Performance evaluation and characterization of a locally designed water pump

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Abstract. Voltron, a locally designed water pump, is widely used among farmers in Central Luzon of the Philippines. The study aimed to evaluate the performance of the Voltron water pump. Voltron was tested at different pump shaft speed settings of 450, 600, and 700 rpm and with different blade (impeller vanes) numbers of 6, 8, 9, and 10 using V-belts and B-section pulleys transmission. The highest pump efficiency of 62.5% was observed using an 8-vane impeller under a 700-rpm setting. Currently, farmers utilized the 8-vane impeller under a 600-rpm setting. Statistical analysis showed that there is no significant difference between the pump efficiencies on the set pump shaft speeds, but there is a significant difference in the set number of vanes. On the other hand, the effects of pump shaft speed, the head, discharge, and fuel consumption increased as rotational speed was increased. The difference is around Php 17.61 per ha per day of operation favoring the usual setting upon the computation of the fuel cost. However, the 8-vane impeller under a 700-rpm setting will be more economical in the long run as it is determined to be more efficient than the normal setting being used by the farmers.

1. Introduction

Successful agriculture depends on the accessibility of water to farmers to increase cropping intensity and productivity. Aside from the seasonal rainwater, the utilization of a pumping system enables the farmers to draw water from existing open surface water resources (e.g., rivers, creeks, shallow groundwater) available within the area. The most common type of pump being utilized by farmers in the Philippines is the centrifugal pump.

In Vietnam and Thailand, farmers used an energy-efficient alternative to centrifugal pumps called Axial Flow Pumps or AFPs. According to the Cereal Systems Initiative for South Asia (CSISA) Factsheet (2014), AFPs can save more than 50% of the diesel/energy compared to the conventional centrifugal pumps when the lift is not more than 3 meters (9.84 feet). Since AFPs may only be used for lowland rice irrigation, local farmers in Region III developed a pump design that they claim to be as energy efficient as AFPs. The local pump design is called a Voltron pump as shown in Figure 1.
Figure 1. Field installation of the Voltron pump.

The Voltron pump uses an impeller in a volute casing submerged in water instead of a propeller as in AFPs. However, the Voltron pump can lift water with heads of more than 3 meters. The Voltron pump could be considered a centrifugal pump. A centrifugal pump is a rotating machine in which flow and pressure are generated dynamically. A centrifugal pump delivers useful energy to the fluid or “pumpage” largely through velocity changes that occur as this fluid flows through the impeller and the associated fixed passageways of the pump [2].

It is also a “rotodynamic” pump, namely, a radial-type centrifugal pump. The fluid enters the impeller axially through the inlet eye and is then forced to rotate by the impeller vanes. While rotating inside the impeller, the fluid moves outward, thus gaining an increase in pressure with a parallel increase in kinetic energy. The high velocity at the impeller exit is transformed into a pressure increase through the pump casing and discharge nozzle [3].

Just like many AFPs, the Voltron pumps are normally powered by a single-cylinder engine. Despite lacking technical information on pump performance, this peculiar pump setup is locally produced and continuously gaining popularity among local farmers in the Central Luzon of the Philippines.

This study aimed to determine the performance characteristics of the Voltron pump to validate the local farmers’ claims on pump performance. The effect of varying the shaft speed and the number of impeller blades (vanes) on the pump’s performance was likewise studied.

2. Materials and Methods

2.1. Preliminary Data Gathering
A survey was conducted to gather sufficient information about the operation of the Voltron pump in selected areas of Region III. The Voltron pumps have an overall length of at least 3.05 meters (10 feet). The usual number of impeller vanes was eight (8). A 6-inch reducer elbow (to 4-inch) at the discharge side was normally used. The elbow reducer can be rotated so that the discharge port can be directed as preferred. Farmers normally set the pump shaft speed between 300 and 600 rpm. The pulley combination varied per farmer, but most utilized a speed ratio of 1:2 (4-inch diameter pulley for the engine and an 8-inch diameter pulley for the pump). Double sheave pulleys were used to reduce belt slippage. A 5.5 kW (8 hp) diesel engine was commonly used primarily because diesel fuel is a lot cheaper than gasoline. Data gathered from these interviews served as the basis for setting the operational speed and number of vanes of the pump during testing.

2.2. Fabrication of Voltron pump
The Voltron pump (with a clutch system) used in the study was fabricated in a local shop in Brgy. Lagundi, Plaridel, Bulacan, Philippines. The fabricated Voltron water pump had a semi-open type of impeller made from MS plates and has an outside diameter of 29 cm (Figure 2). The volute casing and elbow reducer were constructed using gauge 16 GI sheets. The long shaft used was 1-inch cold-rolled steel and was supported by three pillow block bearings. A universal joint was used as coupling to facilitate a slight angle difference in elevation during pumping operation.

Shafting supports were made of GI pipes, flat bars, and angled bars. The engine base was constructed using 1.5-inch of steel angle bars. The pump has an overall 8-feet length as opposed to the usual 10-feet basically to fit in the testing facility’s reservoir.
2.3. **Method of Test**

The pump was tested following PAES 115:2000 - Centrifugal, Mixed Flow and Axial Flow Water Pumps – Methods of Test at the Mechanical Testing Facility of the Agricultural Machinery Testing and Evaluation Center (AMTEC-UPLB), Los Baños, Laguna, Philippines. The schematic diagram of the test setup is shown in Figure 3.

A Yanmar TF 90 MLY diesel engine with 7.1 kW (9.5 hp) output power was used for this study to set an allowance for higher speed settings and possible higher power requirements. Based on the survey, the usual engine used by local farmers was 5.5 kW (8 hp). The said engine was mounted on a steel base, while the pump was submerged at a height from the water source.

The pump was connected to a torque transducer using 2B pulleys with diameters of 203 mm (8 inches) and 114 mm (4.5 inches) respectively and two pieces of B-69 V-belts. The other end of the torque transducer was driven by the diesel engine, which was also connected using similar belt-drive transmission. A 10-ml pipette attached to the engine’s fuel tank and a stopwatch was used to measure the fuel consumption of the engine. The pressure gauge (head measurement) was only connected at the discharge side since the suction side of the pump was submerged underwater.

2.4. **Design of Experiment**

The experiment employed a Split Plot Design using a Completely Randomized Design. ANOVA was used to determine the interaction between pump shaft speed and the number of vanes. On the other hand, the speed for response variables such as pump efficiency, total head, water discharge, and fuel consumption were analyzed using the Statistical Tool for Agricultural Research (STAR) 2.0.1. When there were no significant differences found between the set interaction, the Least Significant Differences (LSD) Test was used at α=0.05. However, when significant effects were found on an interaction, means
were separated using Tukey’s Honest Significant Difference Test at α=0.05 with R version 3.6.1. The
Shapiro-Wilk test and Bartlett’s test were used to identify its normality and homogeneity, respectively.

The test was divided into two parts: (a) determination of the effect of shaft speed (450 ±10 rpm, 600
±10 rpm, and 700 ±10 rpm) on the pump’s performance, and (b) determination of the effect of the
number of impeller vanes (6, 8, 9, and 10) on the pump’s performance. Based on the interview, the usual
speed for the pump ranges from 300 to 600 rpm while the usual blade number of the impeller is 8 vanes.
The 300-rpm speed from the interview was not achieved in the study because its discharge was
insufficient for data collection and analysis. On the other hand, 6, 9, and 10 impeller vanes were
additionally chosen as the angles will be more exact in comparison with 7 vanes, which translated to
easier fabrication.

Before starting the test, the height of the water level, the eye of the impeller, and gauge pressure was
obtained with respect to the ground as references for computation. During testing, the following data
were obtained and/or measured: 1) Level of water from the eye of the impeller, cm; 2) Pump shaft speed,
rpm; 3) Torque transducer speed, rpm; 4) Engine speed, rpm; 5) Torque, kg-m; 6) Reading of pressure
gauge on the discharge side, psi; 7) Time to consume 10 ml of fuel, s; 8) Water discharge, kg; 9) Time
elapsed from initial to the final weight of water discharge, s.

Relative humidity and ambient temperature measurements were also gathered during the testing
proper with the use of a hygrometer. The following pump performance information were also
determined: 1) Total Head (m) vs Discharge Capacity (L/s); 2) Waterpower (kW) vs Discharge Capacity
(L/s); 3) Pump Input Power based on shaft torque (kW) vs Discharge Capacity (L/s); 4) Fuel
Consumption (L/hr) vs Discharge Capacity (L/s); 5) Pump Efficiency (%) vs Discharge Capacity (L/s).
All equations and computations used were based on PAES 115:2000.

3. Results and Discussion

3.1. Pump characteristics curves

From the pump characteristic curves (Figures 4 to 7), the general trend observed was the indirect
proportionality of the total head and discharge. The total head decreased as the discharge increased.
Compared with most centrifugal pumps, the Voltron pump efficiency peak at a certain point then
decreases after. However, the pump efficiency increases with head and discharge with 9 and 10 vanes
at 700 rpm shaft speed settings. Also, waterpower and fuel consumption increased as head, discharge,
and pumps shaft speed increased. Work done on the fluid and energy transfer (from mechanical power
to fluid power) only occurs because of the vanes. Also, the pump performance characteristics and the
overall efficiency depend mainly on the vane shape and number of vanes [3].

The highest pump efficiency obtained was 62.5% at 8 vanes with a 700-rpm setting (Figure 8). From
the result of ANOVA in Table 1, the interaction of all sources of variation for pump efficiency and the
head is highly significant. From the results of Tukey’s HSD test based on pump shaft speed (Table 2),
there is no significant difference between the pump efficiencies of the set pump shaft speeds at a 95%
level of significance. However, there is a significant difference between pump efficiencies (except for 8
and 9 blades) at a 95% level of significance based on the number of vanes (Table 3).

| Sources of Variation               | F value | P-Value |
|-----------------------------------|---------|---------|
| No. of vanes                      | 119.06  | 0.0000b |
| Pump shaft speed                  | 13.49   | 0.0004b |
| No. of vanes x Pump shaft speed   | 11.00   | 0.0001b |
| CV(a)%=5.44                       |         |         |
| (b)%=9.82                         |         |         |

a significant,
b highly significant
c not significant
Table 2. Effect of pump shaft speed on characteristics of the locally designed pump.

| RPM | Pump Eff. (%) | Head (m) | Discharge (L/s) | Fuel Consumption (L/hr) |
|-----|----------------|----------|----------------|-------------------------|
| 450 | 39.84 a         | 4.08 c   | 13.50 c        | 0.46 c                  |
| 600 | 48.59 a         | 5.82 b   | 28.77 b        | 0.99 b                  |
| 700 | 47.23 a         | 6.89 a   | 36.63 a        | 1.75 a                  |

*a Means in the same column followed by a common letter(s) are not significantly different at the 95% level by Tukey’s HSD.

Table 3. Effect of the number of vanes on characteristics of the locally designed pump.

| Blades | Pump Eff. (%) | Head (m) | Discharge (L/s) | Fuel Consumption (L/hr) |
|--------|----------------|----------|----------------|-------------------------|
| 6      | 40.50 a, b     | 5.17 a   | 25.95 a        | 1.11 a                  |
| 8      | 53.56 a        | 5.99 a   | 27.32 a        | 1.06 a                  |
| 9      | 51.83 a        | 5.97 a   | 25.84 a        | 1.11 a                  |
| 10     | 35.00 b        | 5.27 a   | 26.08 a        | 0.98 a                  |

*a Means in the same column followed by a common letter(s) are not significantly different at the 95% level by Tukey’s HSD.

Figure 4. Pump characteristic curve of Voltron with 6 vanes at different pump shaft speed.

Figure 5. Pump characteristic curve of Voltron with 8 vanes at different pump shaft speed.
Figure 6. Pump characteristic curve of Voltron with 9 vanes at different pump shaft speed.

Plots in Figure 8 conformed with the findings of Chakraborty et al. [5]. Since 8 and 9 vanes have no significant difference, the trend for 450 rpm can be treated in a generally decreasing manner while the other two showed an increasing then decreasing behavior.

The result of other ANOVA on other response variables such as head, discharge, and fuel consumption manifested that the interaction between the number of vanes and pump shaft speed also have significant differences. As such, the data were further analyzed using Tukey’s HSD.

Based on Tukey’s HSD as presented in Tables 2 and 3, the head, discharge, and fuel consumption based on pump shaft speed have significant differences between each other. Meanwhile, they have no significant differences based on the number of vanes. As apparent in Figures 4 to 7, the total head, discharge, and fuel consumption increases as the pump shaft speed increases.

The highest total head obtained was 7.54 meters with 8 vanes at 700 rpm (Figure 5) while the highest discharge capacity of 37.47 L/s was obtained with 10 vanes at 700 rpm (Figure 7). Moreover, the highest fuel consumption obtained was 1.97 L/hr using 6 vanes at 700 rpm (Figure 4). From Figure 9, it could be observed that fuel consumption at 450 rpm and 600 rpm for all number of vanes is almost the same. On the other hand, the lowest pump input power (1.06 kW) was obtained using 6 vanes at 450 rpm setting while the highest (6.11 kW) was obtained using 6 vanes at 700 rpm (Figure 10). Meanwhile, the pump input power obtained at the farmer’s setting of 8-vane, 600 rpm was 3.38 kW (Figure 10).
Overall, the behavior of the performance characteristics of this locally designed pump is similar as in the study of Chakraborty et al. except for the effect of increasing the number of vanes on the head. Congruent to the study of Liu et al., the study of Chakraborty et al. also concluded that increasing the number of vanes entailed increasing the head of the pump. The increasing head was due to increasing the number of vanes which increases the friction losses [7]. On the contrary, this effect was not present on the behavior of the locally designed water pump as the total head has no significant difference between the number of vanes. This may be because of the way it is operated locally—submerged underwater—unlike other centrifugal pumps being used by farmers that are operated above the water level and have a suction head.

3.2 Fuel cost for operation and time to irrigate
The highest pump efficiency of 62.5% was observed using an 8-vane impeller under a 700-rpm setting. It has a total head of 7.54 m, a discharge capacity of 35.60 L/s, fuel consumption of 1.58 L/hr, and an input power requirement of at least 4.22 kW (almost 6 hp).

Given one-hectare land with diversion water requirement (DWR) of 2 L/s per hectare and the performance data of this setting, the time and fuel cost for the operation were computed. With a discharge capacity of 35.60 L/s, the time to irrigate a hectare of land was estimated to be around 1.35 hours under lowland conditions. Assuming Php 45.00 per liter of diesel fuel, the said setting costs around Php 95.87 per hectare.

Since the farmers normally use the 8-vane impeller under 600 rpm setting as per the survey, the time and fuel cost for the operation under this setting were also computed and presented in Table 4. The 8-vane impeller under 600 rpm setting’s time to irrigate a 1-hectare land was around 1.54 hrs under lowland conditions. Accordingly, the cost was around Php 78.26 per hectare under lowland conditions. These computations are only applicable for farm sites with elevation from a source of lower than 7.5 meters and 6.2 meters for the 700 rpm and 600 rpm settings, respectively. These are also applicable using the 4-inch diameter discharge as opposed to the original size of 6-inch diameter.

| Setting          | Discharge (L/s) | Time (hr) | Fuel consumption (L/hr) | Fuel consumed (L) | Price of fuel (Php/L) | Fuel cost (Php) |
|------------------|-----------------|-----------|-------------------------|-------------------|-----------------------|-----------------|
| 8-vane, 700 rpm  | 35.60           | 1.35      | 1.58                    | 2.1               | 45                    | 95.87           |
| 8-vane, 600 rpm  | 31.19           | 1.54      | 1.13                    | 1.7               | 45                    | 78.26           |

\[\text{Assumption only}\]

The difference in time for irrigation was around 11.4 minutes (in favor of the 8-vane, 700 rpm setting), while the difference in fuel cost was around Php 17.61 per hectare per day of operation (in favor of 8-vane, 600 rpm). Although the fuel cost per hectare per day of operation was less in the usual setting, farmers should be informed that it is more efficient to use the 8-vane, 700 rpm setting as it has the highest pump efficiency based on the results of this study. Its discharge is also higher than the usual setting, which will entail greater savings in the long run of the operation.
4. Conclusion

The highest pump efficiency of 62.5% was observed using an 8-vane impeller under a 700-rpm setting. Based on the results of Tukey’s HSD test, this efficiency is significantly different from the other pump efficiencies.

Statistical analysis also showed that there is no significant difference between the pump efficiencies on the set speeds. However, there is a significant difference in the set number of vanes at a 95% level of significance. In contrast with the findings of Liu et al. and Chakraborty et al., the behavior of the performance characteristics varies according to the effect of the number of vanes. On the other hand, the head, discharge, and fuel consumption increased as rotational speed increased just as Chakraborty et al. argued.

Finally, assuming a diversion water requirement (DWR) of 2 L/s per hectare and a fuel price of Php 45.00 per liter, the difference in fuel cost between the 8-vane impeller under 700 rpm setting and the usual setting of 8-vane impeller under 600 rpm setting is around Php 17.61 per hectare per day of operation. Although the fuel cost is less in the usual setting, the 8-vane impeller under the 700 rpm setting is better in the long run as it is more efficient than the usual setting. Thus, the 8-vane impeller under the 700-rpm setting is recommended for farmers’ use.

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