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Research Paper

Lab performance testing of a small Banki-Michell hydraulic turbine for remote applications

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A B S T R A C T

For decades, hydropower has been the most important renewable energy source in the world. The use of Banki-Michell turbine (B-M) in small hydropower constitutes an attractive solution for rural electrification in developing countries and off-grid applications. This robust turbine is easy to design and to construct and not expensive. A test bench (JLA 29) for remote applications was installed at the Aero-Thermo-Mechanics Department of the Brussels Polytechnic School of ULB to test this type of turbine. This paper aimed to present the efficiency results of the installed Banki-Michell turbine test bench for remote applications and these results helped to design a typical turbine adapted for remote sites such as the Ryamukona site located in Burundi. Two series of B-M turbine tests were carried out, by varying the flow rate using the turbine control valve opening placed inside the distributor and also by controlling the turbine speed using a Sinamics S 120 drive. The efficiency of the turbine varies between 40 and 60% for a flow range varying between 15 and 20% of the nominal flow. According to the tests made with a discharge above 20%, the efficiency of the turbine can reach easily 75 %. Based on this turbine efficiency, a typical B-M turbine of an electric power of 79.5 kWe turbine was designed for Ryamukona site which is a remote site located in Burundi.

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1. Introduction

Hydropower is a renewable and low polluting energy source that produces electrical energy using an equipment showing a high global efficiency [1]. It shows low operating and maintenance costs and offers reliable and flexible operation with a very long lifetime (30-40-50 years or even more) [1]. Production at large scale of hydroelectricity needs large investments and can cause negative social and environmental effects, such as population and fish migration. Developing countries can avoid large investments in hydroelectricity plants, flooding of large land areas and the dramatic changes imposed to aquatic ecosystems by exploiting the potential of small hydropower for small rivers [1] instead of large hydropower plants.

Small hydro turbines, such as the Banki-Michell or crossflow turbine, are simple to design and manufacture [2, 3]. In comparison with other conventional turbines that are also used in hydropower generation, such as Francis, Turgo and Pelton, the advantage of the Banki turbine is that its performance remains quite constant over a large range of the discharge rate and the maintenance of the turbine can be done easily by local engineers and technicians [2, 3]. Crossflow turbine is a two-stage turbine in just one wheel and the contribution of power transfer in each stage has been a subject of theoretical and experimental investigations for some decades, with results that vary significantly among the investigators [4]. Several studies have been carried out on the Banki-Michell turbine, we can cite the design of a new Banki-Michell type turbine for electricity production from pressurized pipes proposed by Sammartano et al. [5], the experimental and numerical analysis made by Sinagra et al. (2015) [6], the numerical and experimental investigation of a crossflow water turbine made by Sammartano et al. (2016) [7], the design of Cross-flow turbine for variable operating conditions made by Sinagra et al. (2014) [8].

This paper aims to present a test bench installed in the ATM laboratory of the Université Libre de Bruxelles (ULB) of a typical Banki-Michell (B-M) turbine named JLA 29. The Banki-Michell turbine took the name of the Belgium company that manufactures this turbine, JLA Hydro. The experimental system is made of lower and upper reservoirs, PVC pipes of a diameter 300 mm, a JLA 29 turbine of a maximum mechanical power of 7.3 kW, an induction motor to load the turbine and a speed controller made by a Sinamics S 120 drive. The water was supplied in the upper reservoir by an isolated pump, driven by an electric motor of 9.5 kW maximum power. The main measurement devices were made by a volumetric flow meter, a torque and speed meter, a pressure sensor, a thermocouple sensor to measure the temperature and the acquisition was managed by the interface of LabView 2017. Two series of tests were realized in order to analyze the performance of the Banki-Michell turbine. It is to be noted that, beyond 20% of the nominal flow, the turbine efficiency is around 70% and the efficiency can reach 74 – 75% when the test is done with at least 50% of the nominal flow. The tests were carried out either by controlling the supplied flow rate or the rotational speed of this impulse turbine.

2. Experimental facility

Experiments were performed in the hydraulic laboratory of the department of Aero-Thermo-Mechanics (ATM) of the Université Libre de Bruxelles (ULB). The system is made with a typical Banki-Michell turbine named JLA 29 which is illustrated on Figure 1. The JLA 29 turbine is namely composed by two components namely the nozzle and the runner. The water passes through the rotor twice, from the periphery toward the center, and from the inside to the outward periphery. Theoretically, the first passage of water in the rotor resulted to 75% of energy transfer while the second passage of water resulted of 25 % of energy transfer [2, 3].

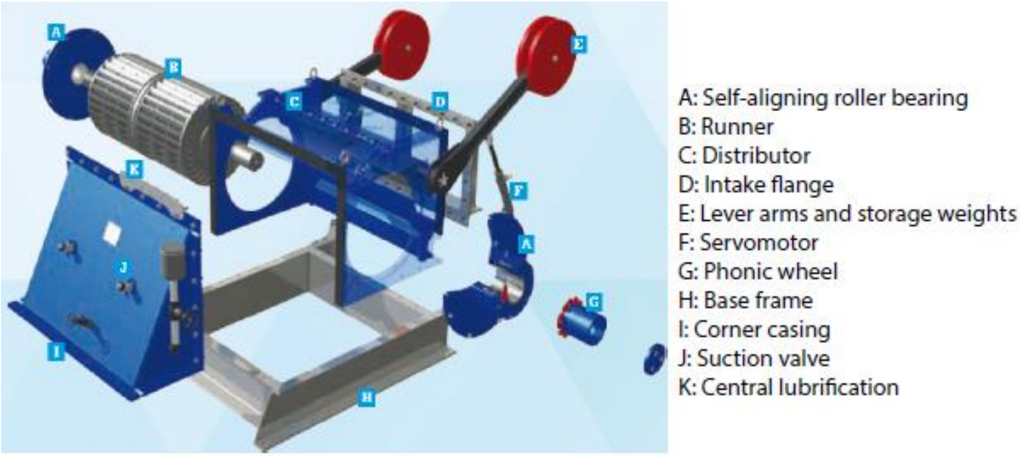

Fig 1. Detailed components of JLA 29 turbine [9].

In addition to the turbine, the Figure 2 shows that system is made of water pumping to charge the water in the upper reservoir and the JLA 29 turbine is connected to an asynchronous motor. The system operates in open loop mode due to the inadequate flow rate provided by the pump, which has a flow rate of 38.9 l/s while the turbine requires a flow rate of 195 l/s when the turbine operates with a head of 5.0 m. The turbined water is ejected through an exit canal located in the laboratory. The inlet pressure of the turbine is given by the pressure exerted by the water under the effect of the head difference between the upper reservoir and the rotation axis of the turbine. The channel and the tank used as the upper reservoir have approximately a volume of 28 m^3.

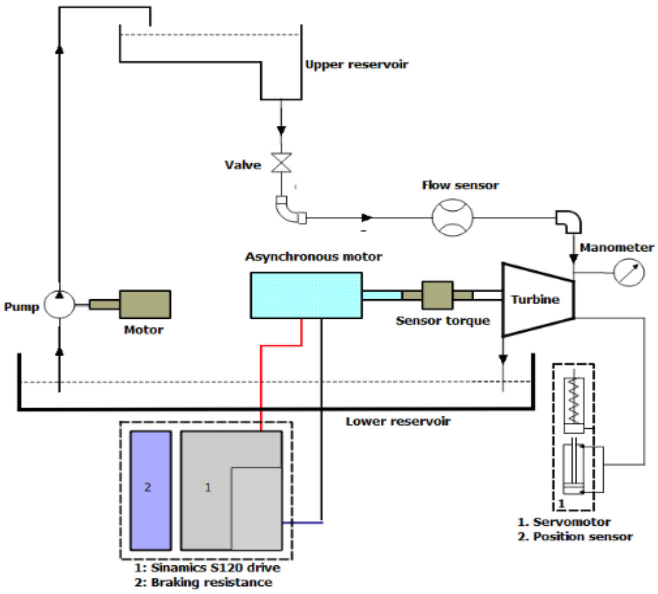

Fig 2. Global view of the ULB-ATM experimental facility.

The turbine is connected to the upper reservoir via a 10 bar PVC pipe with a nominal diameter of 300 mm. The design of the penstock took into account the nominal flow rate of the turbine and the energy losses caused by the configuration of the pipe system from the tank to the admission element of the Banki turbine. Then, the energy losses of the system is about 0.63 m. In order to investigate the performance of the Banki turbine, measurements of the physical parameters of the turbine are done: the flow rate, the inlet pressure in the upstream of the turbine, the torque and the rotational speed on the axis of the turbine.

The turbine efficiency is then computed through the ratio between the mechanical power and the hydraulic power P_h defined by Eq. (1).

$$\eta_t = \frac{P_m}{P_h} = \frac{T.\omega}{\rho.g.Q.H} \tag{1}$$

with η_t the global mechanical turbine efficiency, Pm the mechanical power [W], Ph the hydraulic power [W], T the mechanical torque [Nm], ω the rotational velocity [rad/s], Q the discharge [m^3/s], H the net head [m], ρ the water density [kg/m^3] and g the gravity acceleration [m/s^2].

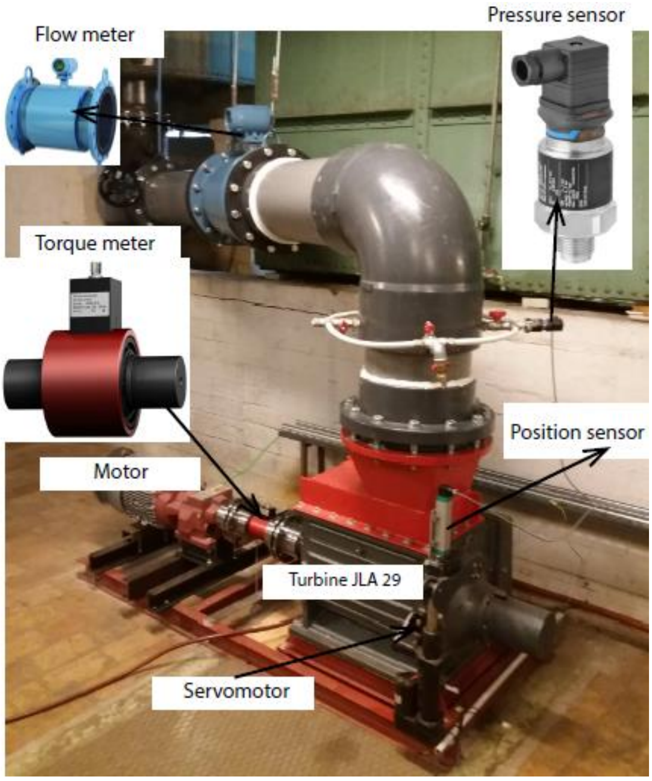

Fig 3. Test stand equipped with JLA 29 turbine.

The water flow in the turbine was measured by a Rosemount 8750 W Magnetic Flowmeter, which creates an electromagnetic field profile that ensures accuracy in the turbulent, transitional and laminar flow regimes. The flow meter has an accuracy of ± 5% of maximum value [10]. The pressure at the inlet section of the turbine is measured by a Cerabar PMC11 made by Endress+Hausser®. The pressure meter is located at the upstream of the turbine and the pressure meter is calibrated to make measurements in the range of 400 mbar to 8 bar. As mentioned in Eq. (2), the hydraulic head H is then equal to the sum of the pressure head $\frac{p}{\rho.g}$, the kinetic head $\frac{v^2}{2.g}$ and the elevation head z. The hydraulic head consists of the height difference between the water level in the upper reservoir and the central axis of the turbine [11]. In the case of this experimental system, we used an existing upper reservoir and a channel to evacuate the turbined water, which caused the limitation of the hydraulic head to 5 m.

$$H = \frac{p}{\rho g} + \frac{v^2}{2g} + z \tag{2}$$

As depicted in Figure 3, JLA 29 turbine is coupled on the same axis to an asynchronous motor, which is a Siemens geared motor with a reduction ration of 5.17. According to the nameplate of the motor, it is characterized by a 1500 rpm rotational velocity, a frequency of 50 Hz and 7.5 kW of active power. In order to avoid the runaway of the turbine, the generator is controlled by mean of a Sinamics S120 drive. This drive used to control the turbine speed includes a power module that controls the induction motor and electricity supplied to the dissipation resistance.

A torque meter, installed between the turbine and the asynchronous generator, is calibrated to measure the shaft torque of the turbine up to 1000 Nm [12]. The torque is transmitted from the turbine shaft to the generator shaft. On another side, the Dataflex 42 is calibrated to measure the rotational speed in a range from 0 to 2000 rpm. The used torque meter is a typical device made by KTR and the accuracy of the device is about 0.1 % of the maximum limit. The torque sensor is connected to the shaft by means of two typical flexible couplings Radex® N, which is a flexible coupling rigid in torsion that allows a compensation of the misalignment of the shaft caused by expansion of the turbine shaft for example. According to the valve opening, a linear sensor from Gefran is used to control its position inside the nozzle. Such a sensor is characterized by a piston stroke of 100 mm and moving at a maximum speed displacement of 10 m/s [13]. In order to analyze the water temperature at the inlet and outlet of the turbine, two thermocouples were placed downstream and upstream of the turbine. Finally, the acquisition and control system is managed by a LabView 2017 software, to process voltage into measured variables and process the performance parameters of the turbine. Additional parameters are calculated by the program, such as the hydraulic power P_h, shaft power P_m, the efficiency η_t and the effective head H for the turbine. Table 1 illustrates the description of the used devices on the test bench and their range of precision.

According to error analysis, Dieck (2007) and Biau (2011) [14, 15] states that the uncertainty interval u of each measurement is composed of two components, the systematic error and the random error as calculated by the Eq (3). Given a function F of n parameters, the calculation of the systematic error B_F is carried out according to the formula of Eq. (4).

The random error S_F is realized through the formula of Eq. (5) and shows that the random error for a function F is the ratio between the standard deviation σ_F and the square root of the total population number n_F. However, systematic errors are mitigated during calibration and installation of the sensors while random errors are also minimized during the acquisition programming.

$$u = \pm k_{95}\sqrt{(B_F/2)^2 + S_F^2} \tag{3}$$

$$B_F = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial F}{\partial x_i}\Delta x_i\right)^2} \tag{4}$$

$$S_{\overline{F}} = \frac{\sigma_F}{\sqrt{n_F}} \tag{5}$$

Results are saved in an Excel file for which the program took a mean of 100 samples. For instance, tests done at rotational speed close to the rated one, the obtained efficiency is accompanied with an absolute uncertainty and relative uncertainty of ± 0.18 and 2.2% respectively.

Table 1. Details of the characteristics of measuring instruments.

Instrument description	Quantity to measure	Range	Uncertainty (%)
Rosemount 8750 W magnetic flow meter	Water flow rate into the turbine	0-200 l/s	± 0.25
Cerebar PMC11 pressure transducer	Gauge pressure at turbine inlet	400 mbar-8 bar	± 0.5
Dataflex 42 torque sensor	Torque of the turbine	± 1000 Nm	± 0.1
	Rotation speed	Max: 2000 rpm	± 0.1
Termocouple K	Inlet and outlet temperature	Max: 1100°C	0.5 to 5°C
Gefran linear transducer	Stroke	0-100 mm	± 0.05
NI DAQ usb 6211	To send voltage signal to computer	± 10 V DC	n/a

3. Control system

Actually, micro-turbines such as Banki-Michell can operate connected to an existing electric network in which the frequency is maintained by the network. On another side, the Banki-Michell turbine can operate as an off-grid turbine and the generated electricity is consumed locally. In this case, the frequency is linked to the one required by the household appliances and it is controlled via controlling the rotational speed of the turbine.

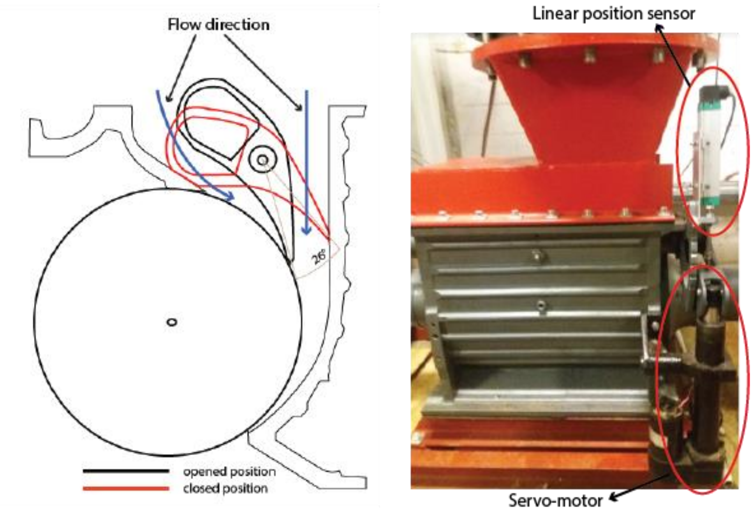

Fig 4. Components of the turbine flow control system.

In the case of the Banki-Michell turbine test bench installed at ULB-ATM, tests are carried out by controlling two parameters such as the water flow and the turbine speed. Related to the water flow control, nozzle includes a control valve that controls the quantity of water jet leading the runner of the turbine by opening or closing the valve. This typical control allows the turbine to operate over a wide range of water flow according to the available water. Figure 4 shows that the maximum angle between the wall edge of the injector and the body edge of the open valve is equal to 26°. The opening of the injector valve is controlled by a servo-motor that is controlled by a Gefran linear transducer. This linear sensor is characterized by a stroke of 100 mm. Then, the shaft power and the hydraulic power can be defined as function of the position of the control valve. Related to the speed control, the turbine speed is controlled via a Sinamics S 120 drive that controls the motor speed connected to the turbine via a flexible couplings Radex® N. The motor speed N (rpm) is linked to the frequency according to the equation 6, where f is the frequency (Hz) and p the pair of poles of the generator.

$$N = \frac{60.\mathrm{f}}{\mathrm{p}} \tag{6}$$

According to the Sinamics S 120 drive, Figure 5 shows the connection of the main parts of the used S120 drive, which is mainly composed by:

- ✓ An active interface module: it is connected to the AC grid, the module integrates a clean power filter to protect the system against harmonics,
- ✓ An active line module: it is used to allow the conversion from AC to DC currents which is distributed across DC bus to the motor module,

- ✓ A motor module: it consists in a power electric drive circuit and control of feedback interfaces for the operation of one or more induction motors.

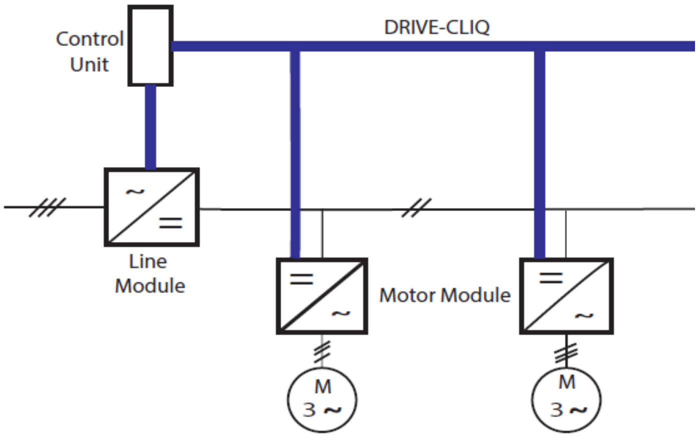

Fig 5. Schematic view of the Sinamics S120 drive connection [16].

4. Theoretical framework of Banki-Michell turbine

The Banki-Michell turbine also called Crossflow turbine consists of a runner and a nozzle as illustrated on the Figure 1. The nozzle has a rectangular cross section and leads the water jet into the runner at the same angle of attack. The runner of crossflow turbine consists of longer circular blades in the transverse direction that is welded onto the two or more circular discs [17]. The shaft of the B-M turbine can be connected to another rotating machine depending to the need, such as need of electricity production, water pumping, milling machine etc. The JLA 29 turbine is a good choice for small hydropower applications and it is designed to operate in head range of 2.5 m to 80 m [9]. In the case of the test bench installed at ATM Many studies were conducted on the main topic of Banki-Michell (B-M) turbine efficiency focused on low head operating conditions. The special feature of the Banki-Michell turbine consists in that the shape of the efficiency curve remains flat over a wide range of flow rate [2, 18, 19]. Mockmore and Merryfied (1949) made experimental tests on a B-M turbine characterize by a runner which has a diameter of 332 mm and a width 305 mm. The turbine reached a maximum efficiency of 68% when operating with the flow rate equal to 62 l/s at a head of 5 m [3]. The study made by Aziz and Desai focused on 27 crossflow pico-turbines at hydraulic laboratory from Clemson University and got a maximum efficiency in the range of 60 to 70% [20]. Those studies were made when taking into account the number of blades, the ratio between internal and external diameter and angle of attack. A research conducted by Olgun on 4 crossflow turbines revealed that the turbines can reach an efficiency 72% efficiency at a head of H = 8.0 m [17].

5. Experimental results and discussion

For the Turbine JLA 29, a preliminary test and two series of tests were performed in order to analyze the performance of the turbine according to the flow variation. For the preliminary test, the turbine efficiency is plotted in function of flow variation. The flow variation is ensured by varying the position of the control valve inside the injector in the range of 30 to 100%. In this case, the braking of the turbine was done automatically using a braking curve implemented with the drive control chart (DCC), which is a software integrated into the Starter of Sinamics S120 drive. As depicted in Figure 6, the turbine efficiency varies between 40 and 60 % for a nominal flow varying from 15 to 20%. Beyond 20% of the nominal flow, the turbine efficiency is around of 70% and it can reach 74 % when the test is done with 50 % of the nominal flow. During this test, the rotational speed of the turbine varies depending on the available quantity of water. The test bench installed at ULB-ATM lab is equipped with a Banki-Michell turbine operating with a single control valve. Based on the literature of the turbine Banki-Michell such as [3, 18], we can conclude that the turbine efficiency curve remains more or less flat for operation with a flow rate greater than 50 % of the nominal flow rate.

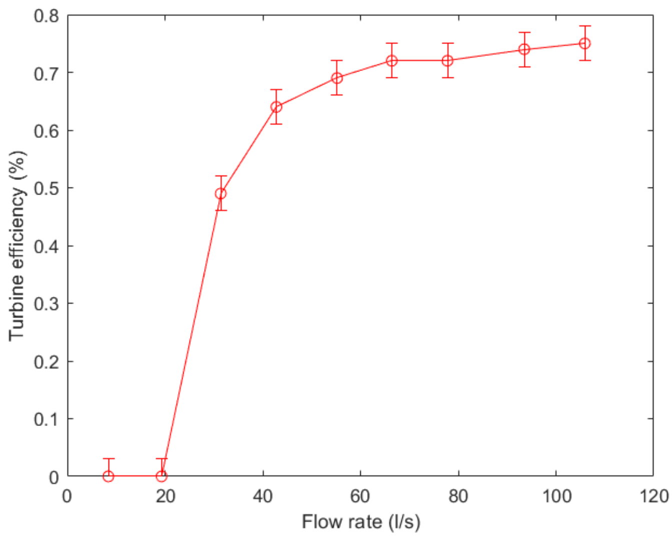

Fig 6. Turbine Efficiency curve of JLA 29 turbine.

Series of tests were performed when the JLA 29 turbine operates at constant speed while varying the openings valve from 30 to 100 %. The turbine speed was fixed via a control panel of the Starter which is a software that pilots the Sinamics S120 drive. The turbine efficiency is obtained as a function of the flow rate for a certain rotational speed.

As illustrated at Figure 7, the measurements of the turbine efficiency were done when varying the rotational velocity in the range from 121 to 294 rpm. The turbine efficiency results have shown that optimal energy transfer occurs when the turbine rotates at a rotational speed close to the nominal speed of the JLA turbine. The turbine efficiency varies in the range of 61 to 75% when the turbine rotates at 294 rpm. Notice that over a head of 5 m, the JLA 29 turbine is designed to rotate at 292 rpm.

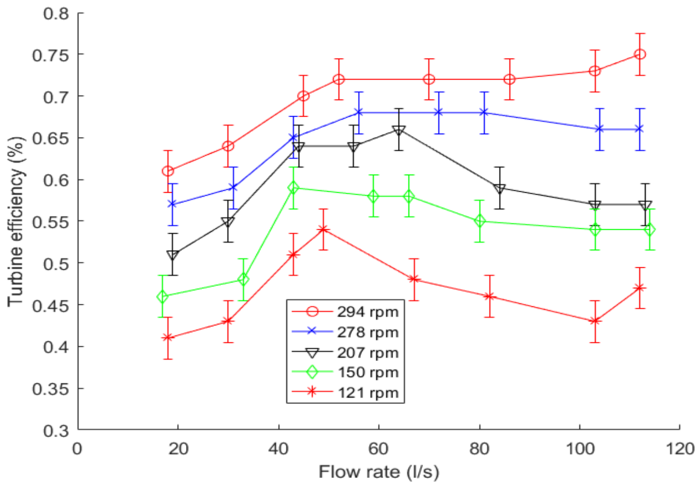

Fig 7. Turbine efficiency curves at constant rpm.

According to the Figure 7, the JLA 29 turbine has a good efficiency equal or greater than 60% for operation at rotational speed close to its optimal speed when test are done with valve openings equal or greater than 30%. In the case of the produced mechanical power, Figure 8 shows that the extracted mechanical power varies in the range of 0.5 to 3.2 kW. The mechanical power varies linearly according to the quantity of water turbinated by the turbine.

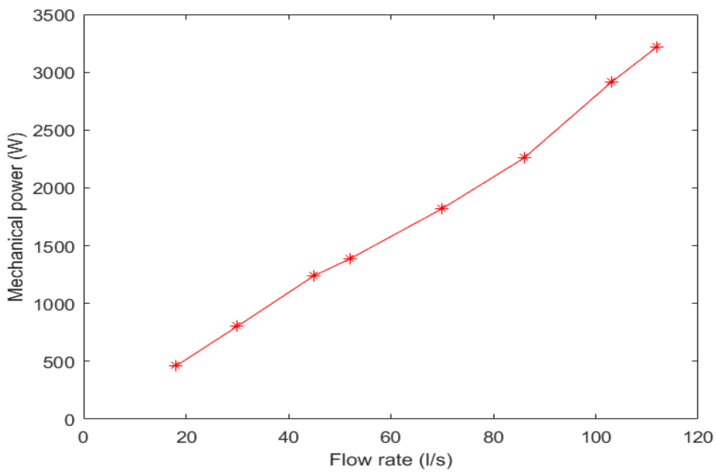

Fig 8 Mechanical power curve of the JLA 29 turbine at N=294 rpm.

Other series of tests have been carried out to analyze the behavior of the turbine when it operates at variable speed at a certain valve opening. In this case, the position of the control valve remained constant and only the speed of the turbine was changed using the Sinamics S120 drive. The turbine efficiency curves plotted at Figure 9 shows that the efficiency varies between 14 and 80% for a maximum valve opening. In case of a valve opening of 30%, the turbine efficiency varies between 15 and 52%. Due to the operating conditions of the Sinamics S120 drive, it was not possible to carry out turbine tests for speeds above 294 rpm. Then, the speed of the JLA 29 turbine was varied from 32 to 294 rpm.

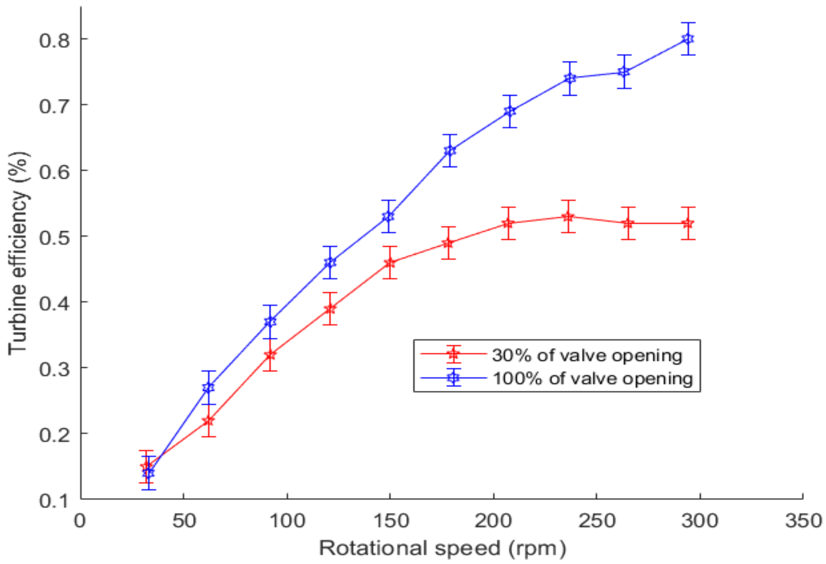

Fig 9. Turbine efficiency curves for variable RPM.

6. Cavitation phenomena caused by the valve control

As depicted in the Figure 10, the injector of the B-M turbine is equipped with an aileron control valve type which controls the water director to the rotor. On one side, this valve has good performance and this aileron valve is subject to the phenomenon of cavitation when the opening position of this control valve is less than 50% [2]. On the other hand, according to the experience of JLA hydro engineers, it has been noticed that the JLA 29 turbine operating at partial flow rates presents the same cavitation phenomenon from operating head greater than 20 m. In practice and in order to avoid this cavitation phenomenon, the turbine is kept running at fully load, otherwise, the turbine is stopped.

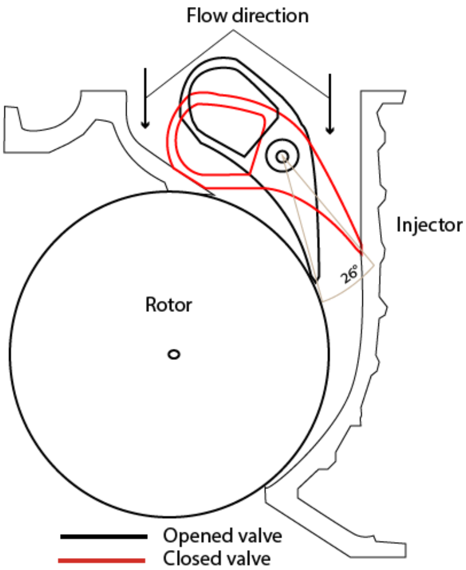

Fig 10. Opened and closed valve of the JLA 29 turbine.

7. Design of the turbine for the Ryamukona site

For the case of the Ryamukona site, a flow study characterizing the site was carried out and the results gave a nominal flow of 1.18 m^3/s. To this end, the performance tests of the Banki-Michell turbine were carried out in order to verify whether the behavior of this turbine was well suited to the hydrological behavior of the Mwogere river.

Indeed, the purpose of this section is therefore to size a suitable turbine for the Ryamukona site according to the available results [21, 22]. Table 2 contains the used parameters for the design of the Banki-Michell turbine adapted to the Ryamukona site in Burundi. Both turbinable flow and head used for this designed turbine resulted from the measurements results carried out for the Mwogere river [21]. The turbinable flow (Q) and the head (H) are in order of 1.0 m^3/s and 12.0 m respectively. As depicted in Figure 11, the main role of injector is to redirect water to rotor with an adequate angle of attack (α_1). In this case, the angle of attack is fixed to 20° [22] and the water flow is characterized by an injection angle (θ) of 90° [9]. The outer diameter D_1 is a fixed parameter depending to the constructor of the turbine [4, 12, 22]. In this case, the diameter is fixed to 300 mm.

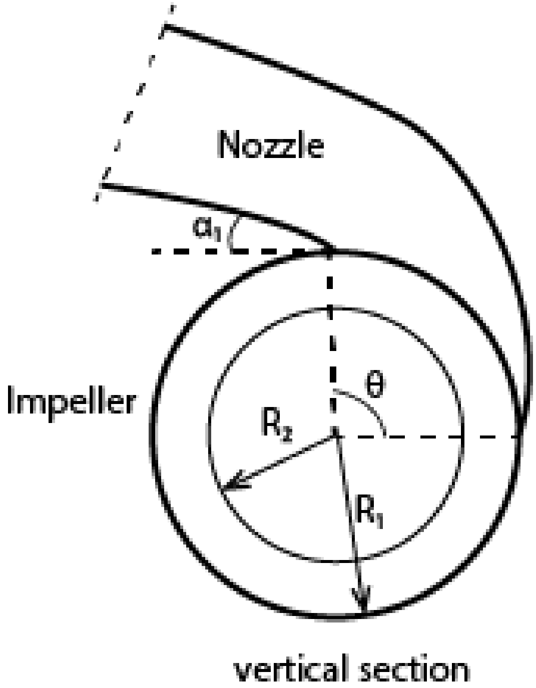

Fig 11. Section view of rotor and injector of a B-M turbine [22].

Table 2. Design parameters of the B-M turbine.

Parameters	Values	SI unit	Description
H	12	m	Total head
Δh	0	m	Energy losses
H_N	12.0	m	Net head
Q	1.0	m^3/s	Discharge
g	9.81	m/s^2	Gravity acceleration
η_t	0.75	%	Turbine efficiency
R_1	0.3	m	Outer radius
R_2/R_1	2/3	-	Diameter ratio
R2	0.3	m	Inner radius
α_1	20	Degree	Attack angle
θ	90	Degree	Injection angle

The section is aimed to calculate the runner width, the speed of rotation, the runway speed, the theoretical power of the designed crossflow turbine and the electric power produced by the system.

- **Runner width**: the thickness of the water jet which passes through the turbine runner must not exceed approximately one third of the external diameter of the turbine. Then, the runner width is calculated using the formula (7) [22].

$$B_R = \frac{1.36.Q}{D_1\sqrt{H_{net}}} = 1.3\,\mathrm{m} \tag{7}$$

- **Turbine speed**: the optimal speeds is calculated using the Eq. (8) [22], based on fixed blade angle α_1 of 20°, an external runner diameter of 300 mm and a total head of 12 m that characterize the site.

$$N_T = \frac{40\sqrt{H_{net}}}{D} = 462\,\text{rpm} \tag{8}$$

- **Runway speed:** the runway turbine is calculated in function of the turbine speed N_T as showed in the Eq. (9) [22].

$$\mathrm{N_{Tr}} = 1.8.\mathrm{N_t} = 845.5\,\text{rpm} \tag{9}$$

- **Power calculation**: taking the turbine efficiency of 75%, the mechanical power (kW) available on the turbine shaft is calculated by the Eq. (10).

$$P_m = QgH\eta_T = 88.3\,\text{kW} \tag{10}$$

- **Electric power**: taking a generator efficiency of 90%, the electric power is equal to the product of available mechanical power and the electrical efficiency. The electric power is then equal to 79.5 kWe.

According to the population living in the villages that are close to the Ryamukona site, the area has around 600 households that need electricity for their socio-economics development [21]. The hydroelectric production with this turbine appears insufficient in view of the site's electricity needs. A solution for using another complementary source of electricity production such as photovoltaic can already be planned for this Ryamukona site.

8. Conclusions

This paper aimed to present the results of the performance tests carried out on a typical Banki-Michell turbine named JLA 29. After installing the test bench, two major test campaigns were performed at constant and variable speed in order to analyze the performance curve of the Banki-Michell turbine. The test results indicated an efficiency of the turbine in the order of 60 to 80% for an opening of the injector valve that varies between 30 and 100%. This test bench of a typical crossflow turbine is operational at the ULB-ATM laboratory mainly for remote applications. As perspective, this type of turbine could be used in rural areas such the Ryamukona site localated in Burundi and should to produce approximately a maximum electrical power of 79.5 kWe, this may contribute to the improvement of the socio-economic conditions of this rural area (and of other locations in Africa or South America), by supplying electricity to approximately a population of 18864 located in six villages of the Kabarore commune.

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