

Performance Characteristics of a Reciprocating Piston Pump Driven by a Wind Machine

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Abstract: The torque applied by a reciprocating pump on a wind machine axis is a fluctuating torque. The energy furnished by the pump on the wind machine axis is absorbed mainly in raising the water and the piston when the latter moves up. This has a direct adverse effect on the starting speed. The lower the maximum torque to be overcome, the easier will the wind machine start. If the necessary torque is high, a faster wind speed is required to start the wind machine. The operating time of the machine is consequently reduced. It is therefore desirable to reduce the starting torque, and hence to make the starting easier.

This paper presents a theoretical study to reduce the starting torque of a non-conventional reciprocating piston pump by controlling the stroke volume of the pump or by controlling the flow rate of the piston pump. These two methods are the best to control, smooth and reduce the starting torque of the pump by drilling a very small hole in the piston. The effect of this hole is that at very low speed (at starting) all water that could be pumped is leaked through the hole. This is the main important of the hole which made the pressure on the piston is very low and as a result the starting torque is low. The quantity of water leaking through the hole is small compared to the normal output of the pump. Finally the comparison between normal and leakhole piston pump and the effect of this leakhole on the cavitation phenomena are studied.

Keywords: Wind machine, Starting torque, Normal piston pump, Leakhole piston pump, Performance, Characteristics

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1. Introduction

When the pump is directly coupled to the wind machine, the simplest description of the starting behavior of a water pumping system is the static description, in which the starting torque of the rotor is equal to the maximum torque required by the pump at the starting wind speed. The required starting torque of the piston pump is at least three times the average torque. This means that the pump needs a high wind velocity just to be started. Therefore researches tried to perform the optimum matching between the pump and the wind machine. Especially, the torque characteristics of the wind machine-reciprocating piston pump combination [1-2].

Previous work on matching of pump and windmill has been done in [3-4]. References [3] presented some specific examples for wind pumping system to illustrate how an optimization procedure is effective in maximizing system output. Reference [4] gave a more generalized presentation that illustrates how operating points may be predicted for wind

system driving speed-dependant and constant-speed load. Reference [5] used the procedure given in [3] and [4] to select the optimum pump type which will be matched optimally with a given windmill and the optimum windmill which will be matched optimally with a given pump, but neither the rotor characteristics as a function of wind speed nor the hydraulic characteristics of the pump have been studied, and consequently the starting behavior and the off-design performance have not been considered. He stated that the wind regime characteristics of the site affect the selection of the suitable water pumping systems, and it is needed to construct a procedure to relate the wind regime characteristics, with rotor and pump characteristics.

In [6] the effect of rotor parameters on the output energy of wind energy conversion systems was studied and the results of investigation showed that the blade setting angle is the most important parameter which affects the system performance.

References [7-8] dealt also with the problem of matching between rotor and pump but all of them

were carried out for a specific site and the results depend on the experimental data obtained in the site.

Positive displacement pump, as normally be used, requires an average torque independent of speed, which is not matched to the rotor output as a function of wind speed. This problem can be solved by using a variable stroke reciprocating pump [9, 10].

In this paper a procedure for calculating design parameters of wind machine-pump unit will be studied. The proposed design procedure is based on the proper matching between design of a wind machine and that of a pump that; leads to the best performance of the combined wind turbine-pump unit. For the realization of this purpose the following matching conditions have been taken into account, the power out put from the wind machine and the speed of rotation of the pump.

If a pump is coupled to a wind rotor at a given wind speed (V) the rotor will turn at a speed that the mechanical power of the rotor is equal to the mechanical power exerted by the pump.

- The Power output from the wind machine is equal to the power input to the pump

$$\eta_m P_m = P_{hydraulic}$$

$$\eta_m \frac{1}{2} \rho_a C_p \pi R^2 V^3 = Q \rho_w g H = \gamma Q H$$

- The speed of rotation of the pump is equal to the speed of rotation of the wind machine

$$N_{pump} = N_{turbine}$$

If a certain gear ratio (K) is used, therefore

$$N_{pump} = K N_{turbine}$$

2. Application

Let us evaluate the force which acts on the piston rod during the upward stroke of the piston. If P is the weight of the moving parts, H is the total static head, A_p is the cross-sectional area of the piston and γ is the specific weight of the water. Then the vertical force F which has to be overcome for raising the water is:

$$F = P + \gamma A_p H$$

If the radius of the crank shaft is (a), the moment (T) to be overcome is:

$$T = KaF = Ka(P + \gamma A_p H) = KaP + \frac{30}{N} \gamma Q H$$

Where K is the gear ratio, $N =$ rps (rotational velocity).

The lower the maximum torque to be overcome, the easier will the wind start. It is

therefore desirable to reduce the starting torque (T). To reduce it, and hence to make the starting easier, various actions are possible.

3. Characteristics of a Normal Piston Pump

A piston pump is a positive displacement pump; this means that for each stroke the same volume of water is displaced, independent of head or speed of operation. The behavior of this pump is shown as follow.

- The instantaneous torque is given by (T_i)

$$T_i = \bar{T} * \pi \sin \theta$$

- The average torque is given by (\bar{T})

$$\bar{T} = \frac{1}{2\pi} \rho_w g H V_s = \frac{1}{2\pi} \rho_w g H A_p S$$

- The instantaneous flow rate is given by (Q_i)

$$Q_i = \bar{Q} * \pi \sin \theta$$

- The average flow rate is given by (\bar{Q})

$$\bar{Q} = \frac{\Omega}{2\pi} * V_s = \frac{\Omega}{2\pi} * A_p * S$$

4. Theoretical Model of a Leakhole Piston Pump

In order to improve the starting behavior of a wind machine equipped with a reciprocating pump. One can drill a very small hole in the piston as shown in Figure (1). The main effect of this leakhole is reducing the starting torque by making the pressure on the piston is very low, because of all water could be pumped is leaked through it. For most leakholes the length L , is only few times the diameter (d). This means that the pipe flow formulas cannot be used, but that the expressions for orifice flow must be used.

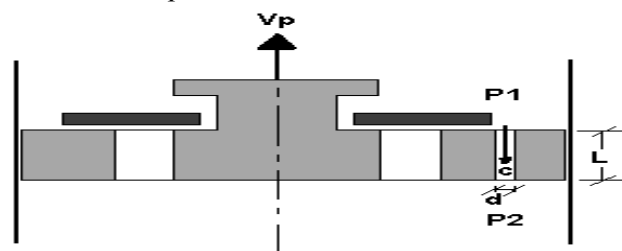


Fig.1 Schematic drawing of a piston pump with a leakhole

4.1 Main Parameters for a Leakhole Pump

As shown from the above figure of a theoretical model of a leakhole pump, there are two main parameters, velocity of flow in the leakhole (C) and the diameter of a leakhole (d). these two parameters are very important to know the amount of flow leaked through a leakhole (ΔQ) and to know the effect of a leakhole on reducing the starting torque. These parameters are proved and their equations are:

- The velocity of flow in the leakhole is

$$C = \sqrt{\frac{2gH}{f}}$$

- The diameter of a leakhole is given by

$$d^2 = D_p^3 * \sqrt{\frac{\eta_v S^3 X_d^3 \rho_w f}{32 C_{P_m} \eta_m \rho_a R_T^5}}$$

This expression can be simplified with the following values.

$\rho_w = 10^3 \text{ kg/m}^3, \rho_a = 1.2 \text{ kg/m}^3, f = 2.75 =$ throttling factor

This gives $d^2 = 8.4625 D_p^3 * \sqrt{\frac{\eta_v S^3 X_d^3}{C_{P_m} \eta_m R_T^5}}$

Where,
 $\eta_v =$ volumetric efficiency, $S =$ stroke of piston, $X_d =$ design tip-speed ratio and $C_{P_m} =$ max. power coefficient.

$$d = 2.9 D_p^{\frac{3}{2}} * \left(\frac{\eta_v S^3 X_d^3}{C_{P_m} \eta_m R_T^5} \right)^{\frac{1}{4}}$$

- The flow through the leakhole is

$$\Delta Q_1 = \frac{\pi}{4} d^2 * \sqrt{2gH} * f^{-\frac{1}{2}}$$

$$V_p = \frac{d^2}{D_p^2} * C = V_o =$$

$$\Omega_o * \frac{1}{2} S \Rightarrow \sqrt{\frac{2gH}{f}} = \frac{D_p^2}{d^2} * \Omega_o * \frac{1}{2} S$$

- The flow through the leakhole is given by

$$\Delta Q_1 = \pi \frac{\Omega_o}{\Omega} \bar{Q} = \frac{\pi}{\omega_1} \bar{Q}$$

4.2 Characteristics of a Leakhole Pump

- The instantaneous torque is given by (T_p)

$$T_p = \bar{T} * \pi \omega_1^2 * \sin^3 \theta$$

- The average torque is given by (\bar{Q}_p)

$$\bar{T}_p = \bar{T} * \frac{2}{3} \omega_1^2 \Rightarrow \Omega \langle \Omega_o$$

$$\bar{T}_p = \bar{T} \left\{ \frac{2}{3} \omega_1^2 + \frac{2}{3} (1 - \omega_1^2) \sqrt{1 - \frac{1}{\omega_1^2}} \right\} \Rightarrow \Omega \rangle \Omega_o$$

- The instantaneous flow rate is given by (Q_p)

$$Q_p = \bar{Q} (\pi \sin \theta - \frac{\pi}{\omega_1})$$

- The average flow rate is given by (\bar{Q}_p)

$$\bar{Q}_p = \bar{Q} \left\{ \sqrt{1 - \frac{1}{\omega_1^2}} - \frac{1}{\omega_1} (\frac{\pi}{2} - \theta_o) \right\}$$

$$\theta_o = \arcsin(\frac{\Omega_o}{\Omega}) \text{ Where}$$

The instantaneous torque and discharge as a percentage of ideal average torque and discharge of a normal piston pump is shown in the following Figures (2, 3).

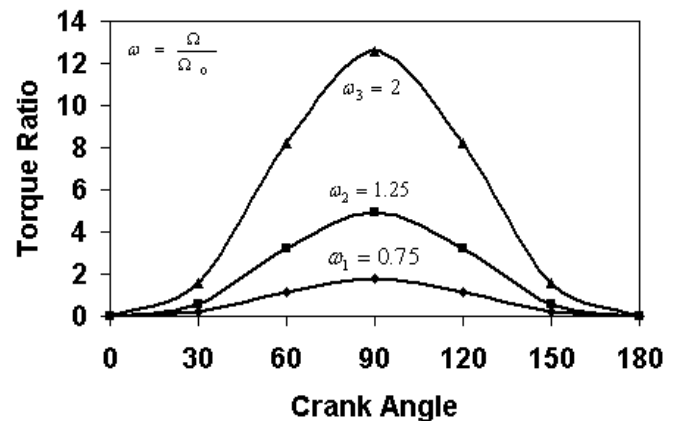


Fig.2 Torque fluctuation in a piston pump with a leakhole

$$\frac{T_p}{\bar{T}} = \pi \omega_1^2 * \sin^3 \theta$$

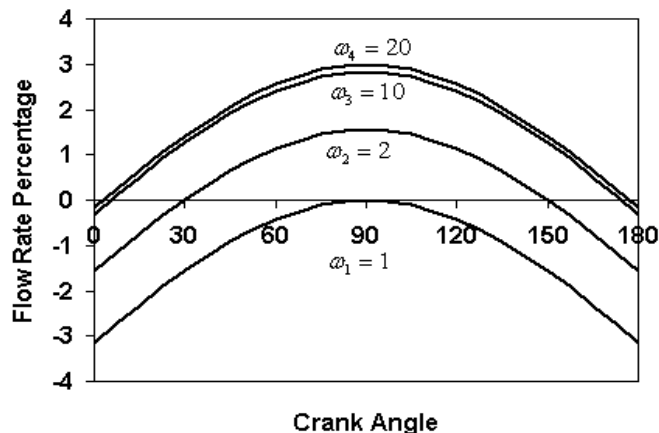


Fig.3 Flow Rate (discharge) of a piston pump with a leakhole

$$\frac{Q_p}{Q} = \pi \sin \theta - \frac{\pi}{\omega_1}$$

5. Comparison between Normal Piston Pump and Leakhole Piston Pump

In this comparison, there are two terms we comparison between them. These two terms are: the output discharge (flow rate) of the pump and the torque of the pump.

- Output discharge of the pump

We notice from Figure (4), the output discharge from a normal piston pump is higher than that of a leakhole piston pump due to the quantity of water leaking through the hole.

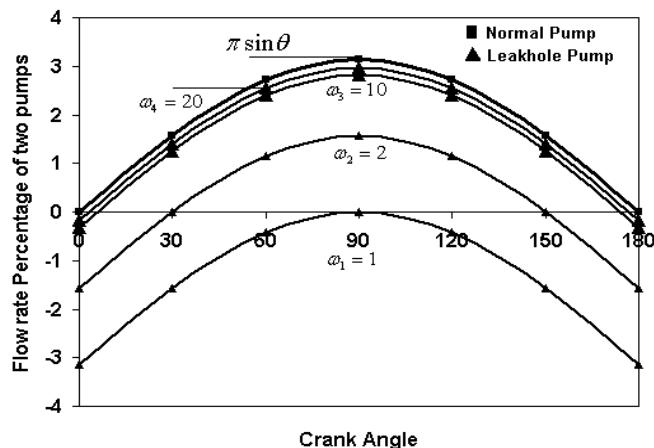


Fig.4 Comparison between the flow rate of a normal piston pump and a leakhole piston pump

- Torque of the pump

We notice from the following figure (5) that the torque of a leakhole pump is less than the torque

of a normal pump at starting, but the maximum torque is the same for the two types and the torque of a leakhole pump is decreasing again. This is the main purpose for using a leakhole piston pump to smooth the torque at starting in order to make the matching of a piston pump to a wind machine is easy without any problem.

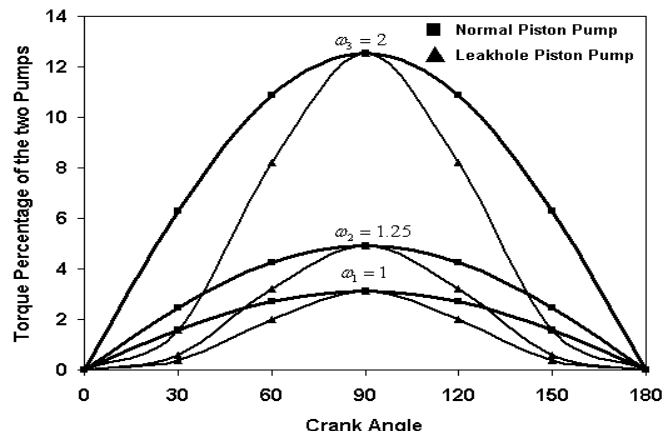


Fig.5 Comparison between the starting torque of a normal piston pump and a leakhole piston pump

6. Effect of the leakhole on the cavitation phenomena

Basic Parameter for a normal pump is given by the following equation

$$\frac{P_{atm}}{\gamma} = \frac{P_1}{\gamma} + H_s + \frac{u_1^2}{2g} + h_B$$

$$\frac{P_1}{\gamma} = \frac{P_{atm}}{\gamma} - (H_s + \frac{u_1^2}{2g} + h_B)$$

Where h_B = losses in suction side

From the above equation, $\frac{P_1}{\gamma}$ always less

than the atmospheric pressure $\frac{P_{atm}}{\gamma}$, this means that at

the entrance of the pump, the pressure is less than the atmospheric pressure. This phenomenon knows as Cavitation Phenomena. The value of this Cavitation can be calculated from the following equation:

$$H_{V_1} = H_s + \frac{u_1^2}{2g} + h_B$$

Where

$$u_1 = \frac{Q}{A_1} = \frac{4Q}{\pi d_1^2}$$

Where d_i = entrance diameter of the pump, Q = flow rate of the pump

$$H_{V_1} = H_s + \frac{16Q^2}{2g * \pi^2 d_1^4} + h_B$$

$$h_B = K_B Q^2$$

Where K_B = loss coefficient

$$H_{V_1} = H_s + \left(\frac{8}{\pi^2 d_1^4 g} + K_B \right) Q^2$$

From the above equation we can notice that the value of Cavitation at the entrance of the pump depend on three factors, these factors are suction head (H_s), entrance diameter of the pump (d_i) and flow rate of the pump (Q). The maximum value of

Cavitation theoretically is given by ($\frac{P_{atm}}{\gamma} = 10$ m),

this means that the suction head must be always less than 10 m for water. As we known that the output discharge of a leakhole piston pump is less than a normal pump. This is due to the effect of a leakhole. This means that the value of Cavitation in the case of a leakhole piston pump becomes less than in the case of a normal pump, and this better to overcome the Cavitation Phenomena at the entrance of the pump, and this is will make the performance of the pump is better.

7 Conclusion

In this paper, the effects of a leakhole in the piston of a reciprocating piston pump on reducing the starting torque were investigated theoretically. Results showed that a leakhole method is the easier method to perform the optimum matching between a reciprocating piston pump and a wind machine and to improve the starting behavior of the pump.

Also the comparison between a normal piston pump and a leakhole piston pump is studied. The results showed that the output discharge from a normal piston pump is higher than that of a leakhole piston pump due to the quantity of water leaking through the hole and this is the main purpose for using a leakhole piston pump to smooth the torque at starting in order to make the matching of a piston pump to a wind machine is easy without any problem.

Finally the effect of the leakhole on the phenomena of cavitation showed that the value of cavitation of a leakhole piston pump became less than of a normal pump due to leaked flow rate from a

leakhole, and this is excellent to improve the performance of a piston pump.

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