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Energy Saving in a Variable-Inclination Archimedes Screw

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Abstract

An analysis was undertaken of a new development of Archimedes screw consisting of a variable-inclination screw suitable for applications in which the downstream level may vary (e.g. sea level). As a result the energy consumption when the downstream level is low is less than that of a conventional, fixed Archimedes screw. In addition, investment costs are lower as a result of less expensive civil work being required. Moreover, this screw can also act as a check gate because it has a float at his downstream end. The flow rate for different rotational speeds was measured and a good fit was obtained with a developed graphical model. This paper analyses the operation of an Archimedes screw prototype pump of variable inclination and models its behavior. Its energy consumption is then measured and compared with that of conventional fixed inclination screw pumps.

Keywords: Archimedes screw; Discharge flow rate; Elevation height; Conventional pump; Variable inclination pump

Introduction

The Archimedes screw is a device for lifting water to low heads which dates back to the third century BC and is still in use today. Its main advantage is its effectiveness when lifting low-head debris-laden water. Though technological advances have logically seen various modifications to the device since its first use to the present day, its operating principle remains the same. Its principle applications are in drainage water pumping stations and water treatment plants. It has also proved valuable in installations where damage to aquatic life needs to be minimized. Given the antiquity of the device and the consequent empirical knowledge that has been acquired, little is to be found in the literature on its technical aspects. A manual was however written by Nagel [1] for the design of installations with this type of pump in which he explains a graphical method for calculating the flow rate in a screw pump according to the screw's geometry and rotational speed. Wijdieks and Bos [2] proposed a simple empirical equation to obtain the discharge from an Archimedes pump,

$$Q = k.n.D^3 \left[\frac{m^3}{s} \right] \tag{1}$$

Where: k is an empirical coefficient which depends on the shape of the screw, characterized by: S/D, d/D, and the inclination β [2], n is the turning speed (rev/s) and D is the outer diameter (m).

Rorres [3] developed computer software to find the volume of water lifted in one turn of the screw depending on the inner radius and pitch. From this he was able to obtain the optimum geometry values that maximize water volume per turn. However, the programme does not take into account the losses which occur in the gap between the screw and the casing. The screws are driven by electric motors the sizing of which depends on two basic factors: The discharge flow rate and the elevation height. Discharge can be regulated through advances in the control of motor turning speed, either through the use of variable frequency drives [4] or a gear reduction system. This paper analyses a new development of the conventional Archimedes screw. The modification involves variation of the inclination of the screw depending on the downstream water level, thereby obtaining a considerable energy saving in those applications in which the downstream level is variable (i.e. sea level).

Description

The pump used in this study was designed and manufactured by B&G BUERA Ltd. under patent No. ES 1 051 874 U. It has a variable inclination capability through the incorporation of a shaft perpendicular to the input section and a float in the output section which additionally allows the pump to act as a check gate. The pump screw is comprised of a tubular carbon steel shaft onto which is welded a three-bladed helix of cold-rolled carbon steel sheet. Steel terminations are screwed onto the ends of the shaft and the support flanges are fixed onto these. The exterior cylinder of the device is also made from carbon steel sheet and is TIG welded. There is also a support frame where the pivotal shaft of the pump is mounted which can be fully removed from a sub-frame embedded in the concrete sidewalls which acts as a runner. The presence of neoprene perimeter strips which act as hydraulic seals impede any manner of filtration or contraflow as a result of the arrangement of these intermediate elements between the flow inlet and outlet. The pump dimensions are as follows: outer diameter 1500 mm; shaft diameter 750 mm; total length 4500 mm; pitch length 1500 mm; blades 3 and blade gap 5 mm (Figure 1). The pump's asynchronous motor is located in the pump input section, transmitting motion via a transmission connected to a reduction gearbox located near the input below the level of the water. The transmission system has no
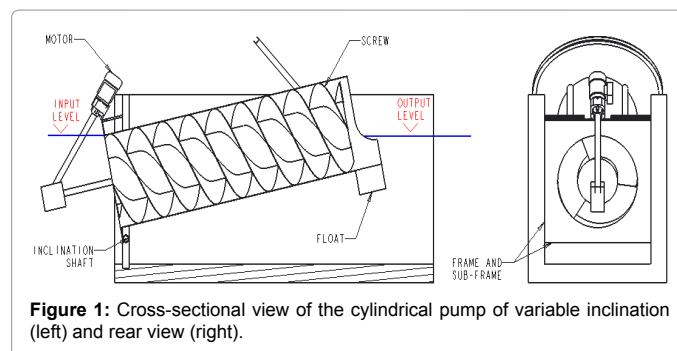

Figure 1: Cross-sectional view of the cylindrical pump of variable inclination (left) and rear view (right).

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intermediate pulley-based mechanism, thereby reducing mechanical losses.

Methodology

In the analysis of the device, a comparison was made of data measured in situ with data obtained through modelling. Therefore, once the model had been calibrated flow rate values could be obtained without the necessity of making a reduced-scale model. Analysis of the screw involved measuring the flow rate and energy transferred for different rotational speeds. Measurement of the difference in head between the inlet and outlet of the pump was performed using a piezometric tube. Flow rate was measured using an Acoustic Doppler Current Profiler (ADCP). The ADCP emits sound signals below the audible range which strike the water particles below. The sound waves are scattered back from particles suspended in the water producing an echo which is detected by the ADCP enabling it to determine the water speed and depth. Using these data, the ADCP calculates the flow rate. The amount of energy transferred was calculated by adding together the potential and kinetic energy of the water at the input and output of the device. Evidently, in this calculation the potential energy term has greater weight than the kinetic energy term given that the increase in flow speed is almost zero. Nonetheless, it was possible to calculate the flow speed at the input and output of the device by measuring the wet cross-section at the two ends of the device. A graphical method was used [1] to calculate the volume of the water trapped in one of the screw chutes, the length of which is equal to the pitch. This was done by representing the intersection points of the water surface and the blade. In this method, the projection of the screw helix is represented onto a plane which perpendicularly intercepts the axis, giving two lines which correspond to the upper edge of the blade and the contact point of blade and axis. The screw is represented horizontally, so the water surface is drawn with an inclination equal to the inclination of the screw which facilitates graphical representation of the projection lines of the intersection of the surface of the water with the blade. The idea is to make a projection of this surface onto the cross-section perpendicular to the screw axis. The starting point with this method is to project onto the cross-section perpendicular to the screw axis the intersection points of the water surface with the screw blade (A, B,...H). Following this, in order to draw the upper and lower limits of the water surface in each chute in the plane perpendicular to the axis, the segments bounded by the intersection points are divided into equal parts and this division is taken to the circular cross-section. When doing this, it should be remembered that the displacement is angular not linear, as can be seen in Figure 2. Once all the intersection points have been found, they need to be joined in such a way that the whole area that lies below the lines C-D and G-H represents that part of the chute which is completely full, in contact with the two delimiting walls (Figure 3). Following this, the portion of this volume which is not maximally connected with the walls of a chute is calculated. For this, the shaded area of Figure 4 is divided into equal parts, calculating for each of these parts the trapped water volume (Figure 5).

$$l1 + l2 = \frac{\alpha_1 + \alpha_2}{2.360} \cdot 2 \cdot \pi \cdot \left(r + \frac{R-r}{z} \cdot N \right); \quad x = \frac{R-r}{z}; \quad (2)$$

Where:

l_n : Arc length of each portion (m).

α: Angle of the perimeter of the portion analysed (º).
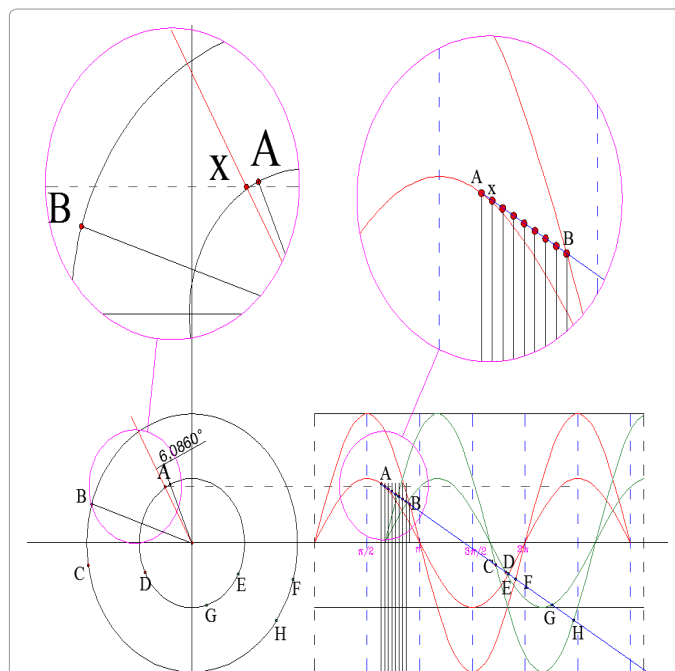
x: Width of each portion (m).

Figure 2: Transferring an intermediate intersection point to the circular cross-section (graphical method).
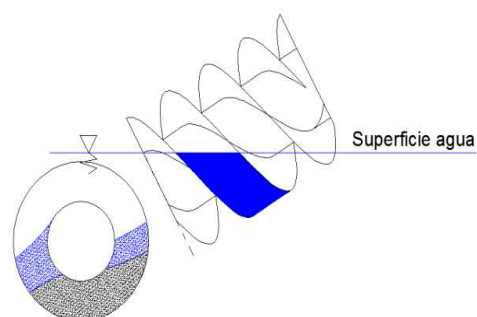

Figure 3: Projection of the volume of water contained in a chute (graphical method).
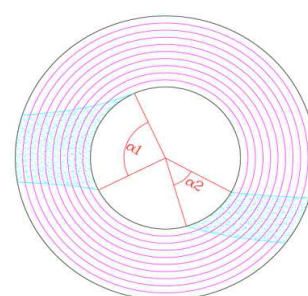

Figure 4: Cross-section division of the screw for analysis of water volume not in maximum contact between blades.

R: Outer screw radius (m).

r: Inner screw radius (m).

z: Number of divisions made (dimensionless).

N: Position of the portion under study, ordered from innermost to outermost (dimensionless).
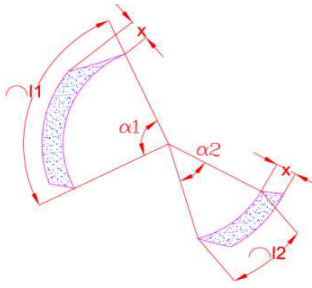
Figure 5: Dimensions considered for calculation of the unit volumes of water of the areas not maximally connected between blades.
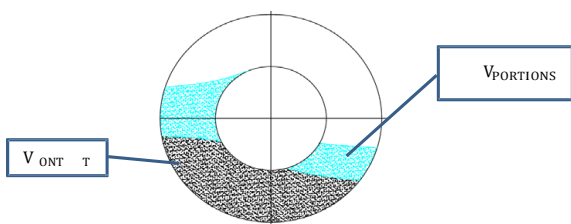

Figure 6: The graphical procedure and calculation of areas.

So, the volume of each portion can be calculated as:

$$l1 + l2 = \frac{\alpha_1 + \alpha_2}{2.360} \cdot 2 \cdot \pi \cdot \left(r + \frac{R-r}{z} . N \right); x = \frac{R-r}{z} . h \left[m^3 \right] \quad (3)$$

So, the volume discharged in each turn of the screw will be:

$$V_c = a . V_u \left[m^3 \right] \quad (4)$$

Where "a" is the number of screw blades and V_U the unit volume present between two screw blades, with V_U being:

$$V_u = \sum V_{PORTIONS} + V_{CONTACT} \quad (5)$$

The graphical procedure and calculation of areas was performed using Autocad software [5] which allows us to know the shaded area through the use of a specific function (Figure 6). From volume V_c, the discharge can be calculated with the following equation, by applying an empirical coefficient [1]:

$$Q_n = 1.15 \frac{V_c n}{60} \quad (6)$$

Finally the leakage loss (Q_1) is calculated according to blade gap (S_{sp}) and pump diameter (D) [1]:

$$Q_1 = 2,5 . S_{sp} . D . \sqrt{D} \left[\frac{m^3}{s} \right] \quad (7)$$

The lifted discharge would therefore be:

$$Q_c = Q_n - Q_1 \quad (8)$$

Field Results

After processing the data, the flow rate and transferred energy were calculated for two rotational speeds (Table 1). It can be seen that when increasing the rotational speed the flow rate, logically, also increases. It is also the case that when increasing the volume of water in the pump and, therefore, its weight, the angle of inclination decreases slightly. The k coefficient values (eq. 1) are relatively low compared

to those presented in Wijdieks and Bos [2]. If the data taken in situ are compared with the theoretical calculation of the flow rate using the graphical method described above, it can be seen that the values obtained are very similar. Global efficiencies, i.e. the ratio between hydraulic power output and electrical power input were measured, but have not been presented due to a problem of an oversized motor in the prototype which produced abnormally low efficiency values. Wijdieks and Bos [2] reported values of between 0.65, for small diameter screws, and 0.75, for large diameter ones.

Comparison of the Variable Inclination and Conventional Pump

To show the energy saving that the installation of a variable inclination pump entails in comparison with a conventional Archimedes screw, modelling using the graphical method was performed of an Archimedes screw of the same geometric characteristics as the variable inclination pump analysed in this paper, but with a fixed inclination of 30º (conventional pump). The same pitch, number of blades and outer and inner diameter of each blade were considered. It was also considered that both pumps work under the same rotational regime, taking into account for each flow rate calculation the same flow loss factor for leakage. For comparison purposes, the energy saving of the variable inclination pump vs. the conventional pump is represented in Figure 7. The energy savings attained when the pump is of variable inclination can be clearly seen. The energy saving is greatest when the head difference is smallest and falls as the head difference between the inlet and outlet of the pump increases.

Economic Study

Table 2 shows the costs of the pump and civil works of the two cases studied. It can be seen how the total cost of the conventional

$n(rpm)$	$Q_m \left(\frac{m^3}{s} \right)$	$\beta m (^0)$	$H_m (m)$	$Q_c \left(\frac{m^3}{s} \right)$	$\Delta \frac{Q}{Q_m}$	K_c $(eq 1)$
20	0.396	11.67	0.334	0.410	0.035	0.352
40	0.882	10.59	0.321	0.900	0.021	0.392

Table 1: Results of the measured and calculated variables. Q_m: measured flow rate, β: pump inclination, H: transferred energy, Q_c calculated flow rate.
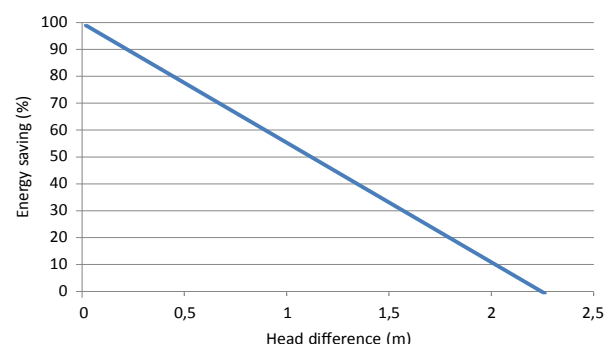

Figure 7: Energy saving of the variable inclination pump as a function of head difference.

Concept	Conventional pump	Variable inclination pump
Pump	€ 80,000	€ 110,000
Civil works	€ 105,000	€ 47,000
Total	€ 185,000	€ 157,000

Table 2: Partial and total costs of the two pump types.

pump is greater than that of the variable inclination pump as a result of the higher cost of the civil works. The reason for this is that in a conventional pump, it is necessary to build a semi-circular casing and to anchor the shaft, while in the case of the variable inclination pump, it is only necessary to construct a frame to which to attach the pump. It is therefore concluded that the variable inclination pump is more economic from both an investment and energy consumption point of view.

Conclusions

The energy consumption of the variable inclination pump was compared with that of a conventional fixed inclination pump and it was observed that significant energy savings can be attained when the downstream water level is low. The cost of the device and civil works is also lower for the variable inclination pump, making it a more recommendable option. The method of calculating the volume of water raised by the pump according to its geometry and rotational speed gave good results when compared with data taken in situ. This allowed us modeling of the performance of the pump for other conditions.

References

1. Nagel G (1968) Archimedean Screw Pump Handbook. RITZ Pumpenfabrik OHG, Schwäbisch Gmünd.

2. Wijdieks J, Bos MG (1972) Drainage principles and applications. International Institute for Land Reclamation and Improvement. Wageningen, The Netherlands.

3. Rorres C (2000) The turn of the screw: Optimal design of an Archimedes screw. Journal of Hydraulic Engineering 126: 72-80.

4. Burt C, Piao X, Gaudi F, Busch B,Taufik N (2008) Electric Motor Efficiency under Variable Frequencies and Loads. Journal of Irrigation and Drainage Engineering 134: 129-136.

5. Autocad (2012) Drawing software. AutoDesk Inc.