THE COIL PUMP - THEORY AND PRACTICE

LA POMPE SOLENOIDE - THEORIE ET PRATIQUE

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Summary

An old idea for a simple pump has been developed and from laboratory investigations a theory has been produced which satisfactorily predicts the pump's behaviour. A low cost stream powered version of the pump was built and successfully tested in a local stream.

Résumé

Des essais en laboratoire ont permis de mettre au point une théorie qui rend compte très correctement du comportement d'une pompe simple, dont l'idée est ancienne. On a pu construire une version peu coûteuse de ce type de pompe, qui a été essayée avec succès dans un cours d'eau.

1. Introduction

In his book entitled "Cyclopaedia of Science and Arts", Abraham Rees (1819) describes a pump allegedly invented by Mr. A. Wirtz in 1746. Though this is the first documented reference for this pump we feel that its origin may lie in much earlier times in China.

In work carried out recently (Morgan (1979), Stucky et al (1981)) a variety of names have been used for the pump, for example, the spiral pump, manometric pump and hydrostatic pump. For our work we have called it the Coil Pump.

This pump is simple both in construction and operation. It consists of a length of flexible tube wound around the inside or outside of a cylindrical drum which is partly submerged in water with the axis of the drum parallel to the water surface. One end of the pipe is secured to the drum and left open and this forms the inlet. The other end of the pipe is connected via a sealed rotary joint to the delivery pipe. An isometric sketch of the layout of our laboratory pump is shown in Figure 1.

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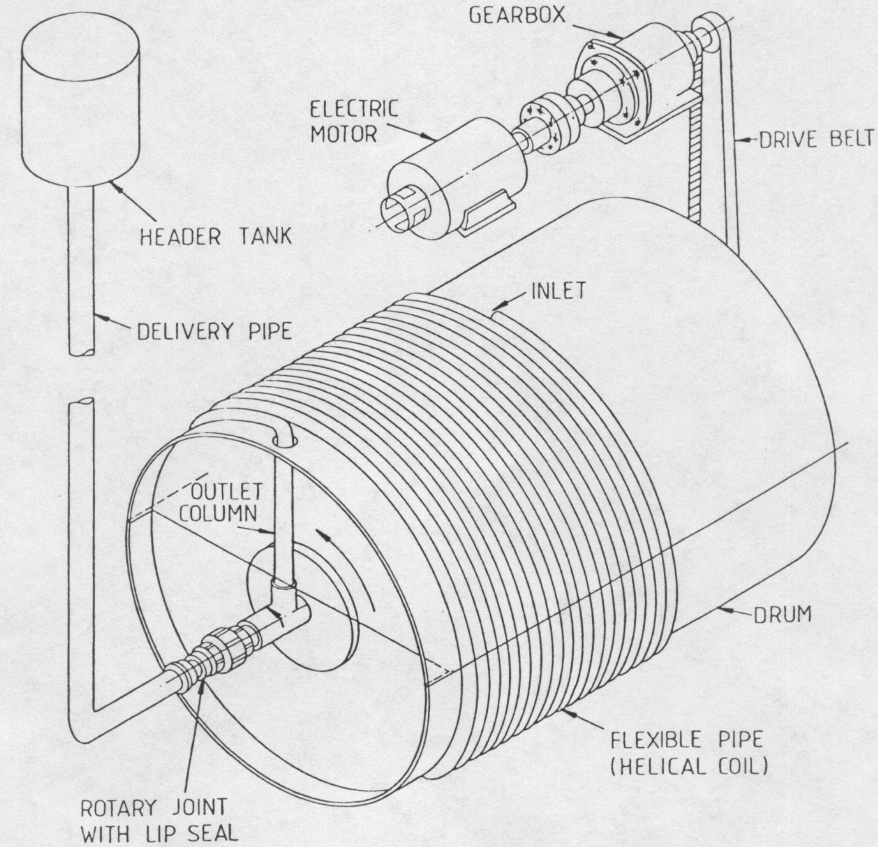


Laboratory coil pump   Fig. 1   Pompe solénoïde de laboratoire

Rotation of the drum causes the inlet end of the pipe to take in alternate plugs of air and water. The ratio of the lenghts of these plugs is determined by the depth of immersion of the drum. The plugs then move along the helical pipe towards the outlet and after passing through the rotary joint they travel up the delivery pipe to the header tank. The pressure that is required to force the plugs up the delivery pipe is developed by each water plug acting as a manometer and sustaining a pressure difference across the plug. The sum of all these pressure differences equals the pumping head.

Laboratory tests have been carried out on the coil pump at Loughborough University and a theory for predicting the behaviour of the pump has been developed. Later a stream powered version of the pump was built and tested in a local stream.

2. Theoretical aspects of the pump's behaviour

2.1 Cascading Manometer

When the coil pump is stationary or rotating the pressure head difference across the pump is developed by means of a cascading manometer which is equivalent to an unwound helical coil; see Figure 2. The head difference across the manometer is balanced by the sum of the head differences across the water plugs, that is

$$H_T - H_A = h_1 + h_2 + h_3 + \ldots\ldots h_N$$

where H_T is the absolute pressure head at the outlet,
H_A is the atmospheric head,
and N is the number of coils or manometric loops.

If the air were incompressible then $h_1 = h_2 = h_3 = \ldots\ldots h_N$.

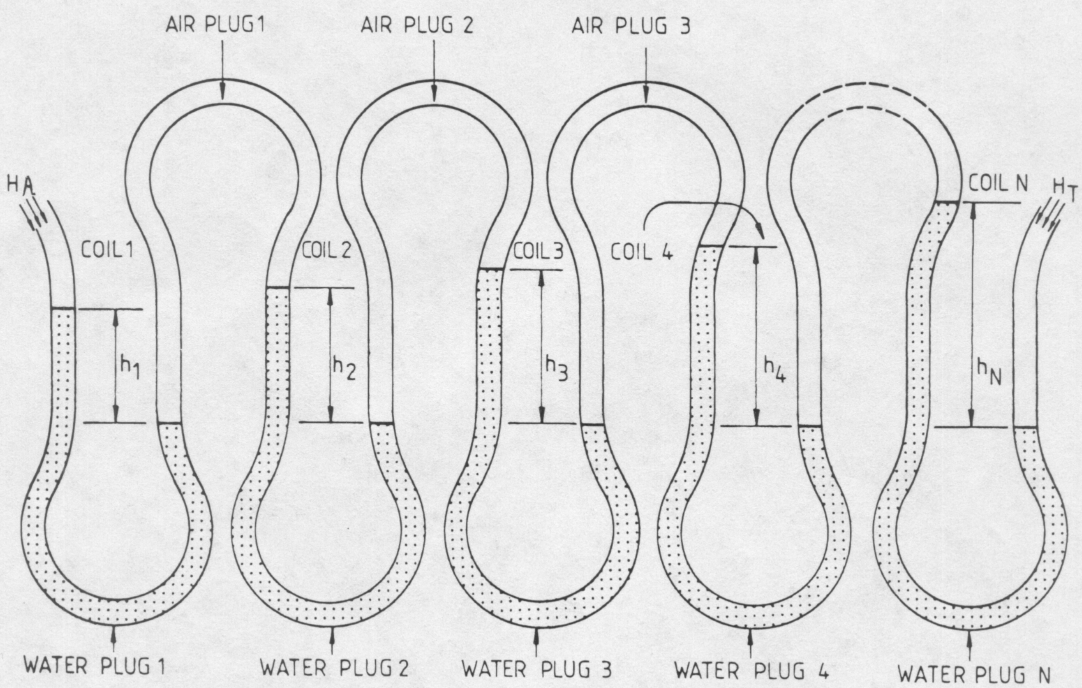
2.2 Contraction of the air plugs

Assume that in Figure 2 air plug 2 is bounded by water levels XX and YY before the compression effects have been considered. Increasing the air pressure H_2 will cause a contraction of the air plug and a rise in either level XX or YY will follow. A rise in level YY would reduce the pressure head difference across the coil and if this argument is applied to all the coils, the pump could not function. A rise in level XX is assumed therefore for all the coils. Calculations on the lengths of the air plugs in the pump suggest that $P.V^{1.15}$ = constant is valid, where P is the absolute pressure in the air plug and V is the volume of the plug.

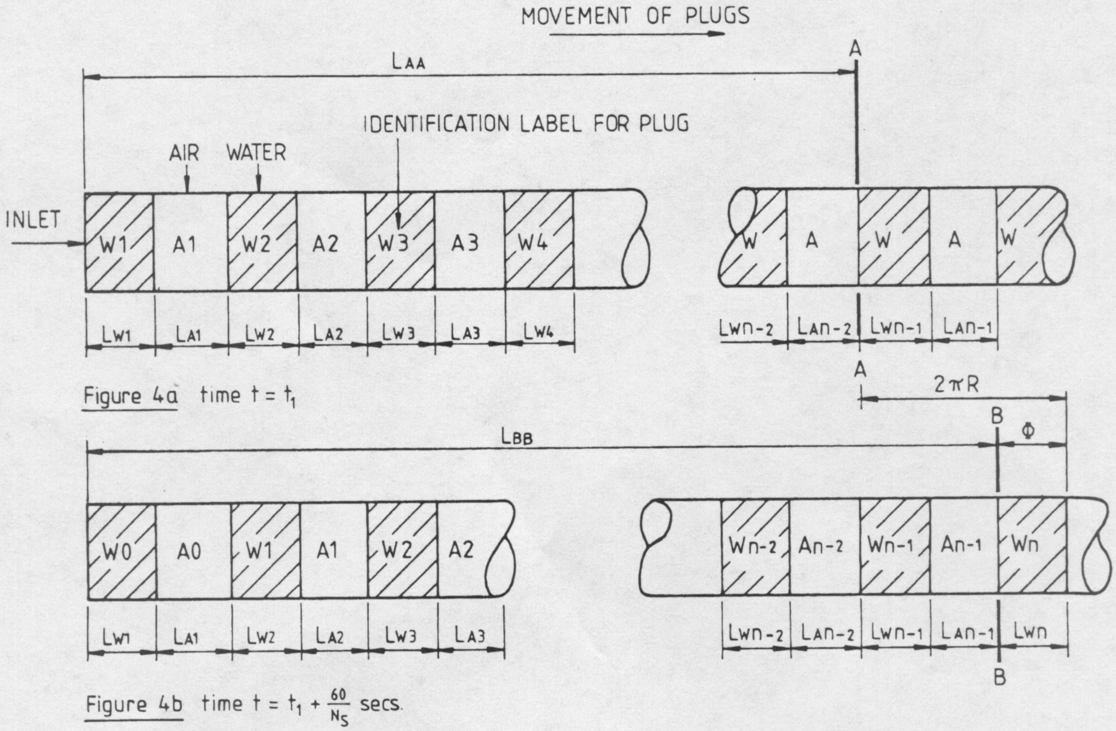
$$\therefore\ P_1 V_1{}^{1.15} = P_2 V_2{}^{1.15}$$

or assuming a constant pipe diameter for the helical coil

$$H_A . L_A{}^{1.15} = H_n . L_{A.n}{}^{1.15}$$



Cascading manometer Fig. 2 Tubes manométriques en cascade



Movement of plugs in helical pipe — Fig. 3 — Mouvement des masses d'eau dans un tuyau en hélice

where H_n = absolute pressure head in air plug A.n,
L_A = length of air plug A.n at atmospheric pressure,
and $L_{A.n}$ = length of air plug A.n under a pressure head H_n.

$$L_A - L_{A.n} = L_A\left(1 - \left(\frac{H_A}{H_n}\right)^{0.87}\right) \tag{1}$$

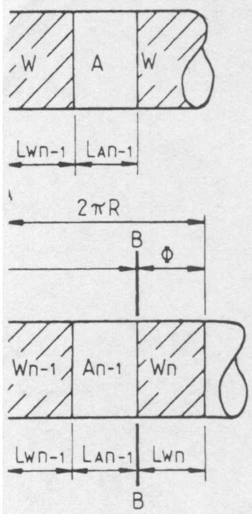
2.3 Movement of air and water plugs

Consider the pump rotating and visualise the helical coil as a straight stationary pipe with plugs of water and air moving along it.

An air plug travelling along the pipe from the inlet will become compressed by the pressure build up towards the outlet, therefore every point on the pipe will have a different air plug length associated with it. A similar argument can be applied to the water plugs except that the change in plug length is caused by water moving from one plug to the next (see section 2.4). Figure 3a shows the position of a set of plugs in the pipe at time t_1 where plug numbers W.2, A.2 etc. are just identification labels whereas the plug lengths $L_{W.1}$, $L_{A.1}$ etc. refer to fixed positions in the pipe.

On Figure 3a the distance from the inlet side of water plug W_n (line AA) to the pipe inlet is

$$L_{AA} = L_{W.1} + L_{A.1} + L_{W.2} + L_{A.2} + \ldots L_{W.n-2}\ L_{A.n-2} \tag{2}$$



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(2)

In exactly one revolution of the drum the arrangement of plugs will be as shown in Figure 3b with a new water plug W.1 and a new air plug A.1 having entered the pipe.

From Figure 3b

$$L_{BB} = L_{W.1} + L_{A.1} + L_{W.2} + L_{A.2} \cdots\cdots L_{W.n-1} + L_{A.n-1} \tag{3}$$

where L_{BB} is the distance from the inlet side of W.n (line BB) to the inlet.

$L_{BB} - L_{AA}$ is the distance moved by W.n in one revolution of the pump and if no additional air compression occurred in any of the air plugs during that revolution then $L_{BB} - L_{AA} = 2\pi R$, where R is the radius of the helical coil.

Taking Φ_n as the relative movement of W.n towards the inlet which is caused by the compression of all the following air plugs during the movement of W.n from the pipe position where its length is $L_{W.n-1}$ to a position where its length is $L_{W.n}$ then

$$L_{BB} - L_{AA} = 2\pi R - \Phi_n \tag{4}$$

but $\quad 2\pi R = L_{W.1} + L_A \qquad (5)$

and so substituting equations (2), (3) and (5) into equation (4) we have

$$\Phi_n = L_{W.1} - L_{W.n-1} + L_A - L_{A.n-1} \tag{6}$$

If all the water plugs are the same length then equation (6) will become

$$\Phi_n = L_A - L_{A.n-1} \tag{7}$$

If Δ_n is the relative movement of water plug W.n towards the inlet which is caused by the compression of the following air plugs during the movement of W.n from the inlet to the position where its length is $L_{W.n}$ then

$$\Delta_n = \Phi_2 + \Phi_3 + \cdots\cdots \Phi_n \tag{8}$$

Φ_1 does not exist since $L_{W.o}$ is non-existant.

Substituting equation (7) into (8) and adjusting

$$\Delta_{n+1} = \Delta_n + L_A - L_{A.n}$$

If δ_n and δ_{n+1} are the angles subtended at the centre of the coil by Δ_n and Δ_{n+1} respectively (see Figure 4a) then

$$\delta_{n+1} = \delta_n + \frac{(L_A - L_{A.n})}{R} = \delta_n + \frac{L_A}{R}\ \left(1 - \left(\frac{H_A}{H_n}\right)^{0.87}\right) \tag{9}$$

from equation (1).

2.4 Spillback

As the water plug W.n moves along the helical coil, the cumulative compression of all the following air plugs causes the inlet end of the water plug (level XX in Figure 2) to rise until it reaches the crown of the coil. Any further compression of the air plugs causes water from plug W.n to spillback through A.n-1 into W.n-1.

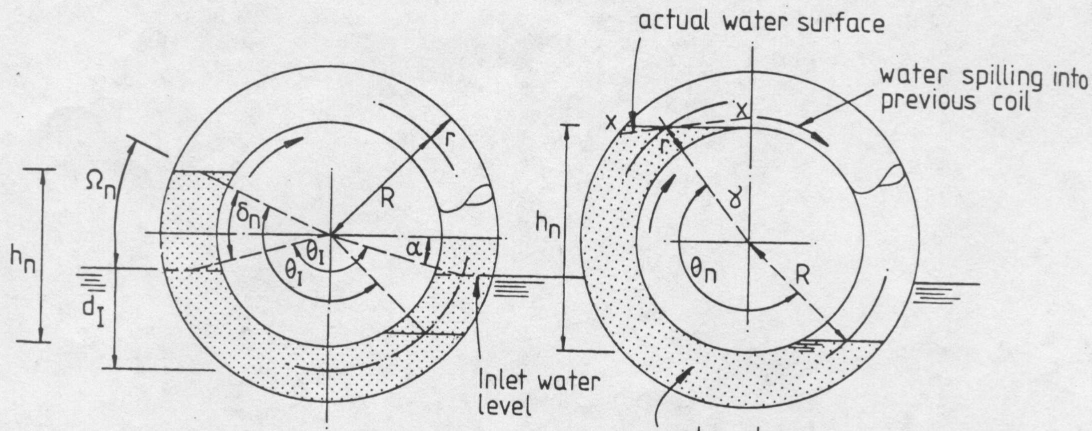


Fig.4a. levels where spillage does not occur

Fig.4b levels where spillage is occuring

Water levels in coils — Fig. 4 — Niveaux d'eau

If in Figure 3a water is spilling back from W.n+1 to W.n and W.n is spilling into W.n-1 then the inlet sides of plugs W.n and W.n+1 will both be in position XX as shown in Figure 4b. As W.n moves from a position where its length is $L_{W.n-1}$ to a position where its length is $L_{W.n}$ and it is spilling, then the relative movement of the inlet side of this plug towards the inlet will be zero and $\Phi_n = 0$; equation (6) can become

$$L_{W.n} = L_{W.n} + (L_A - L_{A.n})$$

Substituting equation (1) for $L_{A.n}$ we get

$$L_{W.n} = L_{W.1} + L_A\left(1 - \left(\frac{H_A}{H_n}\right)^{0.87}\right) \tag{10}$$

2.5 Water levels developed in the coils

For a coil that is not spilling Figure 4a shows that the head difference across plug W.n

$$h_n = R\left[\cos\left(\pi - \frac{\theta_1}{2} - \delta_n\right) + \cos\left(\frac{\theta_1}{2} - \delta_n\right)\right] \tag{11}$$

where θ_1 is the angle subtended by the water plug, just after it has entered the pump and theoretically

$$\theta_1 = \frac{L_{W.1}}{R} = 2\cdot\cos^{-1}\frac{(R - d_I)}{R}\ . \tag{12}$$

In equation (11) δ_n can be calculated from equation (9).

When a water plug is spilling back, the upper water level will be close to the crown of the pipe. Viscous forces will assist in "pulling" the water over the crown into the previous plug but it is assumed that the maximum water level is as shown by the horizontal line XX on Figure 4b.

From Figure 4b spillback just starts to occur when

$$\delta_n = \pi - \gamma - \frac{\theta_1}{2} \quad \text{where} \quad \gamma = \cos^{-1}\frac{(R - r)}{R}$$

then the criterion for no spillback in a coil is

$$\delta_n < \pi - \gamma - \frac{\theta_1}{2} \tag{13}$$

The head developed across a spilling water plug is

$$h_n = R[\cos\gamma + \cos(\gamma + \theta_n - \pi)] \tag{14}$$

where

$$\theta_n = \frac{L_{W.n}}{R} \text{ and } L_{W.n} \text{ can be calculated from equation (10).}$$

Equations (11) and (14) can be used to calculate the head differences across all the coils in the pump except one, this is in water plug W.s immediately following the first spilling plug. Here W.s has gained water by spillback but lost none since it is not spilling itself. For a particular plug this situation will only last for one pump revolution.
The length of W.s is

$$L_{W.s} = L_{W.1} + R\left(\frac{\theta_1}{2} + \delta_{s+1} - (\pi - \gamma)\right) \tag{15}$$

where δ_{s+1} is the total rotation of the first spilling plug and

$$R\left(\frac{\theta_1}{2} + \delta_{s+1} - (\pi - \gamma)\right)$$

is the length of water spilling into W.s up to the time when δ_{s+1} occurs.

The head difference across W.s is

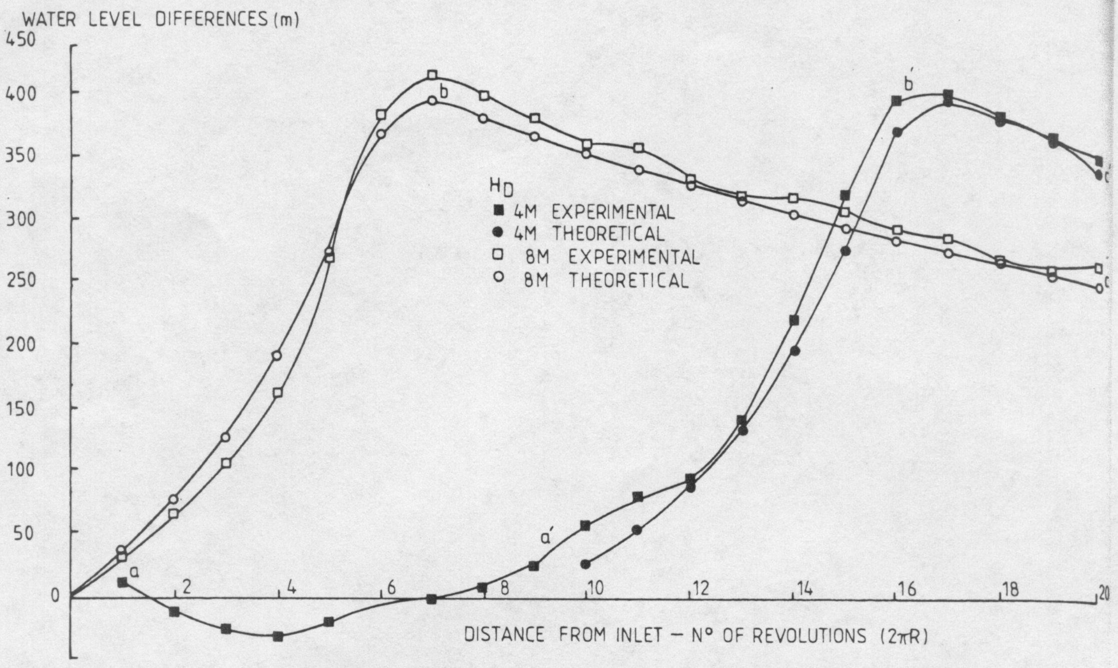
$$h_s = R[\cos(\pi - \frac{\theta_1}{2} - \delta_s) + \cos(\delta_s + \frac{\theta_1}{2} - \theta_s)] \tag{16}$$

where $\theta_s = L_{W.s}/R$ and δ_s is the total angular rotation of W.s.

2.6 The significance of the water levels in the coils

Figure 5 shows the measured water level differences in the coils of the laboratory pump under two different pumping lifts. (The pumping lift H_D is the height of the header tank above the pump; see section 2.7). From the inlet end the curves (a to b and a' to b') rise exponentially where no spillback occurs. Once water is spilling, the water level differences slowly decay towards the outlet (b to c and b' to c').

The shape of the level difference curve is fixed for a particular pump and its position on the horizontal axis (as in Fig. 5) is determined by the need for the sum of level



Theoretical and experimental water level differences — Fig. 5 — Différences de niveau calculées et mesurées

differences in the coils to equal the pump outlet pressure head. This is shown in Figure 5 where the curve a to c for the higher head is displaced to the left of a' to c'. In fact with the 4 m lift, the first 8 coils on the pump could be removed without affecting its performance.

If, on this laboratory pump, the lift is increased above 8 m then curve a to c would move further to the left and an unacceptable water level difference would be set up across the first coil causing the pump to "backfire". This condition represents the limit of a pump's capability to lift water.

When a pump configuration is known or assumed, the water level difference curve can be calculated (as below) and from this the minimum number of coils required can be found for any outlet pressure head. The relationship between lift and outlet pressure head is explained in section 2.7.

The water level difference curve for a pump is determined by starting the calculation at the inlet and a small level difference in the first coil, say 1 mm, is assumed. The level differences in successive coils are then calculated using equation (11) until spillback occurs (governed by equation (13)). The level difference across the last non-spilling plug W_S is then recalculated using equation (16).

The spillback part of the curve is found by progressively calculating the water level differences from the outlet using equation (14).

The level difference across the first coil at the inlet is then adjusted and the calculation repeated until the air pressure in plug A_S immediately before the first spilling plug is approximately the same for the "spilling" and the "non-spilling" set of calculations.

2.7 The delivery pipe

An investigation into the behaviour of the air and water plugs in the delivery pipe is best carried out by analysing the position of the plugs at regular time intervals for one revolution of the pump.

Figure 6 shows the position of the air and water plugs in a vertical delivery pipe at a particular time.

The absolute pressure head at the bottom of the delivery pipe H_T is given by

$$H_T = K_{W.1} + K_{W.2} + K_{W.3} + \ldots\ldots + K_{W.M} + H_A \tag{17}$$

If H_D is the height of the end of the delivery pipe above the axis of the pump then

$$H_D = K_{W.1} + K_{A.1} + K_{W.2} + K_{A.2} + \ldots\ldots K_{A.M-1} + K_{W.M}$$

In both these equatios M is the number of water plugs in the delivery pipe. This varies with time and it depends on the lengths of the air and water plugs in relation to the length of the delivery pipe.

A complication with this type of two phase flow is that an air plug moving up the pipe will rise up through the water plug above it causing water to run back from a higher to a lower plug.

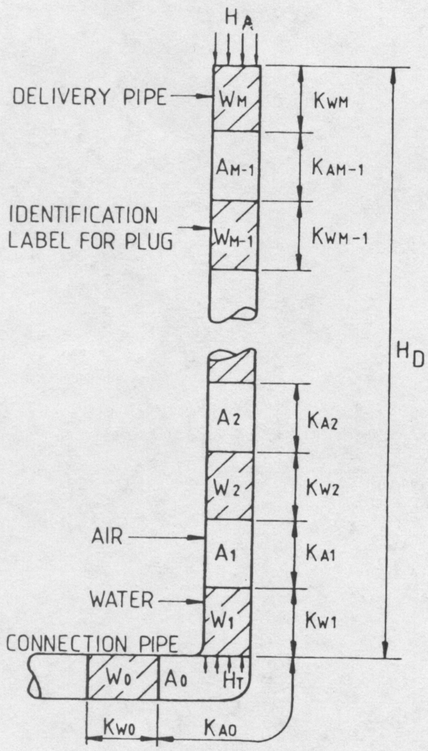


Fig. 6

Plug positions in delivery pipe

Position des masses d'eau dans le tube de refoulement

The relative velocity between the air and the water plug is denoted by V_a which is assumed to be constant along the delivery pipe. On Figure 6 the water plugs W_1 to W_{M-1} will lose as much water as they gain.

$$\therefore\ K_{W.1} = K_{W.2} = K_{W.3} = \ldots\ldots = K_{W.M-1} \tag{18}$$

If plug W_o loses no water as it moves from its position on Figure 6 to the position of plug W_1 then

$$K_{W.1} = K_{W.o} + V_a.t_p \tag{19}$$

where t_p is the time taken for A_o and W_o to enter the delivery pipe. If this occurs in one pump revolution then $t_p = 60/N_s$ where N_s is the speed of rotation in revs/min and t_p is in secs.

By continuity $K_{W.o} = L_{W.1}$ therefore using equations (18) and (19) the lengths of plugs $K_{W.1}$ to $K_{W.M-1}$ can be calculated; this leaves the length $K_{W.M}$ unknown.

On Figure 6 plug W_{M-1} will be losing water as it moves up to the outlet and it will gain once air plug A_{M-1} reaches the outlet so

$$K_{W.M} = K_{W.M-1} - V_a t_q$$

where t_q is the time taken for the whole of the last air plug A_{M-1} to leave the delivery pipe and $t_q = 60/N_S\ (L_A/2\pi R)$.

The length of the water plug leaving the delivery pipe per revolution equals $L_{W.1}$.

If the air plugs have maintained a constant self weight through the pump, then the length of any air plug A_n is given by equation (1) where $H_n = K_{W.n+1} + K_{W.n+2} + \ldots\ldots K_{W.M} + H_A$. For the position shown in Figure 6 the lengths of all the air and water plugs can be calculated, therefore H_T can be found from equation (17).

A short time later all the plugs will have moved upwards and part of W_M will have spilled out. H_T will have now changed and so the number of the lengths of all the plugs have to be recalculated starting from the top of the delivery pipe.

Generally H_T will have one minimum and one maximum value per pump revolution. Figure 7 shows an example of the measured and predicted pressure head (H_T) variation where the header tank was set 7.00 m above the pump axis. A value of V_a of 0.25 M/sec was found from experimental results and used in the calculations.

V_a varies with both the flow rate and the pipe diameter and more work is required before this relationship can be predicted with accuracy.

2.8 The pump discharge

Theoretically the steady pumping rate for a coil pump should be

$$Q_p = N_S \pi r^2 \cdot L_{W.1}$$

where r is the diameter of the helical pipe and $L_{W.1}$ is the length of the water plug taken in at the inlet.

With no dynamic losses $L_{W.1} = \theta_1.R$ where θ_1 is determined from equation (12), however in reality $L_{W.1}$ is better defined as

$$L_{W.1} = \theta_1 R \pm \text{change in length}$$

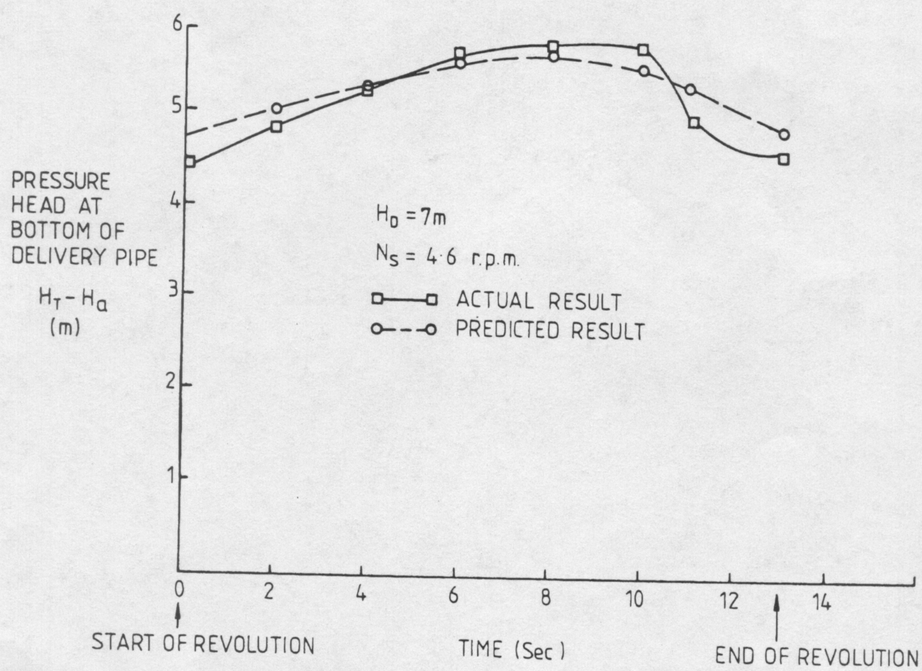
Logically this change in length should be a reduction because of the dynamic losses at the inlet. Surprisingly the measured lengths were on average 4% greater than the theoretical lengths. Further work will be required to explain this enigma but at present we feel that a 4% error is acceptable.

3. The stream powered pump

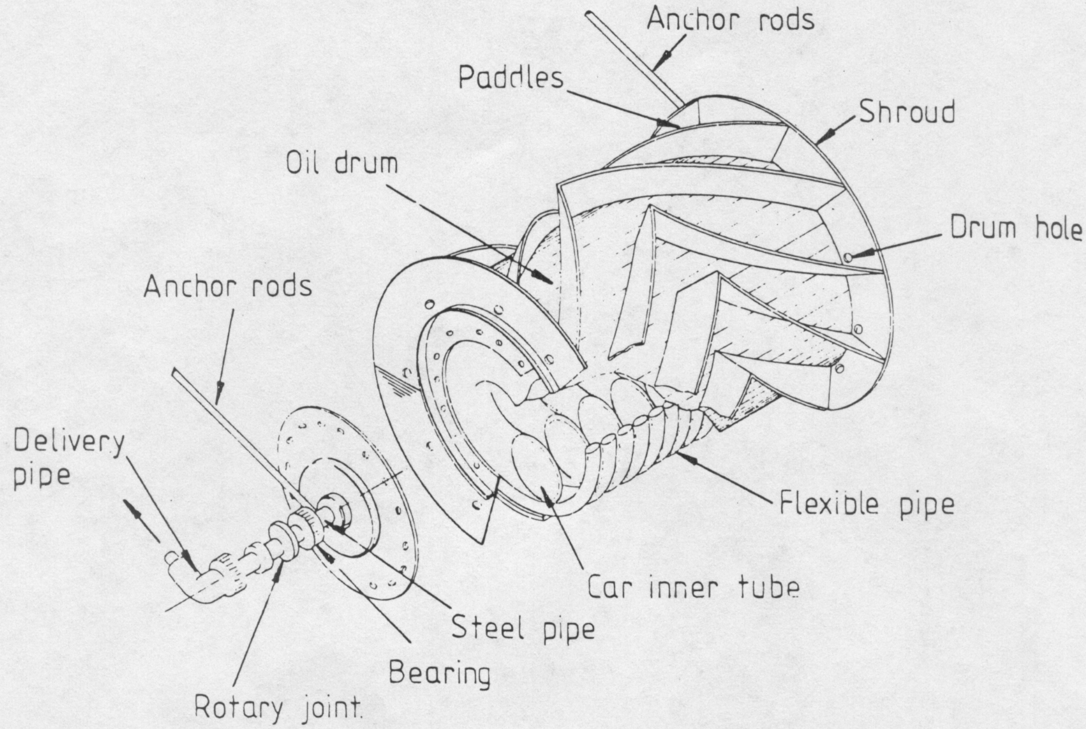
Because of the ability of the coil pump to work at low speeds and also because of its simple construction, we decided to concentrate our efforts on a practical low-cost stream-powered version. The details are as follows: 0.25 mm diameter flexible plastic pipe is wrapped around the inside of a 50 gallon oil drum forming 26 coils and it is held in position by a number of inflated car tyre inner tubes. These tubes also provide buoyancy for the drum when it is working in a stream or river.

Chevron shaped paddles made of scrap sheet steel are spot welded onto the outside of the drum and an annular shaped shroud is added to prevent the sideways movement of water, these form the paddles of the waterwheel which powers the pump and details are shown in Figure 8. This paddle arrangement was chosen because laboratory tests indicated that the chevron shape produced more power than a flat surface and also its performance was more stable under a wide range of depths of immersion.

The bearings and holding mechanism for the pump/waterwheel consist of two short lenghts of galvanised steel pipe, one attached to each end of the oil drum via a standard



Theoretical and experimental values for pumping head — Fig. 7 — Valeurs theoriques et expérimentales de la pression de sortie



Stream powered coil pump — Fig. 8 — Pompe solénoïde actionné par un courant d'eau

pipe flange. A loose brass pipe-support ring encompasses each steel pipe and acts as a simple bearing whilst a metal rod attached to the ring at one end and looped over a scaffolding pole (driven into the river-bed) at the other end forms the anchor for the pump.

The end of the flexible helical pipe is connected to one of the galvanised steel pipes inside the oil drum. Next to the bearing ring on this pipe is the rotary joint which consists of two rubber lip seals which bear on the pipe and which are held in a casing made up of standard p.v.c. pipe fittings. The rotary joint in turn is connected to the delivery pipe.

The pump shown in Figure 8 was tested in a local stream and it lifted water to a height of 9.50 metres at a rate of 4 l/min when the stream velocity was 0.80 m/s. The pump operated with a stream velocity as low as 0.40 m/s, but at a reduced performance.

Using the oil drum as a basis for the pump, the flow can be increased by (1) using a larger diameter helical pipe, (2) by using a second helical pipe connected to the same outlet, or (3) by increasing the stream velocity. The pumping head can be increased by adding more coils by continuing the helix back along the inside of the original helix.

4. Conclusions

- Though the idea of the coil pump has been gathered dust on some forgotten shelf for centuries, it is worthy of further investigation and development.
- The theory given in this paper does not describe in detail all the inner workings of the pump but it does predict the behaviour of the pump with sufficient accuracy for most design purposes.

- The stream powered pump we developed is only one version of a wide range of possible pumps. Further work in this field may well produce other useful forms of the coil pump.
- The coil pump will not replace or supercede any of the existing types of pump, but it may provide an additional form of water raising device which could be useful for small scale irrigation and water supply projects, particularly in developing countries.

Acknowledgements

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Notations

A_n	Identification tag for an air plug in the delivery pipe
A.n	Identification tag for an air plug in the pump
d_I	Depth of immersion of drum
H_A	Atmospheric pressure head
H_D	Height of the outlet of the delivery pipe above the pump axis
H_n	Absolute pressure head where air plug length equals $L_{A.n}$
H_T	Absolute pressure head at the pump outlet
h_n	Water level difference of plug W.n
L_A	Length of the air plug in the pump under a pressure of H_A
$L_{A.n}$	Length of an air plug in the pump under a pressure of H_n
$L_{W.n}$	Length of a water plug W.n at a particular point in the pump
$L_{W.s}$	Length of the water plug following the first spilling plug
$K_{A.n}$	Length of air plug A_n at a point in the delivery pipe
K_W	Length of water plug W_n at a point in the delivery pipe
M	Number of water plugs in the delivery pipe
N	Number of coils on the pump
N_s	Speed of rotation of the pump
n	Number of air or water plugs between the plug under consideration and the inlet
P	Absolute air pressure
Q_p	Pumping discharge
R	Distance from drum axis to the longitudinal centre line of the helical pipe
r	Diameter of helical pipe
t_p	Time for plugs A_o and W_o to enter the delivery pipe
t_q	Time taken for an air plug A_{m-1} to leave the delivery pipe
V_n	Volume of air at pressure P_n
V_a	Relative velocity of an air plug to a water plug moving up the delivery pipe
W_n	Identification tag for a water plug in the delivery pipe

W.n	Identification tag for water plug in the pump
W.s	Identification tag for the water plug following the first spilling plug
Δ_n	Relative movement of the water plug towards the inlet as the plug moves from the inlet to a position where its length is $L_{W.n}$
Φ_n	Relative movement of the water plug towards the inlet as the plug moves from a position where its length is $L_{W.n-1}$ to a position where its length is $L_{W.n}$
γ	Angle subtended at the centre of the helix by a circumferential distance from the maximum water surface to the crown of the pipe
δ_n	Angle subtended by Δ_n at the centre of the helix
θ_n	Angle subtended at the centre of the helix by a water plug of length $L_{W.n}$