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Harvesting wind energy with pyroelectric nanogenerator PNG using the vortex generator mechanism

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ABSTRACT

This paper describes an experimental study of wind energy harvesting by pyroelectric nanogenerator PNG composed by PVDF film and vortex generator called turbulator. We have used wind tunnel equipped with DAkkS calibrated flow calculation system for the air flow velocity measurements and has velocity interval from 1 m/s to 25 m/s. The characteristic of the air flow are well controlled and presents an uncertainty budget below 1.4% in the open test section of the wind tunnel. A study of the response of the PNG as a function of air flow velocity was carried out. We have demonstrated the capability of the mechanism "PVDF film + vortex generator" PNG for producing uninterrupted current when subjecting to wind flow and its signal increases with the increase of the wind velocity without saturation. Thus, our PNG based on commercial 9 μm-PVDF film was able to output a current of 0.109 μA/cm2 for 25 m/s of wind velocity. The peak power density was 2.82 μW/cm2, which is comparable to previous developed PNGs. We have presented the output power of our device stored in 1 μF capacitor with demonstration examples of loading charges. These results offer opportunities for self-powered devices on a very large scale of wind energy.

1. Introduction

Recently, the need for electrical energy is increasing in a context characterized by global environmental challenges. A lot of efforts are then devoted to the development and utilization of renewable and green energy resources. Also, the fast growing market of solid-state electronics is directing the development of devices with ultra-low power consumption. These devices are, in generally, self-powered using ambient energy from mechanical, thermal, solar, and chemical sources [1–5]. In this direction, nanogenerators [6–8] have been designed for energy harvesting from mechanical photovoltaic [9], triboelectric [10], thermoelectric [11,12], ferroelectric [13], piezoelectric [14,15], pyroelectric energy [16,17] and combinations thereof for powering small mobile and wireless devices.

In this context, many research works have been focused on wind energy which is a very good source of electricity supply for its characteristics (environmentally preferable, affordable and inexhaustible). In fact, some researchers developed the wind nanogenerators by the fabrication of micro-turbines [18–20]. But the main inconvenient of these micro-turbines is that there are generally bulkier than is required for powering microelectronic devices. Many other works have used piezoelectric devices to harvest wind energy for low power generation [21–23]. One of the piezoelectric materials very used in these studies, is the flexible PVDF film. S. Orrego et al. presented the experimental study of wind energy harvesting by self-sustained oscillations of a flexible piezoelectric PVDF membrane fixed in a novel orientation called the "inverted flag" [24]. Also J. Zhang et al. used the flexible PVDF material to develop a rotational piezoelectric energy harvester for efficiently harvesting wind energy [25]. The results of these works are very encouraged but the major inconvenient comes from their complex mechanism and their limitation to the low velocity of the wind flow. In the other hand, many researchers have exploited the pyroelectric property of the flexible PVDF film to perform the pyroelectric nanogenerator called PNG. In fact, A. Cuadras et al. proposed pyroelectric cells based on PZT and PVDF films as thermal energy harvesting sources [26]. The energy harvest is derived from heating and cooling temperature fluctuations generated by air currents applied to the pyroelectric converters in order to supply low-power autonomous sensors. Recently, F. Gao et al. have developed a self-sustaining PNG driven by water vapor and air flow [27]. They used the water

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absorption which released a heat upon evaporation and vapor condensation on a surface of the PVDF film as a source of energy for the PNG. We notice from these research works that the main difficulty of the PNG is to have a mechanism that causes fluctuation of the temperature on the surface of the material continuously to have the production of pyroelectric current. Also it is noteworthy that the air flow is used as one of the environmental elements that contribute in the variation of the temperature.

As a solution, we have proposed in this work, the insertion of a turbulator [28] called also vortex generator in the flow passage to enhance the convective heat transfer between the PVDF film and the wind flow. The vortex generator is used as a mechanism which produces local and continuous turbulences and fluctuation of the temperature on the surface of the PVDF film subjected to a constant wind flow. The obtained electric energy, in this case, is uninterrupted and can be used for providing low-power convenient to electronic devices. This energy can also be accumulated in a capacitor for high-power usage. The self-sustaining pyroelectric nanogenerator PNG driven by wind flow would provide a new strategy to recover energy from wind in environment and industry.

The experiment was performed inside a calibrated wind tunnel, which was recently renewed and adapted for all kind of anemometry measurements in accordance with ISO 17025 standards. The air flow velocity is measured with a DAkkS calibrated Pitot static tube anemometer from 1 to 25 m/s.

We first present, in Section 2, the theoretical mechanism describing the convection heat exchange in the vicinity of the interface fluid flow/solid. The detailed of the new experimentation based on the study of the response of flexible PVDF pyroelectric film as function of air flow velocity in wind tunnel will be presented in Section 3. Finely we discuss, in Section 4, the results of the response of the PVDF film.

2. Theoretical background

The pyroelectric effect consists in a generation of the spontaneous polarization (P_s) when its temperature (T) changes,

$$dP_s = pdT \tag{1}$$

$$\text{with } p = \frac{dP_S}{dT} \tag{2}$$

p is called the pyroelectric coefficient

Considering a pyroelectric material including charge collection electrodes then the pyroelectric current I_P can be written as:

$$I_p = pS\frac{dT}{dt} \tag{3}$$

S is the active surface area and dT/dt is the time derivative of the temperature.

In the other hand, heat exchange by convection can be used to create temperature fluctuation and to generate the pyroelectric current. In fact, when a fluid flows over a pyroelectric material, convective heat flow affect its thermal equilibrium and consequently induces a change in the charge state of the pyroelectric material.

Generally, the heat flow exchanges δQ/dt (in Watts) between a fluid and a solid, by convection mode, is described by the Newton equation given by:

$$\delta Q/dt = h.(Tp - T\infty).dS \tag{4}$$

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The direct estimation of the heat exchange δQ from Eq. (4) is difficult because h is a function of several variables like the fluid characteristics, the nature of the flow, the temperature and the shape of the exchange surface. That is why, for the heat exchange study by convection, we determine the Reynolds number Re and the Nusselt number Nu (Eq. (5) and (6)). The Reynolds number allows us to determine the fluid flow characteristics and the Nusselt number estimates the importance of convection phenomena at the solid fluid interface. We also use the Hilpert correlation [29] presented in Eq. (6) to evaluate the evolution of the Nu as function of Re and also the Prandlt number Pr.

$$Re = \frac{U_\infty.d}{\nu} \tag{5}$$

$$N_u = C.Re^m.Pr^{0,35} \tag{6}$$

Where d is the dimension of the solid (m), U_∞ is the velocity of the fluid flow ($m\,s^{-1}$), ν is the kinematic viscosity of the fluid ($m^2\,s^{-1}$). C and m are two constant which vary according to the defined interval of Ref. [29].

From the characteristics of the fluid flow in forced convection regime and in the vicinity of the solid fluid interface, it is well known that when Re » 1, the heat exchange between the surface and the fluid flow increases significantly. Considering our practical case in which the air flow velocity varies from 1 m/s to 25 m/s, the Reynolds number is more greater than unity (Re » 1) indicating that a significant heat exchange can occur in the vicinity of solid fluid interface. The generation of fluid vortex "vortex generator" enhances this heat exchange [28], allowing an exploitable responses of the pyroelectric film.

3. Experimentation

3.1. Wind tunnel description

The wind flow is generated in a closed circuit wind tunnel with open test section (Fig. 1a and b) intended for the calibration of all kind of anemometers in the range from 1 to 25 m/s. It is equipped with 22 KW 3 phases motor connected to the blower. The plan of the open test section is 1 m^2 and its length is 1.3 m.

The wind velocity is controlled by a computer through an interface known as the flux calculation system named (WESTIBOX) connected to the frequency converter. A calibrated Pitot static tube is connected to the WESTIBOX to control and to measure the air flow velocity; also a calibrated hygrometer is placed inside the wind tunnel and before the open test section and connected to the WESTIBOX to measure the temperature and the humidity of the coming wind flow (Fig. 1c). This system is developed by the company Westenberg-Engineering (Cologne, Germany) and calibrated with the international DAkkS standard. A pressure balancer is located between the collector and the divergent to evacuate the overflows and maintaining a constant pressure in the measuring section. The open test section is located in a closed box with controlled temperature and humidity.

3.2. Measurements

We have used a commercial 9 μm-thick poled flexible PVDF film with two 35 nm aluminum layers deposited onto both faces of the PVDF film by vacuum sputtering. The pyroelectric coefficient of this film is defined in the datasheet of the manufacturer as 27.15 $\mu C/m^2$ K. We had previously studied its pyroelectric response to a chopped Laser radiation [30].

To study the signal of our PNG, we have used the oscilloscope MSO2024 and an amplification circuit (Fig. 2). We have added to the current-voltage amplification a circuit Band pass filter in the input. This filter is placed in the amplifier circuit to eliminate the electromagnetic noise produced by the three-phase asynchronous motor of the blower and by the frequency inverter which controls the motor. The PNG signal was amplified and then displayed in the oscilloscope and in the PC.