An Analysis of the Wind Rope Pump System

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Abstract

The Nicaraguan wind rope pump avoids a number of the technical complications inherent to the classical windpump, especially the starting problem and the occurence of dynamic peak loads. The wind rope pump starts smoothly and can achieve system efficiencies comparable to the piston pump. As a result, the rotor and the tower can be very lightweight, resulting in significantly lower production and installation costs than for a classical windmill (typically 25-35%). This opens up a new market of wind pump users, e.g. small farmers.

The present paper gives a description of the wind rope pump system using a stationary approach. Expressions are derived for the system efficiency and long-term output of the wind pump in a Weibull wind regime. It is shown that a properly maintained wind rope pump can have a higher output and better availability than a classical wind pump; typically a higher matching ratio would be used ($x_d \approx 1.4$). The use of the device in Nicaragua, however, seems not to optimize the average water output. The question therefore arises whether the critical design parameters, i.e. the design pump speed, rated wind speed and the matching ratio, are carefully chosen.

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List of symbols

A	rotor swept area $[m^2]$
D_w	pump wheel diameter $[m]$
E_h	hydraulic energy output of the system $[J]$
$G(x)$	Gamma function of the wind speed $[-]$
P	rotor shaft power $[Js^{-1}]$
P_h	hydraulic power of the system $[Js^{-1}]$
Q	rotor shaft torque $[kgm^2s^{-2}]$
Q'	effective load torque $[kgm^2s^{-2}]$
Q_p	pump torque $[kgm^2s^{-2}]$
R	rotor diameter $[m]$
T	time period for average output calculation $[s]$
V	wind speed $[ms^{-1}]$
$\overline{V}$	average wind speed at site $[ms^{-1}]$
V_c	critical pump speed $[ms^{-1}]$
V_d	design wind speed of the system $[ms^{-1}]$
V_p	pump piston speed $[ms^{-1}]$
V_s	starting wind speed corresponding to the critical pump speed $[s^{-1}]$
c_P	rotor power coefficient $[-]$
$c_{P,max}$	optimum rotor efficiency $[-]$
$(c_P\eta)$	overall conversion efficiency of the system $[-]$
c_Q	rotor torque coefficient $[-]$
$c_{Q,o}$	torque coefficient corresponding to λ_o $[-]$
$f(x)$	Weibull probability density function of the wind speed $[-]$
i	transmission ratio $[-]$
k	Weibull shape factor $[-]$
k_E	Weibull energy pattern factor $[-]$
n	rotor rotational speed $[s^{-1}]$
n_c	critical rotor speed corresponding to the critical pump speed $[s^{-1}]$
n_c^*	dimensionless critical rotor speed $[-]$
n_d	rotor speed at design wind speed $[s^{-1}]$
x	$(= V/\overline{V})$ dimensionless wind speed $[-]$
x_d	$(= V_d/\overline{V})$ dimensionless design wind speed $[-]$
x_r	dimensionless rated wind speed of the system $[-]$
x_s	dimensionless starting wind speed of the system $[-]$
η_m	mechanical transmission efficiency $[-]$
η_p	overall pump efficieny $[-]$
η_{vol}	volumetric efficiency $[-]$
λ	tip speed ratio $[-]$
λ_d	tip speed ratio at design wind speed $[-]$
λ_o	tip speed ratio corresponding to $c_{P,max}$ $[-]$
η	overall efficieny of the system $[-]$
ρ_a	density of air $[kgm^{-3}]$
ϕ_l	pump leakage flow $[m^3s^{-1}]$

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1 Introduction

The Nicaraguan wind rope pump is quite a unique concept. It can be conceived as an extension of the popular rope pump technology in Nicaragua, producing larger pumping volumes than the handpump[1]. From a windpump perspective it can be classified as a second-generation system, but it also exhibits many characteristics typical for artisanal technology. Indeed, the existing wind rope pump models in Nicaragua are very lightweight constructions based on locally available materials and using basic workshop equipment only. Apart from the rope pump, characteristic features are: a six-bladed, low-solidity rotor, a hinged side vane and a very light, steel lattice tower. The overall weight of the wind rope pump is well below 200 kg, allowing fast and easy transport and installation using a regular pick-up car. The Nicaraguan wind rope pump is produced and sold by workshop AMEC in Managua, which started production back in the early nineties. At present there are some 350 units sold and operating in the country [1]. Typical uses are livestock watering, sometimes combined with irrigation, and small-scale irrigation on the parcel combined with domestic water supply.

The wind rope pump builds forth on the philosophy behind the Nicaraguan hand rope pump, which puts forward the condition that the user should be able to rely on himself for operating and maintaining the device, even in remote areas. A typical user has little money available for servicing and counts with basic technical skills only. By consequence, the working principle of the system and its components must be obvious to him; the choice of materials may not be critical; maintenance and repair may not involve any specialised tools or equipment; and maintenance and most repair operations can be done by just one person. This concept is very different from the technology-driven approach behind the traditional windpumps, even those from the second generation. Notwithstanding the success of the hand rope pump in Nicaragua, it does not automatically translate to the wind rope pump for two reasons: (1)

[1]Alongside other driving systems such as the bicycle pump, the animal traction pump and the motor pump.

the wind rope pump is much more complex and costly than the handpump; (2) it typically fullfils a water demand for other classes of users than those served by the hand rope pump. By consequence, the user profile, water delivery requirements and user expectations may be substantially different. More information about the implementation and use of the wind rope pump can be found in [2][2].

The use of the rope pump has a decisive impact on the design of the whole windpump, enabling the unique, lightweight construction that would have been impossible to achieve using a normal displacement pump (typically a single-action piston pump). Previous efforts in Nicaragua with second-generation windpumps encountered very serious problems and had to be abandoned[3]. The smooth operation of the rope pump causes a continuous loading of the rotor and the pump, which reduces the forces on the structure. In particular, the dynamic peak loads caused by accelerating the water column by a piston pump at higher pumping speeds, are absent in the wind rope pump. The characteristics of the rope pump further suggest an improved starting behaviour compared to a conventional windpump, which would mean a better yield at low wind speeds.

The purpose of the present paper is to review and analyse the operation and performance of the wind rope pump system and provide some recommendations for its design. The presented analysis is also valid for other models of wind rope pumps such as, for example, in Indonesia reported by Ushiyama [3]. As far as known to the authors, however, the Nicaraguan model is the only wind rope pump based on a standardised design that is sold commercially and in significant numbers. Other wind windpump models driving a rope pump should be classified as fully artisanal and based on local materials and empirical work. About the rope pump itself there exists a host of literature; see, for example [4]. The operating principle and the hydrodynamic behaviour of the rope pump have been described by Smulders and Rijs in [5].

2 Construction of the Wind Rope Pump

The AMEC rope windpump consists of a rope pump connected to a wind rotor on top of a tower (see Figure 1). The transmission is made of a large rope that turns in a loop on an upper pulley fixed on the rotor axis and a lower pulley on the pump shaft. The rotor head carries the rotor and the tail arm and is offset from the axis of orientation. The head assembly can turn freely around the vertical (yawing) axis. The tail arm with the hinged side vane keeps the rotor aligned upwind and, at higher wind speeds, prevents upspeeding of the rotor by turning it gradually out of the wind. If the head makes more than one turn, the transmission rope falls off and the windpump stops functioning; then someone has to put the rope back in place. In Nicaragua this peculiarity does not cause serious inconveniences,

[2]This evaluation report describes the activities and findings of a larger project, funded by DGIS (The Netherlands), to assess the wind rope pump technology and prepare its dissemination to other countries in Latin America. The overall assessment was quite positive, although several caveats were found. Both authors were involved in some technical aspects of this project. As far as known, [2] is still the most recent detailed publication on the wind rope pump available.

[3]Here reference is made specifically to the CWD-IMEP project in the eighties, which attempted to produce and disseminate the CWD 5000 windpump in Nicaragua. Henk Holtslag, who was assigned to this project by CWD, continued in Nicaragua after the project was stopped. Based on the earlier experiences he traced the innovative approach to windpumping which eventually led to the current design and its production and sales by AMEC.

because the wind direction is fairly constant in the local trade wind regime[4].

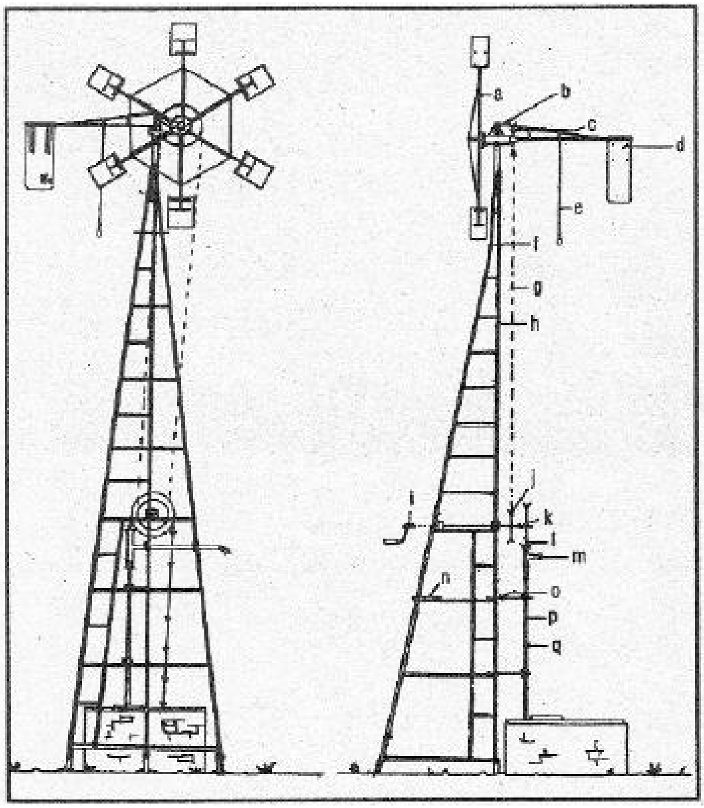

Figure 1: *Schematic drawing of the Nicaraguan wind rope pump showing its main components: the low-solidity rotor with six blades; the tail arm with the hinged side vane; the slender, 3-legged tower; the pulley-and-rope transmission system running outside the tower; and the rope pump installed directly above a covered well (picture from [2].)*

The rotor is made from steel spars that are welded onto a tubular rotor shaft. Near the hub, the spars are reinforced with angle bars and tension rods to give sufficient strength and stiffness to the rotor. The blades are made from galvanised steel and have a curvature of 10% of the blade chord. Each blade is bolted onto two steel supports welded on the spars. The rectangular blades have a small linear twist. The rotor is very characteristic, since the blades only cover the outer part (annulus) of the rotor area. As a result, the rotor produces a high torque at a very low weight but the maximum power coefficient c_P is low if related to the full swept area (estimated about 0.13 [2]). The 10 and 12-ft. models have 6 blades; the small 8-ft windpump has 4 blades. The elegant, lightweight tower has three legs; one side is flat, giving room for the transmission which runs just outside the tower. The flat side also facilitates the assembly. The total tower weight is just about 100 kg.

The rope pump is very similar to the hand pump but more heavy-duty. On the pump shaft there are now two pulleys, the transmission pulley and the pump wheel. All pulleys are made of rubber segments cut from old car tires, which are tightly fixed on a welded spoke structure. The rubber gives good grip for the polypropylene ropes. The tube material used is regular gas

[4]Versions of the wind rope pump that do not have this limitation, such as the *multigiratorio*, are under development.

piping. The pulleys are bolted onto the shaft so that they can easily be replaced or removed. The transmission ratio between the rotor and the pump can be adjusted by mounting pulleys with different diameters.

3 The Wind rope pump System

The system analysis presented in this paper is based on a methodology by Lysen [6]. The efficiencies of the three principal subsystems of the wind rope pump are modelled as a function of their rotational speeds and the wind velocity: the wind rotor; the transmission; and the rope pump. These are combined into an overall system efficiency "from wind to water". The analysis is stationary, which implies that the driving (rotor) torque always balances the load (pump) torque. The behaviour of the subsystems is described sith simple analytical relations. The outcomes of the model are the hydraulic power output P_h as a function of the wind speed, and the amount of water produced E_h over a longer time period T in a Weibull wind regime (typically a one-year period). Both quantities provide insight in the overall performance of a windpump and whether such a system is well-matched to the prevailing wind climate. Although the predicted outputs may be less accurate in absolute terms, the model is useful for comparing the performance of different windpumps and to analyse the effect of design parameters.

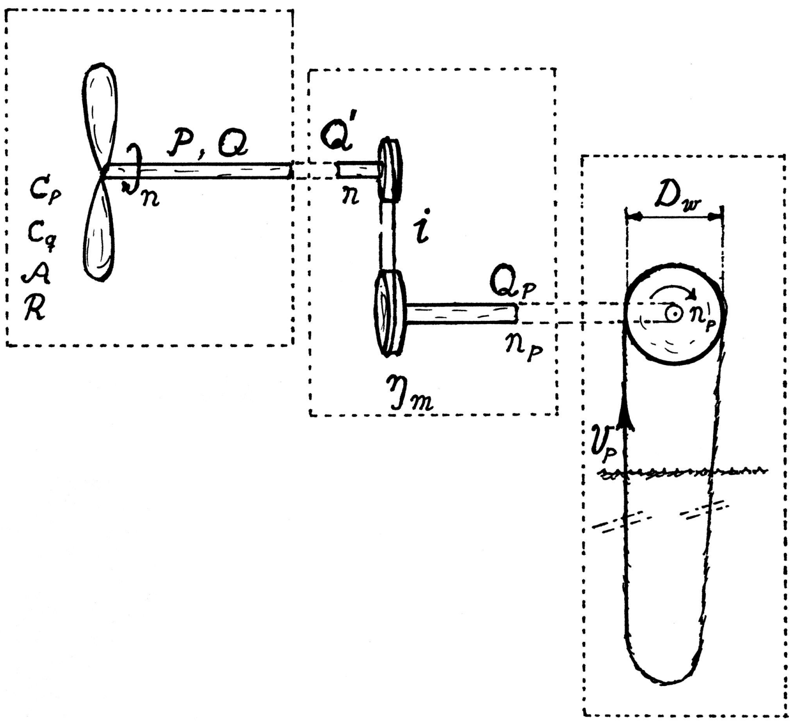

Figure 2: *The wind rope pump system comprising the three main components: the wind rotor, the transmission and the rope pump.)*

3.1 The Wind Rotor

The performance of a wind rotor can be expressed in terms of shaft torque Q and power P:

$$Q = \frac{1}{2}\rho_a c_Q V^2 AR \tag{1}$$

$$P = \frac{1}{2}\rho_a c_P V^3 A \tag{2}$$

Here V is the wind speed, R the radius of the wind rotor and A the swept area, while ρ_a is the air density; c_Q and c_P are the rotor torque and power coefficient respectively. With n being the rotor speed, the tip speed ratio λ relates the speed of the blade tip to the wind speed V:

$$\lambda = \frac{2\pi n R}{V} \tag{3}$$

The coefficients c_Q and c_P in (1) and (2) are a function of λ. Note also that, as $P = 2\pi n Q$:

$$c_P = \lambda c_Q \tag{4}$$

Lysen proposes the following linear relation for the torque coefficient which is quite acceptable for the slow running rotor of a windpump:

$$c_Q(\lambda) = c_{Q,o}(2 - \frac{\lambda}{\lambda_o}) \tag{5}$$

The corresponding relation for c_P is quadratic and reaches a maximum $c_{P,max}$ for $\lambda = \lambda_o$, with the corresponding torque coefficient being equal to $c_{Q,o}$:

$$c_P(\lambda) = c_{P,max}\frac{\lambda}{\lambda_o}(2 - \frac{\lambda}{\lambda_o}) \tag{6}$$

Both $c_{P,max}$ and λ_o depend on the rotor design. A properly designed slow running wind rotor can achieve $c_{P,max} \approx 0.3$.

3.2 The Transmission

The transmission of the wind rope pump is modelled by its speed ratio and the mechanical losses due to friction. The speed ratio i depends on the diameters of the transmission pulleys on the pump shaft and the rotor axis. For a rotational speed of the wind rotor n and a given pump wheel diameter D_w, the corresponding velocity of the pump rope V_p is:

$$V_p(n) = n\pi D_w / i \tag{7}$$

The mechanical efficiency of the transmission η_m is defined as the fraction of the input torque that effectively transforms into a lifting force in the pump rope. We assume η_m to be constant, i.e. independent of the operating speed n. For a given pump torque Q_p, the effective torque load Q' on the rotor axis exerted by the pump will then be:

$$Q'(n) = \frac{Q_p(n)/i}{\eta_m} \tag{8}$$

For simplicity, other sources of mechanical losses, such as friction in the bearings of the rotor axis, are assumed to be included in η_m.

3.3 The Pump

The working principle and hydrodynamic behaviour of the rope pump have been described in [5]. For the analysis of the wind rope pump system, the pump is characterised by the pump torque Q_p and by the volumetric efficiency η_{vol}. The force in the pump rope is constant, once the pump starts lifting water; therefore the pump torque is constant as well. This occurs above a minimum speed of the pump rope, the critical pump speed V_c.

$$Q_p(n) = Q_p \qquad (V_p \geq V_c) \tag{9}$$

The volumetric efficiency is governed by the following relation:

$$\eta_{vol}(n) = 1 - \frac{V_c}{V_p} \qquad (V_p \geq V_c) \tag{10}$$

Below the critical rope speed V_c, the pump torque and the volumetric efficiency are zero. Note that the rope velocity is related to the angular speed of the wind rotor by equation (7). The volumetric efficiency of the pump is a direct measure of its energy efficiency in terms of water lifted per unit of input energy.

3.4 Coupling of System Components

Coupling of the pump to the wind rotor is governed by the condition of torque balance. This condition together with (7) defines the operating point of the rotor-pump combination for any given value of the wind speed V. The effective torque from (8) must match the rotor torque Q and with (1) we find:

$$Q' = \frac{1}{2}\rho_a c_Q V^2 AR = \text{constant} \tag{11}$$

Because the torque load is known, c_Q can be calculated. Since λ is a function of c_Q, the corresponding rotor speed n is now known. We will express the variables for any point of operation (n, λ, V) in relation to the design point values of the system. The *design* wind speed V_d of the system is defined as the wind speed at which the rotor operates at its maximum efficiency $c_{P,max}$. The tip speed ratio at at V_d is λ_o as follows directly from (6). Hence:

$$\lambda_d = \lambda_o \tag{12}$$

The rotor speed at V_d is n_d and the torque coefficient $c_{Q,o}$. The rotor torque at the design point is then:

$$Q(V_d) = \frac{1}{2}\rho c_{Q,o} V_d^2 AR \tag{13}$$

Since the load torque is constant, the rotor torque must be constant to this value for any stable working point of the system and by combining with (11) we find:

$$c_Q V^2 = c_{Q,o} V_d^2 \tag{14}$$

Subtituting (3) into this equation and using:

$$\frac{\lambda}{\lambda_o} = \frac{n}{n_d}\frac{V_d}{V} \tag{15}$$

we find the following relation relating the rotor speed n to the wind speed V:

$$\frac{n}{n_d} = 2\frac{V}{V_d} - \frac{V_d}{V} \tag{16}$$

Recurring to (6), we can also write c_p in terms of V and V_d, making use of (15) and (16):

$$c_P(V) = c_{P,max} \frac{2\left(\frac{V}{V_d}\right)^2 - 1}{\left(\frac{V}{V_d}\right)^4} \tag{17}$$

In fact, the relations (15), (16) and (17) hold for any wind rotor loaded by a constant torque, since we only used Q' is a constant. Equation (17) presents the power output of the rotor as a function of the wind speed. As one can see, the windmill will only turn for wind speeds above $\frac{1}{2}\sqrt{2}V_d$; below this wind speed, the torque produced by the wind rotor is insufficient to overcome the load torque.

We use (15) and (16) to express the volumetric efficiency of the rope pump in terms of the wind speed V. We first observe that the rope pump starts delivering water above the critical rope velocity V_c. This speed corresponds to a unique rotor speed n through the transmission relation (7), which is linear. We define this speed as the critical rotor speed n_c, at which the system starts delivering water. With the design point value n_d, we now write n_c dimensionlessly as $n_c^* = n_c/n_d$. This critical speed is a design parameter of the system defined by the rope pump. The relation for the volumetric efficiency (10) now becomes:

$$\eta_{vol} = 1 - n_c^* \frac{n_d}{n} \tag{18}$$

Substitution of (16) into (18) gives the volumetric efficiency as a function of the wind speed:

$$\eta_{vol}(V) = \frac{2\left(\frac{V}{V_d}\right)^2 - n_c^*\left(\frac{V}{V_d}\right) - 1}{2\left(\frac{V}{V_d}\right)^2 - 1} \tag{19}$$

4 The Hydraulic Power of the Wind Rope Pump

The hydraulic power P_h of a pump is equal to the input power times the overall pump efficiency η_p. For the rope pump, η_p is equal to the volumetric efficiency η_{vol} as shown in [5]. We combine the pump efficiency and the transmission efficiency into one overall efficiency η and find, using (2) and relating V to the design wind speed V_d:

$$P_h(V) = (c_P\eta)\frac{1}{2}\rho V_d^3 A\left(\frac{V}{V_d}\right)^3 \tag{20}$$

Now by substitution of (17) and (19) into (20) and writing $(c_P\eta)_{max}$ instead of $(c_{P,max}\eta)$, we obtain the hydraulic power as a function of the wind speed V:

$$P_h(V) = (c_P\eta)_{max}\frac{1}{2}\rho_a V_d^3 A\left(2\,\frac{V}{V_d} - n_c^* - \frac{V_d}{V}\right) \tag{21}$$

This expression holds for $V \geq V_s$ since η_{vol} is zero for $V < V_s$. Then the hydraulic power output is also zero. From (20) and (21) we find the following relation for the overall system performance:

$$\frac{(c_P\eta)}{(c_P\eta)_{max}} = \frac{2\frac{V}{V_d} - n_c^* - \frac{V_d}{V}}{\left(\frac{V}{V_d}\right)^3} \tag{22}$$

The *starting* wind speed V_s is the wind speed at which the rope windpump starts delivering water and follows from:

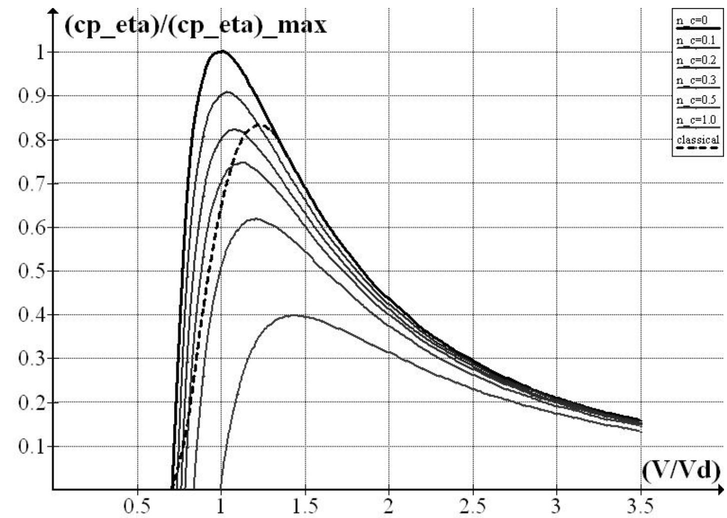

Figure 3: *Graph showing the overall system efficiency* $\frac{(c_P\eta)}{(c_P\eta)_{max}}$ *as a function of the wind speed* (V/V_d) *for a range of* n_c^**-values. The case* $n_c^* = 0$ *is equivalent to a piston pump with a constant torque. The* $(c_P\eta)$*-curve of a real piston pump, which requires a much higher torque to start, is approximated by the dashed line (for a Weibull shape factor* $k = 2$ *and* $V_d = \overline{V}$*).*

$$2\left(\frac{V_s}{V_d}\right)^2 - n_c^*\left(\frac{V_s}{V_d}\right) - 1 = 0 \tag{23}$$

which renders one real solution for V_s/V_d:

$$\frac{V_s}{V_d} = \frac{1}{4}\left(n_c^* + \sqrt{n_c^{*2} + 8}\right) \tag{24}$$

In case of zero leakage, $n_c^* = 0$ and $V_s = \frac{1}{2}\sqrt{2}V_d$. For a real rope pump with $\eta_{vol} < 1$, the starting wind speed will be higher.

Figure 3 shows the overall system efficiency as determined by (22) for a range of n_c^*-values. One can observe that the optimum shifts towards higher values of V/V_d with increasing n_c^*. By differentiating with respect to V/V_d, it follows from (22) that the optimum efficiency corresponds to $V = V_d\sqrt{1 + n_c^*}$. A volumetric efficiency of 90% ($n_c^* = 0.1$) should be attainable for a properly constructed and maintained rope pump. Note also that the case $n_c^* = 0$ is equivalent to an ideal piston pump without a starting problem, i.e. with a constant torque load. For a classical windpump equipped with a real piston pump, the starting wind speed is much higher than the stopping wind speed and the system will not always be running (see [6]). The dashed line in Figure 3 shows an approximated $(c_P\eta)$-curve for a typical system. One can see that this efficiency is lower than that of the wind rope pump in an important range of wind speeds.

5 The Energy Output in a Weibull Wind Regime

The long-term output depends on the hydraulic power of the wind pump (21) and the wind regime at the site. We assume this to be governed by a Weibull distribution with an average wind speed $\overline{V}$. The choice of the design speed V_d related to the average wind speed $\overline{V}$

determines the matching of the windpump to the local conditions and whether it performs satisfactorily. We therefore introduce the dimensionless wind speed x as:

$$x = \frac{V}{\overline{V}} \tag{25}$$

Then the dimensionless design wind speed is x_d and the hydraulic output from (21) becomes:

$$P_h(x) = (c_P\eta)_{max}\frac{1}{2}\rho_a A\overline{V}^3 x_d^3 \left(2\,\frac{x}{x_d} - n_c^* - \frac{x_d}{x}\right) \tag{26}$$

With $f(x)$ the Weibull probability density function[5], the hydraulic output of the windpump E_h averaged over a sufficiently long period T is:

$$E_h/T = \int_0^\infty P_h(x)f(x)dx \tag{27}$$

We recur to the output of an ideal windmill system, i.e. a system which always operates at its optimum efficiency $(c_P\eta)_{max}$, to define the reference output $(E_h/T)_{ref}$:

$$(E_h/T)_{ref} = \frac{1}{2}\rho(c_P\eta)_{max}A\overline{V}^3 k_E \tag{28}$$

In (28) k_E is the socalled energy pattern factor[6]. Now (26) can be written in a compact form as:

$$P_h = (E_h/T)_{ref}\frac{x_d^3}{k_E}\left(2\frac{x}{x_d} - n_c^* - \frac{x_d}{x}\right) \tag{29}$$

Above a given *rated* wind speed x_r the power is held constant to the rated output P_h by the tail vane system:

$$P_r = (E_h/T)_{ref}\frac{x_d^3}{k_E}\left(2\frac{x_r}{x_d} - n_c^* - \frac{x_d}{x_r}\right) \tag{30}$$

We also observe that the rope windpump starts producing water at the starting wind speed x_s. The average hydraulic output of the rope windpump E_h/T is found by substituting (29) and (30) into (27). We obtain:

$$\frac{E_h/T}{(E_h/T)_{ref}} = \frac{x_d^3}{k_E}\int_{x_s}^{x_r}\left(2\frac{x}{x_d} - n_c^* - \frac{x_d}{x}\right)f(x)dx + \frac{P_r}{(E_h/T)_{ref}}\int_{x_r}^{\infty} f(x)dx \tag{31}$$

This expression provides a yard-stick for the overall efficacy of the rope windpump system compared to an ideal windpump. It is dependent on three parameters: x_d, n_c^* and k_E (or k), the former two being determined by the system design, and the latter being given by the site wind regime. The starting wind speed x_s depends on n_c^* and x_d and is calculated directly from (24). The rated wind speed x_r depends on the design of the rotor head and the tail construction.

The second integral at the right-hand represents the hydraulic output produced during the hours with wind speeds above x_r. It can be evaluated by partial integration and, using the G-function (see footnote 5), is equal to:

[5] The expression for the Weibull probability density function, $f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1}\exp\left(-\left(\frac{V}{c}\right)^k\right)$, can be written as a function of the dimensionless wind speed x as $f(x) = kGx^{k-1}exp\left(-Gx^k\right)$, in which G depends on k through the Gamma function Γ as follows: $G = \Gamma^k(1+1/k)$. Note also that $f(x)dx = f(V)dV$.

[6] The energy pattern factor k_E represents the difference in output estimated by using $\overline{V^3}$ instead of $\overline{V}^3$. k_E is a function of the Weibull shape factor alone according $k_E = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)}$.

$$E_r = \frac{P_r \exp(-G x_r^k)}{(E_h/T)_{ref}} \tag{32}$$

The n_c^*-term in the first integral in (31) can also be solved analytically and is:

$$E_l = \frac{n_c^* x_d^3}{k_E} \left(\exp(-G x_s^k) - \exp(-G x_r^k) \right) \tag{33}$$

This term represents the loss of hydraulic output of the system due to the leak flow ϕ_l in the rope pump, which is linear in n_c^*. We can now write (31) as:

$$\frac{E_h/T}{(E_h/T)_{ref}} = \frac{x_d^3}{k_E} \int_{x_s}^{x_r} \left(2\frac{x}{x_d} - \frac{x_d}{x} \right) f(x) dx - E_l + E_r \tag{34}$$

The remaining integral in (34) is identical to the output of a constant-torque load between x_s and x_r. The significance of the loss term E_l depends on the leak flow ϕ_l and on the matching of the system, i.e. the choice of x_d. The contribution of E_r to the output is small for a constant-torque system if $x_r \geq 2x_d$ (see [6]) .

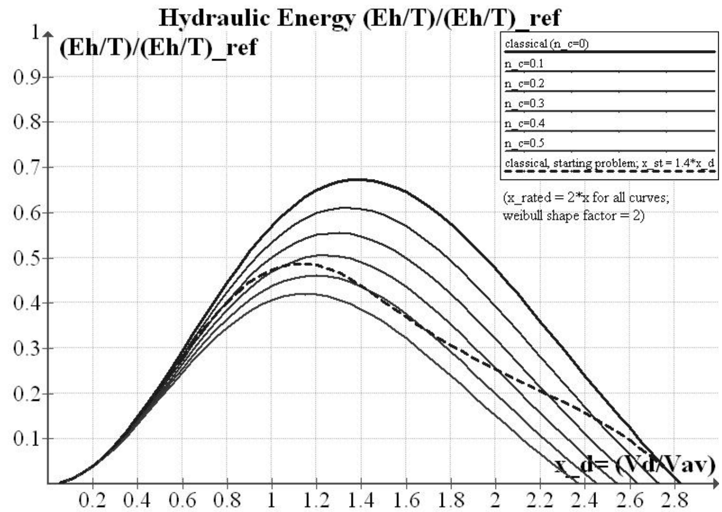

Figure 4: *Graph showing the average hydraulic energy delivered by the system* $(Eh/T)/(Eh/T)_{ref}$ *as a function of the matching wind speed* $x_d = V_d/\overline{V}$. *The case* $n_c^* = 0$ *is equivalent to an ideal piston pump; the dashed line representes the output for a piston pump with starting problem (classical wind pump). The wind rope pump has a significantly larger output at higher matching ratios (*$x = 1.2 - 1.8$*).*

The average hydraulic energy delivered by the system is shown in Figure 4 as a function of the matching parameter $x_d = V_d/\overline{V}$. As in Figure 3, the case $n_c^* = 0$ is equivalent to an ideal piston pump, while the dashed line representes the output for a real piston pump (classical windpump). The curve $n_c^* = 0.1$ should be representative for a good rope pump. One can see that the long-term output of the system deteriorates quickly if the pump leak flow becomes larger. This is likely to occur over time due to pump wear and stresses the importance of maintenance of the rope pump.

One can also observe the much better output of the wind rope pump system for higher matching ratios ($x = 1.2 - 1.8$) compared to the classical wind pump with a starting problem[7]. This difference in output is exclusively obtained from the extra running hours of the wind rope pump and therefore also represents an equivalent advantage in availability. Even with a significant leak flow ($n_c^* \geq 0.2$), this advantage still exists. For smaller values of x, this difference disappears, as the piston windpump will become so lightly matched that it is always running. This is in fact how a classical windpump is typically matched ($x \approx 0.8$).

6 Performance under Field Conditions

The evaluation project of the wind rope pump technology attempted to assess the technical performance of the wind rope pump (see [2]). The data obtained at most provide an indication that the system behaviour is in agreement with the analysis presented in this paper. In order to assess the conversion efficiency of the wind rope pump, detailed measurements should be carried out under controlled conditions. One can, however, also follow a heuristic approach by considering that the major causes of underperformance are: (1) leakage of the pump; (2) misalignment of the wind rotor to the wind; (3) inappropriate matching of the wind pump to the local wind regime.

The pump leakage can be checked directly on the pump, bearing in mind that the design speed of the rope pump itself is typically about 1 m/s (piston speed). A good rope pump should attain about an efficiency of 90% at the design speed, which will drop in case of excessive wear. The piston speed should also not exceed about 2 m/s, above which water is spilt all over the place, and hydrodynamic and mechanical friction increase quickly. The rated speed of the wind rotor should therefore be chosen not higher than about twice the design wind speed ($x_r = 2x_d$). Observation of some systems operating in the field gives the impression that higher piston speeds do occur. The alignment of the rotor and the rated wind speed are not easily verified under field conditions. The short-term measurements in [2] suffered from high turbulence and variability in wind direction related to the site conditions.

Figure 4 suggests a superior output and availability of the wind rope pump at higher matching ratios ($x_d = 1.2 - 1.8$). Calculations using the design parameters of some installed systems show that such high matching ratios are actually applied. One should observe, however, that the use of the wind rope pump by small farmers in Nicaragua is not ruled by optimizing the long-term output. Instead, the wind pump is operated for a few hours per day, until sufficient water has been pumped. This "programmed use" is possible thanks to the local wind climate, with high wind speeds during the afternoon in the dry season. The strong winds enable the use of a large rope pump and in fact, the available wind potential is strongly underexploited. The use is implicitly dictated by minimizing the pumping time, which is achieved by running the wind pump near or above the rated wind speed and using a large pump.

For unattended use, the optimization of the long-term output and availability is much more critical, especially if the system is supposed to deliver water at lower wind speeds as well. Cattle farmers are a second target group for the Nicaraguan wind rope pump and it would be

[7]One should note that the rotor of the Nicaraguan wind rope pump has a lower c_P-value than a classical windmill. Since the pump efficiencies at the design point are similar ($\approx 80 - 90\%$), one would need to compare a larger wind rope pump with a somewhat smaller classical wind pump. On the other hand, the wind rope pump is faster running and designed for higher wind speeds, giving more power at the same diameter. Considerations of this kind make a comparison between both systems less straightforward.

worthwhile to know the performance of these systems. Therefore more field information needs to be collected. Insight in the proper matching of the system becomes especially important if the wind rope pump is to be transferred to other countries with a wind climate different from Nicaragua.

7 Conclusions

The presented system analysis can serve as a reference for assessing the performance of a wind rope pump system and estimating the correct choice of the principal design parameters, i.e. the design wind speed, the design pump speed, and the rated wind speed. Calculations of the the long-term output and number of pumping hours in a Weibull regime show a performance superior to that of the classical wind pump. This difference in performance can be ascribed fully to the starting problem of the traditional wind pump equipped with a piston pump.

The wind rope pump avoids a number of the technical complications inherent to the classical windpump, especially the starting problem and the occurence of dynamic peak loads. The wind rope pump starts smoothly and can achieve system efficiencies comparable to the piston pump. As a result, the rotor and the tower can be very lightweight, resulting in significantly lower production and installation costs than for a classical windmill (typically 25-35%). One should bear in mind however, that a direct comparison between both wind pump technologies is less straightforward, since the product and maintenance philosophy, track record, manufacturer profile and the typical user groups, are quite different.

The analysis shows that a properly maintained wind rope pump can have a higher output and better availability than a classical wind pump; typically a higher matching ratio would be used ($x_d \approx 1.4$). The current use of the device in Nicaragua, however, seems not to optimize the average water output. The question therefore arises whether the critical design parameters, i.e. the design pump speed, rated wind speed and the matching ratio, are carefully chosen. More insight in the performance of the wind rope pump under field conditions would be recommendable to support the dissemination of this technology to other regions.

8 Acknowledgements

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