The Use of Progression Cavity Pumps in the Exploitation of Geothermal Energy from Deep Boreholes

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Abstract. In the article, we aim to demonstrate the use of progression cavity pumps in the exploitation of geothermal energy from deep boreholes. The progression cavity pumps presented in the article are the kind generally used to extract oil from deep boreholes. The former provide a very large amount of power while overcoming the pressure elevations of extraction. Their capacity is relatively small, up to 0.005 m³/s. It is expedient to use such pumps during the exploitation of geothermal energy when we do not have sufficiently powerful centrifugal pumps at our disposal and when the exploitation of thermal water is intended for the purposes of health tourism.

Keywords: deep borehole, geothermal energy, stator, rotor
1 Presentation

A progression cavity pump is, in essence, composed of two spiral elements (a rotor and a stator) positioned one into the other. The internal element revolves around its longitudinal axis, and the elements are spaced apart. The external element is in possession of one thread or tooth more than the internal.

The internal element must be fitted into the external element so that all of its threads are in constant contact with the external element. The peaks of the curves of the two elements must be consistent with the cross-sections on each of their teeth.

The cross-section of the spiral elements consists of a pair of profiles obtained from the amalgamation of the epicycloids and the hypocycloid, the generated circular curve of which is of the same diameter as is the distance between the longitudinal axes of both elements.

The spiral winding of the elements around their rotational axis generates spaces between the two, the length of which is equal to the outer extreme of the spiral. As the internal element rotates, the spaces spirally move along the external element.

As long as the internal element is run on more than one revolution, the pump will enable extraction under pressure. The pressure of the fluid inside will increase only upon the first revolution.

This kind of movement creates a system of closed spaces, separated from one another and restricted with the aid of the rotor and the stator, that move axially from the suction to the pressurisation of the fluid.

Due to this principle, filling of the pump is achieved[1]:
- In a way that is reversible and self-filling,
- Without the use of any control valves,
- In a way that ensures a constant stream, absent of hydraulic shock or hydraulic pulsation.

- In a way that allows for movement of both runny and viscous fluids, even when they contain solid particles or gases.

Fig. 1. The state of the rotor inside the pump

In Figure 1, in which the stator (displayed in a longitudinal cross-section) is immovable, this principle is schematically illustrated. Here, the rotor revolves in a clockwise direction. Spaces are formed between the two elements and are opened to the left when the rotor is revolving. The mutually separated spaces travel to the opposite end, where they slowly decrease in size and disappear.

In Figure 2, the principle is shown in divisions, in accordance with the various states of the stator, rotor and the movement of fluid inside their spaces.

Fig. 2. The state of the rotor inside the pump
From the figure, it is evident that the fluid moves from left to right. The filling and the emptying (the suction and the pressurising) of the pump are isolated from one another due to the constant act of tightening.

In a case in which the rotor begins to revolve in the opposite direction (from right to left), it obeys the same principle of filling and emptying, thus the process is reversible.

2 The Theoretical Basics

To ensure the principle of closed spaces, it is necessary to meet two elementary conditions:

1. The rotor must have one tooth less than the stator and each tooth of the rotor must always be in contact with the inner surface of the stator.
2. The rotor and the stator must form two spiral sets of wheels in a state as indicated by the first condition.

2.1 The First Condition

The hypocycloid \( H_1 \), with an \( n \) number of teeth, based in the circle \( C_1 (O_1, R_1) \), touches the hypocycloid \( H_2 \), with an \( n-1 \) number of teeth, based in the circle \( C_2 (O_2, R_2) \), with a ratio of:

\[
\frac{R_2}{R_1} = \frac{n-1}{n} \quad (1)
\]

These two curves form two sets of wheels, one inside the other (Figure 3).

Fig. 3. The curves formed by the sets of wheels in the pump

\( H_1 \) is stationary, while \( H_2 \) moves in a particular direction. The centre of the latter, \( O_2 \), forms a circle with a centre, \( O_1 \), and a radius, \( O_1O_2 \), in the opposite direction. From this, it follows that:

\[
O_1O_2 = E \quad (2)
\]

E - eccentricity of the pump

Throughout this movement, the highest point, \( H_2 \), is in contact with \( H_1 \) and, with the aid of curves, forms closed surfaces, \( S_1 \), \( S_2 \), \( S_3 \), with variable volumes, the sum of which, \( (S_1 + S_2 + S_3) \), remains constant.

If we replace \( H_1 \) and \( H_2 \) with the sheaths \( E_1 \) and \( E_2 \) (Figure 4), with identical circle curves, \( C \), of any diameter, \( D \), the centre of which would describe \( H_1 \) and \( H_2 \), the primary characteristics will remain constant and the first condition will thus be fulfilled.

Fig. 4. Replacement of the circle curves in order to confirm the first condition

2.2 The Second Condition

In order for the second condition to be fulfilled, the profiles \( E_1 \) and \( E_2 \) must move longitudinally, as spirals, the highest ratio of which is in accordance with the ratio of the number of teeth.

The spiral thread of the surfaces \( S_1, S_2, S_3 \) can be achieved between the two spiral elements, the length of which is equal to the height of the external element.

In order to achieve a complete tightening of the pump, the length of the rotor and stator must be at least equal to the height of the stator.

The portion of the rotor and stator contact lines that can be found between high and low pressure areas form a line of leakage.

3 General Description

Progression cavity pumps are composed of two basic elements, the rotor and the stator. The geometry of these two elements is such that it ensures two or more series of separate openings or spaces. While the rotor revolves inside the stator, the spaces move in a
spiral formation from one end of the stator to the other, thereby creating a pumping process. The drive system drives the latter in an infinite rotation. When the rotor has completed one revolution, its axis is simultaneously rotating in the opposite direction, around the stator, but remains parallel to the stator axis.

This type of movement creates blades, restricted by the rotor and the stator, which move in an axial direction from the suction to the pressuring of the fluid. These parameters are the characteristics of the geometry of a rotor and stator pump.

3.1 Description of the Rotor

The rotor is made of very tough steel and is coated with a resistant material (e.g. chromated) in order to reduce the abrasion caused by the transport of fluid, the latter containing solid particles, and to reduce friction between the rotor and the stator. The ultimate diameter of the rotor is dependent on the possible swelling of the elastomer inside the stator, which can be caused due to a particular pressure, temperature or the fluid itself. The thickness of the protective coat of the rotor is dependent on the nature and composition of the fluid being pumped.

3.2 Description of the Stator

The stator is made up of elastomer, which is resistant to the negative effects of the fluid pumped through it (its composition, solid particles, gases...) and to the temperature in the borehole, i.e. the temperature of the fluid.

This type of pump is most frequently used in the oil industry. It is designed so as to be able to ensure high flow rates at low revolutions, which is why we use it where we expect a high production of fluids.

4 The Operating Principle Behind the Progression Cavity Pump

Poly-curvature pumps consist of a rotor with $L_r$ spirals. The latter continue into one another and are inserted into a stator with $L_s = L_r + 1$ spirals. In their cross-sections, the rotor and the stator have a wavy profile, wherein each spiral responds to a curve.

The relationship between the maximum length of the rotor, $P_r$, and the maximum length of the stator, $P_s$, is equal to the relationship between the curves. The pump's kinematic ratio, $i$, is then:

\[ i = \frac{L_r}{L_s} = \frac{P_r}{P_s} \]  

4.1 The Transfer of Rotation

The transfer of rotation onto the rotor can be performed with the aid of:

- Drive on the surface as well as transfer onto the rotor, with the aid of an appropriate system,
- Drive in the depths, with the aid of an appropriate motor.

4.2 The Basic Parameters for the Achievement of a Maximum Effect

With a progression cavity pump, we may begin pumping as soon as one is installed. The relatively simple machine's efficiency and length of service are dependent on a few basic parameters. The latter are:

- The elastomer:
  - Wear due to abrasion,
  - Gases that penetrate into the material of the elastomer and alter its characteristics,
  - Temperature.
- The speed of rotation is limited by:
  - The instability of the rotor,
  - The friction between the rotor and the stator.

The lubrication and the cooling of the rotor, which are ensured through the transportation of fluid. In the case of an interruption in fluid flow, there is a risk of the elastomer overheating and thus the stator being destroyed.

5 The Installation of a Progression Cavity Pump Inside a Borehole

In general, progression cavity pumps are powered from the surface, with the aid of a drive motor. The installation is depicted in Figure 5 and is as follows:

- The stator is mounted at the end of the tubing,
- The rotor is mounted into the stator and is powered by the drive shaft,
- The drive head is mounted directly over the borehole and absorbs the tension generated by the drive mechanism,
- The motor (an electric motor, a motor with an internal combustion engine, a hydraulic motor...) along with a reductor or speed regulator.
5.1 The Capacity of a Pump

Throughout pump operation, the afore-mentioned spaces move longitudinally from the suction to the pressurisation part, i.e. to the discharge of the pump. During each revolution, the amount or volume of the fluid trapped inside the spaces is the same. Because the volume of the fluid in each part of the pump is the same, the pump operates uniformly, without pulsation. The capacity of the pump, determined with the aid of the volume of the fluid in one revolution, depends on the following variables:
- $E$ - eccentricity of the pump (m),
- $D$ - diameter of the rotor (m),
- $P_s$ - maximum length of the stator (m).

The cross-section is constant and equal to:

$$ A = 4E \cdot D $$

The surface of the cross-section is constant in the entire pump. When the number of revolutions of the rotor is constant, the capacity of the pump is also constant. The following applies:

$$ V = 4E \cdot D \cdot P_s $$

(5)

It follows that the capacity of the pump is proportional to the volume of the cylinder and the number of revolutions of the rotor, as follows:

$$ Q_c = 4E \cdot D \cdot P_s \cdot n $$

(6)

Where the following applies:
- $Q_c$ – capacity of the pump ($\text{m}^3/\text{s}$),
- $n$ – number of revolutions ($\text{s}^{-1}$).

The actual capacity of the pump, $Q_a$, is equal to the capacity of the pump, $Q_c$, minus the so-called capacity of looseness, $Q_s$.

5.2 The Ultimate Pressure in a Pump

Varying amounts of pressure throughout the suction and pressurising in a pump can cause fluid leakage between two consecutive spaces, from the
space with the higher pressure to the space with the lower pressure, thereby forming a pressure gradient along the pump.

The pressure gradient is dependent primarily on the characteristics of the pump. Fluids containing less of a gaseous component (also known as incompressible) generate linear pressure gradients, while fluids containing more of a gaseous component form a rising pressure gradient in the direction from suction to pressurising.

The final pressure in the pump is determined through:
- The number of spaces formed between the rotor and the stator,
- The maximum volume formed by a single space, which is dependent on:
  - The tightness between the rotor and the stator (the diameter of the rotor is slightly larger than the inner diameter of the stator),
  - The properties of the fluid being pumped (a more filled up space is achieved through the pumping of fluids that are more viscous),
  - The geometrical profiles of the pump,
  - The chemical composition, mechanical characteristics and thickness of the elastomer.

The pressure in the pump is determined with the aid of the equation:

\[ \Delta p = \delta p (2n_p - 1) \]  

Where the following applies:
\( \delta p \) – the pressure of the fluid in each space (kPa),
\( n_p \) – the number of curve peaks.

5.3 Moment

As the PC pump is a rotational pump, it forms a moment of inertia throughout initialisation and operation.

The moment of inertia is usually higher at initialisation than resistance is during the course of operation. This is why the drive motor and drive shaft are of such dimensions that, provided sufficient safety measures, they can overcome the moment of inertia upon initialisation.

Throughout operation, the rotation of the rotor allows for the flow of fluid from one area to another, thereby producing pressure differences. The energy needed to cause such a process requires a sufficient moment of inertia of the rotor and drive shaft. Such a moment of inertia is dependent on:
- Hydraulic power proportional to the pressure in the pump,
- Quality chromium plating on the rotor,
- The type of elastomer used,
- The lubricating qualities of the fluid being pumped,
- The length of the pump.

For an approximate calculation of the maximum moment of inertia, we can use the experiential equation:

\[ \Gamma = 1,63 \cdot V \cdot \Delta p \cdot 10^{-5} \cdot \varphi^{-1} \]  

Where the following applies:
\( \Gamma \) - the moment of inertia during operation (dNm),
\( V \) – the volume of the spaces (cm³),
\( \Delta p \) – the pressure in the pump (N/m²),
\( \varphi \) - the efficiency of the pump.

6 The Choice of Pump

Progression cavity pumps are predominantly used in the oil industry[2]. In Slovenia, they are used in Maribor, for the purposes of the exploitation of geothermal water, which is pumped from great depths. When selecting a pump, we must consider the following:
- The characteristics of the borehole,
- The characteristics of the production layer,
- The characteristics of the fluid being pumped,
- The production characteristics,
- The operating conditions.

6.1 The Characteristics of a Borehole

When selecting a pump, we must primarily direct our attention to the following:
- The stator
  - It must be of such dimensions that we are able to insert it into the protective pipes, e.g. the borehole filters,
  - If needed, it is necessary to ensure enough space between the stators and the protective pipes that we may perform interventions intended to resolve issues, e.g. degasification interventions, in the area of the stator,
  - If the stator is implemented underneath the filter system, it is necessary to ensure a large enough space between the stator and the protective pipes.
- The rotor
  - It must be of such dimensions that it can
be inserted into the stator through a system of pressure pipes,
- The tubing,
- The inner diameter of the pressure pipes must be such that it allows for the mounting of a rotor, as well as the movement of the drive shaft.

6.2 The Characteristics of an Aquifer

The diameters of the rotor and the stator, as well as the related capacity and ultimate pressure of the pump, need to be adjusted to the conditions in the production layer, such as the pressure and temperature of the fluid being pumped and the yield of the layer in which the fluid is present.

6.3 The Characteristic of the Fluid

The physical chemical characteristics of the fluid being pumped have a major effect on the choice of elastomer, as well as the surface coating on the rotor. Above all, the following physical mechanical characteristics of the fluid have an effect of the choice of elements within the pump:
- Viscosity,
- Density,
- Content of dissolved gases inside the fluid,
- Chemical composition of the fluid,
- Amount of gases in the fluid,
- Temperature,
- Content of solid particles in the fluid.

6.4 The Capacity of a Pump

The capacity of a pump is dependent predominantly on the position of the pump inside the borehole, with the latter being dependent on:
- The dynamic level of the fluid during pumping,
- Admissible pressure at the mouth of the borehole,
- Abrasion of the pump due to the presence of solid particles inside the fluid.

After we have determined all of the above, we are able to choose the pump that is appropriate in order for us to achieve optimal pump capacity under the given conditions.

7 The Use of PC Pumps in Slovenia

The use of PC pumps is very widespread in the world [4]. Due to their high operational reliability, undemanding maintenance and relatively low purchase, installation and maintenance costs, PC pumps are used primarily in the oil industry.

In Slovenia, PC pumps are currently used only to pump water from deep-lying aquifers. They are used in order to extract geothermal aquifers. They are used in order to extract geothermal water in Maribor.

7.1 The Pumping of Geothermal Water in Maribor

In the year 2011, a project aimed at the extraction of geothermal water from boreholes, carried out on the area of the Stržun forest in Maribor [3], was comprehensively completed:
- MB-1, depth of 1331 m,
- MB-2, depth of 1600 m,
- MB-3, depth of 1603 m,
- MB-4, depth of 1598 m.

The pumping tests, which were carried out on the boreholes mentioned above, have showed that the yield of each individual borehole amounted to about 0.003 – 0.004 m³/s of geothermal water, and that the dynamic levels of rising water were at about 1100 m.

Due to hydrogeological conditions, the installation of centrifugal pumps was not possible.

Following the installation of progression cavity pumps into boreholes, it was found that the pumping capacity was constant and the operational reliability of the pumps exceptionally good. From all this, we can summarise that it would be expedient to install progression cavity pumps for the purposes of exploitation of deep-lying geothermal water aquifers, at least when the exploitation is intended for use in the health tourism industry. When the exploitation of geothermal water is intended exclusively in order to be able to obtain heat energy, however, the value of the investments necessary exceeds their eligibility.

8 Conclusion

In the paper, a method detailing the use of progression cavity pumps in deep boreholes is presented. Progression cavity pumps are used primarily in order to extract oil from deep boreholes when the use of conventional pressure pumps and centrifugal pumps is impossible. In Maribor, we have used progression cavity pumps in order to extract geothermal water from aquifers at depths between 900 m and 1500 m. In this case, use of other types of pumps was impossible. Through the reliable operation of the chosen pumps in Maribor, we have demonstrated that it is possible to successfully transplant technologies from the oil industry into technological solutions needed for the extraction of geothermal waters from deep-lying aquifers.

References

Between Progressing Cavity Pumps and Plunger Pumps. Presented at the SPE Production Operations Symposium, Oklahoma City, Oklahoma, 8-10 March 1997. SPE-16194-MS.

