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Designing locally fabricated wooden piston valves for a low-cost hand pump

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ABSTRACT

Affordable groundwater pumping devices are important aspects of sustainable agricultural growth in Bangladesh. Despite irrigation, pumps are also important for the extraction of safe drinking water in rural areas. This study reports the performance of a newly designed low-cost double-acting reciprocating pump for groundwater irrigation. Instead of traditional leather valves, locally fabricated wooden piston valves (PV) were used in the pump. Four different designs of wooden valves having different open surface area were tested for their performance. The discharge of the pump was found to be very satisfactory (137-160 L/min) at 2m of suction head compared to other similar pumping devices. The pump speed was found to be correlated with the total open surface area of the valve. The coefficient of discharge for all the wooden valves was well over 50% even at higher heads indicating better performance for a reciprocating pump. The overall efficiency of the pump at lower heads ranged around 17-25%, while at higher heads, it ranged around 7-12%. In terms of the design, the PV1 and PV2 was found to have shown better performance indices. These wooden discs were cheap, locally fabricated and hence, would minimize the cost of replacement of the valve if required.

Key Words: *Reciprocating pump, Manual irrigation, Pump discharge; Low-cost irrigation, Rural water supply and Sanitation*

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I. Introduction

Low-cost irrigation technology is important for the rural livelihood of many developing countries. This is because of the fact that farmers' per capita income and investment on agriculture is marginal. In Bangladesh, for example, agriculture is still a subsistence business (FAO, 2015) that require low energy input (Alam et al., 2005). In the irrigation sector, most of the energy inputs are provided for the

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extraction (BEB, 2012) and application of water (Shah et al., 2003) to irrigate field crops. Hence, groundwater irrigation requires the most energy inputs. In order for groundwater irrigation, Bangladeshi farmers mostly rely on shallow tube wells (BADC, 2013) that uses small diameter (5-10 cm) pipes to reach water level at shallow depths. Shallow tube well pipes are usually set within 45m below the ground. Popularly known as deep tube wells (DTW), on the other handhas larger diameter (40 cm) pipes and are set further deep (> 46 m) into the ground. The extraction of the groundwater, however, is carried out by various types and sizes of pumps (Motaleb, 2000). This includes manually operated reciprocating pumps, as well as machine (electric motor/CI engine) operated centrifugal pumps(BARI, 2014).

In case of shallow tube wells, the capacity of the centrifugal pumps used usually ranges from 840-1260 L/min (BADC, 2013). The DTWs use much larger pumps that discharges 3360 L/min (Qureshi et al., 2014). In contrast, manually operated reciprocating pumps in Bangladesh include treadle pumps (TP) andthe Bangladesh No. 6 hand pump commonly known as hand tube wells (HTWs).

The current success of manually operated pumps (TPs and HTWs) has been a factorial of appropriate design (Orr et al., 1991), low cost, effective marketing, and high profits (Orr & Islam, 1988). However, a number of issues are yet to be addressed i.e., low efficiency (Iqbal, 2009), short service life and high frictional losses. Nonetheless, use of TPs and HTWs in irrigated land has been spreading among the farmers of Bangladesh over the recent years.According as the trend of development, it is estimated that more than 30 thousand hectares (FAO, 2015) of land are being irrigated by HTWs in Bangladesh compared to 20 thousand hectares in the year 2000. Farmers choose these pumps because they require small capitalinvestment (Barkat et al., 2015). In addition, the operation and maintenance cost of treadle pumps and HTWs is also very low compared to other mechanized pumps. Moreover, HTWs play an important role in the rural water supply and sanitation system (DPHE, 2013; UNDP-WB, 1993) by providing safe drinking water to rural households. As a result, the manual pumps, particularly HTWshave now become an indispensable part of rural life in Bangladesh.

Reciprocating pumps (HTWs) were introduced to Bangladesh through a project of the United Nations international children's fund (UNICEF) in the mid-seventies (BADC, 2013) mainly to provide safe dringking water. Nonetheless, recognizing its potential, UNICEF and Bangladesh rural development board (BRDB) organized projects called manually operated shallow tube well irrigation (MOSTI) project to promote (Shahabuddin et al., 1987) the use of Bangladesh No. 6 hand tube well (33.6 L/min) for irrigation. The expected command area of a hand tube well is 0.4 hectares although this can easily be increased if the discharge can be increase per stroke. In such case, HTWs can also supplying drinking water to more people in the community reducing workload on the pump. This would be unlike the present scenario where a hand tube well is shared by many people in the rural community(Barkat et al., 2015) and hence, is exposed to heavy workloads. This may often lead to damage of some spare parts of the HTW and account for regular maintenance of the device. Considering this, many researchers and organizations had put their endeavor (Motaleb, 2000) towards construction of a suitable manual pump for multipurpose use.

The most vulnerable part of a reciprocating pump is the piston valve that undergoes continuous friction (Taher et al., 1997) of water and hence requiresfrequent replacement. The available valves in the market are usually made of leather and are expensive. Irrigators and the common users of HTWs do not have the technical knowhow to make their own valve if replacement is needed. As a result, farmers completely rely on the commercial products in the market. It is therefore argued that if the piston valves can be made from durable local materials, the cost of replacement can be reduced significantly. Locally produced materials will also help in generating employment opportunities in the community. The present study was therefore carried out to design a double acting reciprocating pump that would provide more discharge per stroke. This paper also reports the performance of four types of locally made wooden piston valves having different slot openings.

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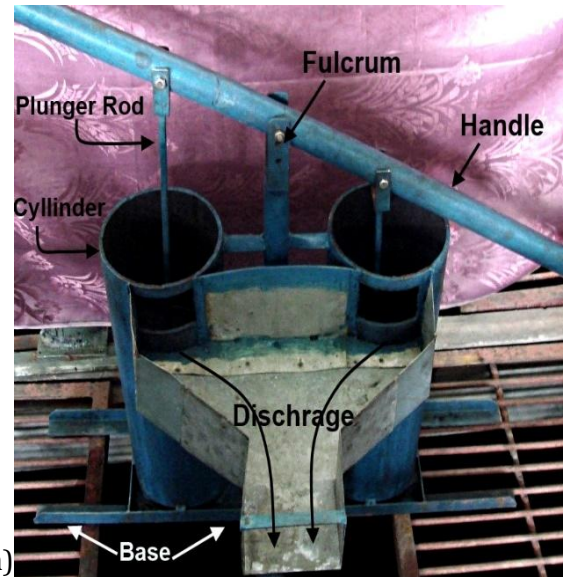
II. Materials and Methods

In the first stage of this study, a reciprocating pump was designed as shown in Figure 01. It looks similar to a treadle pump but unlike pedal operation in TPs, the newly designed pump is hand operated. Therefore, it is a combination of a hand pump and a treadle pump.



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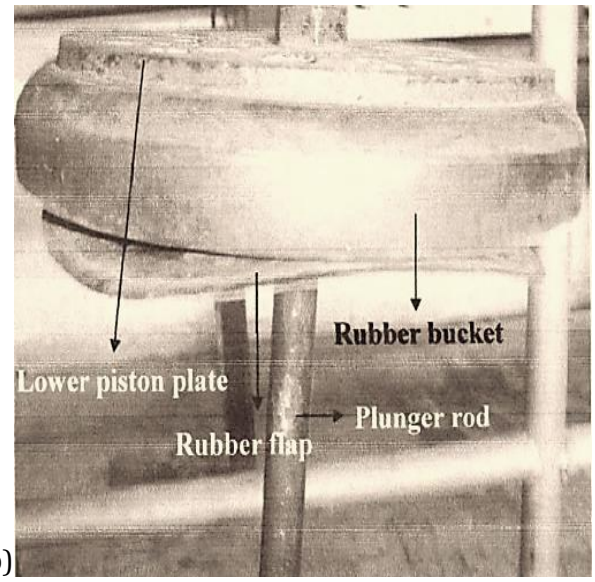

b)

Figure 01. a) Components of the designed pump, and b) valve arrangement inside the cylinder.

The pump was constructed with two cylinders standing side by side. A junction box was used to connect these cylinders to the suction pipe. Table 01 below provides an account of the design parameters of the pump.As shown in Figure 01-b, a rubber bucket was placed at the end of the plunger rod. Inside each cylinder, one wooden piston valve was sandwiched together with the rubber bucket followed by a piston plate. A rubber flap was provided over the wooden piston valve to facilitate the non-return mechanism of the pump.

Table 01. Design parameters of the double acting reciprocating pump

Name	Description
Pump cylinder	Made of GI pipe; Diameter (210 mm)×Height (613 mm)× Thickness (6 mm)
Pump base	Made of MS bar; Length (1.70 m)× Width (0.24 m)
Handle	Made of cast iron; Length of (223 cm)× Diameter (5 cm)
Junction box	Length(64.5cm) × Width (24cm)×Height (4cm)
Fulcrum Stand	Made from angle bar; Height (0.315 m)
Suction Pipe	Made of 60 mm diameter PVC pipe

Piston valves (PV)

Piston valves were made at the workshop with locally available, well-seasoned mahogany wood. The diameter of the valves was 9.52 cm which was equal to the internal diameter of the bucket. The total surface area of valve was thereforecalculated to be 284.88 cm^2.

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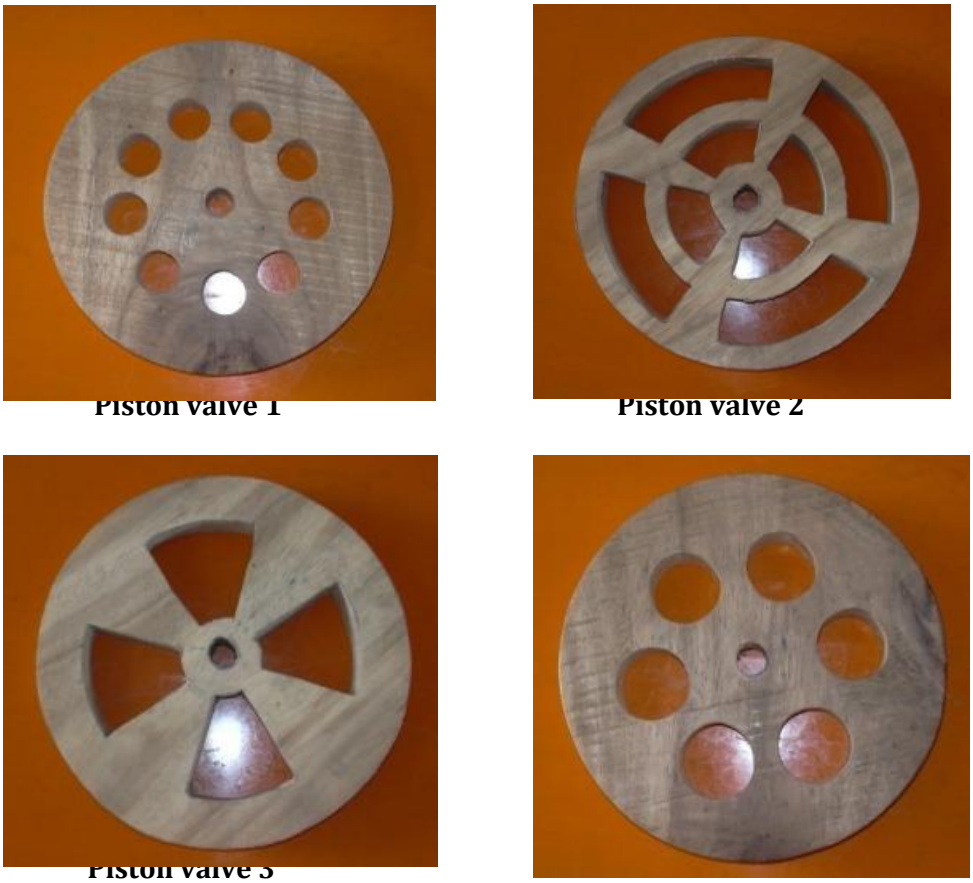

Figure 02. Different types of wooden piston valves designed in the laboratory.

Four designs (Figure 02) of piston valves (PV) were tested in order to find the optimum size and shape of valve slot openings for maximum discharge. The characteristics of the valves have been provided in Table 02.

Table 02. Characteristics of the designed wooden valves

Valve name	Description
PV 1	Wooden disc; Slot size = 4.67 cm^2; Number of slots = 9; Open area = 14.70%
PV 2	Wooden disc; four slots in the inner diameter having slot size of 15 cm^2; four slots in the outer diameter @ 21.33 cm^2; Total open area = 51.01%
PV 3	Wooden disc; Slot size = 30.73 cm^2; Number of slots = 4; Total open area = 43.10 %
PV 4	Wooden disc; Slot size = 9.37 cm^2; Number of slots = 6; Total open area = 19.70 %

Working principle

The pump was a double acting reciprocating pump a having handle to operate the individual cylinder chambers. The pump is so designed that two people can operate it standing opposite to one another using a long handle (Figure 01). When one end of the handle is pushed downward, the piston in the other cylinder moves upward to discharge water. Simultaneously the piston valve in the first chamber goes down and accumulates water in the cylinder. During the next stroke water is discharged from the first cylinder.

Performance evaluation

In order to find out the pump speed, healthy pairs of people (22-28 years of age) were asked to operate the pump. During operation, the number of strokes was counted for a known time using a stop watch. The pump speed, stroke per minute, was then worked out by dividing the number of strokes observed by the recorded time.Volumetric method was used to measure the pump discharge. A

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container (25 L) was used to collect the discharge, and the time required to fill a known volume (20 L) was measured. The discharge was then calculated and expressed by liter per minute (L/min).

Pump slippage

The theoretical discharge is generally taken as equal to the piston displacement volume inside the cylinder. Slip of a pump is the difference (liter per minute) between theoretical discharge (Q_{th}) and the actual discharge (Q_{act}). The %slip of the pump was then determined using the following equation:

$$\% \, slip = \frac{Slip \ of \ the \ pump}{Theoritical \ \ discharge} \times 100 \quad (1)$$

Coefficient of discharge (C_d)

The ratio of the actual volume of water discharged (*L/min*) to theoretical discharge (*L/min*) is called coefficient of discharge and is expressed as:

$$C_d = \frac{Q_{act}}{Q_{th}} \quad (2)$$

Output power

The output power of the pump was calculated from the following expression:

$$P_o = \frac{\gamma \times g \times Q \times H}{1000} \quad (3)$$

Here, the output power (P_o) is expressed in kilowatt (*kW*) when the unit weight of water (γ) is inkg/m^3, acceleration due to gravity (g)is in m/sec^2, the discharge (Q)is in m^3/sec and the total pumping head (H)is expressed in *m.*

Input power

The power input to the pump was calculated from the following expression:

$$P_i = \frac{g \times W \times h}{1000 \times t} \quad (4)$$

Here, the input power (P_i) is expressed inkilowatt (*kW*) when the force exerted by the operator (W) on the handle while pumping is in *kg*, the vertical distance through which the handle moves downwards (h) is expressed in*m*, and the time required for downward movement of thehandle is expressed in seconds.

Pump efficiency

The efficiency of the pump (η_{pump}) was calculated from the following expression:

$$\eta_{pump} = \frac{P_0}{P_i} \times 100 \quad (5)$$

All the tests were conducted on the floor of the sump in the hydraulic laboratory of the Department of Irrigation and Water Management, Bangladesh Agricultural University, Mymensingh. All the tests were carried out under different suction heads (0.5 to 2.0 m) and was replicated thrice. The pump design allows it to vary the stroke length. However, this entire study was carried out under a specific stroke length (0.2 m).

III. Results and Discussion

The performance of the pump varied with the suction head. As can be seen from Figure 03, the piston valve 1 (PV 1) resulted in the highest discharge (316 L/min) at low suction head followed by PV 2 (270 L/min) and PV 3 (262 L/min). Piston valve 4, however, provided the lowest flowrate (229 L/min) at 0.5 m suction head. When the suction limit was increased, the pump discharge declined steadily for PV 1 and PV 4 (Figure 03-a). On the other hand, at suction head 1 m the flowrate under PV 2 and PV 3

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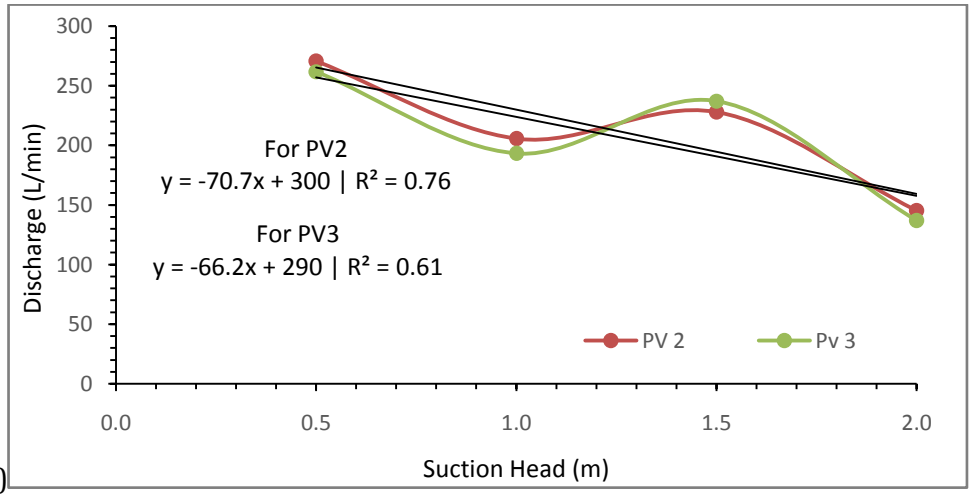
increased slightly before joining the declining trend of flowrate (Figure 03-b). Nonetheless, the flowrate of this double acting pump is comparatively higher than the other manually operated pumps reported in the literature (Iqbal, 2009; Islam, 1981; Taher et al., 1997; Taufiqul et al., 2001).

The performance of the pump in terms of its speed also varied with the suction head. Table 03 provides ans account of the speeds observed at different water levels. The highest pump speed for the valves ranges from 60 to 65 strokes per minute. The results also suggests that PV2 would be the best choice for deeper water levels as it offered better speed at 2 m suction head. This is possibly because of the higher amount of open area in the valve (51% for PV2) that provided minimum resistance against the flow of water. According to the standard assessment of Taher et al. (1997), this type of pump offers a better alternative to the traditional treadle or hand pumps used in Bangladesh.



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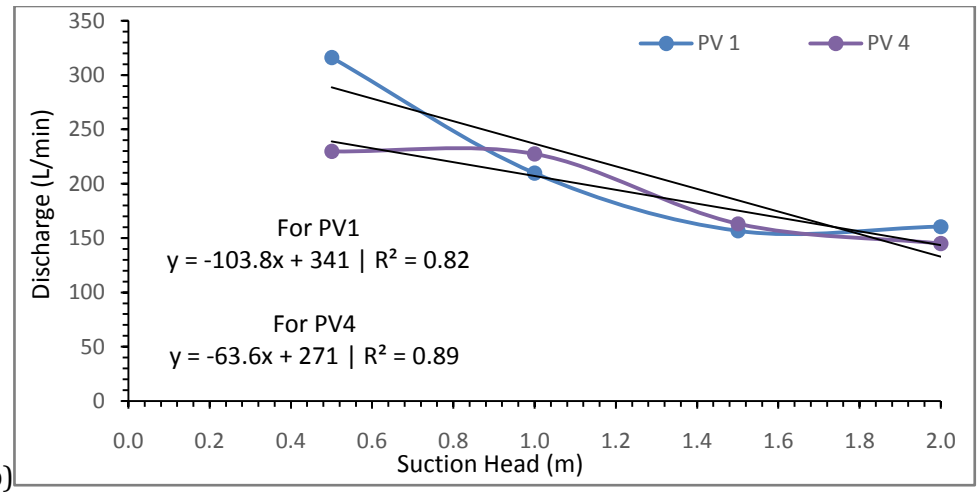

b)

Figure 03. Variable pump discharge at different suction heads

The slippage of the pump under different suction heads have been presented in Tables 03. As expected, the slippage increased with the suction head making it harder for the pump to produce the theoretical discharge. The minimum slippage, however occurred at 1.5 m suction head. Nonetheless, the slippage for all valve types was contained in the range of 41-46%. This is the reason why the coefficient of discharge of the pump was well above 60 percent in all the cases of suction head. The C_d values varied from 0.55 to 0.89 for all valve types. This is indicative of the fact that 1.5 m suction head should probably be the designed head for this pump if PV1 or PV4 type of design is used.

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Table 03. Pump characteristics at different suction head and valve arrangements.

Suction Head	Pump Speed (stroke/min)				%slip				Discharge Coefficient (C_d)			
	PV1	PV2	PV3	PV4	PV1	PV2	PV3	PV4	PV1	PV2	PV3	PV4
0.5	65.3	62.0	63.7	60.7	26.0	26.0	26.0	41.3	0.7	0.7	0.6	0.6
1.0	43.3	56.7	40.0	47.0	26.0	26.0	26.0	26.0	0.7	0.6	0.7	0.7
1.5	30.7	63.0	49.0	32.0	21.0	21.0	21.0	21.0	0.8	0.6	0.7	0.8
2.0	44.3	49.0	34.7	38.3	44.0	46.0	46.0	41.3	0.6	0.5	0.6	0.6

Power requirement

The input power requirement of pump at various heads for piston valve 1, 2, 3 and 4 has been shown in Figure 04. The power requirement of a manual pump depends on the various factors (Abdullah et al., 1992; Taher et al., 1997) including power required to overcome frictional force and primarily to lift water. Moreover,the measurement of input power varies in different circumstances. In particular, the *Pi* depends on the operator's ability to perform at the same level. It was therefore important that the pump operators in this experiment be given sufficient rest in order for them to perform at the same level for a given period of time.

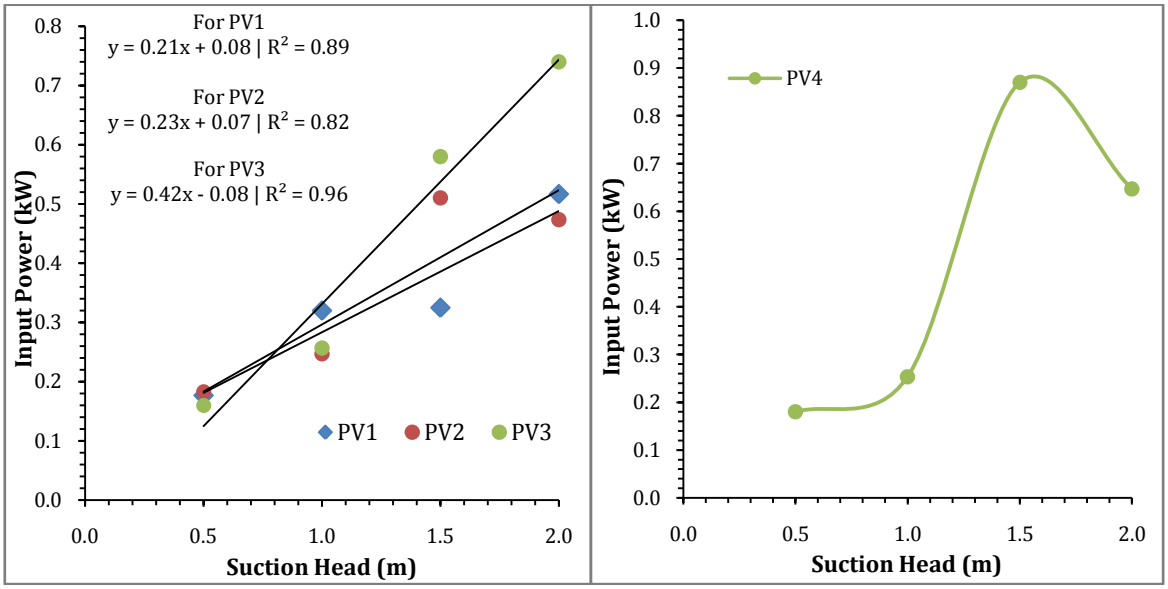

Figure 04. Power requirement of the pump for different valves at varying suction heads.

The input power required to produce pump discharge at various head was found to have ranged from 1.15 to 0.17, 0.55 to 0.16, 0.79 to 0.14, and 0.91 to 0.14 kW for PV1, PV2, PV3 and PV4, respectively.Figure 04 shows that the power requirement of the pump coupled with PV2 and PV3 increased linearly with the suction head. The P_i of the pump for PV4, on the other hand, followed an apparently distinct sinusoidal trend where the power requirement increased up to 1.5m of head and trailed by a decline at 2 m head.

Output power

Output power produced by the pump under different suction heads for different piston valves have been shown in Table 04. It varied from as low as 0.03 *kW* to as high as 0.07 kW. In particular, 0.043 to 0.063 for PV1;0.037 to 0.0670.07 for PV2; 0.033 to 0.07 for PV3 and0.03 to 0.05 for PV4. Interestingly, the pump produced similar output (0.05 kW) for valve PV4 in case of higher heads (1 – 2 m).

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Table 04. Power output of the pump an the overall pumping efficiency

Suction Head (m)	Output power (kW)				Pumping Efficiency (%)			
	PV1	PV2	PV3	PV4	PV1	PV2	PV3	PV4
0.5	0.043	0.037	0.033	0.030	24.65	20.26	21.33	17.56
1.0	0.043	0.046	0.040	0.051	13.75	19.00	15.84	20.24
1.5	0.047	0.067	0.070	0.050	14.49	13.14	12.18	5.76
2.0	0.063	0.053	0.050	0.051	12.31	11.58	6.79	7.77

The variation in output power resulted in the actual performance indices of all the valve types. It was reflected in the pumping efficiency of the device. As can be seen from Table 04, the highest efficiency of the pump was around 25%. This is very satisfactory for a reciprocating pump(Taher et al., 1997). In terms of the valves, both PV1 and PV2 maintained a satisfactory efficiency level (greater than 12%) even at higher heads which is typical in Bangladesh No. 6 hand pumps. However, in general,a tendency of declining efficiency was observed when the suction head was increased.

Comparative analysis

The newly constructed hand pump was compared with the other traditional water lifting devices as given in Table 05. It revealed that the discharge of the new pump at 2m suction head(137-160 L/min) was very satisfactory in comparison with other pumping devices(Abdullah et al., 1992; Khan, 1983).

Table 05. Comparison of the newly designed pump with other traditional pumps

Pump type	Cylinder Diameter (cm)	Valve type		Suction head (m)	Discharge (L/min)	
		Piston	Check		Hand	Pedal
Twin treadle pump	9	Rubber flap valve	Rubber flap valve	2	-	72
Rower pump	5	Leather cup seal mounted on piston component	Molded plastic component with flap valve	2	54	-
Hand pump (Bangladesh No. 6)	10	Cast iron seat valve with leather cup washer	Leather flap with a cast iron counter weight	2	36	-
Double acting wheel pump	-	Flap mounted plastic wheel	Rubber flap mounted plastic	-	35	-
Modified Tara pump	12.7	Plastic annular flap valve mounted on piston component	Plastic annular flap valve	2	28.8	-
Newly built double-acting pump	21	Rubber flap mounted with wooden disc	Rubber flap and GI pipe	2	160 (PV1) 145 (PV2) 137 (PV3) 145 (PV4)	

Moreover, this pump has another advantage over other pumps as it is designed to incorporate valves made of wood. Since wood is readily available in Bangladesh, such kind of valves can be easily fabricated locally if valves are required to be replaced. This would be particularly feasible for minor irrigation projects (Miah, 1991) managed by farmers or small cooperatives. In addition, because of the large amount of discharge, this pump can play an important role in the rural water supply systems already in place (Rahman et al., 2011). The construction cost (approx. BDT 5000) of the pump are also be similar to other traditional pumps as they are built with similar materials.

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IV. Conclusion

Low-cost and efficient pumping technology can play an important role in the rural economy and public health. This can primarily be achieved by providing affordable irrigation facility that can also be used as a source of safe drinking water supply. In this regard, a low cost double acting reciprocating pump was designed in the laboratory. Instead of traditional leather valves, piston valves (PV) made of local wood was used in the pump. Four different designs of valves having different open area were tested. The discharge of the pump was found to be very satisfactory (137-160 L/min) at 2m of suction head compared to other similar pumping devices. The pump speed was found to be correlated with the total open surface area of the valve. The highest pump speed (65 stroke/min) was obtained for PV2 (51% open surface area), and the lowest (30 stroke/min) for PV1 (14.7% open surface area).The coefficient of discharge for all the wooden valves was well over 50% even at higher heads indicating better performance for a reciprocating pump. The overall efficiency of the pump at lower head ranged from around 17-25% while that at higher head ranged from around 7-12%. In terms of the design, the PV1 and PV2 was found to have shown better performance.

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