Water flow energy harvesters for autonomous flowmeters

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Abstract. This paper reports on a water flow energy harvester exploiting a horizontal axis turbine with distributed magnets of alternate polarities at the rotor periphery and air coils outside the pipe. The energy harvester operates down to 1.2L/min with an inlet section of 20mm of diameter and up to 25.2mW are provided at 20L/min in a 2.4V NiMH battery through a BQ25504 power management circuit. The pressure loss induced by the insertion of the energy harvester in the hydraulic circuit and by the extraction of energy has been limited to 0.05bars at 30L/min, corresponding to a minor loss coefficient of $K_{EH}=3.94$.

1. Introduction – Water flow energy harvester concept

Flows and in particular water flows are a powerful source of energy to supply autonomous devices such as flowmeters, with typical applications in agriculture and urban water systems. This paper presents a water flow energy harvester based on a horizontal axis turbine with distributed magnets with alternate polarities at the rotor periphery and with coils outside the pipe (Figure 1). Contrary to most of water flow energy harvesters proposed in the state of the art \cite{1-3}, the choice has been made here to use a horizontal-axis turbine with a low electromechanical coupling to keep the pressure loss below 0.05bar@30L/min. As soon as the water flow enters in the energy harvester, the turbine starts rotating, leading to a rotational movement of the magnets. The movement of the magnets with alternate polarities (Figure 1b) induces a variation of magnetic flux in the air coils, which is finally turned into electricity (Lenz's law). An inlet cone has also been added at the turbine entry to increase the flow speed and then, the rotation speed of the turbine. Finally, the flow energy harvester is symmetric so that it could work in both directions.

Figure 1. (a) Water flow energy harvester concept and (b) Magnets distribution at the rotor periphery
2. Models & equations – Water flow energy harvesters

2.1. Output powers and pressure losses
The output power of a turbine placed in a water channel is given by: \( P = C_p \Delta p AU \), where \( \Delta p \) is the pressure loss induced by the turbine, \( A \) the turbine/channel surface, \( U \) the flow velocity and \( C_p \) the coefficient of power, which corresponds to the efficiency of the turbine, typically around \( C_p = 2-5\% \) for small-scale devices (some cm²). Water flows are then a powerful source of ambient energy with turbines’ output powers reaching some milliwatts with a few L/min. Moreover, the pressure loss induced by the turbine \( \Delta p \) can be expressed by: \( \Delta p = K_{EH} \rho U^2 / 2 \), where \( K_{EH} \) is the minor loss coefficient of the energy harvester. \( K \) is typically comprised between 3 and 8 for turbine flowmeters. Minimizing the pressure loss \( \Delta p \) induced by the turbine and the extraction of energy is a strong constraint that has been solved by using horizontal axis turbines and a low electromechanical coupling (air core coils).

2.2. Turbine design considerations
The turbine has been designed by taking into account the following considerations: firstly, the inlet diameter has been set to 20mm to be equal to the diameter of the channel. Then, four other parameters have to be set: (i) the shape of the blades (NACA, flat plate, cambered plate...), (ii) the number of blades \( N \), (iii) the evolution of the chord \( c(r) \), and (iv) the evolution of the blade angle \( \beta(r) \).

Horizontal axis turbines operate thanks to the lift force which provides motor torque, and are limited by the drag force which creates a resistant torque (Figure 2a). We must therefore select a profile which allows a high lift-to-drag ratio. We have decided to use simple flat plates which proved to be fairly efficient at low Reynolds number (\( Re \approx 10^4 \) in our case) compared to more complex profiles (Figure 2b), and easier to manufacture at small scale. The thickness of the flat blades has been fixed to 500µm in order to avoid potential cracks/breaks. The number of blades is also an important parameter. Overall, a large number of blades enables to decrease the depth of the turbine while maintaining the same motor torque. However, the depth of the turbine must not be too small to incorporate the permanent magnets (Figure 3b). The evolution of the chord allows to fix the rotational speed of the turbine (or in Figure 2a). Small blade angles lead to high rotational speeds but considerable pressure losses. On the contrary, high blade angles induce small pressure losses but low rotational speeds. In this paper, the blade angle follows a linear evolution from \( \beta(0)=10^\circ \) to \( \beta(R) = \theta \), \( \theta \in [10^\circ, 35^\circ] \).

3. Prototype

3.1. Turbines, coils and magnets
The turbine design has been experimentally optimized: more than 40 turbines with various blade angles, blade chords and number of blades have been manufactured and tested (Figure 3a) to maximize the output power of the energy harvester while keeping a low pressure loss. The optimal
design was found to be a $N=6$-blades turbine with a blade angle of $\beta(R)=30^\circ$ and a depth of $H=10\text{mm}$ (Figure 3b), able to generate power from $1.2\text{L/min}$ with an inlet diameter of $20\text{mm}$. Twelve $5\text{mmx5mmx3mm}$ NdFeB magnets have been distributed at the rotor periphery with alternate polarities. Nine coils ($7\text{mm}^3 \times 3000$ turns – $L_c=47\text{mH}$ – $R_c=770\Omega$) have been placed at the outside of the pipe, in front of the magnets, to collect the variation of magnetic flux. The distance between the coils and the magnets is $2\text{mm}$.

3.2. Energy harvester and output voltages

The energy harvester prototype is presented in Figure 3c; the active part sizes $60\text{mmx45mm}^2$. The device has been connected to a standard domestic water line with 3 bars of static pressure and with water flow varying between $U=0$ and $U=20\text{L/min}$. An example of the output voltages of 3 adjacent coils is presented in Figure 3d for $U=10\text{L/min}$, showing that the output voltages of 2 adjacent coils are phase shifted of $120^\circ$.

The pressure loss has been measured in the worst condition with all the coils short-circuited. The pressure loss is equal to $\Delta p=0.05\text{bars}$ at $30\text{L/min}$ in a $20\text{mm}^2$ pipe, corresponding to a minor loss coefficient of $K_{EH}=3.94$, and consistent with the standard minor loss coefficients of turbine flowmeters.

![Figure 3](image)

Figure 3. (a) examples of turbines characterized, (b) optimal design, (c) prototype – side view and top view, (d) output voltages at $10\text{L/min}$ in open circuit (3 adjacent coils) and (e) power management circuit managing the 9 coils and recharging a 2.4V NiMH battery

4. Power management circuit and delivered output powers

4.1. Power management circuit

The 9 coils have been connected to a storage capacitor $C_s=4.7\mu\text{F}$ through diode bridges (BAS70). A BQ25504 circuit has been used to recharge a 2.4V NiMH battery and placed right after $C_s$ (Figure 3e). The MPPT ratio of BQ25504 circuit has been set to 50% of the energy harvester’s open circuit voltage. Then, every 16s, a research of the MPPT is performed by the power management circuit, maximizing the extraction of energy from the water flow energy scavenger.

4.2. Output power, rotation frequency and power supply of WSN
The energy harvester connected to its power management circuit starts to recharge the battery from 1.2L/min (4.8µW) and up to 25.2mW are harvested at 20L/min. The output powers as a function of the water flow are introduced in Figure 4a. The rotation frequency of the turbine is almost linear with the flow, as presented in Figure 4b, and comprised between 2.5Hz@2L/min and 25.8Hz@20L/min. To note that the rotation frequency of the turbine is impacted by the extraction of energy (-20% when energy is extracted), but remains linear. Then, the rotation frequency of the turbine can be directly used to measure the flow. This has been done by adding a turn counter on one coil (Figure 3e): the turn counter generates pulses each time the coil voltage reaches a maximum. Finally, the pressure drop induced by the turbine and the energy extraction is lower than 0.05bars on the whole operating range (1.2L/min-30L/min), as targeted; and, one of the lowest of the state of the art.

(a) (b)

Figure 4. (a) output power vs water flow with the power management circuit – table & graph, (b) rotation frequency with and without energy extraction

This power has finally been used to supply a wireless sensor node (Bluetooth Low Energy) counting the number of rotations performed by the turbine (Figure 3e) and sending it by RF to a smartphone. The wireless sensor node is continuously connected to the 2.4V battery and exploits low-power modes to minimize its power consumption, waking up every 256 pulses thanks to a prescaler.

Conclusions & Perspectives

We have reported on a water flow energy harvester exploiting a horizontal axis turbine with distributed magnets at its periphery and coils at the outside of the pipe, with the aim of keeping a low pressure loss, typically under 0.1bar at 30L/min. The turbine has been experimentally optimized to maximize output powers and minimize head losses. The water flow energy harvester has been connected to a power management circuit to recharge a 2.4V NiMH battery from 1.2L/min (4.8µW); up to 25.2mW are generated at 20L/min. As targeted, the pressure loss is low, equal to 0.05bar@30L/min which corresponds to a minor loss coefficient of $K_{EH}=3.94$ for the energy harvester, and one of the lowest of the state of the art. Finally, the proportionality between the rotation speed of the turbine and the flow can be used to turn this energy harvester into an autonomous flowmeter. The next step is to test this water flow energy harvester in an irrigation system to measure and optimize flows and water consumption.

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