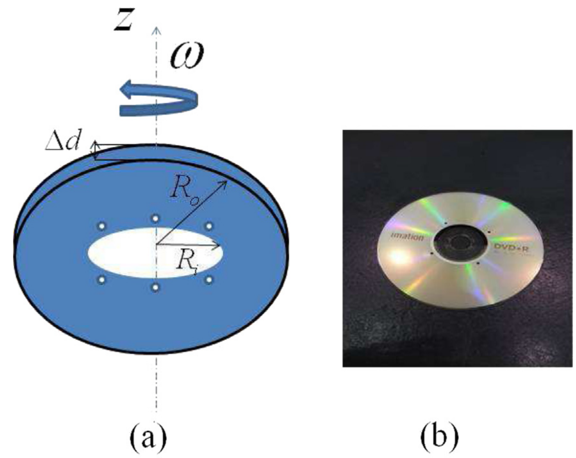

Fig. 2. (a) Schematic diagram of two neighboring discs, (b) photo of a 120 mm disc with exhaust orifices.

2.2. Working principles and numerical simulations

The bladeless system works due to the fact that a viscous drag force is generated due to the velocity gradient present between a compact disc and working fluid acting in the direction of the relative velocity of the fluid. Assuming the fluid is injected at a velocity $\boldsymbol{U}$ through a stationary disc as shown in Fig. 2(a), the relative velocity of the disc is $-\boldsymbol{U}$. 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 τ_w:

$$\tau_w(r) = \mu_f \frac{\partial \boldsymbol{U}_\theta(r,z)}{\partial z} \tag{1}$$

The shear stress τ_w gives rise to a torque Π on the disc, which can be calculated by integrating the elemental torque as

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

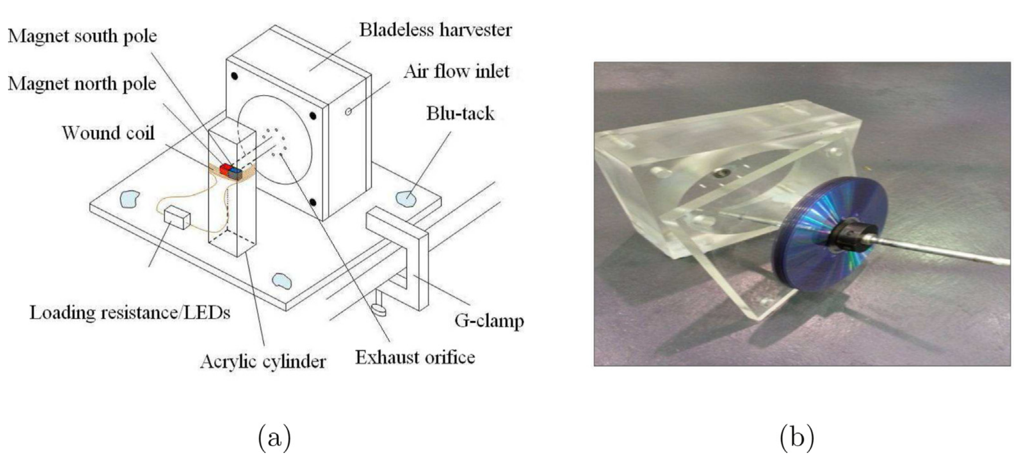

Fig. 1. (a) Schematic of a bladeless electromagnetic energy harvester, (b) photo of compact discs.