Novel archetype of fluid-based energy generation system from human footsteps

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Abstract-Increased agitation for environmental pollution, renewable energy harvesting systems have emerged as one of the key technologies globally. This work represents a novel, clean, and environmentally friendly renewable energy generation technology that harvests energy from human walking. The mechanism is based on two tiles structure paver in which a syringe is connected through unidirectional valves and mini hydro-generators that convert kinetic energy into electricity utilizing fluid movements by the flow-control mechanism. This energy harvesting mechanism can produce average output energy of 2.5J and more per step during typical human weighing 800 newton walking for 6mm depression of the paver. The system is easily replicable and can be established with ease to power up lamps and emergency lighting systems etc. Compared to other energy harvesting paver systems, this system is eco-friendly and cost-effective. This novel fluid-based footstep energy harvesting mechanism has substantial possibility as an effective renewable energy system for developing and developed countries.

1. INTRODUCTION

The global energy demand has increased by 5.2 gigajoules per capita from 2009 to 2019 thus increase in demand raised carbon dioxide emission by 4423.8 million tons in ten years ^[1]. Climate change due to “Enhanced Greenhouse Effect” is considered a major threat to environment. Studies have shown that carbon dioxide contributes roughly two-thirds to the effect of “enhanced greenhouse effect” ^[2]. It is projected that the global greenhouse gas emission will increase by 21.9 % within 2050 ^[3]. According to recent studies there is consensus across recent scenario that renewable energy and energy efficiency is the most feasible direction to meet climate objectives ^[4]. According to the data provided by ‘climate watch’ heat and electricity generation of energy sector was solely responsible for more than 30% of global greenhouse gas emission in 2016 ^[5,6]. It has become eminent to utilize renewable energy sources to reduce the effects of ‘Enhanced Greenhouse Effect’. Production of energy from human locomotion is not a new idea. Various types of methods are used. Inertial energy harvesting being one of them. Kornbluh et al.^[7] designed a shoe to harvest inertial energy using dielectric elastomer. In their experiments, they obtained a maximum output

energy of 0.8J. Gorlatova et al.^[8] designed numerous energy harvesting wireless devices placed around different parts of human body. These devices produced varying amount of energy from 155 μ W to 202 μ W. On two separate occasions, experiments done by Huang et al.^[9] & Buren et al.^[10] for inertial energy harvesting, they got around 100-200 μ W of maximum energy output.

Piezoelectricity is another method to harvest energy from human locomotion. Antaki et al.^[11] designed a shoe with piezoelectric array within the midsole area for conversion of mechanical energy into electrical energy. Their experimental results show that 676-2100 mW of electricity can be produced by jogging. Qian et al.^[12] designed a piezoelectric boot energy harvester. Experimental results show 8.5-9.3 mW of energy can be generated with a average speed of walking. Roundy et al.^[13] designed a piezoelectric vibration based generator. Their experimental results show a maximum of 375 μ W energy production. Wen et al.^[14] designed a multi-stage force amplification frame piezoelectric energy harvester, which can harvest 50.8 mW of energy. Kymissis et al.^[15] designed devices capable of “parasitically” harvesting energy from shoes while walking. Their experiments show that their Polyvinylidene fluoride stave generation can produce 1.1 mW of energy.

Another approach for harvesting energy from human locomotion is electromagnetic based energy harvesting system. Donelan et al.^[16] designed a biomechanical knee brace energy harvester. Their experiments demonstrated that 4.8 ± 0.8 W of energy can be harvested, while requiring little extra effort from the user. Taliyan et al.^[17] designed a footstep energy harvesting device using dc generator. Their experimental results show that 3-5J of energy can be produced with each step. Liu et al.^[18] designed an energy harvesting paver which experimentally harvests 1.8J of energy per step. Ang et al.^[19] designed a footstep power generator from kinetic energy capable of generating 0.2900W of energy, shown from experimental results. Dibin et al.^[20] designed an in-shoe energy harvester. Their experimental results show that 55.6 μ J of energy per step can be generated. Romero et al.^[21] designed a device which generates energy from body motion to power biomedical devices. From their experiments, 2.35 μ W of energy

can be generated by this device. Even though generated energy from human locomotion is quite low there are still opportunities to improve overall efficiency. There are some existing ways to harvest energy from footsteps, some of which are still being developed & some have been commercialized already. One of them are, Pavegen,^[23] it is already available in the market. It produces 5W of energy from continuous steps & is made from recycled items. But it is expensive, not suitable for low population density area & leaves carbon footprints. Another device is Piezoelectric tiles, designed by Bobby et al.^[24] which is easily replaceable & low maintenance. But it is also easily damaged, highly temperature sensitive. In-shoe energy harvester^[25,26] on the other hand is comfortable, cheaper, portable & provides sufficient amount of energy. Some disadvantages of this are limited application of the harvested energy & exposure to foreign factors such as water & mud. Liu et al.^[18] designed energy harvesting paver can be easily constructed & provide with good energy output but needs more maintenance & may not be comfortable for the user. Heel strike-induced airflow footstep energy harvester designed by Fu et al.^[27] can be easily constructed & replaced but has a low energy output & is not suitable for low population density area. Mamun et al.^[28] designed a footstep energy harvesting system using hydro-generator has sufficient power output & can be constructed with cheap, locally available materials. As it has moving parts, it'll need more maintenance, can be damaged due to improper use & not suitable for low population density area. This work represents a novel fluid based energy harvesting paver from human footsteps. In this paper a fluid flow simulation, numerical simulation and experimental data has been introduced.

2. IDEA CONCEPT

Study of biomechanics shows the direction of force exerted on ground has a vertical and horizontal component and has peak vertical component once per cycle^[29]. Peak vertical force exerted to the ground by walking and running ranges between $Mg-3Mg$ ^[30]. The design concept of our mechanism intends to utilize the peak vertical force generated by walking or running and converting the force into electrical energy using principles of fluid mechanics. A single unit of the design consists of a syringe with two pathways connected to unidirectional valves, a mini water turbine generator and a separate water chamber. The plunger of the syringe is covered and fixed to a top plate which receives the vertical force and pushes the plunger to exert fluid through a unidirectional valve and rotate the turbine of the generator. After releasing force from the top plate, helical springs connected to each corner pushes the top plate to its initial position along with the plunger. The latter process creates a negative pressure inside the syringe and activates the other check valve which allows water from a small chamber to refill the syringe. The whole process acts simultaneously. An isometric view of the whole design is shown in Fig. 1. The power generated from the footsteps is stored in capacitors instantly and released to a charge controller which limits the charge flow for charging battery at a safer rate. The flowchart is shown in Fig. 2. To collect maximum output from the whole system the design of water turbine generator consists of a

stator and a rotor comprised of pelton wheel and permanent magnet.

Fig. 1

Fig. 2

3. MATHEMATICAL CALCULATION

The flow inside a pipe is considered laminar flow according to Reynolds number. Let the force on the plunger be F and A_s , A_n be the cross-sectional area of the syringe and nozzle respectively. The force on the plunger adds pressure $p_1 = \frac{F}{A_s}$ inside the syringe. Applying Bernoulli's equation for the syringe,

$$p_0 + \frac{p_1}{\rho g} + \frac{v_s^2}{2g} = p_0 + \frac{v_n^2}{2g}$$

Where v_s is the velocity of flow inside the syringe and v_n is the velocity inside the nozzle. The velocities are related via continuity equation:

$$A_s \times v_s = A_n \times v_n$$

So calculating the velocity through the nozzle, we have,

$$\frac{F}{A_s \rho g} + \left\{ \frac{1}{2g} \times \left(\frac{A_n v_n}{A_s} \right)^2 \right\} = \frac{v_n^2}{2g}$$

$$v_n^2 \left(1 - \frac{A_n^2}{A_s^2}\right) = \frac{2F}{A_s \rho}$$

The hydropower from the nozzle will be,

$$P = \frac{(A_n v_n) \times \rho g \times \frac{v_n^2}{2g}}{1000} KW$$

The major loss from the system can be frictional head loss which can be calculated using Darcy's equation.

$$h_l = \frac{fLv^2}{2gD}$$

Fig. 3 Vertical Ground Reaction Force of an adult walking at normal speed [31]

4. MATERIALS AND METHODS

4.1 FLUID FLOW SIMULATION

Mathematical modelling shows that generation of power mostly depends on velocity of fluid from nozzle and the area of the nozzle. The highest possible value of v_n depends on low area of the syringe and low difference between A_n and A_s . However, high power does not necessarily mean high energy. ANSYS CFD software was used to see how the velocity and pressure inside a syringe was influenced by applying load on the piston of the syringe Fig.6-10. As per simulations, it can be said pressure inside the syringe remains maximum and the minimum value can be observed at the end of the nozzle.

Fig.4 Syringe Diameter 27mm; Nozzle Diameter 1.5mm

The velocity of the fluid inside the syringe works disproportionately to the pressure of the fluid. As it shows the velocity can be found maximum at the end of the nozzle and minimum inside the barrel.

Fig.5 Syringe Diameter 27mm; Nozzle Diameter 1.5mm

Fig.6 Syringe Diameter 27mm; Nozzle Diameter 1.5mm

Fig.7 Syringe Diameter 50mm; Nozzle Diameter 1mm

Fig.8 Syringe Diameter 50mm; Nozzle Diameter 1mm

4.2 PROTOTYPE EXPERIMENTATION

The prototype of the mechanism was developed using low-cost timber, a 50 ml syringe with barrel and nozzle diameter of 27mm and 1.5mm respectively, 4 helical springs, a polyvinyl chloride (PVC) tube of 1.5 mm inner diameter and 2 one-way check valves. The experiment was conducted using a subject of 50-kilogram mass applying load on the top plate with depression of 6mm according to the allowed standards of Americans with Disabilities Act (ADA)^[32] Fig.9-10.

Fig.9 Syringe Diameter 27mm; Nozzle Diameter 1.5mm

Fig.10 Syringe Diameter 27mm; Nozzle Diameter 1.5mm

A mini water turbine generator with capacity to generate maximum 12 volts and 10 watts of power was used in the experiment.

5. RESULTS

To verify the output power of the energy harvesting mechanism, we tested it using a multimeter. It turns out that the mechanism can generate peak 12 volts and 10 watts of power for this specific type of generator at its specified conditions from a subject weighing 490 N. However, the maximum amount of energy that can be generated in our system could not be tested due to the limited capacity of our water turbine generator. The result is shown in Fig.10. Our mathematical analysis can predict the maximum outcome in this mechanism. Commercially available syringes with barrel diameter and nozzle diameter of 27mm and 1.5 mm can generate around 2.5 Joules from a subject weighing 800N while walking at normal speed. Analysis in Fig.11 shows the approximate energy that can be generated utilizing velocity jet from the syringes without considering any losses for turbine generators based on the VGRF data from the work of Bovi et al. ^[31]. The analysis was done by feeding the VGRF data to our mathematical model.

Fig. 11 Vertical Ground Reaction Force of an adult weighing 800N walking at normal speed for a barrel diameter and nozzle diameter of 27 mm and 1.5 mm, respectively.

The standard syringe of the mentioned diameters cannot utilize full potential of the syringe and peak force generated from walking. Thus, the system requires an optimum syringe design to utilize the peak powers to generate highest energy.

Fig. 12 Vertical Ground Reaction Force of an adult weighing walking at normal speed for a barrel diameter and nozzle diameter of 50mm and 1mm, respectively.

The syringe with the barrel diameter and nozzle diameter of 50mm and 1mm, respectively can utilize peak power and has the potential to generate highest energy for displacement of 6 mm.

6. DISCUSSION

As review represented in the paper, this work has the capability to produce higher energy output compared to most of the outputs mentioned in other literatures. Most of the previous work shows the maximum output power from the generators. However, high output power does not necessarily indicate higher energy generation. Liu et al.^[18] showed their novel paver has the capacity to generate 1.8 Joules of energy from a person weighing 800 N. The biomechanical knee brace energy harvester designed by Donelan et al.^[16] shows that they can generate electricity at 4.8 ± 0.8 W of power. The in-shoe energy harvester designed by Dibin et al.^[20] can generate 55.6 μ J of energy per step. Our analysis indicates our system has the capacity to generate 2.58 Joules of energy from a subject weighing 800N. The generated energy can reach up to 4.4 Joules depending on the design of the syringe. However, the analysis does not consider any system loss. In our analysis, we neglected losses of head due to sudden contraction and losses of head due to bends and elbow. Which can be countered with proper designing of the syringe and connections. Maximum possible efficiency of pelton wheel impulse turbine can reach up to 95%, and even in micro scales the turbine generator can reach 90% efficiency^[33]. It can be a prospective solution for energy harvesting paver system that can generate high amounts of energy compared to most works in this field. Considering all the facts our mechanism exceeds most of the works in other literatures.

7. CONCLUSION

In this research we presented design, analysis, modeling, simulations and experiments of a novel fluid-based energy harvesting system. The novel mechanism has the potential to utilize energy with high efficiency compared to other mechanisms from human walking. Despite all optimizations there can be no prime design that can utilize maximum output from every subject while walking, fast walking or running. The condition varies from weight and other parameters of a subject. Based on the simulations the syringe with measurements of 50mm and 1mm of barrel and nozzle respectively can be considered as the optimum design for maximum cases. The simulations show it has the input energy of 4.4 J approximately which is significantly higher than maximum literatures. In the prototype design we excluded two extremely important parts. To make the system more sustainable the turbine generator requires a covering and a pathway to recycle the water usage. It is also very important to build a closed system to avoid evaporation loss for commercial usage. Thus, this novel mechanism has promising prospective as renewable high efficiency energy harvesting paver.

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