Starting Effects on the Performance of a Reciprocating Piston Pump Driven by a Wind Machine

MAHMOUD MOHAMED EL-GHOBASHY EL-HAGAR

Mechanical Engineering Department
Faculty of Engineering
Jazan University
KING OF SAUDI ARABIA (K.S.A)
m_elhagar@yahoo.com

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 using new methods, for example, changing the wind machine parameters, such as the aerodynamics configuration of the rotor and blade elements, or by studying the effect of wind speed velocity on the starting torque. Also by controlling the stroke volume of the pump or by controlling the flow rate of the piston pump. The last 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.

Key – words

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

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 [1-5].

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.

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

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

$$\eta_m \frac{1}{2}\rho_a C_P \pi R^2 V^3 = Q\rho_W gH = \gamma QH$$

- 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 is used, therefore

$N_{Pump} = K\, N_{Turbine}$, where K = Gear ratio

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:

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

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. Methods used to reduce the starting torque

3.1 Changing the Rotor diameter (D_T)

As shown from the equation of starting torque

$$T = KaP + \frac{30}{N}\gamma QH$$

$$\eta_m P_m = P_{hydraulic} = \gamma QH = \rho_W gQH$$

$$P_m = \frac{1}{2}\rho_a V^3 \frac{\pi}{4} D_T^2 C_P$$

For slow wind turbine (multi-bladed) the mechanical power of a windmill is given by

$$P_m = 0.15 D_T^2 V^3$$

Therefore the equation of the maximum torque is given by

$$T = KaP + 4.5\eta_m \frac{D_T^2 V^3}{N}$$

For reducing the starting torque of wind machine, the diameter of the rotor (D_T) should be reduced but the output power of a wind machine is reduced. The effect of reducing the rotor diameter on the starting torque is shown in the Figure (1).

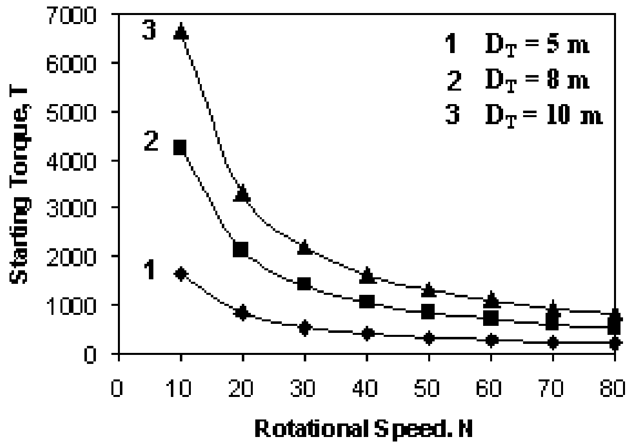

Fig.1 Effect of changing the Rotor Diameter on Starting Torque

3.2 Effect of wind speed (V) on the starting torque (T)

As shown from the equation of starting torque

$$T = KaP + 4.5\eta_m \frac{D_T^2 V^3}{N}$$

For reducing the starting torque of wind machine, the wind velocity (V) should be reduced. The effect of reducing the wind velocity on the starting torque is shown in the Figure (2).

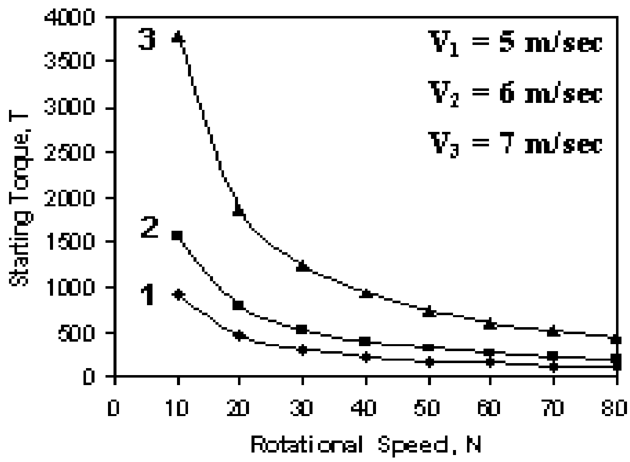

Fig.2 Effect of changing Wind Speed on Starting Torque

3.3 Effect of reducing the flow rate (Q) on the starting torque

As shown from the equation of starting torque

$$T = KaP + \frac{30}{N}\gamma QH$$

From this equation we notice that, as the value of flow rate of the pump reduced, we can smooth the starting torque. This effect can be made by making a small hole in the piston which is useful at starting by making some leakage in water at low speed which reduces the force acting on the piston and smoothing the starting torque. This effect is the same of the idea of a leakhole pump which will be discussed later. The effect of reducing the flow rate on the starting torque will be shown in Figure (3).

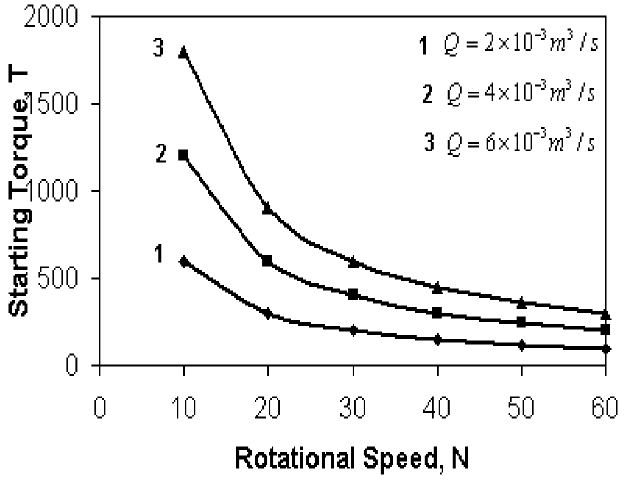

Fig.3 Effect of reducing the Flow Rate on Starting Torque

3.4 Changing the piston cross- section area (A_P)

As shown from the equation of starting torque

$$T = Ka\,(P + \gamma A_P H)$$

From this equation we notice that, we can smooth the starting torque by reducing the cross-sectional area of the piston by drilling a very small hole in the piston. The effect of this leakhole is that at very low speeds (at starting), all water that could be pumped is leaked through the hole. This implies that the pressure on the piston is very low and as a result the starting torque required is low. If the speed is high, then the quantity of water leaking through the hole is small compared to the normal output of the pump and the pump behaves as a normal pump. The idea of a leakhole piston pump will be discussed later. This effect of changing the piston cross-section area shown in Fig.(4).

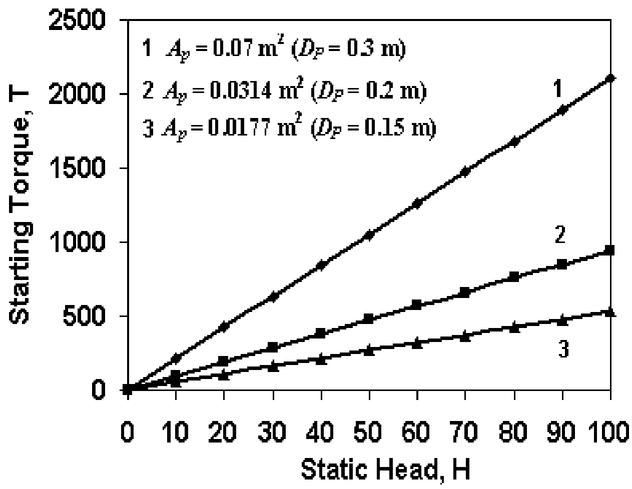

Fig.4 Effect of changing Piston cross-sectional area on Starting Torque

Before we start to talk about a leakhole piston pump, we must make brief instruction about a normal piston pump, especially about the characteristics of it , to make later a comparison between it and a leakhole pump, especially for the starting torque of both.

4. 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 ($\bar{Q}$)

$$\bar{T} = \frac{1}{2\pi}\rho_W\, gHV_S = \frac{1}{2\pi}\rho_W\, gHA_P S$$

- The instantaneous flow rate is given by (Q_i)

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

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

$$\bar{Q} = \frac{\Omega}{2\pi} * V_S = \frac{\Omega}{2\pi} * A_P * S$$

5. 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 (5). 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.

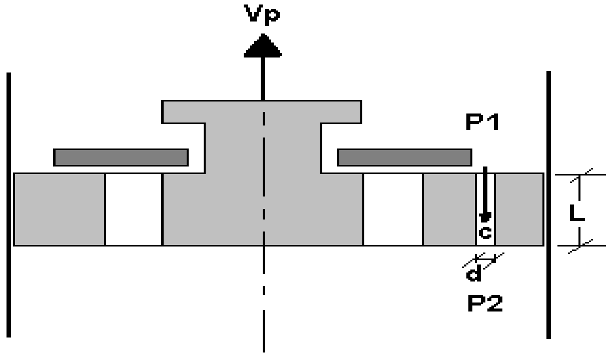

Fig.5 Schematic drawing of a piston pump with a leakhole

5.1 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.

$\rho_W = 10^3 kg/m^3, \rho_a = 1.2 kg/m^3, f = 2.75 =$ 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,

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

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

- T he 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

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

5.2 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 (6, 7).

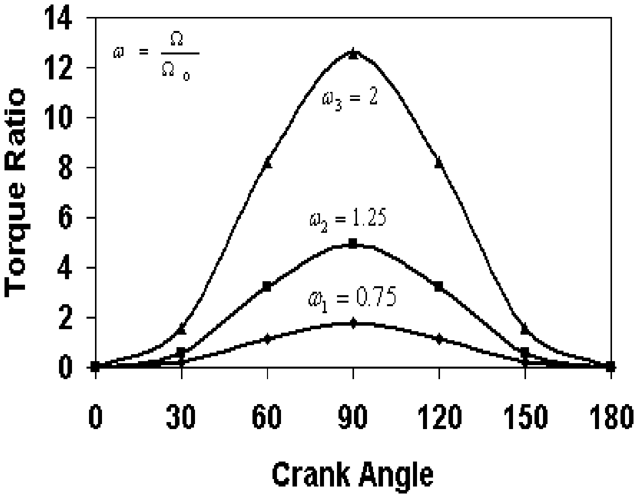

Fig.6 Torque fluctuation in a piston pump with a leakhole

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

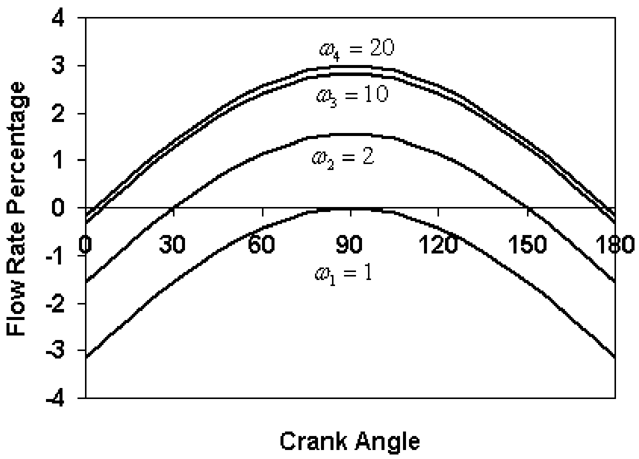

Fig.7 Flow Rate (discharge) of a piston pump with a leakhole

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

6. 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 (8), 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.

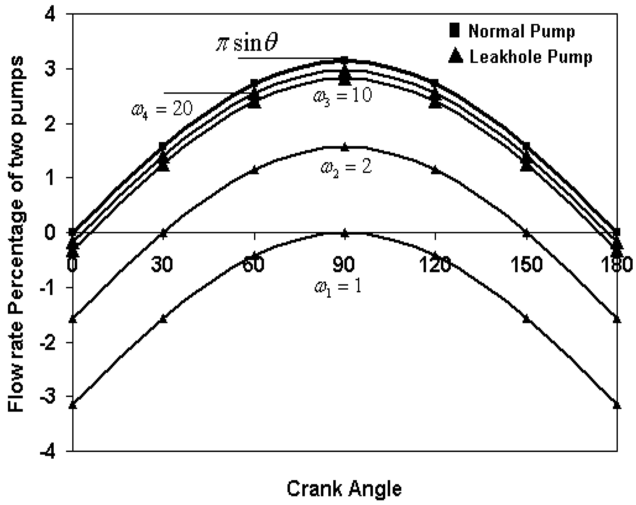

Fig.8 Comparison between the flow rate of a normal piston pump and a leakhole piston pump

- Torque of the pump

We notice from the following figure (9) 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.

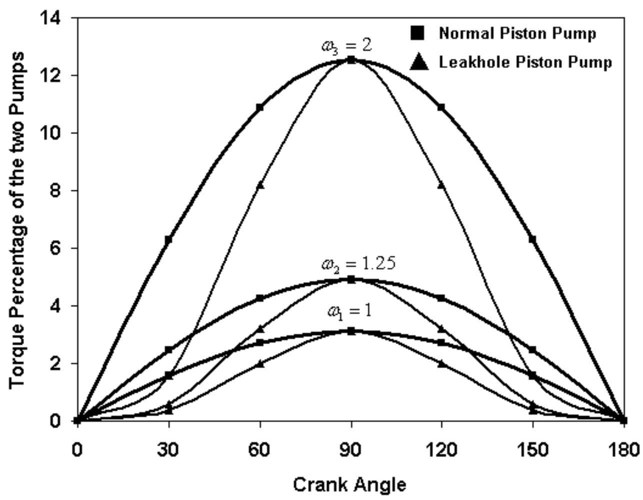

Fig.9 Comparison between the starting torque of a normal piston pump and a leakhole piston pump

7. 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_1 = 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

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

From the above equation we can notice that the value of Cavitation at the entrance of the pump depend on three factors, theses factors are suction head (H_S), entrance diameter of the pump (d_1) 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.

8. Conclusion

In this paper, the effects of wind machine parameters, aerodynamics configuration of the rotor, wind speed velocity, stroke volume of the pump and 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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