hool

Afdeling der Technische Natuurkunde

Vakgroep Transportfysica

PUMP RESEARCH BY CWD: THE INFLUENCE OF STARTING TORQUE OF SINGLE ACTING PISTON PUMPS ON WATER PUMPING WINDMILLS

Cleijne, H., Smulders, P.
Verheij, F., Oldenkamp, H.

October 1986 R 815 I

PUMP RESEARCH BY CWD: THE INFLUENCE OF STARTING TORQUE OF SINGLE ACTING PISTON PUMPS ON WATER PUMPING WINDMILLS

Cleijne, H., Smulders, P.
Verheij, F., Oldenkamp, H.

October 1986 R 815 D

Paper of the 6th European Wind Energy Conference, October 1986, Rome

TECHNICAL UNIVERSITY EINDHOVEN
Faculty of Physics
Laboratory of Fluid Dynamics and Heat Transfer
WIND ENERGY GROUP
P.O. Box 513, 5600 MB Eindhoven, Netherlands

CONSULTANCY SERVICES
WIND ENERGY
DEVELOPING COUNTRIES

P.O. BOX 85
3800 AB AMERSFOORT
THE NETHERLANDS

PUMP RESEARCH BY CWD: THE INFLUENCE OF STARTING TORQUE OF SINGLE ACTING PISTON PUMPS ON WATER PUMPING WINDMILLS

H.CLEIJNE, P.SMULDERS, F.VERHEY, H.OLDENKAMP

SUMMARY

Piston pumps are difficult to match to windmills. In first approximation the pump demands a constant torque for all rotational speeds. For this reason the combination of windmill and pump reaches its maximum performance for a single windspeed called the design windspeed.

At standstill the mill only starts running when the windspeed is higher than about 1.5 the design windspeed. It stops only when the windspeed drops below V_{stop} which is lower than the design windspeed. In the intermediate region the windmill is sometimes running, sometimes standing still. By this fact the overall efficiency is lower than can be expected theoretically.

The introduction of start helps can improve the start behaviour considerably.

A newly developed start help i.e. the floating valve is presented in this paper. A simple theoretical model of the floating valve is given, which is in fair agreement with the performed experiments. The pump with floating valve was tested under laboratory conditions as well as under field conditions. Comparison of the performance of a mill equipped with a normal pump and a pump with a floating valve showed an improved start behaviour and a 60% increased overall efficiency.

LIST OF SYMBOLS

A	rotor area	$[m^2]$
A_p	piston area	$[m^2]$
C_p	rotor power coefficient	[-]
F_{stat}	pump rod force	[N]
g	gravitational acceleration	$[m/s^2]$
h	pump head	[m]
P	power	[W]
Q_{pump}	pump torque	[Nm]
V	wind speed	[m/s]
V_{cl}	closure piston speed	[m/s]
q	flow	$[m^3/s]$
s	pump stroke	[m]
α	crank angle	[rad]
η_{mech}	mechanical efficiency	[-]
η_{vol}	volumetric efficiency	[-]
ω	rotational speed	[rad/s]
ω_{cl}	closing rotational speed	[rad/s]
ρ_a	air density	$[kg/m^3]$
ρ_w	water density	$[kg/m^3]$
λ	tip speed ratio $\omega R/V$	[-]

H.Cleijne, P.Smulders,
F.Verheij, H.Oldenkamp
Technical University Eindhoven
P.O.Box 513
5600 MB Eindhoven
The Netherlands

1. INTRODUCTION

CWD (Consultancy Services Wind Energy Developing Countries) is an organization initialized and funded by the Netherland's Ministry of Development Cooperation. It aims to help governments, institutes and private parties in the

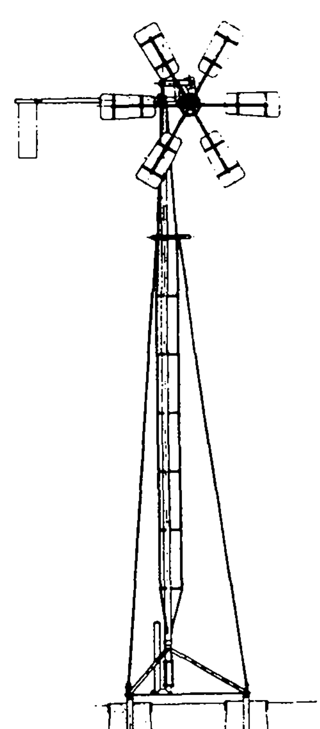

Figure 1. CWD 2000 windmill

Third World in their efforts to use wind energy and general to promote the interest for wind energy developing countries. The emphasis of the activities of CWD is on water pumping windmills directly coupled to single acting piston pumps.

Participants in CWD are DHV Consulting Engineers (Amersfoort), Eindhoven University of Technology, Twente University of Technology and ILRI, Institute of Land Reclamation and Improvement (Wageningen).

CWD's research areas with respect to pumps are:

- dynamical forces of piston pumps at high rotational speeds (forces due to acceleration, friction losses and shock forces due to delayed valve closure);
- minimizing these forces;
- behaviour of passive valves controlled only by hydrodynamic forces;
- improvement of the start behaviour by changing pump characteristics.

This paper will mainly deal with the last aspect. In section 4 the floating valve is presented. The reasons for the start problems of windpumps are briefly discussed in section 2.

The experiments presented in this paper were performed on a CWD-designed windpump, the CWD 2000. The CWD 2000 (see fig.1) is a small water pumping windmill of 2 m. diameter, especially designed for regions with low windspeeds. It has a tip speed ratio of $\lambda = 1.3$ and a solidity of 0.35. The typical design windspeed is about 3.5 m/s. The rotor is directly coupled to a surface suction pump of 67 mm. diameter by means of a crank mechanism which has an adjustable stroke between 2.5 and 10 cm.

At the design windspeed the mill delivers 25000 l. water a day at a 5 m. static head. Its total weight is only 150 kg.

2. START AND STOP BEHAVIOUR [1,2]

Piston pumps are a rather difficult load for windmills. In first approximation the average torque demanded by a piston pump is constant for all rotational speeds. As a consequence the combination of windmill and piston pump has one optimal wind speed, for which the overall efficiency $C_p\eta$ reaches a maximum (fig 2). $C_p\eta$ is defined as the ratio of net delivered hydraulic power and power available in the wind.

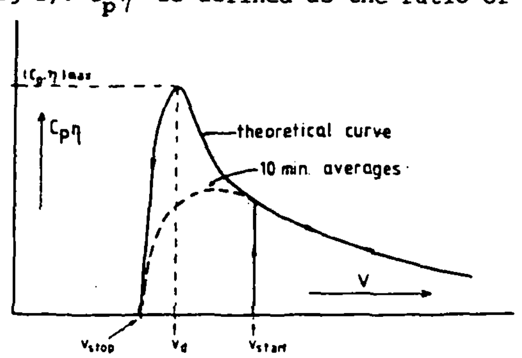

Figure 2. Power coefficient $C_p\eta$ with hysteresis region

$$C_{p\eta} = \frac{P_{hydr}}{\frac{1}{2}\rho_a V^3 A} \tag{1}$$

in which ρ_a denotes the air density, V the wind speed and A the area swept by the rotor.

The hydraulic power is defined as

$$P_{hydr} = \rho_w\, g\, h \cdot q \tag{2}$$

in which ρ_w denotes the water density, g the gravitational acceleration, h the pump head and q is the discharged flow.

Assuming that friction losses can be neglected, a constant force F is exerted on the rotor's crank:

$$F = \rho_w\, g\, h\, A_p \tag{3}$$

in which A_p denotes the piston area. The rotor experiences a torque of sinusoidal shape equal to

$$Q_{pump} = F_{stat} \cdot \tfrac{1}{2}s \cdot \sin\alpha \qquad 0<\alpha<\pi \tag{4}$$

s denotes the pump stroke and α is defined as the crank angle measured from the bottom dead center.

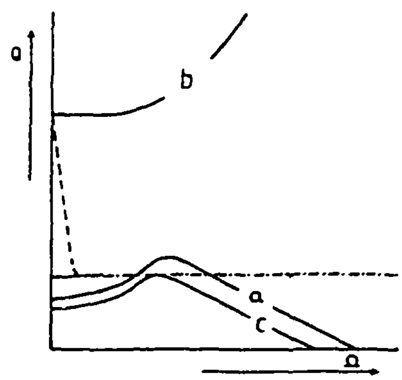

Figure 3. Torque characteristics of rotor and pump a) design windspeed, b) start windspeed c) stop windspeed

$Q_{pump} = 0$ in the down ward stroke. At high rotational speeds the rotor experiences only the average torque $\bar{Q}_{pump}$ demanded by the pump.

$$\bar{Q}_{pump} = F_{stat} \cdot \tfrac{1}{2}s \cdot \tfrac{1}{\pi} \tag{5}$$

This is because the large rotational energy of the rotor prevents large variations in the rotational speed (fig.3a).

When the rotor has to start after a period of standstill the situation is different. No energy is stored in the rotor so now the rotor has to overcome the maximum torque which is π times the average torque. Therefore the start speed V_{start} is considerably larger than the design wind speed (fig.3b).

The stop wind speed V_{stop} is that wind speed for which the maximum rotor torque is equal to the average pump torque (fig.3c).

Because V_{stop} and V_{start} have different values the performance curve contains a hysteresis region [3]. In this region the mill is either running or standing still dependent on the wind history. Without any start help V_d lies in the hysteresis region. This means that at the design windspeed V_d the running of the windmill is not assured. In measurements of $C_{p\,max}$ (10 min. averages according to the IEA recommendations) a lower maximum than the theoretically predicted value is found.

3. LEAK HOLE

A common solution to improve the starting behaviour of a waterpumping windmill is to reduce the torque of the load at low rotational speed.

Presently all CWD piston pumps are equipped with a leak hole through the piston. At low rotational speed the pressure drop over the leak hole is low, thus little starting torque is demanded by the pump, which enables the rotor to accelerate. At higher rotational

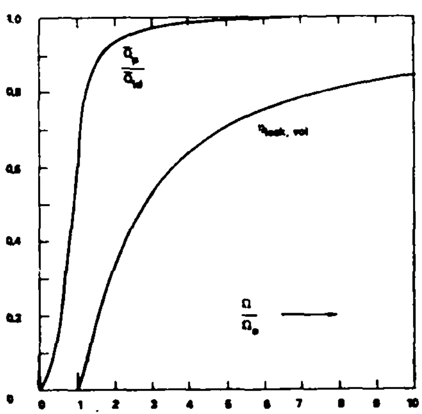

Figure 4. Characteristics of pump with leak hole

speed the pressure drop increases rapidly, proportional to the flow speed squared in the leak hole. At the moment the pressure drop over the leak hole balances the delivery head, the pump starts discharging water. In experiments at the Eindhoven testfield the application of a leak hole caused an improvement in overall measured efficiency C_p and an improved starting behaviour [5].

In fig.7 the volumetric efficiency is given as function of dimensionless rotational speed. η_{vol} is defined as the ratio of discharged water per stroke and the stroke volume.

Although the leak hole offers a good possibility to improve the starting behaviour of a water pumping windmill it has also some disadvantages.

- A compromise has to be sought between good starting behaviour and limited efficiency loss at design conditions. Normally CWD accept a 10% efficiency loss at design conditions.
- At low rotational speeds the pump discharges no water, but demands already considerable torque (67% of the average design torque at the speed where the pump discharges water for the first time).

In the next section a new concept will be presented. A concept which combines the advantages of a normal valve and a pump equipped with a leak hole.

4. THE AUTOMATIC REGULATED LEAK HOLE

The disadvantages can be resumed as follows:

- the leak hole is too small for low rotational speeds, hence the pump demands considerable torque without delivering water;
- the leak hole is too large for high speeds, resulting in a loss of mechanical efficiency at these higher speeds.

A solution for these problems is the design of a piston valve which is kept open at low speeds and closes at high speeds.

The viability of this concept was proven in experiments at the Eindhoven test field using a electronically controlled piston valve in a CWD 2000 mill. At low speeds the valve was kept open by an electro-magnet. Above a certain speed the magnet was switched off and the valve acted as a normal valve [5]. By choosing the right switching speed the measured power coefficient could be improved considerably. The start speed of the mill decreased in comparison with a windmill equipped with a standard leak hole.

4.1 The floating piston valve

Of course an electronically controlled piston valve is not a practical solution which can be applied in developing countries. However in the next sections it will be shown that the same results can be obtained by using a floating piston valve. The average density of the valve is much lower than that of water so that

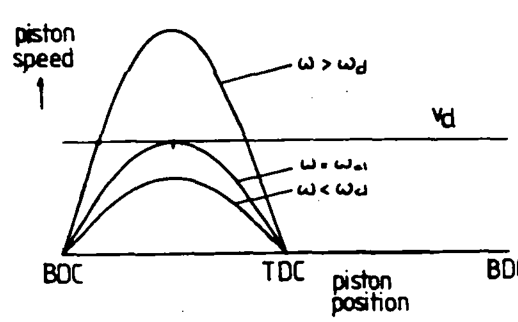

Figure 5. Principle of the floating valve

it has a large buoyancy. At low rotational speeds the floating valve remains open, so the pump demands no torque. At a certain piston speed V_{cl} the hydraulic force over the valve becomes big enough to balance the buoyance force and hence the valve closes.

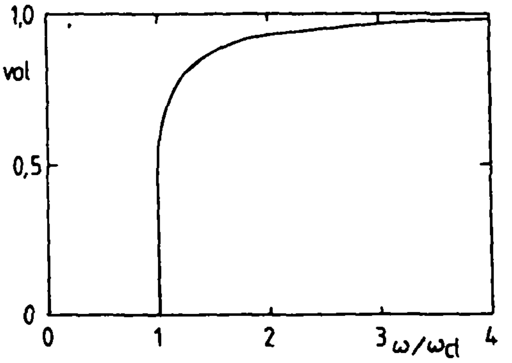

Figure 6. Volumetric efficiency of the floating valve

The rotational speed at which the valve closes for the first time is called ω_{cl} and is equal to $\omega_{cl} = V_{cl} \cdot {}^{s}/_{2}$. For this rotational speed the valve closes at 90° from the bottom dead center of the pump.

At higher rotational speeds the valve closes earlier and ultimately it approaches the behaviour of a normal valve (see fig.5). The volumetric efficiency of a pump with a floating piston valve is given by the following expression.

$$\eta_{vol} = \tfrac{1}{2}\left(1+\sqrt{1-(\omega_{cl}/\omega)^2}\right) \quad \text{for } \omega>\omega_{cl} \qquad (6)$$
$$\eta_{vol} = 0 \qquad \text{else}$$

This is displayed in fig.6.

The theoretical value for the mechanical efficiency is $\eta_{mech} = 1$, for all values of ω. This is in contrast with a pump containing a leak hole. A pump with a leak hole essentially has a mechanical efficiency lower than 1.

4.2 Laboratory tests

Before a pump with a floating valve was installed at the testfield, it was tested under laboratory conditions. For pump testing the Eindhoven University owns a pump test rig. In this rig the pump is driven by an electric motor at a constant rotational speed. Further the rig is equipped with a pressure vessel, used to simulate the pump head and for the simulation of line friction 100 m. of 1½" gaspipe was installed.

The following quantities are measured:

- pump rod force with strain gauge force transducer;
- pump rod speed with a magneto-inductive speed transducer;
- discharged flow with a magneto-inductive flow meter;
- pressures at several places with strain gauge pressure transducers.

To collect the data from the transducers the pump test rig is equipped with a data-acquisition system, consisting of an IBM-XT personal computer containing a Metrabyte data-acquisition card.

In fig.7 and 8 the results of experiments with the floating valve are reported. The valve gap height of the valve was varied in a range of 3 mm. through 6 mm. The pump head in this experiment was 8 m. In fig.7 the ratio of

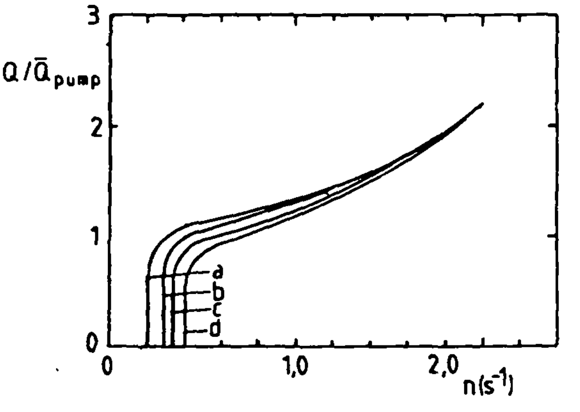

Figure 7. Measured torque divided by average pump torque $\bar{Q}_{pump}$ with valve gap height
a) 3 mm.
b) 4 mm.
c) 5 mm.
d) 6 mm.

measured torque and ideal torque (equation (5)) is given as a function of rotational speed. At high rotational speed flow friction in the pump and the lines causes the demanded average torque to increase. From these measurements a maximum mechanical

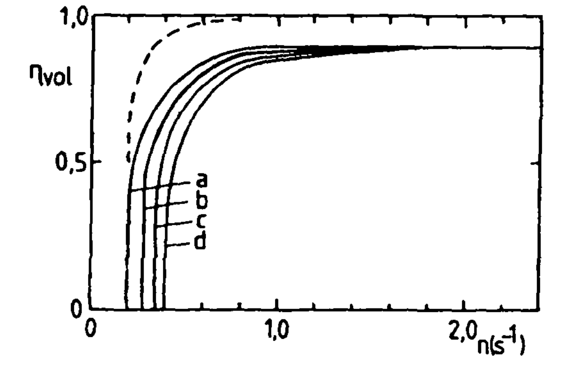

Figure 8. Volumetric efficiency measured at pump test rig, valve gap height a) 3 mm. b) 4 mm. c) 5 mm. d) 6 mm. theoretical η_{vol}.

efficiency $\eta_{mech} = 0.73$ could be derived. This value is almost immediately attained after the pump starts discharging water and is comparable with values in earlier measurements on pumps with normal valves. In fig.8 the volumetric efficiency as a function of rotational speed is given. Comparison with theory shows qualitative agreement. The difference can be explained by leak. The maximum η_{vol} is 90% at high rotational speeds. This means that there is 10% leak through the pump. The rotational speed at which the pump starts discharging water is sharply defined and can be adjusted by changing the valve gap height or the buoyancy of the valve (the latter is not shown in the graphs).

4.3 Field experiments [4]

After the laboratory experiments on the floating valve had shown to be promising a pump with a floating valve was mounted under a CWD 2000 windpump and was tested at the Eindhoven testfield.

The measurements were performed according to the IEA recommendations using 10 minutes averages for wind speed, wind direction, power output and the derived overall power coefficient $C_p\eta$. These measurements were elaborated using the bin sort method with a bin width of 0.5 ms^{-1}. The average wind speed during the test period was only 1.9 m/s, and no wind speeds larger than 6 m/s occurred. In fig.9 the frequency distribution of the windspeed is given. The pump head was kept at 10 m.

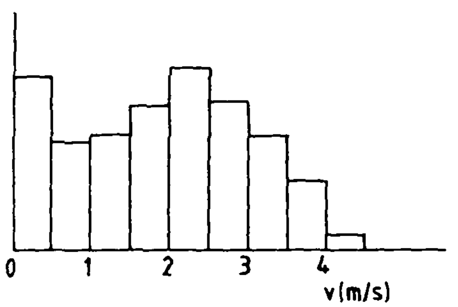

Figure 9. Wind speed distribution during measuring period

In fig.10 the result of these measurements is summarized. The $C_p\eta$ curve is shown as a function of the wind speed. In the same figure results are displayed from earlier test periods when the mill was equipped with a standard leak hole and with the electronically controlled valve as described in section 4. Also a measurement using a pump without leak hole is shown.

The difference in performance for a pump with the floating valve and the pump with the leak hole is striking.

The $C_p\eta_{max}$ is improved from 0.13 for the pump with leak hole to 0.21 for the pump with the floating valve. In comparison with the pump without any start help the start speed is improved by a factor 2.

Finally the theoretical curve is displayed for a rotor with a $C_{p,max}$=0.29 (CWD 2000) coupled to a pump with a constant torque load and mechanical efficiency of 0.73 as measured in the

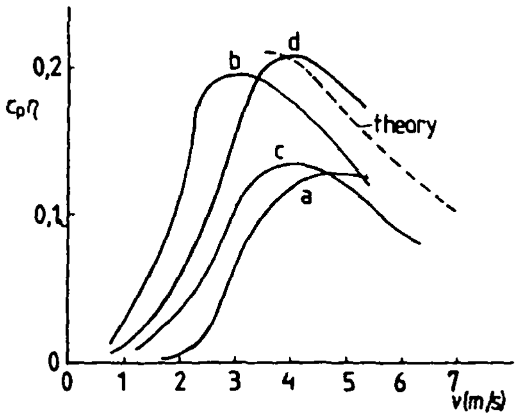

Figure 10. Measured $C_p\eta$ as a function of windspeed
a) normal pump b) pump with electronically controlled valve c) with leak hole
d) with floating valve

pump test rig. Combining these values results in a value of $C_{p,max}$ = 0.22 which matches perfectly with the measured value. Because the latter was measured and averaged over 10 minutes intervals this can only mean that the windmill was always running at its design wind speed.

CONCLUSION

Windmills coupled to piston pumps have start problems. This reduces the performance at the design wind speed, because at the design wind speed it is not running all the time.

The use of a leak hole improves the start behaviour and thus the maximum power coefficient $C_p\eta$.

The performance is further improved by application of a floating valve. With this valve an improvement of $C_p\eta_{max}$ of 60% was attained. Further it was proven that at the design wind speed the mill was always running.

The use of a floating valve can reduce the cost of pumping water.

REFERENCES

[1] Eric Lysen - Introduction to Wind Energy - C.W.D., P.O. Box 85, Amersfoort, The Netherlands - CWD 82-1, 2nd edition, 1983
[2] Gerard de Leede - The influence of rotor inertia and leakage on the starting behaviour of a windmill driving a piston pump, (in Dutch) - R-486-S, February 1982 (*)
[3] Joop van Meel, Paul Smulders - Are the IEA Recommendations sufficient for windmills driving piston pumps? - BWEA conference, London, May 1986
[4] Joop van Meel, Henk Oldenkamp - Field performance monitoring system for water pumping windmills - Wind Engineering, vol.8, no.4, 1984
[5] Henk Oldenkamp, Niko Pieterse - Field measurements on the CWD 2000 between 85-03-28 and 85-08-10 - R-756-D, November 1985 (*)