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Development of a novel, robust, sustainable and low cost self-powered water pump for use in free-flowing liquid streams

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ABSTRACT

The design of water supply infrastructure depends on local conditions such as geophysical features, available technology, traditions, culture, and available human and economic resources. The costs for designing, building, maintaining, monitoring, and replacing the required infrastructure escalate when any of these factors is inadequate or insufficient. Furthermore, effects of global climate change increase the risk associated to existing infrastructure, calling for more robust, flexible, and adaptable technologies. We present the design and development of the first physical prototype of the Filardo Pump™, a low-cost, robust, sustainable, water-powered pump that addresses these challenges with many advantages over existing technologies: 1) it requires no external energy source, 2) it works immersed in a free-flowing, unaltered body of water, 3) it is operable in shallow water and low flow conditions, 4) it has low cost and low weight relative to work performed, and 5) it can be made small for households or scaled up for industrial applications. We show proof of concept for this novel pump and describe its development through scaling geometrical aspects and testing different materials for its operation. The proposed technology presents an opportunity for low-cost, sustainable, low carbon footprint water supplies for households, agricultural and industrial applications everywhere, not just in the rural developing world.

1. Introduction

After the Millennium Summit in 2000 and the approval of the Millennium Declaration [1], the objective of improving the water supply and sanitation sectors has played an important role in the political agenda of many countries. One of the principal goals for achieving environmental sustainability is to reduce by half the population without access to safe drinking water and sanitation by 2015. According to the United Nations [2] 11% of the global population – 783 million people – remain without access to an improved source of drinking water, and based on current trends, it is estimated that 605 million people still lacked coverage at the end of 2015. Improving coverage for rural populations is of particular concern: in 2010, 96% of the urban population had access to improved drinking water, compared with 81% of the rural population. According to the World Health Organization (WHO) and UNICEF [3] 83% of the population without access to an improved drinking water source lived in rural areas.

The disparities in the penetration of drinking water coverage between rural and urban areas clearly show that alternative approaches are required to reach more isolated or energy-poor regions. In this manuscript we present the development of the first physical prototype of a novel pump technology (invented by B. Pietro Filardo, Pliant Energy System, LLC. USA). We investigate the size and spacing of the primary pump components as well as the geometry and tuning of their support structure for efficient conversion of river kinetic energy to water lift and supplied flow rate. The presented technology is demonstrated to be robust, flexible and adaptable: it does not require an external power source, is low cost, can operate in extreme conditions (e.g. shallow water levels, debris-laden flows, or low flows), has low weight relative to work performed compared with other existing solutions, is scalable, requires little maintenance, and it can be implemented in rural areas with local materials. The Filardo Pump has the potential to transform the societal and economic conditions of a significant fraction of the population without water access by increasing quality of life,

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gender equity (in the absence of water infrastructure the labor of women represents the dominant supply of water [4,5]) and productivity of households and communities.

2. Current water lifting technologies and performance of those exploiting renewable energy sources

Water lifting mechanisms can be classified by either the water source in use, the technology implemented by the mechanism, or by the power source required to operate them [6]. Available water sources are ground water, surface water, and rain water. Water lifting technologies include: rope and bucket (loose, through a pulley, or on a windlass), bucket pump, rope pump, suction plunger hand-pump, direct action pump, deep-well piston pump, deep-well diaphragm pump, centrifugal pump, electrical submersible pump, axial flow pump, and hydraulic ram. Power sources are: human power, animal traction, wind driven, photovoltaic systems, engines (electrical, petrol, or diesel), and self- or water-powered technologies. A comprehensive description of the above mentioned technologies is reported by Fraenkel [7] and updated by Fraenkel and Thake [8]. These reviews show that despite important advancements, there is currently no technology capable of solving the water crisis in rural communities. We explore some of the disadvantages of human-, solar-, wind-, and water-powered devices below.

With respect to human powered mechanisms, Fraenkel [7] states that the costs of water-lifting human power devices is considerable and even more expensive than modern, green technologies such as solar photovoltaic panels, in addition to being plagued by maintenance problems [9]. In an attempt to address such disadvantages, variations of rope and washer pumps [10], treadle pumps [11], and flow reciprocating pumps [12] have been developed. However, such variants require special machinery and parts for maintenance and repair, affecting their sustainability and do not reduce the high costs associated with the opportunity cost of their dependance on human labor.

Solar power mechanisms suffer either from high cost per kW capacity installed, or the use of relatively sophisticated and often fragile mechanical components. First, the cost of traditional pumps powered by photovoltaic systems (PV) comes from the necessity of conversion of energy from light to electricity to mechanical force, which requires the coupling of the PV system with an existing lifting mechanism. Second, the reliability and complexity of solar thermal pumps (traditional pumps driven by closed cycle heat-engines) comes from the sophistication of the components used and solar collectors, which unfortunately are fragile. Finally, absent an energy storage device (e.g., battery) these pumps are dependent on daylight.

Wind powered mechanisms can also be divided into those powered directly by wind (i.e., mechanical energy), and those that utilize wind-generated electricity [13,14]. Regardless of the type, wind powered pumps are highly efficient in converting harvested energy into useful work, require low maintenance and can operate in a wide wind speed range. However, they have significant disadvantages that include their high initial capital cost, their size, the skills required for assembly, the intermittency of the wind resource, and their maintenance costs [15].

In the area of self-water-powered devices, waterwheels, such as the Noria, are limited in the maximum lift by their own radii while the Spiral waterwheel pump can lift water to a height several times its diameter [7,8]. For both devices the only precise machined components are the bearings and the rotating coupling that connects the pipe exiting the hub of the device to the outlet pipe for the Spiral pump. These pumps have significant disadvantages which include their initial capital cost, strong foundation requirements, and vulnerability to flood events.

Another relatively simple mechanism is the ram pump [7]. This device requires precision machined parts and a supply of water under pressure, i.e., a head differential and sealed penstock. Additionally, the coil pump and its commercial adaptation, the sling pump, operate under the same concept as self-powered devices. The coil pump is in principle an Archimedes screw operating in a horizontal plane with a coiled pipe and the sling pump adds a propeller to the design [16]. Both devices require sufficient water depth to submerge the mechanism and enough current to power them. Both designs are also limited in the maximal lift and the flow rate delivered. While a review of current patents shows a diverse range of water powered pumps, most of them require expensive machined parts [17,18].

Among the technologies presented, considerable work has gone into the application of renewable energy sources for water delivery. Gopal et al. [19] classified and reviewed different water pumping technologies based on five renewable energy categories (solar-PV, solar thermal-ST, wind, biomass, and hybrid, with no reports found for the last two).

For PV systems a wide range of applications and flow rates are found. Pande et al. [20] presented a drip irrigation system delivering 3.4–3.8 L/h against a static head of 7.1–10.2 m, Qoainder et al. [21] reported an irrigation and water supply system delivering 4.17 ML/h, and Daud and Mahmoud [22] a 2083 L/h system delivering at 37 m of head. Despite the important flow rates, Laleman et al. [23] cited several environmental impacts of such technologies, which consume large amounts of energy and emit green house gases during manufacturing, assembly, transportation, and recycling, not to mention the relative high capital costs required to procure the PV power source.

For ST systems, Sumathy et al. [24,25] report a system delivering 7.1 L/h at 10 m of head, and Wong and Sumathy [26] another one performing at 16.7–29.2 L/h at 10 and 6 m, respectively. Gopal et al. [19] listed low thermal conversion efficiency, as well as costly and unsafe working fluids among other limitations of such systems.

For wind driven systems, performances up to 3425 L/h and dynamic heads up to 50 m have been demonstrated for small capacity turbines (2.5 kW) with the downsides of mechanical and aerodynamic noise [27,28], indirect contributions to climate change [29], initial capital requirements, and impacts on animals [30].

An additional renewable energy source to consider is hydrokinetic. As with the previous sources, water supply is achieved by coupling a turbine (usually underwater) with a generator and a water pump. The key concept is that hydrokinetic devices extract the kinetic energy from the flowing water instead of potential energy from falling water [31]. Vermaak et al. [31] and Güney et al. [32] present a review of turbines and generators but no further applications for water pumping are presented. In terms of disadvantages, Vermaak et al. [31] reports high generator coupling cost due to underwater placement for horizontal axis turbines, and a starting mechanism for vertical axis turbines with low starting torque. On the other hand, Güney et al. [32] reports that the cost of generating hydrokinetic energy is strongly influenced by the power density of the stream. Also, hydrokinetic energy systems suffer similar disadvantages as wind driven systems such as high initial capital cost and environmental impacts.

2.1. The Filardo Pump

A sketch of the Filardo pump concept is shown in Fig. 1. It uses elastic materials to harness river kinetic energy to pump water. Fig. 1 (*upper left*) shows two elastic materials (hereafter called ribbons) with a membrane in the middle. By applying an external force via a tensioning element, such as tension lines, a deformation is induced within the ribbons and three pinch points (points where