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Full Length Article

Human exhaled air energy harvesting with specific reference to PVDF film

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A B S T R A C T

Spirometer is a medical equipment used to measure lung capacity of a human being. It leads to diagnosis of several diseases. The researchers worked on harvesting energy from human exhalation while carrying out measurements using spirometer. A prototype has been developed using piezoelectric material i.e. PVDF (polyvinylidene fluoride) film as sensor. This paper presents the methodology and experimentation carried out for exhaled air energy harvesting using PVDF film. Experimental results obtained are encouraging. Measurements are also carried out on various subjects having different height, weight, age and gender. Data analysis shows variation in the energy harvested with different physical parameters and gender. Experimentation shows that voltage generated due to exhaled air is promising for harvesting.

1. Introduction

Human body, as a biological resource, contains enormous amount of energy. It is possible to extract this energy in two modes, active and passive. In active mode, energy can be extracted from different human body motions which need an extra effort like walking, arm & finger movement, jogging etc. [1,2]. For example (a) paddling with legs on bicycle can generate energy in a dynamometer attached to the bicycle wheel and (b) deriving energy from a dancing floor coated with piezoelectric material [3] etc. Passive mode involves energy extraction from natural movements of human organs and muscles, without any extra effort, such as breathing, blood pressure, body heat, heart and chest wall movement etc. [1,4]. Power extracted is more in active mode as compared to that in the passive mode. Starner [5] has developed a shoe in which PZT is mounted and claims 8.4 W of useable power generation from walking. Survey has been carried out for availability of different human mechanical energies by the author. It has been reported that in active mode electric power extraction is more than the passive counterpart [6]. The above research papers have not considered energy harvesting from the forceful exhaled air of human beings [7].

2. Literature survey

Energy harvesting can be carried out with different sensors viz: piezoelectric, thermoelectric, wind generator etc. Piezoelectric sensors are widely used for transforming mechanical vibrations into electrical signals. They are available in natural form like quartz; tourmaline etc. as well as they can be synthetically prepared such as Zinc oxide (Zno), Aluminum Nitride, polyvinylidene fluoride (PVDF) etc. A significant amount of research for human energy harvesting in active and passive mode using piezoelectric material has been reported by many researchers up till now. The review articles by Sodano et al. [8,9], Priya [10], and Mhetre et al. [11] provides a comprehensive coverage of the recent developments in piezoelectric energy harvesting from different human motions. Various energy harvesting prototypes and their analytical models has been developed and analyzed for their efficiency and power magnitudes by the authors. Authors, Paulo et al. [12] have presented energy harvesting from passive motions of human beings using piezoelectric, thermoelectric, electromagnetic sensors for different medical devices.

Literature survey reported that wind energy available from exhalation can be harvested using wind generator and piezoelectric means. Wind generators developed up till now are for low velocity natural wind ranging from 2 m/s to 10 m/s e.g. Mohamed et al. [13] worked on Darrieus turbine, vertical axis wind turbines (VAWTs) for small scale power generation. Detailed numerical analysis to improve wind turbine efficiency is carried

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out by the author. CFD analysis of new turbine shapes increases efficiency by 10% than regular airfoils. Dikshit et al. [14] reported a design of a vibrator having a piezoelectric discolor attached to a shaft which is driven by a windmill. Priya et al. [15] have built up a piezoelectric windmill having twelve piezoelectric bimorph transducers arranged around the circumference of a wind mill shaft. A fan is attached at the end of a wind mill shaft to harvest wind energy (Piezoelectric Bimorph is an invention of a Baldwin Sawyer [16]. It is a cantilever beam having two layers, one is piezoelectric and other is metal). Myers et al. [17] reported a cost effective wind mill for wind energy harvesting with 18 piezoelectric bimorphs and associated structure made up of plastic parts. But they were unable to overcome frictional losses due to gear assembly, in their prototype. In the US patent [18], inventor Shashank Priya, designed six different windmill structures attached with piezoelectric bimorph for low air velocity harvesting. Li et al. [19] reported the experimentation carried out on a wind mill model placed in a wind duct. PVDF films were placed on wind turbine for extracting wind energy. Goreke et al. [20] worked on development and characterization of wind turbine blades based on savonius architecture. Work is carried out by the authors to maximize the rotational speed of blades at normal respiration rate. Development of turbine for energy harvesting for MEMS spirometer with its simulation is reported in the paper. In research paper [21], authors Sun et al., reduced the thickness of PVDF film by a top down reactive ion etching process to increase capability of generating voltage from low air flow speed of respiration. Thickness, air flow speed, and voltage output is estimated and checked with simulated respiration. But real life human being testing is not carried out to test the voltage generation capability of the film. Wang et al. [22] presented the development of a peak flow meter in which air flow measurement and power generation from exhalation is carried out. Wind turbine with axial flux permanent magnet generator is designed to get energy. But power generation from human beings is not investigated. Storage mechanism is one of the important components of energy harvesting process. Discussion about the improved performance of Li-ion battery due to nano sized lithium ion phosphate material with its characterization is presented in [23] by the authors Satyavan et al. Authors, Ananthavel et al., in paper [24], presented a discussion about superconducting magnetic energy storage system with reference to the power enhancement related to the power transfer capability of power transmission line.

Another approach to extract energy from exhaled air is from temperature gradient of exhaled air by thermocouple. Many researchers worked on heat energy extraction from human body temperature gradient using thermocouples [25–27,28]. Exhaled air has a passage from mouth through many lung parts attaining core body temperature. This produces two to three degrees temperature difference between exhaled and inhaled air. This temperature difference as heat source can be utilized for energy harvesting. But low exhaled air temperature gradient (2–3 °C) imposes many problems for harvesting heat energy using thermopiles. Hence this approach is not considered in this paper.

Literature review reports that energies from breathing process has been harvested up till now by following ways: chest or abdomen wall movements during breathing, air available from natural breathing process and from diagnostic lung assessment devices [1]. Lung diagnostic equipment utilizes forceful human exhalation from mouth in the device for lung assessment. In this process air forcefully moves out of the lung's bronchial air sacs to the external environment at a little higher temperature [7]. This forceful human exhalation is a primary source of energy with high velocity, temperature gradient and chest wall motion. Energy harnessing from voluntary forceful exhalation in diagnostic equipment called spirometer is addressed in this research paper.

Fig. 1 (1a: Flow rate-Lung volume graph, 1b: Lung volume–time graph) shows standard spirometric graph available from spirometric test as mentioned in ATS standard [29].

It is observed that (Fig. 1a and b) flow rate and volume reaches to the maximum value of 8–10 L/s and 5–6 L during first few seconds of exhalation depending upon individual's lung capacity. This reports some important points regarding exhaled air energy harvesting: 1. Availability of variable air force for few seconds during test. 2. Small range of flow rate and volume i.e. availability of limited and low air force during test. 3. Variation of exhaled air force according to physical parameters (height, weight, age) and gender of human beings. 4. Dimensional limitation of the pipe for placement and arrangement of harvesting sensor, without disturbing the exhaled air flow.

Energy harnessing using piezoelectric material from exhaled air, available in spirometer during lung assessment is discussed in this paper. Calculation, simulation and experimentation carried out in this context are demonstrated. Paper outline is as follows: Section 3: Pressure analysis of the exhaled air in the spirometer pipe; Section 4: Experimentation on PVDF film; Section 5: Discussion about result; Section 6: Conclusion.

3. Pressure analysis of exhaled air in a pipe

An arrangement used in medical equipment, called 'Spirometer', is used for experimentation. Spirometer is a diagnostic instrument used by the physicians for assessing lung capacity. Subjects' exhaled air velocity and volume is measured with a sensor placed in a pipe. 'American Thoracic Society' (ATS) guidelines have been followed in selection of mouthpiece and pipe [29]. Fig. 2 shows schematic arrangement and Fig. 3 gives out a detailed geometry of pipe and sensors.

In the proposed arrangement, mouthpiece is placed close to the mouth of a subject, under test. Care has been taken with placement of assembly such that the exhaled air is directly forced in the pipe, without any pressure loss. An air flow sensor, a thermistor, and polyvinylidene fluoride (PVDF) film, an energy harnessing sensor, are placed in a pipe, after the mouthpiece (Fig. 3). PVDF film used is laminated in a polyester (Mylar) sheet (measurement SPECIALTIES, US). This experimental set up is used throughout for all experimentation. Spirometer is developed first; using thermistor hence pipe with both the sensors placed is considered here (Figs. 2 and 3) for pressure analysis.

In spirometric test air flow, volume and exhalation time is analyzed for determining lung capacity. Hence pilot study has been performed for obtaining flow rate and velocity of normal healthy persons. Measurements were carried out with 22 subjects (17 male and 5 female; 20 years age; weight = 60.27 ± 13.86 kg [mean ± SD]; height = 1.70 ± 0.11 m; mouth diameter = 0.009 ± 0.001 m). Readings were taken for the subjects in a sitting position with steady and stable state by having exhalation in a spirometric pipe as shown in Fig. 2. Spirometric procedure has been followed while recording i.e. taking average of three successive readings, using laboratory equipments.

Observations show that exhaled air velocity varies from 2.2 m/s to 9.9 m/s with (5.66 ± 1.57 m/s, mean ± SD) and exhalation time varies from 2.10 s to 8.21 s (4.42 ± 1.73s, mean ± SD). Male participant (maximum 1.85 m height and 64 kg weight) produces maximum flow rate of 9.9 m/s. Female candidate (max.1.67 m height and 49 kg weight generates 4.7 m/s flow. Thus gender and physical parameters based variations in exhalation velocity is observed. This gives out important points that limited and variable exhaled air is available with short duration for energy harvesting from spirometric test. From this pilot study, values such as 0.009 m mouth diameter, 2–10 m/s velocity range, exhalation time of 4 s are taken further for pressure calculations.

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