LOW HEAD MICRO-HYDRO TURBINES USED FOR EFFICIENCY INCREASE OF SOLAR POWERED IRRIGATION SYSTEMS
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MICRO-HIDROTURBINE DE JOASĂ CĂDERE UTILIZATE PENTRU CREȘTEREA EFICIENȚEI SISTEMELOR DE IRIGAȚII ALIMENTATE DIN PANOURI FOTOVOLTAICE

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ABSTRACT

This paper presents an improved solution for solar powered irrigation systems by integrating low-head micro-hydro turbines for energy recovery when discharging the water from the storage tank. The proposed solution is justified by the potential energy available when storing water in a tank using pumps powered by PV panels. This energy can be used to provide additional electricity when discharging the water, by placing a low-head micro-hydro turbine at the bottom of the tank. The energy produced can be used for pumping back a fraction of the consumed volume of water, or to ensure the pressure for longer distance irrigation networks. The energy surplus provided by the turbine is necessary especially when irrigating during mornings and evenings, when PV system power production is reduced. A low head micro-hydro turbine suitable for a small scale solar powered irrigation systems was tested on a dedicated testing stand in order to demonstrate its efficiency. The turbine was designed to generate 1 kW of power operating at 2.4 m head and 360 m^3/h flow. The tested model reached a maximum output of 526 W at 2 m head and 240 m^3/h flow. The rotor is made from thermoplastic by 3D printing, thus the flow through the turbine was limited to avoid damaging the blades. The experimental data was compared to the specific data of a small-scale solar powered irrigation system to determine the total efficiency of a hybrid irrigation system. The calculation takes into account the medium flow rate needed for turbine operation during irrigation phase, correlated with the electricity requirements of the pump for obtaining specific flows. The additional power output can increase the global efficiency of a solar powered irrigation system by feeding the electricity back to the pumping unit. For a PV power system that provides 20 kWh/day, the turbine can ensure around 22.5% of the energy needed for irrigation.

REZUMAT

Această lucrare prezintă o soluție îmbunătățită pentru sistemele de irigare cu energie solară prin integrarea micro-hidroturbinelor de joasă cădere pentru recuperarea energiei la golirea apei din rezervorul de stocare. Soluția propusă este justificată de energia potențială disponibilă atunci când se stochează apă într-un rezervor de acumulare, folosind pompe alimentate de panouri fotovoltaice. Aceasta poate fi valorificată prin amplasarea unei micro-hidroturbine de joasă cădere în partea inferioară a rezervorului. Astfel, turbina poate furniza energie electrică suplimentară la descărcarea apei. Energia produsă poate fi utilizată pentru pomparea înapoi a unei fracțiuni din volumul de apă consumat sau pentru asigurarea presiunii pentru rețele de irigare pe distanțe mai lungi. Surplusul de energie produs de turbină este necesar mai ales la irigarea dimineața și seara, când producția de energie a sistemului fotovoltaic este redusă. O microturbină pretabilă pentru sistemele de irigare de mică putere care utilizează energia solară a fost testată pe un stand dedicat pentru demonstrarea eficienței acesteia. Turbina a fost proiectată să genereze o putere de 1 kW funcționând la o cădere de 2.4 metri și un debit de 360 m^3/h. Modelul de turbină testat a furnizat o putere maximă de 526 W la o cădere de 2 metri și un debit de 240 m^3/h. Rotorul este realizat din termoplastic prin printare 3D; prin urmare, debitul prin turbină a fost limitat pentru a evita deteriorarea palelor. Datele experimentale au fost comparate cu datele specifice ale unui sistem de irigare la scară mică, alimentat din panouri fotovoltaice, pentru a determina eficiența totală a sistemului hibrid de irigare. Calculul ține cont de debitul necesar pentru funcționarea turbinei în faza de irigare, corelat cu necesarul de energie electrică pentru obținerea debitelor specifice. Energia electrică adițională obținută poate crește randamentul global al sistemului de irigare cu energie solară prin alimentarea pompei instalației. Pentru un astfel de sistem care furnizează 20 kWh/zi, turbina poate asigura până la 22,5% din energia necesară pentru irigare.

INTRODUCTION

The development of efficient and affordable PV systems is at hand for implementation in agriculture within solar powered irrigation systems. Moreover, some agricultural activities can be combined with solar systems, including crops, livestock, greenhouses and other agriculture domains that require electricity. Integrating renewable energy systems in agricultural infrastructure can be a promising solution for sustainable development. Moreover, considering that 70% from the world freshwater is used in agriculture (*UNESCO, 2019; Garcia-Espinal et al., 2024*), designing efficient technologies and equipment to be used for watering crops is of significant importance. For irrigation purposes, Lorentz solar water pumps provide special designed DC pumps suitable for operation in remote PV irrigation system. They can be used along with increased efficiency PV panels in portable systems that can be deployed wherever needed.

The pump can have a timer switch that offers the advantage of a time-controlled water-saving system. Precise timing must be set in accordance with the dependence of the solar cells power generation on the intensity of the sun radiation. The plants have to receive irrigation at the exact moment when the soil beneath is dry and needs watering the most. Water savings compared to general irrigation are achieved by using drip irrigation, thus avoiding watering unused areas and consequently weed growth *(Jandova et al., 2022).* The problem that arises when implementing PV systems for irrigation is that the timing of maximum power generation and the period needed for irrigation does not overlap. The solution for this issue is to use storage systems that can ensure the use of electricity at the time needed, when access to the grid is not possible. The most accessible solution is to use batteries for storing the energy during most active sunlight hours. Irrigation systems require reservoirs or tanks to be filled to ensure the proper flowrate when needed. Since potential energy is available when storing water in a tank, then a low-head micro-hydro turbine placed at the bottom of the tank can be added into the system to provide additional electricity when discharging the water. Considering that irrigation is performed during mornings and evenings, when the PV system power production is reduced, the energy surplus provided by the turbine is not only necessary, but makes the irrigation system more reliable and versatile. Among all types of irrigation systems, micro-irrigation is the most efficient way of irrigating crops according to *Evans et al., 2018*. The mentioned study shows that micro-irrigation has 60% less water waste comparing to the flood irrigation method. In this irrigation type, a water pump supplies water with pressure into the pipes and drippers. Although renewable energy-powered irrigation systems can improve the productivity of crops, the storage method to be used is still a challenge for large land areas *(Rejekiningrum et al., 2021).* Some studies have raised concerns about the water tank costs. *Soenen et al., 2021* conducted a techno-economic comparison between battery and tank-based water pumping systems, concluding that the lifecycle cost (LCC) of tank-based systems is 22% higher than that of battery-based systems in terms of using domestic water supply. An optimization study carried out by *A. Mazloumi et al. (2023)* on a water tank storage-based solar-powered system showed that the cost of water supplied in the case of tank-based systems was lower compared to battery or diesel-based systems, but the tank size was limited to 10 m^3. Therefore, the sizing of the tank can pose a challenge and the optimum storage volume must be identified. For example, building a 200 m^3 water tank to meet water needs cannot be feasible given the required cost of construction, materials, and labour (*Jahanfar et al., 2022*). In another study, the cost of the tank-based systems increases twice that of the battery-based systems when scaling up *(Attia et al., 2022*).

Given the aspects mentioned above, if the envisaged project requires water storage tanks, then the use of complementary low-head micro-hydro turbine can be a solution for increasing the global efficiency of the PV irrigation systems. The downside of using the turbine is the impact of the hydraulic parameters, resulting in a reduced flow rate downstream. The hydraulic head, as the main flow parameter, is strongly modified by the presence of the turbine which causes the main head loss of the entire installation and hence the reduced flow. This happens because the turbine transforms most of the water pressure into mechanical energy, which the generator then converts into electrical energy. This drawback is not significant where reduced flow is needed, as the case of drip irrigation. Likewise, some irrigation systems already have regulating valves for adjusting the flow, in order to have a longer irrigation time with a limited flow, to avoid the quick discharge of the storage tank. If needed, the local pressure loss can be overcome by an increased head or by reducing the friction loss in pipes. The different opinions regarding the selection of suitable storage for PV irrigation systems have determined the development of various optimization models. The total efficiency of the system can be increased by using an intelligent system based on SCADA or IoT, like the one depicted in *Kun et al., (2021)*.

Obstacles in expanding solar power generation to other purposes such as irrigations, involve the cost of solar cells and the dependency on weather conditions. The efficiency and performance of photovoltaic panels are tied to environmental variables, including climate factors.

Bălăceanu et al., (2024), highlighted the influence of the environmental factors on the PV panel performance and proposed the use of simulation software to ensure the best results in terms of efficiency when placing the panels. Recent developments in electronics allowed the implementation of a network acquisition system based on multiple sensors for automatic irrigation and fertilization, which can reduce water consumption by 74.92% (*Karunanithy et al., 2020*). *Matheswaran et al. (2021)* carried out a performance evaluation of standalone solar powered water irrigation system using DC pump. The good results recommend the system as a suitable candidate for the replacement of the existing grid connected pumping system. Few articles have been published on optimizing renewable energy-powered irrigation with battery or tank storage. The identified literature mostly uses the life cycle cost and either loss of load or loss of power supply probability as optimization criteria (*Khatib et al, 2021; Irandoostshahrestani et al., 2023)*. Another approach of storage suitable for irrigation systems is to use compressed air that enhances the environmentally friendly and efficient operation of drip irrigation systems. Conventional storage methods commonly used in photovoltaic-powered drip irrigation systems, such as elevated tanks and batteries, have notable technological, economic, and environmental limitations. Thus, a group of researchers presents a novel photovoltaic drip irrigation technology (CAES-PVDI) that uses solar energy as the exclusive source of power, enabling stable and cost-effective high-quality drip irrigation using compressed air *(Junjie et al., 2024).* The appropriate solution for storage must be customized depending on the project and takes into account many aspects such as: irrigated area, daily solar irradiation, investment and life-cycle cost, environmentally friendly solutions, environmental protection conditions. Each solution has advantages and disadvantages as stated by *Jahanfar et al., (2022)*, who performed a comparative study of solar water pump storage systems. The authors concluded that battery storage provide a constant power to pump, which results in a higher life span of the pump but has a significant replacement and maintenance cost. On the other hand, water tank storage has high life span, but presents challenges in building and installation of high-capacity water tanks.

None of the previous articles approaches the use of other means of producing electricity such as hydro-turbines connected within the PV irrigation system for increasing their efficiency. Clearly, some benefits can arise, as the global efficiency of the pumping system can be increased. However, a more in-depth analysis is required and will be performed in this paper, emphasizing the power output of water turbines operating in solar powered irrigation systems.

MATERIALS AND METHODS

The micro-hydro turbine suitable to use in a small scale solar powered irrigation system was tested on a dedicated stand specially designed for performing tests on low head turbines. These turbines are an environmentally friendly way to generate electricity by using a certain flow and a relatively low head of at least 1 meter, allowing water to pass through and be discharged at a lower level. Kaplan turbines offer good efficiency when operating at low head and despite their complexity, can be a suitable option for producing electricity within storage tank-based irrigation systems. Compared to other propeller or crossflow turbines, the Kaplan reaction turbine can be a solution at hand with sufficient performance even with fixed rotor blades and guide vanes. The turbine was designed, built and optimized using the methodology for conventional Kaplan turbines, noting that the installed flow rate and reduced head determined the optimization and adaptation of the rotor and stator according to recent parameters identified in literature *(Różowicz et al., 2019).* The overall dimensions were correlated with the water drainage section at the bottom of the upper tank of the test stand as recommended by *Peczkis et al., (2021)*. The microturbine is made up of 3 main elements:

1.The base plate - consists of a lower flange (5) which performs two functions: at the lower part it ensures the sealing of the flange (4) glued to the transparent plexiglass tube (2) by pressing it against the bottom of the tank (3) using six screws (15). At the upper part, this plate constitutes the support for the guide vanes system which are fixed between the upper and lower plates, thus strengthening the entire assembly.

2.The upper plate (8) - has attached the hydrodynamic profiled cone with a set of screws (13), which consists of a core (7) that directs the flow towards the turbine rotor and has a glass bearing (11) at the bottom, where the shaft goes through. The plate has 16 holes through which the screws (14) that fix the guide vanes (6) are screwed into the base plate. At the top, another bearing is provided for the shaft (9). A conical housing (10) is also centrally placed using a set of screws (12) for supporting the pipe that ensures the connection with the mechanical testing assembly and through which the turbine shaft (9) passes.

3. The turbine rotor (1) - is placed as a continuation of the hydrodynamic profiled cone and has 4 blades with a NACA 2412 profile, having a diameter of 228 mm. The rotor is supported by the hydrodynamic cone and rotates inside the transparent plexiglass tube with an inner diameter of 230 mm.

The plexiglass tube is 2 meters long and is immersed at the bottom in the lower tank. The rotor is fixed to the transmission shaft by a transverse screw and thus the rotational movement is transmitted to the mechanical testing assembly. The basic drawing of the turbine is shown in figure 1.

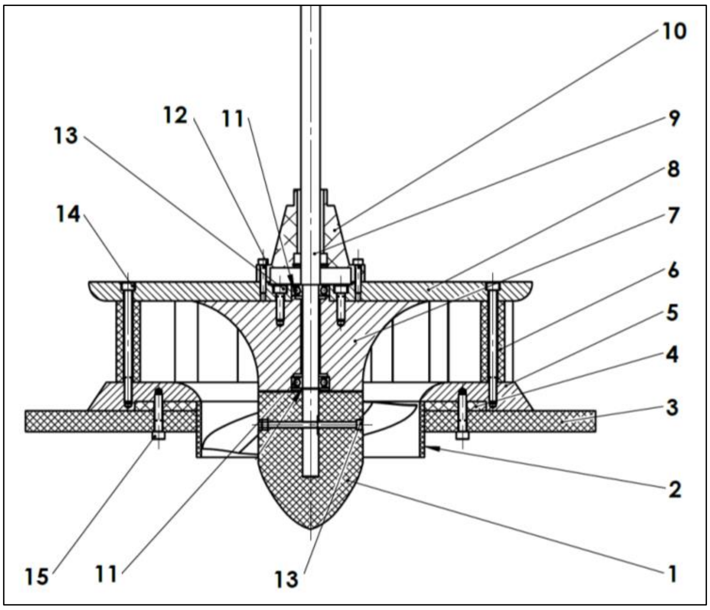

Fig. 1 – Low head micro-hydro turbine drawing

In order to calculate the rotor diameter, the statistical design method of Kaplan turbines can be used, based on the following relations according to *Anton, (1979)*:

$$D = a_D \frac{Q^{0,5}}{H^{0,25}} \qquad a_D = 0{,}37 + \frac{270}{n_s} \qquad n_s = 3{,}16 n \frac{Q^{0,5}}{H^{0,75}} \tag{1}$$

where D – turbine diameter, a_D – coefficient expressed in relation with specific speed, Q – flow through the turbine, H – head of the turbine.

By applying the above formulas, resulted a rotor diameter of 228 mm and a specific speed n_s of 476. The hub diameter is recommended to respect a certain ratio between the total surface area exposed to the flow and the equivalent surface area where only the blades are exposed to flow. Therefore, according to *Anton, (1979),* it is recommended that the ratio between the hub diameter and that of the rotor to be approximately 0.5 for a specific speed of approximately 500, resulting a hub diameter of 110 mm. Taking into account the distance of 1 mm between the tip of the blades and the wall of the draft tube, it results a 230 mm diameter of the plexiglass tube, around the rotor blades. The turbine draft tube is actually the transparent plexiglass tube that connects the two tanks of the testing stand. For the turbine model, a clear straight tube of plexiglass was chosen, although conical draft tubes with an opening angle of 10-12° contribute to a higher efficiency of the turbine *(Anton, 1979).* The straight clear tube was used in order to visualize the phenomena and considering that conical transparent tubes made from plexiglass were not available on the market. For the rotor blades design, the NACA 2412 hydrodynamic profile was chosen, which ensures good results in terms of lift coefficient. The rotor geometry was designed in 3D format and made of ABS on a 3D printer in the form of a compact part, with a transverse hole for the fixing screw. The overall drawing of the rotor in 3D view is shown in figure 2.

The guide vane system of the turbine is made of 16 blades that ensure de flow control and proper direction towards the rotor. In order to obtain maximum efficiency, the blade body must present minimal resistance to the current flow, resulting in a hydrodynamically optimized shape. The thickness of the profile must be large enough to withstand the water pressure in the completely closed position. The positioning angle α_D, between the tip of the trailing edge and the tangent to the circle drawn from centre and passing through its trailing edge must be precisely the angle α from the velocity triangle at the entrance of the rotor, in order not to cause sudden deviations of the current at the entrance. The dimensions of the guiding vanes system were chosen in such a way as to allow opening up to the maximum designed angle and closing to be done between the trailing edge of one blade and the inner surface of the next blade at a maximum of 0.25 of the chord length. For these blades, a symmetrical NACA 0018 profile was chosen that is slender enough to direct the water jet but with an adequate thickness to be securely in place with a M8 screw.

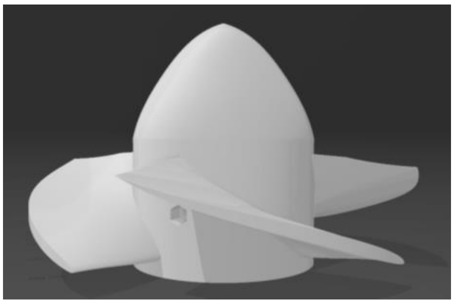

Fig. 2 – Rotor design for the low head micro-hydro turbine

The guide vanes are not adjustable during operation. Their position can be set at different angles before the turbine assembly. For the current testing, the placement angle was chosen to be 35°, according to the velocity triangle. The guide blade height is one of the parameters that, along with the angle α_D and the turbine speed, significantly influences the value of the flow rate Q and the circulation at the rotor entrance, respectively the energy conversion in the turbine *(Anton, 1979)*.

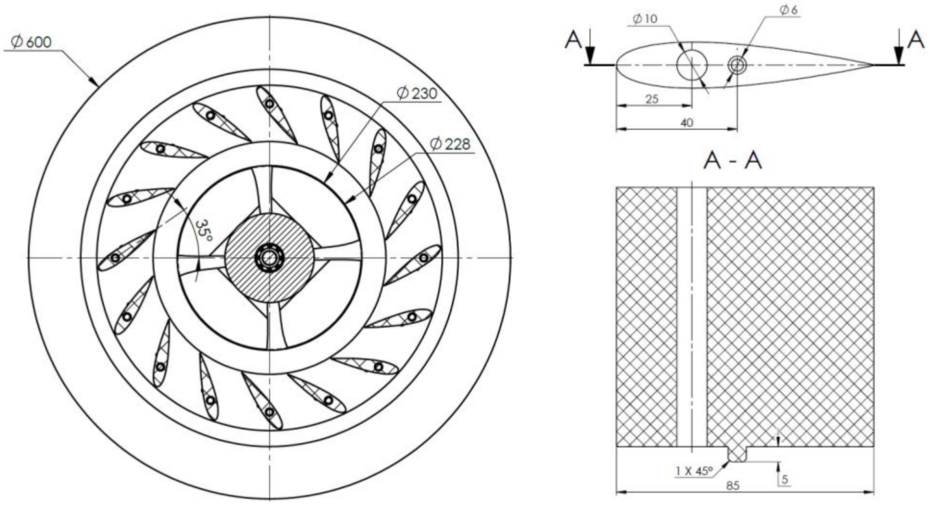

Fig. 3 – Guide vanes design of the turbine

The design of the guide vanes system is presented in figure 3. The base plate flange, the upper plate and the conical housing were made by CNC machining from aluminium. The rotor and the guide vanes were made from ABS using a 3D printer. Two glass bearings were used and the entire assembly was fitted using 16 screws (position 6 from figure 1). A rubber gasket was used to seal the bottom tank and was placed under the turbine assembly presented in figure 4.

Fig. 4 – Low head micro-hydro turbine assembly ready for testing

The turbine has a mechanical testing assembly attached to its upper part. It comprises of an assembly consisting of elastic couplings, a torque transducer and an electromagnetic brake and is capable of performing torque measurements up to 20 Nm and rotational speeds up to 4000 rpm. Figure 5 schematically shows the mechanical test assembly and the related components.

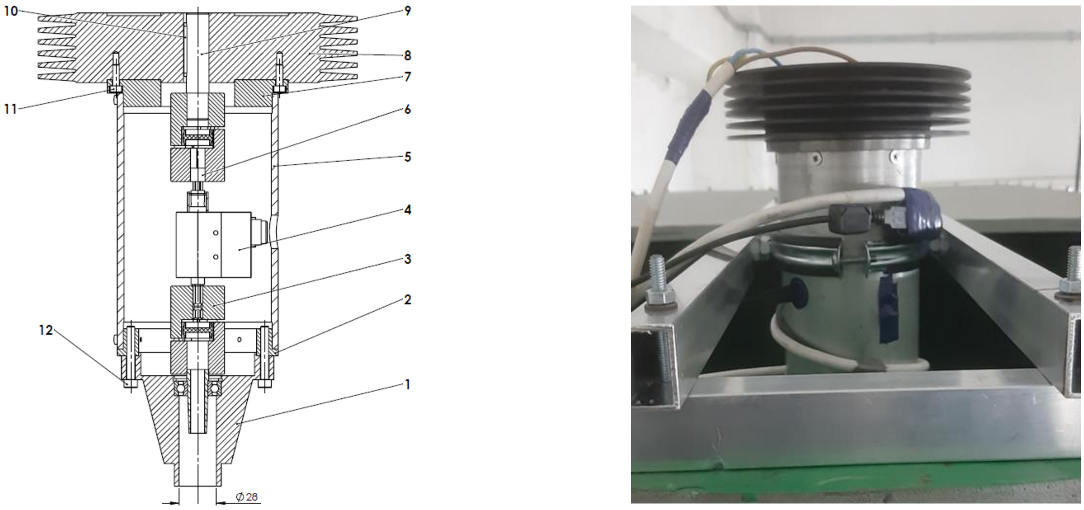

Fig. 5 – Mechanical testing assembly for the low head micro-hydro turbine

The assembly is mounted on the support rod using the conical part (1), which is connected to a plate (2) bolted into a cylindrical housing (5), on which an intermediate flange (7) is supported. This flange also represents the support for the electromagnetic particle brake (8). A shaft (9) transmits the movement from the turbine to this testing assembly through an elastic coupling (3) connected to the torque and speed transducer (4). At the top of the enclosure, the brake is also connected through an elastic coupling (6). The entire assembly is joined using a set of screws (11,12). The mechanical testing assembly is attached to the turbine and the entire assembly is lowered into the upper tank for integration into the hydraulic testing stand.

The turbine was designed to generate 1 kW of power operating at 2.4 m head and 360 m^3/h flow. The tested model reached a maximum output of 526 W at 2 m head and 240 m^3/h flow. The rotor is made from thermoplastic by 3D printing; thus, the flow through the turbine was limited to avoid damaging the blades. The turbine efficiency depends on the flow and head parameters. It can operate at partial load with reduced flow but the efficiency is highly affected where there is no adjustable blade system for the runner and the guiding vanes. Such a system is very complex, adds additional costs, is subject to more frequent wear and tear and requires periodic maintenance. Thus, it is not suitable for small scale microturbines due to the fact that the power increase is not significant in order to justify the additional cost of implementation and maintenance. The turbine can operate in water with sand or some small debris, but overtime, the turbine can be damaged.
To avoid such issues, a screen can be fitted at the discharge pipe that supplies water to the reservoir; it can be cleaned or changed periodically, depending on the water quality.

TURBINE TESTING

The turbine was integrated into a specially designed testing facility. The testing stand comprises of a pumping unit with three pumps (7.5 kW, 120 m^3/h) that circulates water between two overlapping tanks, the lower one with a volume of 3840 litres and the upper one with a volume of 2400 litres, located on a supporting metal structure *(Popescu et al., 2024)*. The pumping unit is connected using a hydraulic circuit made of pipes of 200 mm diameter, which has integrated an electromagnetic flow meter in order to permanently monitor the flow through the stand and turbine, respectively. The connection between the two tanks is ensured by a transparent plexiglass tube. The operation of the stand and data acquisition are performed using a programmable logic controller connected to a PC that can monitor the parameters and store them for further analysis. The low head micro-hydro turbine testing stand and its main components are presented in figure 6.

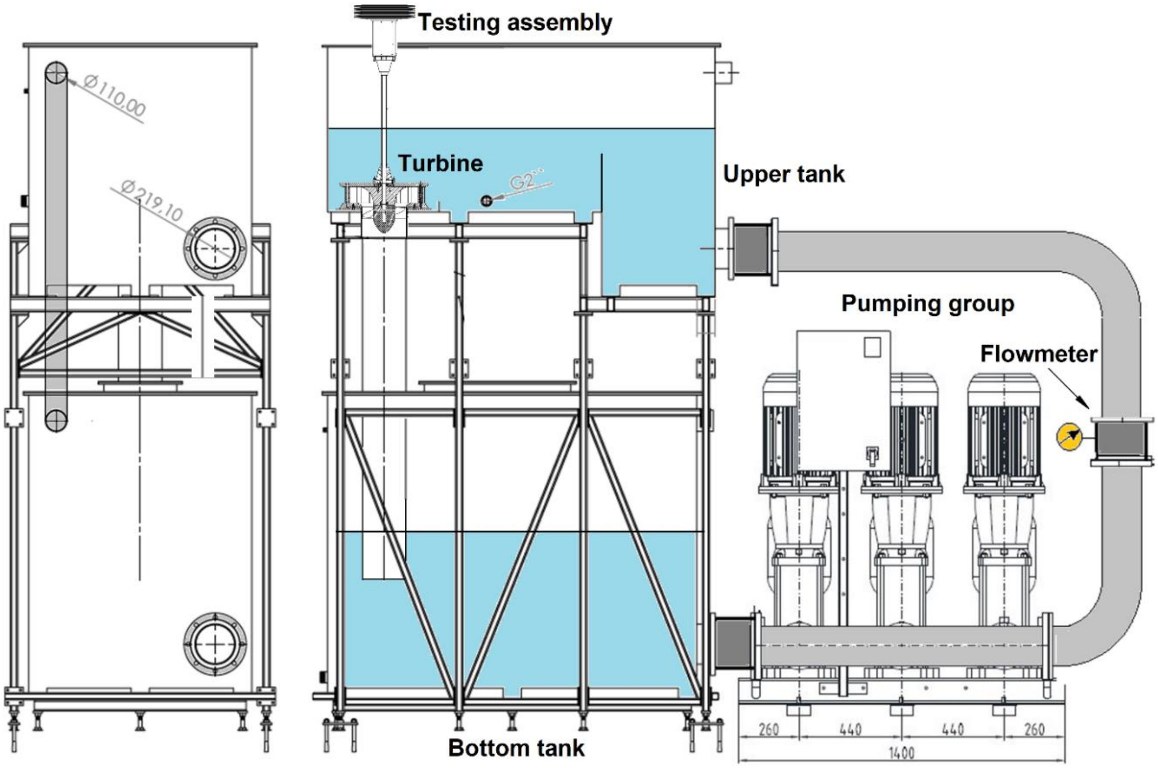

Fig. 6 – The testing stand of the low head micro-hydro turbine

The turbine was placed into position, according to figure 6, with the rotor aligned inside the transparent plexiglass tube. The testing procedure involved the following steps:

- Filling the lower tank to a maximum level, determined so that the volume of water ensures the filling of the entire installation (draft tube + pump + discharge pipe + buffer tank + vertical tube), providing a proper level in the upper tank of about 1 meter above the turbine;
- Setting the working flow rate and monitoring the rotational speed and torque of the turbine after stabilizing the flow regime; by slowly activating the brake, results a progressive increase in the useful torque at the rotor shaft;
- Progressively actuating the brake until the rotor stops and thus the maximum power of the turbine can be determined at a specific flow rate and head.

Figure 7 shows the turbine placed inside the tank, with the rotor protruding into the transparent tube, so that it can be observed during the experiments. In order to ensure a constant head for testing the turbine, the stand pumps are operated by an automatic flow rate adjustment system depending on the level set by the user, through a software application. To determine the energy parameters of the turbine, its shaft is coupled to an electronically adjustable electromagnetic brake and a torque/speed transducer. The recorded values are integrated into a data measurement and storage system in the form of a .csv database.

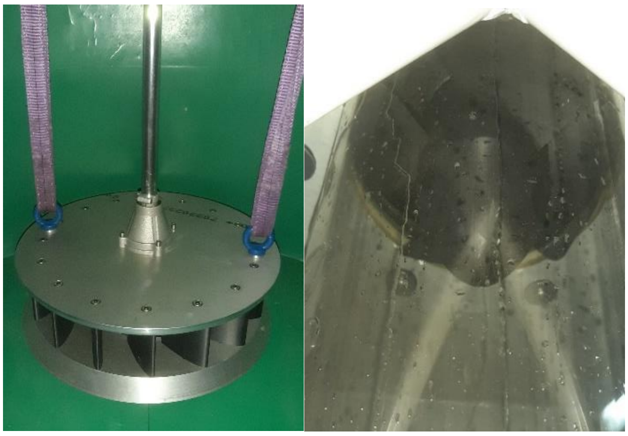

Fig. 7 – The low head micro-hydro turbine during mounting

Aspects from the turbine testing were captured in Figure 8 with details on the data acquisition system, the electromagnetic flow transducer and the transparent Plexiglas tube through which the wake caused by the rotor movement can be observed.

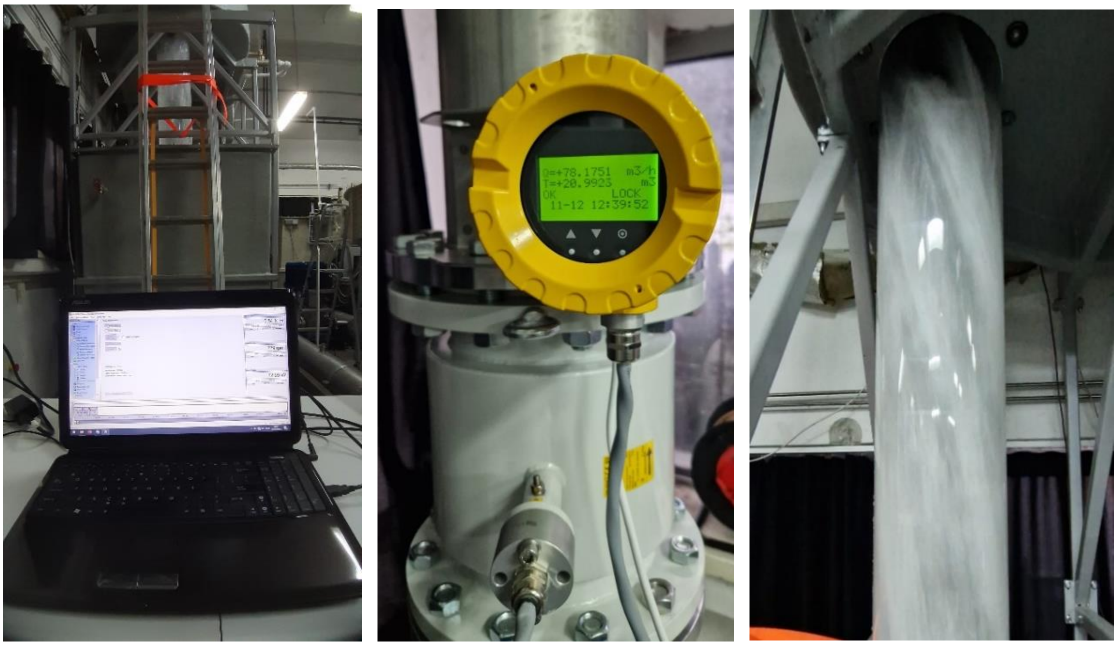

Fig. 8 – Testing of the integrated low head micro-hydro turbine

The rotor used for the experiments, made from ABS thermoplastic, withstood the tests without any damage. For evaluation purposes, this type of material can be used given the reduced operation time, but in real operating conditions, other materials must be considered, such as aluminium or stainless steel. Plastic rotors can be easily damaged by debris and are more prone to wear. The guide vanes and the draft tube should also be manufactured from strong, corrosion resistant materials. The draft tube of the testing stand was made from plexiglass in order to observe the flow around and after the rotor. This material is suitable only for laboratory conditions; for full-scale turbines, this tube must be replaced with a metal pipe.

RESULTS

The maximum flow considered when testing the turbine was of 240 m^3/h, along with a head of 2 meters. The results demonstrated the importance of operating as close as possible to the design conditions, otherwise the efficiency can be greatly diminished. The objective of the tests was to study how the energy conversion occurs at the rotor level in order to improve its efficiency and determine how a low head micro-hydro turbine can be used for efficiency increase in solar powered irrigation systems. In addition to the hydraulic parameters that are critical for maximizing power, the resistant torque of the generator coupled to the turbine must be also taken into account.

The mechanical torque at the shaft resulting from the turbine-generator interaction determines a certain rotational speed and the optimal operating point must be identified through experimental tests. The high torque at the shaft breaks the rotor and a low rotational speed negatively influences the power output. On the other hand, the maximum speed is obtained at idle operating point and the generator load must be adapted to maintain a relatively high rotational speed, while maintaining a useful torque. Thus, such systems require a dedicated power converter unit based on a MPPT algorithm using perturb and observe method, integrating boost and buck converters for powering a considered load (*Chihaia et. al., 2020).* The robust power peak seeking control algorithm also presents a good option for attaining a high operating efficiency by achieving maximum power point tracking through a line search triggered by real-time measurements *(Naik et al., 2024)*. These types of electronic controllers are also used for hydrokinetic turbines and have proven their functionality. The testing results of the turbine are synthesized in the diagram in figure 9, which shows the power output depending on the rotational speed of the rotor.

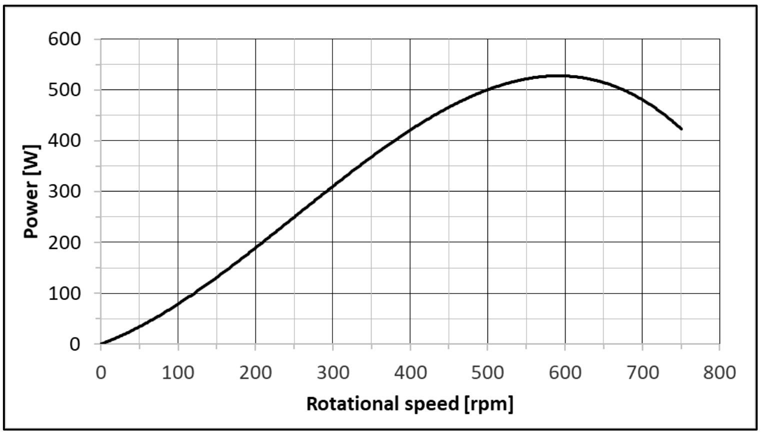

Fig. 9 – The power diagram of the micro-hydro turbine

The curve shows a peak of 526 W at around 600 rpm for the turbine tested at a 240 m^3/h flow and 2 meters head. The efficiency varies depending on the available flow and head reaching up to 40% at the highest power value, as shown in figure 10.

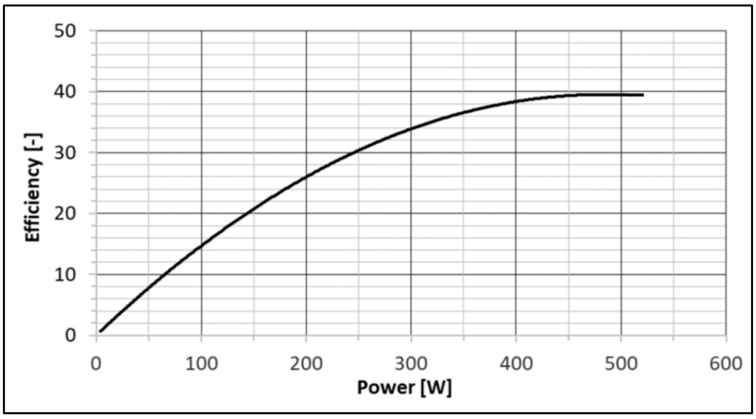

Fig. 10 – Efficiency curve of the micro-hydro turbine

The results demonstrate that a turbine can produce a power of around 500 W placed beneath a tank suspended at about 2 meters, where sufficient flow is ensured, as the case of irrigation systems using storage tanks. This power output can increase the global efficiency of a solar powered irrigation system feeding the electricity back to the pumping unit. In order to demonstrate the feasibility of the system, a reduced scale solar powered irrigation system with a turbine embedded can be designed and studied. The basic operating principle of such systems is presented in figure 11.

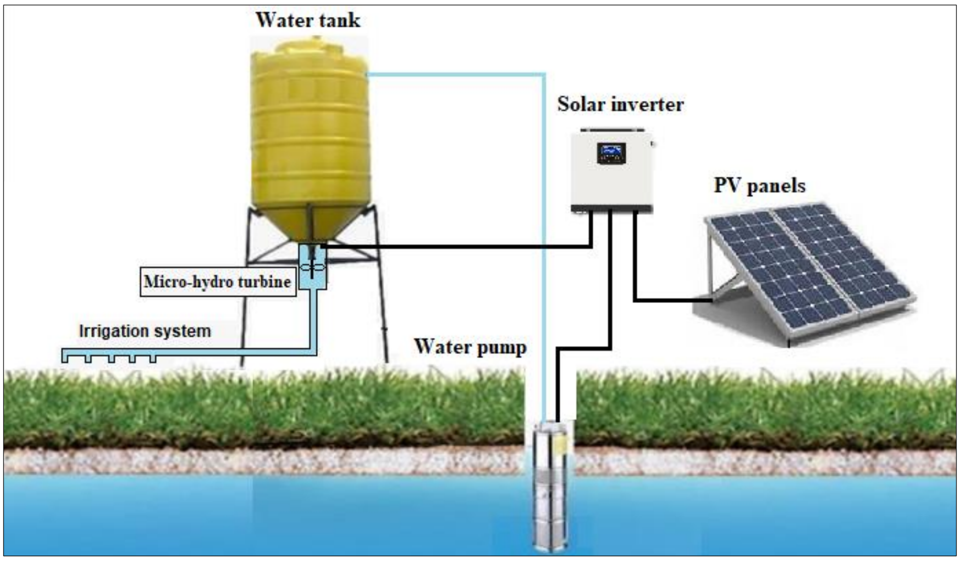

Fig. 11 – Reduced scale solar powered irrigation systems with embedded low head micro-hydro turbine

The water pump creates pressure that fills the tank when supplied with electricity from PV panels. The solar inverters manage the power received by the pump according to the power supplied by the panels, and the batteries state of charge (if the system is equipped with storage). The micro-hydro turbine is placed beneath the tank and supplies electricity when water flows for irrigation. It is also connected to the solar inverter and thus increases the overall efficiency of the system. In order to perform efficiency calculations for the proposed system, the parameters of the involved devices are presented below:

- **PV panels**: 5 x 500 W_{peak}, 2094 x 1134 x 35 mm, half-cut, monocrystalline cells, 21% efficiency;
- **Electric pump** CBM 303/A, 2.2 kW power, 42 m^3/h, head up to 22 meters, single-phase 230V. Another type of pump that can be used for DC application is Lorentz S1-700 model, with a maximum flowrate of 10m^3/h and a power of 750 kW. In this case, 3 pumps can be deployed for ensuring 30 m^3/h at around 2.25 kW similar with the a.c. version.
- **Solar inverter/hybrid inverter**: 3200 W maximum power, off-grid type, single phase 230 Vac output, input from PV panels and hydro-turbine using a power controller and voltage stabiliser;
- **Micro-hydro turbine** of 1 kW maximum power, obtainable at 2.4 m head, with a flow rate of 360 m^3/h and a rotational speed of 850 rpm. The turbine will be connected to a permanent magnets synchronous electric generator with the rated power of 1 kW at 850 rpm, single phase output. Although the generator voltage will be around 230 Vac, due to the variation of the flow parameters, the turbine will have speed variations and thus the output voltage will be affected. To avoid any issues and to safely connect the solar inverter, a voltage stabilizer must be inserted in between in order to handle the voltage fluctuation in the range of 120 V-270 V ensuring a stable output of 230 Vac. If a DC system is considered, then the electric generator will have to comply with 24/48 Vdc voltage with a DC-DC buck-boost converter added to supply a constant voltage.

For an irrigation system, any type of PV panel is suitable as long as the string of panels are compatible in terms of voltage and current with the selected inverter. Lightweight PV panels are at hand because they are easy to handle and can be integrated into a mobile system. A renewable energy mobile containerized system can be deployed for off-grid application based on PV panels and micro-wind turbine in order to directly provide the energy via DC-DC power supply.

This type of application can be intended for irrigation and fertirrigation, in semi-dry and dry-sub-humid arid climates and was developed within a project that envisaged innovative technologies for crop irrigation, *(Onose et al., 2020).*

In terms of energy balance, if a daily electricity production from PV panels of 20 kWh is considered, it results in approximately 9 hours operation time of the 2.2 kW pump. If the flow through the turbine is ensured in the range of 200 to 300 m^3/h flow and a minimum of 2 meters head, then the energy produced can be estimated to be around 4.5 kWh. Thus, across 24 hours, the turbine can ensure about 22.5% of the electricity needed for irrigation.

CONCLUSIONS

The work presented in this paper demonstrated the benefit of using low head micro-hydro turbines for increasing the efficiency of solar powered irrigation systems that use storage tanks. Testing performed with such a turbine in laboratory conditions using dedicated testing stand highlighted the fact that it can supply up to 526 W at 240 m^3/h and 2 meters head, making it a feasible solution for a small-scale irrigation system. The contribution of the turbine is useful because energy surplus is needed especially when irrigating during mornings and evenings, when the power production of the PV system is reduced. The additional power output can increase the global efficiency of a solar powered irrigation system, feeding the electricity back to the pumping unit. For a PV power system that provides 20 kWh/day, the turbine can ensure around 22.5% of the energy needed for irrigation. Given the aspects mentioned above, if the envisaged irrigation systems require water storage tanks, then the use of complementary low-head micro-hydro turbine can be a solution for increasing the global efficiency of the PV irrigation systems. The turbine converts the pressure energy of the stored water into mechanical energy and is suitable where reduced flow is needed, as the case for drip irrigation. Further research must be carried out in order to correlate a proper storage solution for a certain PV panel configuration used in an irrigation system. Renewable energy systems based on PV panels represent the best choice for powering a remote irrigation system without access to the grid. Improved solutions are being continuously developed worldwide and the work presented in this paper gives a new perspective on how to optimize the operation of solar powered irrigation systems in terms of energy efficiency.

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