# Performance Testing of a Windmill-Pump System

**Willem Nijhoff***

Boddenkampstraat 47, 7522 BZ Enschede, The Netherlands

## INTRODUCTION

At the request of Volunteers in Technical Assistance (VITA) – Asia Field Office, the author tested the VITA V-8B windmill from July 2nd to July 11th 1983.

The testing procedure followed was according to the "Standard Testing Procedure for Wind-powered Water Pumps in Thailand" by Marcus M. Sherman, VITA, January 1983.

## DESCRIPTION OF THE WINDMILL-PUMP SYSTEM

The windmill-pump system (type V-8B) under investigation was designed and developed by VITA Incorporation, Asia Field Office, and is a modification of their earlier ptototype V-20B. It is located at Lumpun in the Phattalung province of southern Thailand and used for lifting water from a river into an irrigation canal system. The components of the system (see Fig. 1) are described below:

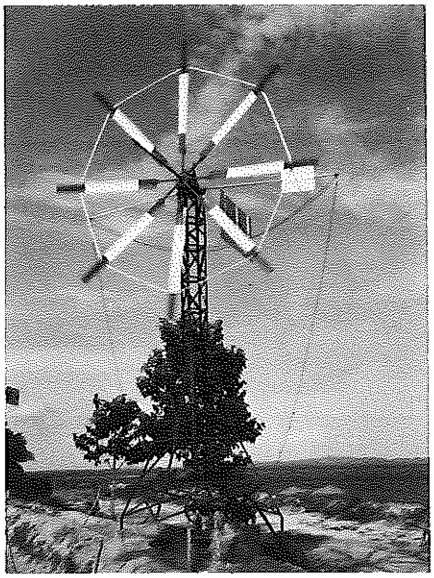

Fig. 1 Windmill-pump system

*Formerly Windmill Consultant to TOOL Foundation, Steering Committee Wind Energy Developing Countries (SWD)

## *The Rotor*

The rotor of the windmill, facing upwind, is 6.1 m in diameter and consists of eight laminated wooden blades with an aerodynamic profile. The blades, 2.445 m in length, are bolted to steel spokes and welded to a steel hub. These spokes ensure a correct setting angle at the root of the blades. At a radius of 2.45 m the blades are inter-connected by supporting tubes to ensure the correct angle of the blades at the outer half of the blades. At this point, the blades are also supported by steel wires and then connected to a central pole in the extended rotor shaft.

## *The Blades*

The blades are made from five layers of wood veneer, glued together and pressed in a mould to obtain the required profile. The leading edge of the blade is rounded and the tailing edge is bevelled. The tip of the blade is rounded to reduce tip losses and noise produced by the blades. The root chord, tip chord, and thickness of the blade are 0.20 m, 0.14 m, and 0.015 m, respectively. The blades are protected by two coatings of aluminium paint and a finishing coat of enamel paint. The smooth finishing contributes to a good aerodynamic performance.

## *The Head Assembly*

The head assembly of the system is shown in Fig. 2. The rotor hub is fixed on a hollow rotor shaft with a key lock. The rotor shaft runs on two self-adjusting pillow blocks bolted to the headframe. In between the pillow blocks a wooden pulley for the belt transmission is fixed on the shaft with a key lock. Four 10 mm steel plate arcs are welded to the headframe on the turntable to support the vertical load. Also, four rollers with brass bushings and a U-shaped groove on the circumference are bolted to the headframe to guide the headframe on the turntable, carry the thrust load, and prevent it from tumbling down.

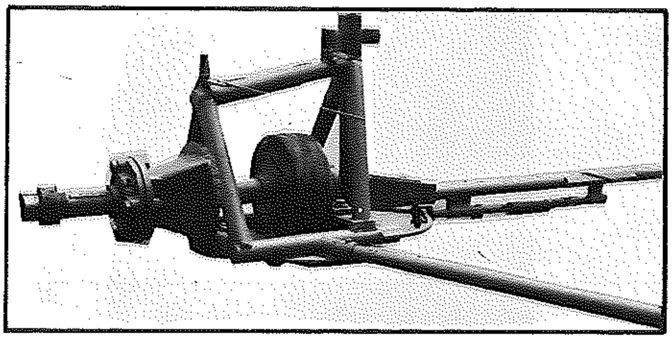

Fig. 2 Head assembly

## *The Tail and Governing Mechanism*

The tail and the governing mechanism of the system are shown in Fig. 3. The tail is connected to the headframe with a vertical centrally positioned hinge. A spring with an adjustable preload keeps the tail perpendicular to the rotor plane. The spring mechanism is designed so

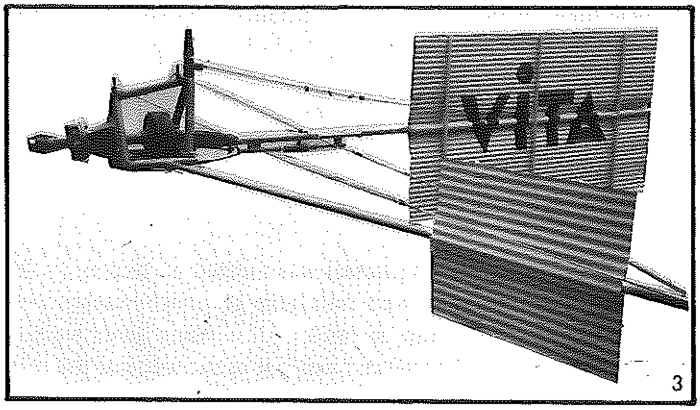


Fig. 3 Tail and governing mechanism

that when this angle changes from 90 degrees to 10 degrees, the tension in the spring is progressively increased. A side-vane, fixed to the headframe, gradually turns the rotor out of the wind at higher wind speeds, and there is always equilibrium between the wind thrust on the side-vane and rotor and the tension on the tailspring. The minimum wind speed at which the rotor starts turning away can be adjusted by changing the preload of the spring. The tail and rotor direction and their mutual position can also be set manually by means of a rope and pulley system connected to the end of the tail, side-vane and auxiliary pole (fixed to the headframe opposite the side-vane). The rope can be manipulated at ground level.

## *The Tower*

The tower is a four-leg lattice steel angle structure; the upper part is equipped with a turntable and the lower part is bolted to a reinforced concrete foundation. The wide-based tower converges in two steps to a parallel top section to prevent the rotor blades hitting the tower. The heights of the rotor shaft and the turntable from the top of the foundation are 7.15 and 7.0 m, respectively.

## *Transmission*

Transmission is by means of a four-inch wide industrial power belt. It transmits the rotation of the rotor shaft directly to the pump drive shaft and provides the option to fix other diameter pulleys on the pump drive shaft to adjust the transmission ratio. This is an easy way to match the pump to the prevailing average wind speed at different seasons. The pump drive shaft runs on three bearings which are bolted onto three slotted angle iron supports. The transmission ratio of the system under test was 0.48.

## *The Pump*

The pump is a modified rotary chain ladder pump where the conventional rectangular gutter with wooden paddles on the chain has been replaced by a six-inch PVC pipe with round rubber washers on the chain. The chain-links and chain-wheels, however, are conventional ones. The performance of this pump was much better than obtained by conventional construction. It is also insensitive to the angle under which the pump is installed. Its volumetric efficiency is relatively high.

## METHODS OF MEASUREMENT

### *Wind Speed Measurements*

The wind speed meter (a cup anemometer) was located at 16.5 m (= 2.7 X rotor diameter) west-northwest from the windmill and fixed on a pole at approximately the same height as the rotor shaft. It gives a readout every ten seconds. All measurements were taken while the cup anemometer was freely exposed to the wind and was not in the wake of the rotor.

### *Water Discharge and Wind Speed Measurements*

For the water discharge measurement a V-notch system (Fig. 4) was used. The V-notch angle is 90° and the maximum height above the vertex is 0.2 m. In the approach canal, a baffle plate was placed to obtain normal velocity distribution in the canal and a surface free of waves. The head was measured upstream, just after the plate, and at a sufficient distance from the weir. The head was measured by a communicating PVC-tube in the canal, and the water level in the outside vertical pipe was observed by means of a float with a needle against a scale measuring in millimetres. The water discharges were measured by noting the ten-second readouts of the

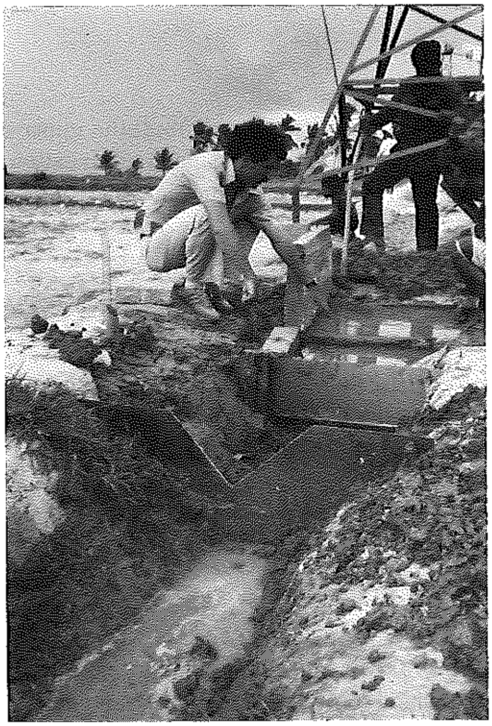

Fig. 4 V-notch flow measuring system

anemometer with simultaneous readings of the V-notch head. More than 1,000 wind speed/water discharge measurements were made during three test sessions.

The accuracy of the V-notch flow measuring system was satisfactory, except for delay in the system caused by the low flows after a period of high flows. In other words, at small flows it takes a long time (about 10 times the measuring intervals of ten seconds) before the new equilibrium is reached. Theoretically, the delay can be reduced by reducing the volume of water in the basin upstream the V-notch weir. This, however, was not possible since in a V-notch flow measuring system the water level has to be measured at a distance upstream equal to at least four times the maximum head to be encountered, but downstream the baffle plate. These conditions determine the minimum distance between the V-notch weir and the baffle plate. The outlet of the pump requires a certain minimum catchment area, so the minimum distance of the baffle plate to the pump outlet is also fixed. Furthermore, measurements should be made where there is no splashing waterflow and the flow has become a little smooth. On the other hand, reducing the volume can also take place by reducing the canal crosssection area. This, however, is also restricted because of certain conditions to be fullfilled by the V-notch system. The minimum distance from any point on the edges of the weir to the sides and bottom of the canal should be at least two to three times the maximum head. The height of location of the V-notch plate is also determined by the water level in the downstream canal; the water level at some distance downstream the V-notch should be below the bottom of the V-notch. These conditions determine the minimum size of the canal upstream. Hence, there is no way to reduce the volume of water in order to decrease the time required for reaching a new equilibrium at varying flows, and considerable deviation at low flows has to be accepted.

### *Rotor Speed and Wind Speed Measurements*

The time interval of each observation was increased from ten seconds to thirty seconds to get more precise rotor revolution countings. Three subsequent anemometer readings of ten-second intervals and the corresponding number of revolutions of the rotor were made. More than 125 wind speed/rotor speed measurements were made during one test session.

## DATA PROCESSING AND RESULTS

To determine the windmill-pump characteristics, the following relations are studied.

### *Pumping Output (Q) vs. Wind Speed (V)*

The range of wind speeds that occured during the test were grouped with class intervals of 0.5 m/s. The V-notch heads in each group, measured from the three test sessions, were averaged and converted to l/s by using the V-notch discharge formulae:

$$Q = 0.0137\, h^{2.5} \tag{1}$$

where $h$ = V-notch head (in cm)

$Q$ = pumping output (in l/s)

If enough data are accumulated for each wind speed group, a plot of these average pumping outputs vs. wind speed would show only limited scatter. The smooth curve drawn through these points (Fig. 5) is called a windmill-pump system output curve.

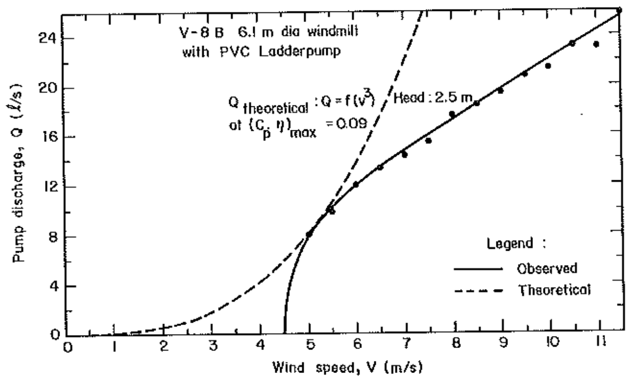


Fig. 5 Windmill-pump system output curve

Due to system hysteresis, in Fig. 5 cut-in wind speed (the minimum wind speed at which the windmill starts delivering water) is shown as 4.5 m/s and is the average of the cut-in wind speed (5.0 m/s) and the wind speed at which the pump stops delivering water (4.0 m/s). System hysterisis is caused by factors such as acceleration, deceleration, stick-slip friction, and flywheel effect.

## *Monthly Pumping Output (MO) vs. Average Wind Speed ($\bar{V}$)*

It is interesting to study the long-term performance of the system. Monthly pumping output, mean pump output and pumping availability have been established for this purpose. The wind speed distribution was calculated for the average wind speeds $\bar{V}$ of 2,3,4,5 and 6 m/s using the value of the probability density function for a Rayleigh distribution (a special case of Weibull distribution with shape factor $k = 2$) as an approximation to the frequency $F(V)$ of wind speed $V$ in steps of 1 m/s ($\Delta V = 1$) thus:

$$F(V) = \frac{1}{2}\,\Delta V\,\pi\,(V/\bar{V}^2)\,\exp\left[-\frac{1}{4}\,\pi\,(V/\bar{V})^2\right]$$

If $\Delta V$ is small, little error is introduced over exact integration. In synthesizing this distribution with the windmill-pump system output curve realistic estimates of monthly pumping output, mean pump output and pumping availability were obtained. The results are shown in Table 1 and the monthly pumping output vs. average wind speed relationship is shown in Fig. 6.

**Table 1**
**Long-term performance measures**

| Average Wind speed (m/s) | Mean Pumping Output (l/s) | Monthly Pumping Output ($m^3$) | Pumping Availability (%) |
|---|---|---|---|
| 2 | 0.14 | 358 | 1.6 |
| 3 | 1.68 | 4,418 | 16.6 |
| 4 | 4.42 | 11,632 | 36.8 |
| 5 | 6.97 | 18,335 | 51.2 |
| 6 | 8.69 | 22,858 | 58.6 |

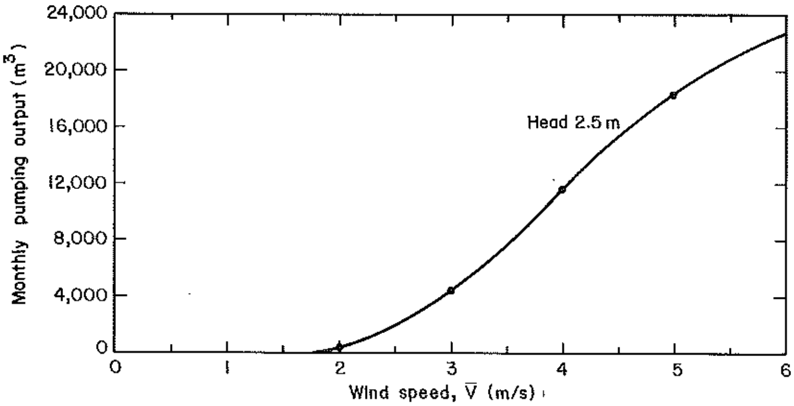


Fig. 6 Monthly pumping output vs. monthly average wind speed

The reason for using the Rayleigh distribution is that it could be specified with a single parameter (mean wind speed) and it closely approximates actual wind speed distributions.

## *Rotor Speed (n) vs. Wind Speed (V)*

The anemometer readings were grouped with class intervals of 0.5 m/s and the number of rotor revolutions in each group were averaged and converted to revolutions per minute (RPM). The results are shown in Fig. 7. Due to system hysterisis, measurements at low speeds (3.5 and 4 m/s) are not reliable and always overestimated, so corrections for this have been made in Fig. 7. It can be noticed from Fig. 7 that due to the pump characteristics the start speed is 4.0 m/s, whereas the cut-in speed is 4.5 m/s.

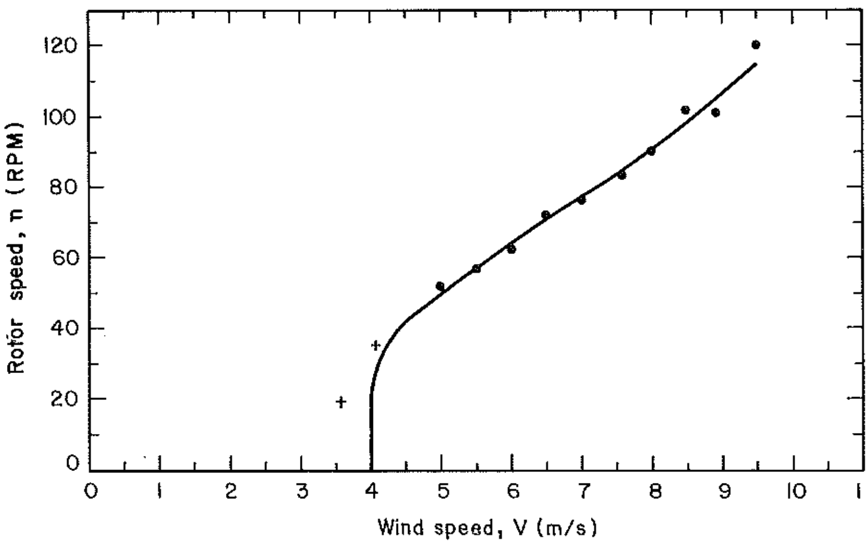


Fig. 7 Rotor speed vs. wind speed

### *Tip Speed Ratio (λ) vs. Wind Speed (V)*

The tip speed ratio is calculated from the following relation:

$$\lambda = 2\pi n R/60V \tag{2}$$

where $\lambda$ = tip speed ratio

$R$ = rotor radius (in m)

$n$ = rotor speed (in RPM)

For the windmill under test it reduces to:

$$\lambda = 0.319\, n/V \tag{3}$$

and the results are shown in Fig. 8. The values $V = 3.5$ and 4.0 m/s are omitted because of the erroneous value for the rotor speed.

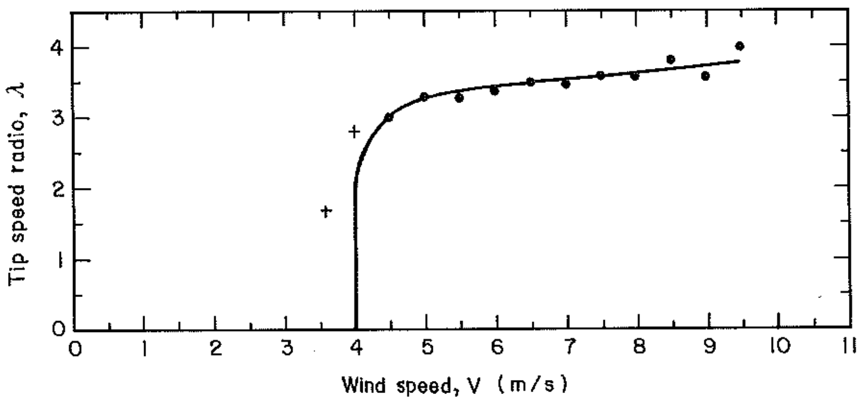


Fig. 8 Tip speed ratio vs. wind speed

### *Volumetric Efficiency ($\eta_v$) vs. Wind Speed (V)*

For a conventional reciprocating pump volumetric efficiency is defined as the ratio of discharge/stroke divided by stroke volume. For the rotary chain ladder pump, it is the ratio of real pumped output ($Q$) to the theoretically possible discharge ($Q_{th}$) at the actual chain speeds. $Q_{th}$ in l/s is given by

$$Q_{th} = V_{chain}\, A \times 10^3 \tag{4}$$

where $V_{chain}$ = chain speed of the ladder pump (m/s)

$A$ = the area of pipe less average area of chain-links and rubber washers ($m^2$)

In the above relation,

$$V_{chain} = \pi\, d\, n_{pump}/60$$

where $d$ = pitch diameter of the chain-wheel of the ladder pump (in m)

$n_{pump}$ = pump drive shaft speed (in RPM)

For the given system with a rotor shaft pulley diameter of 29 cm, pump drive shaft pulley diameter of 60 cm, and 2% beltslip, we can determine the pump drive shaft speed as follows:

$$n_{pump} = 0.98\ (29/60)\ n$$

where the rotor shaft pulley speed is equal to the rotor speed.

For the given system, with $A = 0.0165\ m^2$, eq. (4) becomes

$$Q_{th} = 0.0142\ n \times 0.0165 \times 10^3 = 0.234\ n$$

$$\text{or}\ \ \eta_v = Q/Q_{th} = Q/0.234\ n \qquad (5)$$

The results are shown in Fig. 9.

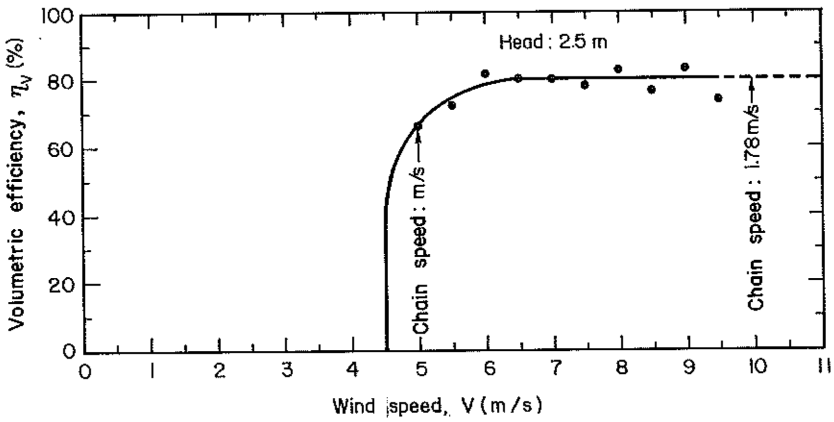


Fig. 9 Volumetric efficiency of PVC-ladder pump

## *Windmill-Pump System Efficiency ($C_p\ \eta$) vs. Wind Speed (V)*

The system efficiency ($C_p\ \eta$) is calculated by equating the power generated by the windmill and the power required for lifting the water as follows:

$$\tfrac{1}{2}\ \rho V^3\ \pi R^2\ (C_p\ \eta) = \rho_w g H Q \times 10^{-3} \qquad (6)$$

where $\rho$ = air density (in $kg/m^3$)

$\rho_w$ = water density (in $kg/m^3$)

$g$ = acceleration due to gravity ($m/s^2$)

$C_p$ = rotor efficiency

$\eta$ = (1 – all mechanical losses in the system)

For the given system, after substituting for the parameters, eq. (6) can be rewritten as

$$(C_p\ \eta) = 1.397\ Q/V^3 \qquad (7)$$

and the results are shown in Fig. 10. The values $V = 4.0$ and $4.5$ m/s are omitted because of erroneous measurements for $Q$.

Assuming a maximum system efficiency = 0.09, eq. (7) can be written as

$$Q = 0.064\ V^3 \qquad (8)$$

and the corresponding theoretical hydraulic power curve is shown in Fig. 5.

The rotor efficiency ($C_p$) could be estimated based on accurate laboratory measurements of mechanical losses, such as friction losses in ball bearings, belt drive loss and pump losses.

## DISCUSSION OF RESULTS AND CONCLUSIONS

From Fig. 5 it can be observed that the actual design wind speed for the system installation at 2.5 m head is 5.2 m/s (at the point of contact between the two curves). This is also indicated by Fig. 10. At $V$ = 5.2 m/s, the pump operates with a volumetric efficiency of 70%. It can be concluded that the system performs best in a wind regime with an average wind speed of 5 to 6 m/s for a head of 2.5 m.

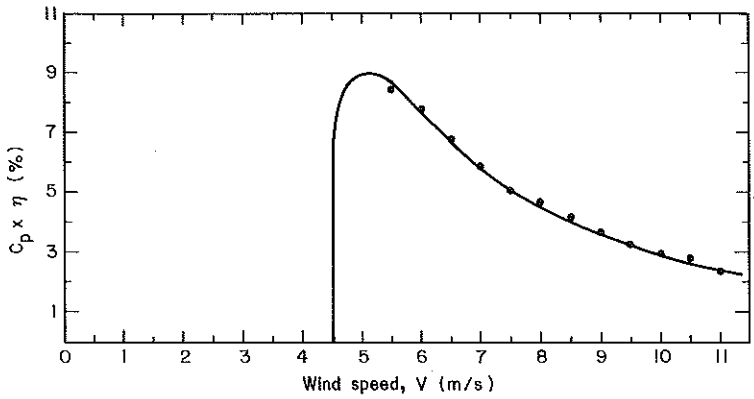


Fig. 10 Total windmill-pump efficiency

For lower heads the transmission ratio can be changed in order to match the power generated by the rotor. For lower average wind speeds, however, the size of the pump has to be reduced along with an appropriate transmission ratio. The latter is necessary to ensure the minimum required chain speed of 0.7 m/s for the pump to deliver water (at a head of 2.5 m) at lower wind speeds and consequently at lower rotor speeds. The size of the pump has to be smaller to match the demanded power by the pump with the generated power at the lower speeds.

## ACKNOWLEDGEMENT

The author is very grateful to Marcus Sherman who was very helpful in assisting with the performance measurements and other measurements at the windmill installation. The author also expresses his thanks to the National Energy Administration of Thailand for loaning the anemometer used for the wind speed observations.