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Design and Experimental Investigation of a Water-Powered Reciprocating Pump Using a Vertical Ultralow Head Water Turbine for a Small-Scale Irrigation System

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***Abstract*—Nepal is a country with several rivers and streams in mountains and lowland regions. Though there are several alternatives to watering the crops, the technology is not mature enough to drive the pump and deliver the same water such that water is available and flowing near the cultivable land. Among the pumping alternatives in different aspects, the use of a piston pump, as a low-speed pump coupled with the vertical ultra-low head turbine (VULHT) is the novelty of this research. The analytical design of the piston pump covered was fabricated for testing purposes. The existing experimental setup of VULHT has been used to test the new pump with minor modifications on it. The testing of the pump with multiple valve openings and stroke length of the piston were compared and concluded the maximum system efficiency of 28.888% at 75 mm stroke length with a flow rate of 0.211 LPS to the gross head of 23 m. In the ideal case of pumping, it can deliver 18,000 liters of water daily with the use of VULHT which can be utilized for small-scale irrigation in suitable areas. The optimization of the system for scaling and operating range has been suggested as a future task.**

***Keywords*—Water-powered, test rig, efficiency, flow rate, head, reciprocating, speed, piston, stroke length**

I. INTRODUCTION

Nepal is an agricultural country with several rivers and streams in mountains and lowland regions. According to the Ministry of Agriculture and Livestock Development, 2022, 28% of the total land in Nepal is suitable for agriculture [1]. Nepal has sufficient water resources but approximately 40% 2 of the total agricultural areas have irrigation facilities and is challenging to develop further in a feasible and best way [2], Among irrigation facilities, only 19% of the land has access to year-round irrigation. The rest of the land in Nepal heavily relies on monsoon rainfall (June to September), leading to unpredictable and extreme weather patterns, including floods and droughts, which reduce agricultural productivity. So, most agricultural lands are left fallow during the post and pre-monsoon season, except for a few areas with irrigation facilities, causing significant crop productivity Loss affects. The rivulets and springs in Nepal provide tremendous opportunities for developing smaller irrigation and water distribution systems, especially in rural areas with water scarcity [3]. Moreover, the irrigation facilities that are available in Nepal are old, inefficient, and poorly maintained, leading to low productivity and loss of water in large volumes [4]. Agricultural productivity remains low in traditional farmer-managed schemes or large public irrigation systems. Major obstacles to increasing agricultural productivity in Nepal include the lack of irrigation [5].

Irrigation is the most essential process for optimum crop production throughout the calendar year. This requires either a large-scale type of central irrigation system for a selected large area or a discrete small-scale kind of irrigation system for a small area. Though the land is cultivable and the environment is favorable for several crops, there is a lack of water supply needed for plants at different times for their growth, agriculture is highly dependent on rainwater in the case of Nepal. Some of the technologies found for small-scale irrigation in Nepal are diesel pump sets, solar and wind pumping, drip irrigation, hydrokinetic pumping, and hydraulic ram pumps. Though there are several alternatives to watering the crops, the technology is not mature enough to drive the pump and deliver the same water such that water is available and flowing near the cultivable land. Due to the lack of suitable technology in rural areas, the pumping of water to even a few heights is challenging for low-scale irrigation. Several concepts of water-powered pumps exist as alternatives to pumping. A comprehensive review conducted by Zambrano J. C. I. et al., 2019, concluded that hydro-powered pumping (HPP) technologies can be summarized in Figure 1 which are possible to use for low-scale irrigation in low-land regions. The symbols (α), (†), and (n) on the figure stand for commercially available, commercially extinct, and noncommercial technologies, respectively [6].

One of the famous water-powered pumps is the hydraulic ram

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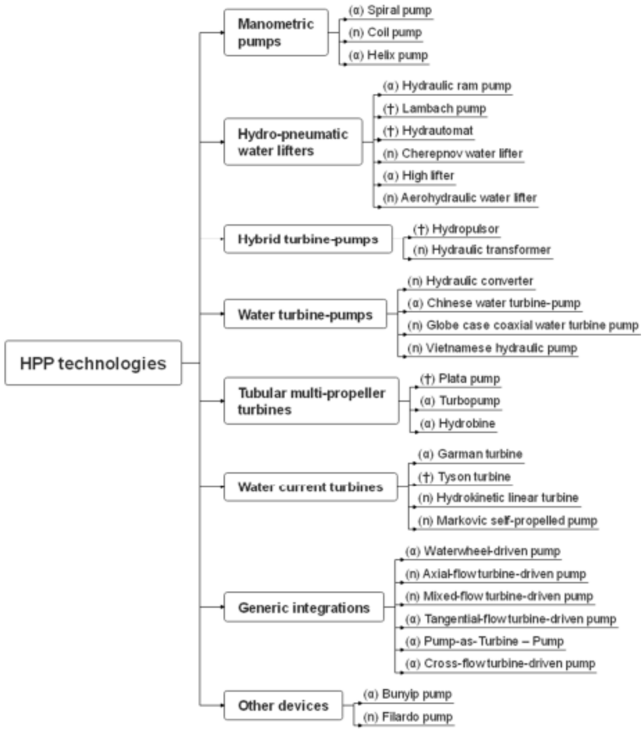

Fig. 1. Classification of HPP technologies and their latest development/production stage

pump which utilizes a small fall of water to lift a fraction of the supply flow to a much greater height. Its mode of operation depends on the use of the phenomenon called water hammer with an efficiency range of 10-25% [7], [8]. Another unconventional alternative to a small water wheel for powering a small pump is the Plata Pump. It has a series of small turbine rotors mounted on a single shaft along the axis of a cylindrical duct, with the overall efficiency measured in the range of 6-30% [9]. Another pump identified is the river current turbine pump developed to operate efficiently entirely submerged to extract shaft power from river currents and used for pumping water using a vertical 4 axis cross-flow turbine like the Derrius windmill. The rotor efficiency was 25 to 30% (as with a small windmill), and an overall system efficiency of 6% was reported, including pipe and pump and transmission losses [7]. The next famous category of the pump is the manometric pumps which consist of any semi-submerged curved pipes winding around a fixed central point or axis, which rotates continuously. Water and air packets alternatively, enter through an open end in each revolution and exit from a rotary fitting joined to a fixed pipe [10]. A cross-flow planar, cross-flow non-planar and axial-flow non-planar pipes are referred to as hydro-powered spiral pump (HSP), hydro-powered coil pump (HCP), and hydro-powered helix pump (HHP), respectively as manometric pumps. Those generally harness the required energy using waterwheels, radial paddles, or axial low propellers relying on the velocity of the water [11], [12]. An efficient pump known as a water turbine

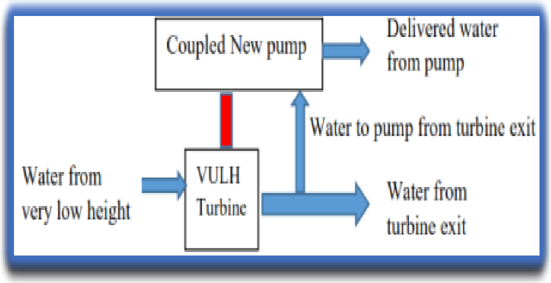

Fig. 2. Conceptual flow diagram of the water-power reciprocating pump.

pump has coaxial joining–through a single shaft [13] or transmission system [14] with an axial-flow turbine and a centrifugal pump fully submerged and operates with the same water. C Yenphayab, 2019, studied an advanced siphon pump for small farm irrigation, concluding that the advanced siphon can deliver water only when the higher level of reservoir supplies the lower area ($\Delta H>0$), while the minimum of ΔH for water transportation is 0.05 meter and the discharge rate will increase when increasing the ΔH, the outlet pipe diameter and shorten the length of the outlet pipe [15]. From different reviews, the approach in this research uses a newly developed turbine known as the vertical ultra-low head (VULHT) hydro turbine [16] for power generation. A ULH is defined as the range of 0.5 – 3 m of the hydraulic head, known as sleeping hydropotentials for power generation [16], [17]. Further, coupled with a new low-speed reciprocating pump, a water-powered pump is combined. One of the biggest advantages of piston pumps among different alternatives is that they can generate relatively high pressures, are more efficient, and have relatively long lifespans than other types of pumps because they do not require a lot of energy to operate [18]. So, this research has been conducted to develop a new technology having a horizontal reciprocating pump tested at laboratory conditions for low-scale irrigation directly coupled and driven by VULHT operating under 0.5 m of head. The importance of the proposed system is even higher when the coupling is also with an electrical generator for electricity generation on a low scale further the pumping attachment. Those are expected to be beneficial for local farmers directly with increment in monetary activities on the local communities in the long run.

II. METHODOLOGY

A. Design and experimental Methodology

Water is freely moving in most parts of the country either in the terai or mountain regions of Nepal. It is possible to develop power from very lowland regions using VULHT. So, a water-powered pump has been selected to investigate within the constraints of application on very low-head, low speed, and low power range such that a new pump can be directly coupled for pumping. This has been conceptualized as presented in Fig. 2 such that the water from low height in the canal makes the VULHT develop power on the turbine shaft releasing the water to the canal or river.

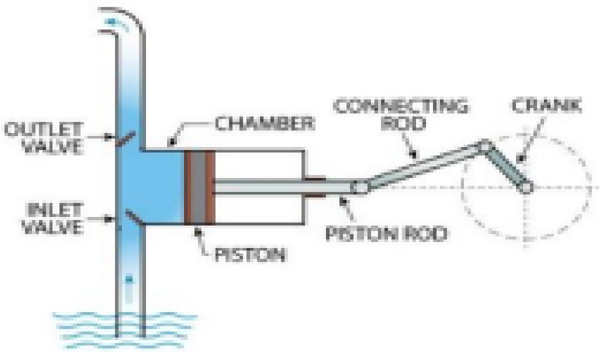

Fig. 3. Typical reciprocating pump.

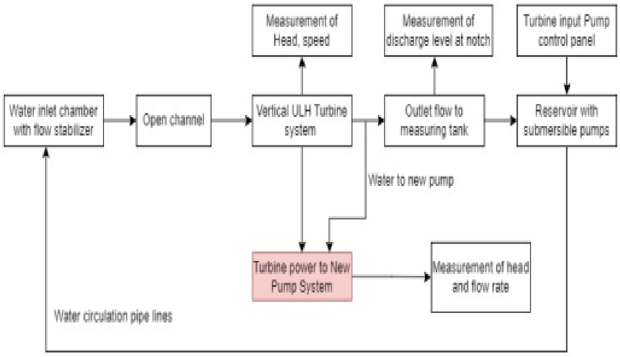

Fig. 4. The operation sequence of the experimental pump.

The power developed on the shaft is directly coupled to the new pump which pumps the water from the exit of the turbine and delivers it to a new height. To take advantage features of the reciprocating pump to lift the water to a few heights has been selected for coupling with the turbine. It consists of a piston reciprocating in a cylinder arrangement connected to a connecting rod. The crank changes the shaft's rotational motion to the piston's linear motion as presented in Fig. 3. The valve activates as per suction and delivery with the movement of the piston one at a time resulting in a pulsating nature of flow delivery [19]. To minimize this nature, an air vessel is used on the delivery side of the pump in general. In this research, the crank, as the disc, is attached to the top of the shaft of VULHT, which drives the pump at low speed in a horizontal plane.

The methodology to explore the concept was planned to be tested over a test rig of VULHT having a turbine available in operating condition. Based on the variables of the test rig, the design parameters for the reciprocating pump were chosen to start an analytical design. The theoretical sizes obtained from the design were used for drafting and fabrication optimizing the availability of components at the local market. The instrumentation required to measure the input and output parameters of the pump was fixed along with the pump required for testing.

The operation sequence has been developed and followed for trial runs as presented in Fig. 4. The flow diagram shows the flow of water, operation sequence, and measurement points with parameters. Water from the pond is circulated by submersible pumps to the inlet chamber of the test rig flowing to the canal and turbine that generates the shaft power coupled to the new pumping system. The water from the outlet of the turbine goes again to the pond through the measuring tank and the same is pumped by a new pump. Different measurements are taken with instruments dedicated to the concerned points. Before conducting the actual test on the pump, several trial runs were covered for smooth operation with minor modifications. When water runs the turbine, the head and flow for it, were measured. The power developed by the turbine coupled to the pump delivers flow to a new height. So, the head and flow rate at different power and speed were measured. For a single flow to the turbine, multiple valve openings have been tested and repeated for multiple flow rates.

B. Design of the reciprocating pump

Prior the design of pump, the data of the available testing facility of the experimental setup was collected and found as follows.

- Test rig Tank Capacity: 6,000 ltr maximum
- Head: 1 m maximum with variation
- Flow rate: 120 LPS maximum with variation of flow with multiple pumps
- Flow measurement: Rectangular notch
- Head measurement: Piezometers
- Type of turbine used: VULHT with 250 W maximum, 54% efficiency at 115 rpm
- Type of loading on the shaft of the turbine: Brake dynamometer/Torque transducer
- Possibility of coupling new end uses: Yes

B.1 Power of the Pump

A test for the present status of the VULHT was conducted to confirm the power output to be used as input to the coupled pump. The observation was recorded and calculated for the power output. Table 1 shows the data for the status of the turbine output power. Input Power to the Turbine is given by Equation (1) and Shaft Power developed on Turbine is given by Equation (2).

$$P(w) = \rho g Q H \quad (1)$$

$$P(t) = \rho g Q H \eta \quad (2)$$

The power supplied to the turbine input power was calculated based on the available head and discharge. Further, the output of the shaft power was determined by taking the efficiency of the turbine to be 40% from the past result and summarized in Table I.

Based on the observation and calculation, the power that can be supplied to the new pump is to be 120 W. So, the design of the reciprocating pump has been detailed with this available

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TABLE I. PRESENT STATUS OF THE TURBINE OUTPUT

Parameters	Symbol	Value	Unit	Remarks
Available head	H_t	0.5	m	
Discharge	Q_t	0.06	m^3/s	
Input water power	P_i	294.3	W	
Turbine efficiency	η_t	40	%	Referred
Turbine Output power	P_t	120	W	Selected

TABLE II. POWER AVAILABLE TO PUMP

Parameters	Symbol	Value	Unit	
Available Power	P_t	120	W	
Pump efficiency	η_p	50	%	Assumed
Useful Power	P_p	60	W	Selected

power from the test rig of VULHT. In this research, the pump was coupled to the turbine shaft, and the available input power to the pump was equal to the turbine's output power (or Shaft power). The power given to drive the pump was then calculated for the efficiency of the pump at 50% as shown in Table 2. The power to drive the pump is given by equation (3).

$$P_P = Pt\eta p \qquad (3)$$

B.2 Selection of stroke length and diameter of piston cylinder
The flow rate from a single-piston reciprocating pump is given by Equation (4), which is dependent on the area and distance of travel of the piston on the cylinder [8].

$$Q_P = ALN/60 \qquad (4)$$

where, A = area of cylinder = $\pi D^2/4$, D = diameter of the piston, L = stroke length of the piston, N = rotational speed of the crank. For a constant speed and flow rate, different pairs of stroke length and piston diameter are possible. Therefore, based on Equation (4), the variation of the stroke length with the diameter has been plotted for various discharge conditions as shown in Fig. 5.
The graph shows that stroke length decreases with the increasing diameter of the cylinder. Also, the higher the discharge, the higher the stroke length and the higher the piston diameter required for the same speed of the pump. For the constant power received, several combinations of head and discharge are possible. Once the cylinder diameter and the stroke length are fixed, the flow rate can be achieved. The head acting on the pump can be calculated using Equation (5).

$$P_P = \rho g Q_P H_P \qquad (5)$$

where, Q_p = discharge of pump in m^3/s and H_p = total head on the pump (static) in m.
The variation in diameter, discharge, and head based on the

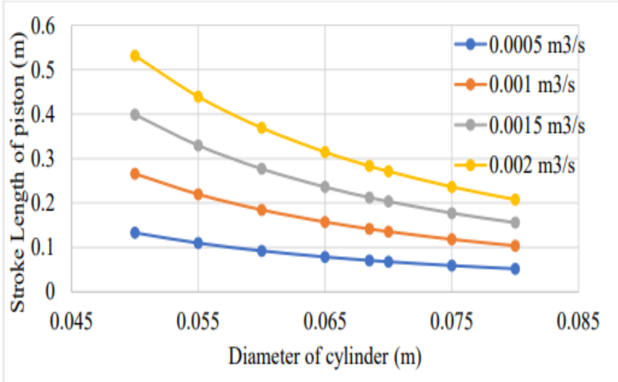


Fig. 5. Variation of the Stroke length with the diameter of the cylinder for different discharges

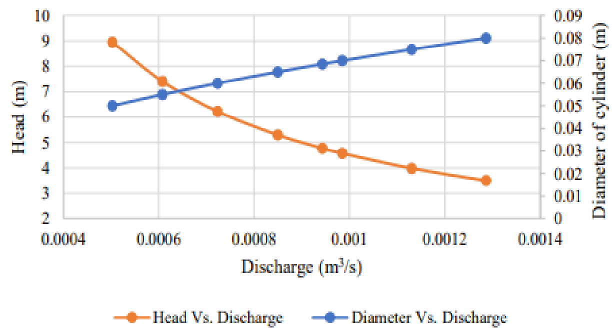


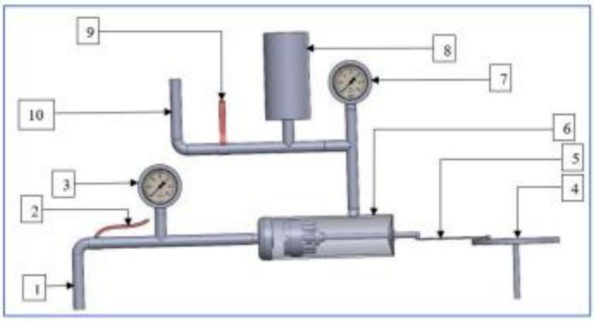
Fig. 6. Variation of pump head and diameter of a cylinder with discharge

TABLE III. SPECIFICATION OF THE SELECTED PUMP

Parameter	Symbol	Value	Unit
Type of pump	Single-acting, Reciprocating		
Power	P_p	60	W
Speed of Pump	N	115	RPM
Diameter of cylinder	D	0.0685	m
Length of cylinder	L	0.133	m
Discharge	Q_p	0.000943	m^3/s
Net Head	H	4.77	m

Equation (4) and (5) is plotted with the discharge as shown in Fig. 6. It summarizes that the head decreases but the diameter of the cylinder required increases with increasing flow rate for the constant stroke length and power supplied to the pump. From several calculations and market availability, a manual-type reciprocating pump with a 68.5 mm diameter cylinder and a maximum stroke length of 130 mm was selected. Based on this selection, the discharge and head of the pump were known to be 0.000943 m3 /s and 4.77 m. The final specification of the selected pump is summarized in Table 3.
On the make-or-buy decision, the manual type of hand pump was chosen from the market as a buy decision to be used with required modifications on it to be coupled with VULHT as presented in Figure 4.5 [20].

Fig. 7. Typical hand pump available at the local market.



1. Suction pipe, 2. Valve at the suction side, 3. Pressure gauge at suction side, 4. Variable stroke rotating disc, 5. Connecting bar, 6. Reciprocating pump, 7. Pressure gauge at delivery side, 8. Air vessel, 9. Valve at delivery side, 10. Delivery pipe

Fig. 8. Assembly Model for the testing arrangement of reciprocating pump.

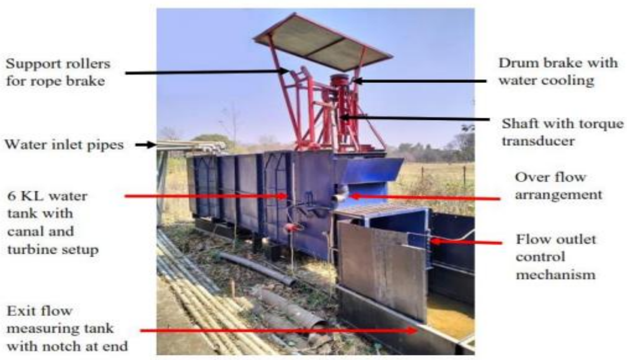


Fig. 9. Available experimental setup of VULHT.

TABLE IV. MEASURING PARAMETERS AND INSTRUMENTS

Parameter	Measuring instrument/ method
Head on turbine	Piezometers
Flow for turbine	Rectangular notch
Speed Turbine/Pump	Optical type tachometer
Pump Suction and delivery pressure head	Pressure gauge
Flow from pump	Bucket volume method

B

The necessary components for assembly have been identified and drafting was covered using SolidWorks 2023. The major components necessary to fabricate were the connecting bar and the crank disc for the coupling of the turbine shaft to the reciprocating pump in the horizontal plane. The CAD model of the pump assembly is presented in Figure 8. The drawing developed was used to fabricate the components at a local fabrication workshop. Other fabrication tasks include pipe fittings and assembly works over the platform of the turbine test rig available as in Figure 9.

III. RESULTS AND DISCUSSION

For the experimental purpose, different parameters were needed to measure using different instruments. Those were followed by preparation for the test and several trial runs to make it ready for final testing.

A. Measuring parameters and instrumentation

There were different parameters to be measured as input and output for the calculation of the efficiency of the pump. The head (Ht) and flow rate are the input parameters whereas the speed of the runner and head (Hp) and flow rate (Qp) from the pump are the output parameters to be measured. The arrangement of the instrumentation was made accordingly for several measurements as in Table 4. Based on those parameters, the observation sheet has been developed.

B. Experimental results and analysis

After the completion of preparation and test runs, the variables identified for testing include the following.

- Multiple valve openings for variation of the head of the new pump
- Multiple flow inputs to the turbine for variation of input power to the new pump

The variation of System efficiency concerning flow rate (system in) for different valve openings for 75mm and 100mm stroke is shown in Fig. 10. The graph indicates that the efficiency increases with an increase in input flow rate for both the stroke and different degrees of valve openings. It was known that the efficiency for a 75mm stroke is more than that of a 100mm stroke. The maximum efficiency for 75mm stroke was obtained to be 28.88% and that for 100mm stroke was obtained to be 25.764% on 100% valve opening. Although the stroke length is higher for the latter case, the rotational speed of the crank mechanism is much higher in the former which results in a higher output flow rate for a 75 mm stroke giving higher overall efficiency than 100 mm stroke. Similarly, the variation of the pump total head concerning output flow rate for different input flow rates for 75 mm and 100 mm stroke is shown in Fig. 11. The graph shows that the pump net head decreases with increasing output flow rate for all system input flow and stroke length. The pump net head and pump output flow is more in 75mm stroke than in 100mm stroke length and increases with the increase in the system input flow rate.

Another plot on the variation of system efficiency concerning the pump total head for different valve openings and stroke

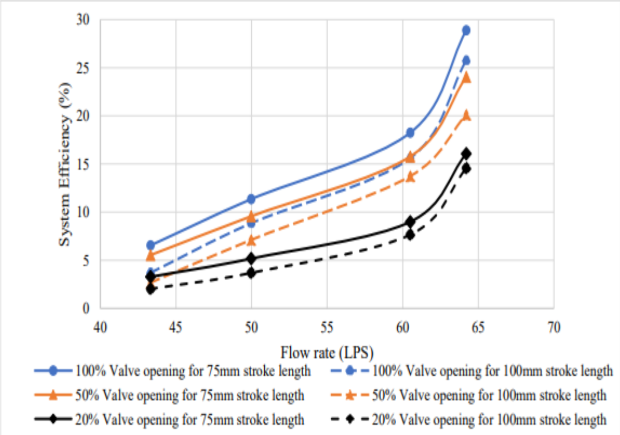


Fig. 10. Variation of system Efficiency with input flow to the turbine.

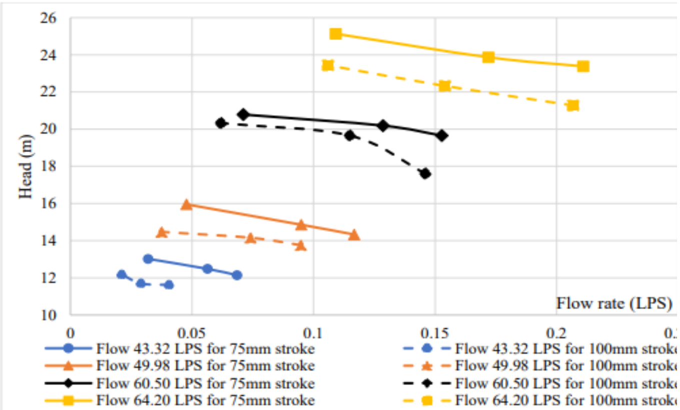


Fig. 11. Variation of Pump total head with pump output flow.

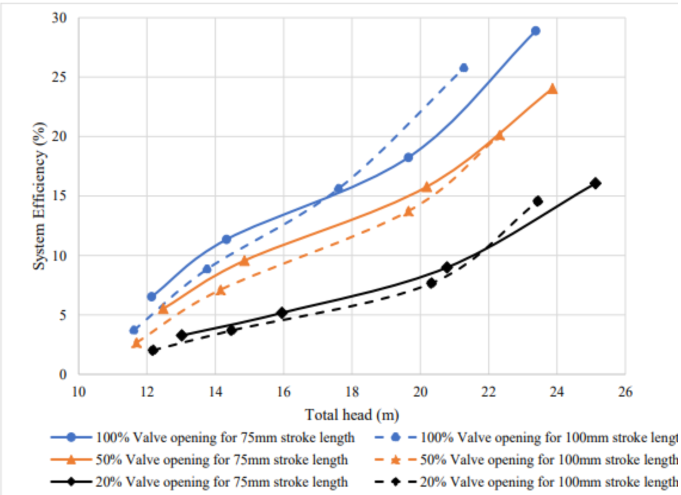


Fig. 12. Variation of System Efficiency concerning pump total head.

length is shown in Figure 12. It shows the system efficiency increases with the increase in pump total head for all three valve openings and stroke lengths. Similarly, the variation of system efficiency with respect to output flow rate for different valve openings for both strokes is shown in Fig. 13. From the graph plotted it is clear that efficiency increases with the increase in

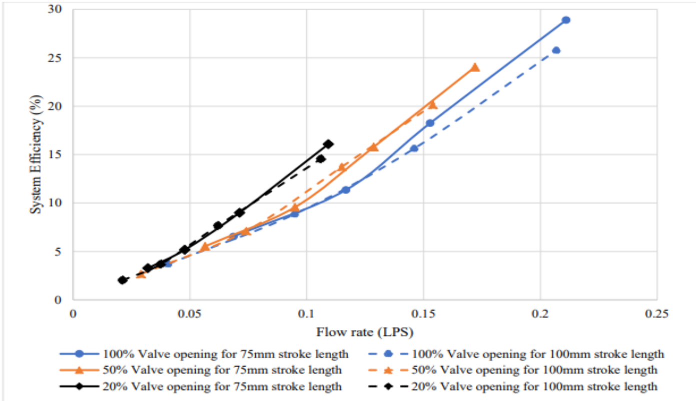


Fig. 13. Variation of System Efficiency concerning output flow rate.

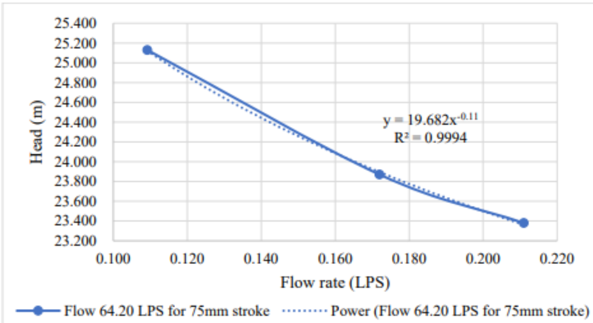


Fig. 14. Variation of pump total head with output flow at maximum efficiency condition.

pump output flow for all three valve openings for both stroke lengths The maximum input flow to the turbine tested of 64.20 LPS with 75mm stroke length of pumping was the condition of maximum efficiency obtained. In that situation, the variation of the pump's total head with the output flow rate is plotted as shown in Fig. 14.

The graph indicates that the pumping capacity of the tested pump can cover the head of 23 m including all losses in the head delivering the flow of 0.211 LPS continuously. It concludes the head it can work against will decrease with the increasing output flow rate of the pump in nature similar to other established pumping technology. The best curve fit obtained is of the power line with an R 2 value of 0.9994 such that the equation developed using MS-Excel as Equation (6) can be used for future applications.

$$H = 19.682Q^{-0.11} \qquad (6)$$

where H = head in m (includes all the losses), Q = flow rate in LPS.

IV. Conclusion

The research on a low-speed reciprocating pump coupled with a vertical ultra-low head hydro turbine (VULHT) for low-scale irrigation was successfully developed and tested. The testing of the pump was carried out with multiple valve openings and variation of input flow for 75mm and 100mm stroke length of the piston. The maximum system efficiency of 28.888% at 75 mm stroke length with a flow rate of 0.211 LPS to the gross head of 23 m was achieved. An equation developed for the head and flow can be used for future applications for pumps of similar specifications. From the experiment, in the ideal case of a pumping scenario, the pump can deliver 18,000 liters of water daily with the use of VULHT. This regular volume of water can be utilized for small-scale irrigation in suitable areas throughout the country. The optimization of the system needs to be covered for scaling and range of operation of the system as a future task through several simulations and testing.

V. Acknowledgment

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