New Type of Reversible, Invertible, Variable Hydraulic Pump/Motor

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ABSTRACT

In this paper a new type of hydraulic motor and pump is presented. The machine is different to those available at the commercial market nowadays. The breaking-through design provides significant improvements and advantages in comparison to older hydraulic machine systems.

KEYWORDS: New type, Pump, Motor, Variable displacement

1 INTRODUCTION

Any of the hydraulic machine types possess principle advantages and disadvantages. Vane machines have smooth displacement and low noise level, but it is economically senseless to create a high pressure vane pump. Piston machines may operate with higher pressures, but they suffer from the pulsations of the flow and noise emissions. Presented concept is a synergetic union of the advantages of the piston and vane machines:

- High volumetric efficiency in the range of the operating pressure up to 30 MPa
- Smooth displacement and pulseless output flow
- Low noise level

Besides that, presented pump has additional enhancements derived from its design:

- Possibility to use polymers while preserving high pressure operating conditions
- Positive operating parameters using water as a working fluid
- Resistance to the returning pulses of the pressure, so called "hydraulic hammer"
- Manufacturability and simplicity of the service and installation

The machine is invertible, reversible and variable displacement. Another advantage of the design is a possibility of the displacement to be adjusted with high speed without applying significant forces.

Firstly we shall discuss basic ideas of the pump concept; in the main part we shall discuss technical enhancements and test results; then we'll provide examples of the applications.

2 DESIGN AND BASIC OPERATION OF THE DEVICE

The presented pump differs from the usual ones, despite the fact that it has some familiar features, originated from the other kinds of pumps and motors. Thus we shall depict its operation and construction ab ovo.

Imagine a revolver shown on Figure 1. Channels are made in said cylinder along an axial direction. The slide valves are mounted inside the channels and are operative to be in a reciprocating motion. Shape of the slide valves is mostly insignificant, but our researches revealed an optimal cylindrical geometry.

One of the rotor ends comprises an annular slot, another one made flat. The annular slot is thinner then channels, providing stiff positioning of the slide valves. The annular slot is a main part of the pumping chamber. Partitions are the two other means, which restrict the pumping chamber. Positions of the partitions are marked on Figure 2. High pressure and low pressure areas are divided by the partitions located in the annular slot. One of the partitions called a "regulating partition" is in contact with the tops of the slide valves and doesn't touch the bottom surface of the annular slot. The second partition called an "insulating partition" is in contact with the bottom of the annular slot.

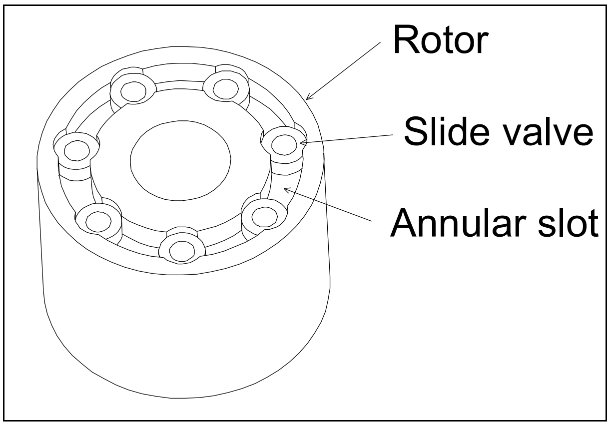

Figure1: Assembly of the rotor with slide valves

Initially, slide valves are pulled into the pumping chamber, while the rotor rotates, after that they slide along the regulating partition and, finally, move in the rotor. The displacement of the working fluid is arisen when the slide valves move along the regulating partition.

A lot of methods exist to make the slide valves reciprocate. In current case we shall describe only one way among the others. The slide valves are provided with protrusions shown on Figure 3, which used to move the slide valves.

As in common, rotor is mounted inside the housing and rotates relative to it. A cam slot is mounted on the housing and is immovable. On Figure 4 the cam slot has a sinusoidal shape and it defines the reciprocating motion of the slide valves along an axis of the rotor, while the rotor rotates. These protrusions may be equipped with rollers or any type of bearings, but we consider the presented system to contain only plain protrusions without bearings. Thus, the protrusions move along a cam slot and make the slide valves to pull into and move out of the pumping chamber.

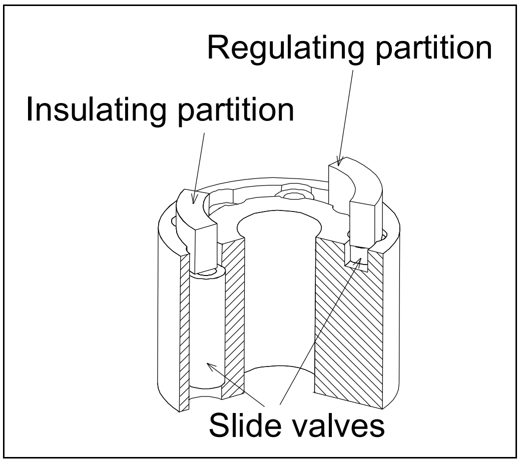

Figure 2: Partitions mounted inside the rotor

The radial section view of the annular slot is shown on Figure 5. The direction of rotation is clockwise. Slide valves seize fluid from the suction area, then slide along the regulating member and transfer fluid into the injection area. It should be noted that the slide valves displace the working fluid by their lateral surfaces, not by their ends. They work similarly to vanes of the vane pump.

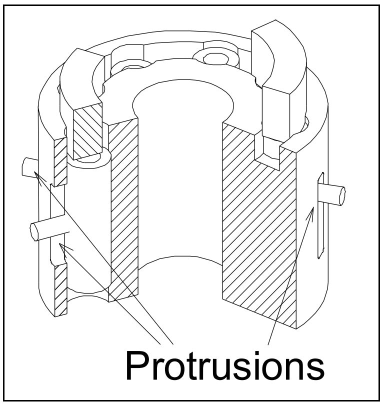

Figure 3: The slide valves trajectory

As we mentioned, while the slide valves displace the fluid, they are fixed not only by the channels of the rotor, but also by the recesses provided in the annular slot. While displacing the working fluid, the slide valves reside in an immovable state. This outstanding feature makes the pump design similar to the vane type, but stiff fixation of the slide valves allows many unique unreachable for vane pumps features to co-exist.

Another significant feature of the presented device is the channels passing through the rotor, connecting opposite ends of the rotor. As it shown on Figure 1 and Figure 5, the slide valves are provided with channels to compensate the pressure of the working fluid acting at both ends of the rotor. The second end of the rotor is flat, so the valves slide along a special member mounted inside the housing.

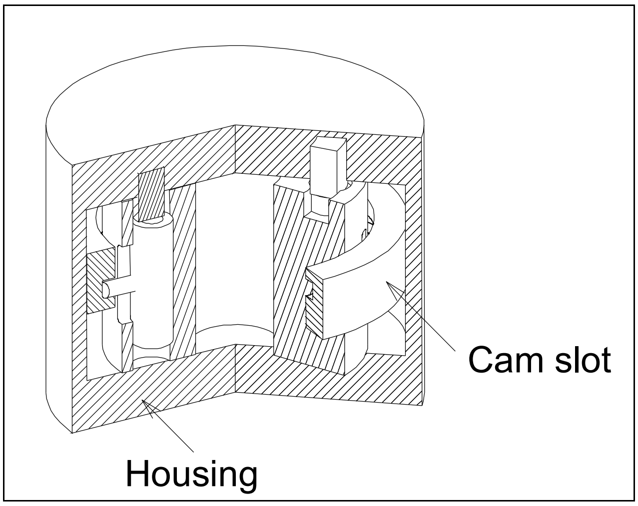

Figure 4: General mounting

It was named a “distributing member”. In this particular case the distributing member is implemented as a part of the housing for the simplicity’s sake, but in the real world embodiments the distributing member must be independent. Also, two crescent recesses are made in this member, which are located opposite the high and low pressure areas of the pumping chamber. The recesses are shown on Figure 5 and 6.

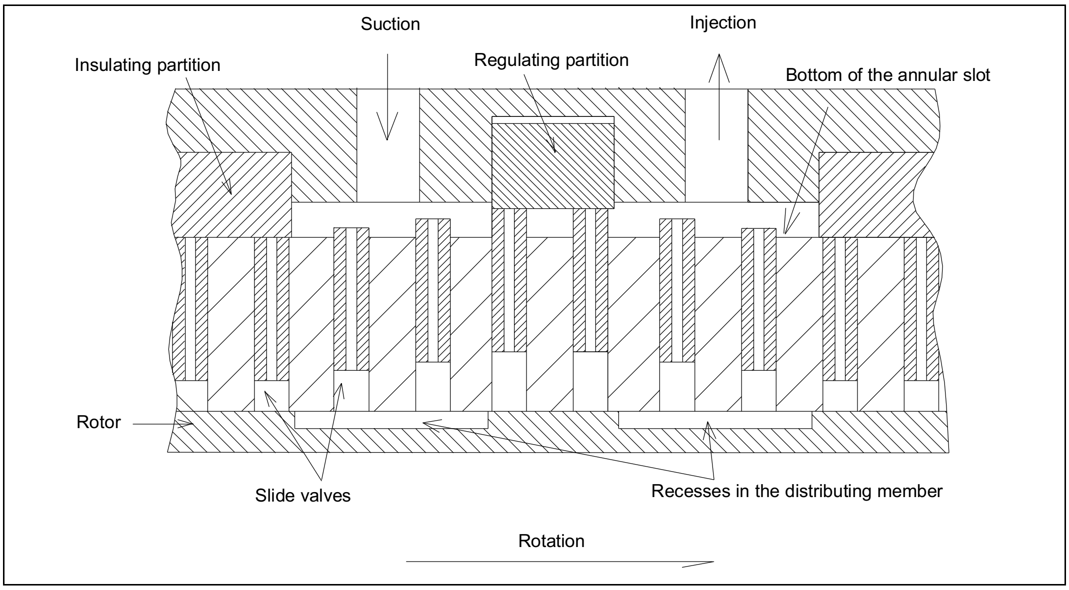

Figure 5: Rotor radial-sectional view

Meant recesses connect adjacent slide valves so, that the second end of the rotor is separated in two zones—of high and low fluid pressure, and their area equals to that in the pumping chamber. Every recess connects the slide valves under the equal pressure. The recess at the suction area is illustrated on Figure 6, while the recess at the injection area is not shown for the simplicity’s sake. Rotor is axially balanced against the hydraulic forces acting on its ends due to the recesses and the channels in the slide valves. One may obtain any pressure of the fluid in the pumping chamber preserving the rotor balanced.

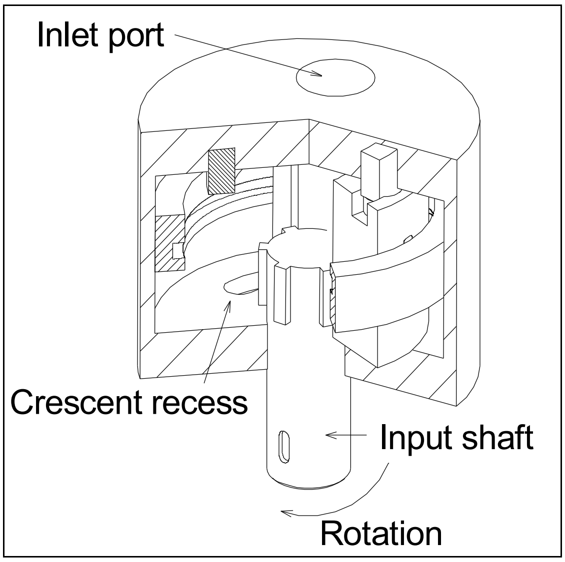

Figure 6: Recess location

Also we would like to pay attention to the balancing of the rotor in the radial direction. It is shown on Figure 7 that the high pressure area is restricted by an insulating partition from one side, also by the slide valve from the other side, by the annular slot and the housing. The resulting radial forces would be eliminated.

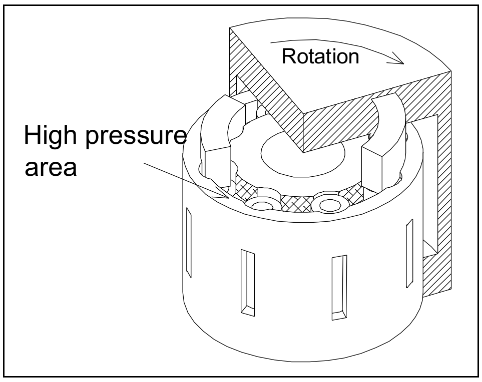

Figure 7: High pressure area

In the design of the pump there are several key features that should be underlined:

- Slide valves are stiffly fixed in the rotor
- Slide valves are hydraulically balanced in an axial direction because of the internal channels
- Rotor is also balanced in an axial direction due to the presence of the crescent recesses in the distributing member and channels in the slide valves
- Rotor is balanced in the radial direction

The mentioned device is a fixed displacement pump, but it may be modified easily to be variable displacement. To obtain such functionality one need to synchronously shift the cam slot and the regulating partition. Moving the regulating partition closer to the bottom of an annular slot makes the slide valves to be less pulled out from the rotor. Smaller part of the slide valve will work as a displacer. Thus, the transferred volume of the fluid between two adjacent displacers becomes lower and the total pump's displacement, consequently, reduces. Moving the partition further from the bottom of an annular slot leads to increasing of the pumping chamber volume and the displacement too.

It is possible to use any kind of rods to control the cam slot and he regulating partition. Such a rod may be connected with any kind of drive on any side of the housing. Usually, the hydraulic control is used to suppress hydraulic forces acting on the mechanical controls. An outstanding feature of this pump is a balanced control, so there's no need in external power drive for this purpose. The result is an easily adjusted simple control system, with small timings.

It is the only one variant of the design presented in this paper. Nevertheless, plenty of specific modifications for any purposes may exist.

One of the modifications comprises two annular slots at the opposite ends of the rotor and two sets of the partitions. Every end of the rotor has an annular slot with the partitions and it works as a separate "sub-pump". When the displacements of the "sub-pumps" are equal, the pump's displacement as a whole is a zero. Machines just transfer liquid inside the housing from one side to the other without any valuable work being done. When the displacement of one "sub-pump" equals zero, and the other one is at its maximum, the overall displacement of the pump is also reaches its maximum. Since the displacement at the opposite end becomes zero, the flow of the working fluid reverses.

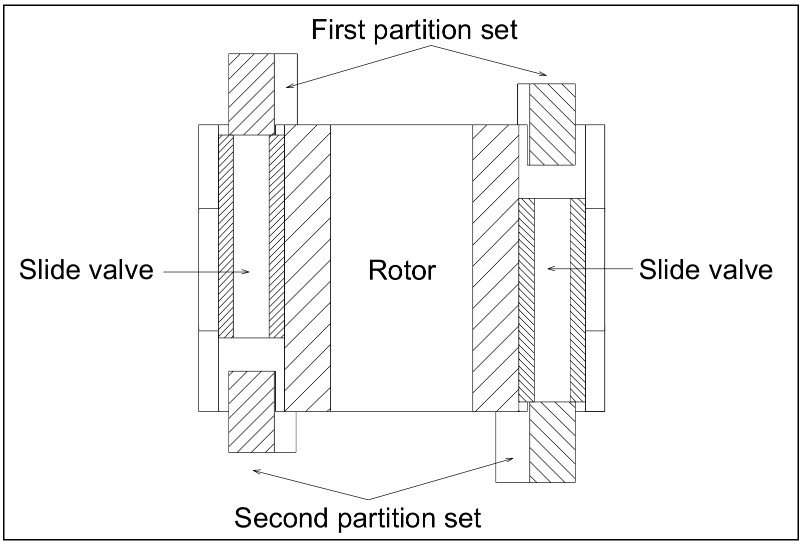

Figure 8: Reversible pump

Another design assumes that two or more pumping chambers locate in the annular slot at the end of the rotor. Using such a multi-chamber rotor one may produce a high torque hydraulic motor. The total torque will be multiplied by the number of the pumping chambers.

The control system of the pump, defining the mutual axial movements of the slide valves, may be located inside the rotor, providing a light and a compact device.

The bearings may be mounted both outside and inside the rotor, allowing the modification of the dimensions and a wide range of possible applications of the machine.

3 ENHANCEMENTS IN OPERATING PARAMETERS AND POSSIBLE APPLICATIONS

In the previous section we focused on the design of the new pump and motor. Several samples were produced for testing purposes. Technical details varied from item to item, but the basic principles kept unchanged. Despite the mentioned differences among the samples, a few comparable advantages were revealed, which were common to both the vane and piston pumps and motors:

- High volumetric efficiency in the wide range of the working fluid pressure up to 30 MPa
- Steady displacement and pulseless output flow
- Low noise emissions
- Possibility to manufacture components from polymers, preserving fine operating conditions
- Fine operating parameters using water as a fluid
- Resistance to the “hydraulic hammer”
- Manufacturability and technological simplicity

Later, we will review abovementioned features in details.

3.1 High volumetric efficiency in a wide variety of working pressures and speeds of rotation

1. Specific design of the hydraulic machine allows balancing of the elements against the fluid pressure.
2. Operating components, displacing the working fluid (slide valves) are stiffly fixed in the pumping chamber and they have cylindrical shape, which is the firmest.
3. The pumping chamber by itself is located at the end of the cylindrical rotor and may have walls (undergo the bending forces) of almost any predefined width.
4. All sliding seals under the load have flat sliding profiles. Since the seal elements are mutually movable, the wear and heating irregularities are compensated.

The features possessed by this kind of vane machines permit the area of operating conditions that were previously exclusive to the radial and axial piston ones in the terms of pressure, while getting fine volumetric efficiency values.

The results of the volumetric efficiency measurements are provided in Table 1.

3.2 Steady volumetric displacement and uniform output flow

The main advantage of the presented pump and motor is an absolutely pulseless output. Fluid displacement (Figure 5 and 9) is caused by the sides of the slide valves, protruded into the annular slot, which forms the pumping chamber inside the rotor. In the process of the fluid displacement, the slide valves move along the surface of the regulating partition at an equal distance to the bottom of the annular slot. Since that, the slide valves are immovable in an axial direction, and while displacing the fluid their lateral surface area remains constant.

Table 1: Volumetric efficiency measurements

	5 MPa	15 MPa	27 MPa
500 rpm	0,98	0,91	0,80
1000 rpm	0,99	0,95	0,88
1500 rpm	0,99	0,96	0,92
2000 rpm	0,99	0,97	0,94
2500 rpm	0,99	0,98	0,95
3000 rpm	0,99	0,98	0,96

Due to the invariable area of the pumping chamber in the transient zone, the displaced volume is proportional to the angle of rotation of the rotor. Then, in case of the constant angular speed of the rotor, the pump possesses an absolutely uniform and steady volumetric displacement. It is a key point of the differences between the present pump and commercially available models of positive displacement pumps, where the dependence of the displaced volume is not a linear function of the angle of rotation of the rotor.

Also, it should be mentioned, that the interference of the axial slide valves movement on the volumetric displacement is neglected by connecting the cavities in the channels of the rotor at the ends of the slide valves with the cavities of the pumping chamber.

The axial movement of the slide valve appears when the slide valve comes from the rotor to the annular slot. The volume of fluid displaced in an axial direction by a slide valve passes through the channel in the slide valve to the area 2. When the slide valve moves back into the rotor, the same amount of fluid is transferred from the area 2 back to the injection area. Recesses on the distributing member connect channels of the rotor under the equal fluid pressure (high or low). Both an axial movement and volume of the slide valve do not interfere with the overall volumetric displacement. Areas 1 and 2 take part in the fluid transfer—one of the areas is a closed volume between two adjacent slide valves; another one—volume of the channels and cavities at the ends of the slide valves.

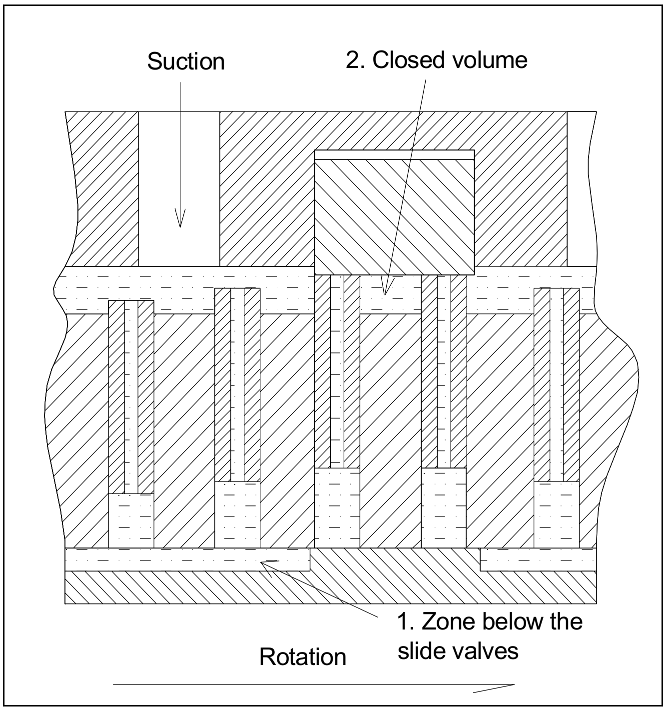

Figure 9: Slide valve volume interference compensation

Two transitional zones compensate operation of each other and with help of the recesses in the distributing member the pump has absolutely smooth displacement, which is only defined by the area of the annular slot in the rotor and the depth of the regulating partition in the annular slot.

This feature allows using this pump as a precise batcher for sensitive hydro-mechanical control systems. Also, the stability of the flow significantly reduces the pulsations in the high pressure hydraulic lines.

3.3 Low noise emissions

The absence of the irregularities of the displacement eliminates one of the significant noise sources. The noise measurements of the experimental 25 cc pump were conducted. The intensity of the noise emissions was obtained without help of an anechoic chamber. No preconditioned anti-ambient and anechoic special rooms were used in the testing. Nevertheless, the sound pressure level was 64 dB(A) for pressure 20 MPa, and the speed of 2500 rpm with maximal flow. Usually, in hemi-anechoic chamber the sound pressure level is less for 2–4 dB(A). So the fair sound intensity evaluation is about 60 dB(A).

Steady input flow and uniform output transfer leave the fluid compression as the main factor of the fluid-borne noise when increasing the level of pressure. But the steady transitional zone of the working fluid, restricted between two adjacent slide valves moving along the regulating partition, allows smooth increasing of the pressure in the transferring closed volume. When the amount of slide valves simultaneously moving along the regulating partition is increased or the transfer of the fluid between the high pressure areas and zones of intermediate pressure through the bumping chains is organized, the compression of the fluid in the closed transitional volume arises. Smooth displacement of the precompressed in the steady transitional zone fluid results in an additional reduction of the noise.

3.4 Polymer components preserving operating parameters

The features of the design, mentioned describing the high volumetric efficiency:

- Discharging of the rotor and slide valves from the pressure forces
- Stiff fixation of the slide valves in the process of the displacement
- Adaptation of the seals to heat deformations and wearing

They reduce material requirements for stiffness of the main pump components, resulting in hydraulic machines of this type made of the polymers (e.g. polyethylene, Teflon®, etc.), producing pressures in the range of 1–10 MPa. Additional reinforcing steel members allow significant increasing of the pressure parameters. Taking into account steady displacement, the batcher-pumps for any kind of working fluid (aggressive acids and alkalis) may be constructed choosing proper materials.

The overall weight of the plastic pump is 5 to 6 times lower then of its competitor's made in the steel.

We have constructed and tested two 25 cc pumps implemented in Teflon® and polyamide. The Teflon® pump is capable of working with any kind of fluid, but it is limited to the working pressure of 1 MPa. It is mainly assumed as an ideal batcher-pump for chemical and food industry.

Polyamide sample have been tested to work with water and oil with pressures up to 10 MPa.

3.5 Water as a working fluid

The main advantages of the water as a working fluid are of common knowledge in hydraulics:

- Lower expenses on pumps and their service
- Reduction of the operational risk and insurance fees caused by non-toxicity and incombustibility of the water
- Environmental impacts elimination during working fluid releases
- End-product contamination risks becomes lower during releases in industrial hydraulic systems
- Water accessibility
- Energetic losses for fluid compression elimination due to small water fluid bulk modulus
- Hydraulic line losses compensation caused by low viscosity of the water
- Stable operation of hydraulic systems (water viscosity value in the range of temperatures Δt=50ºC and pressures Δp=0.1–100 MPa varies by a factor of three only, while the oil viscosity is subject to change for 2 orders in the same range of the conditions)

Problems of the water hydraulics are also widely known, thus preventing it from massive industrial distribution:

- More leakage cased by low viscosity
- Wearing and damage of hydraulic components due to high probability of cavitation and turbulence in water flows in comparison to oil ones
- Aggressive corrosive activity of the water relative to available metallic materials
- Low lubricating properties of water
- Hydraulic hammer amplification in water systems

An opportunity to utilize polymer and composite material components in the presented pump resolves problems of corrosion and lubrication. Polyamide 25 cc pump works in the range of speeds of 200–2500 rpm, giving up to 10 MPa. The adaptive seals provide an opportunity to obtain reasonable volumetric efficiency, thus ensuring that the presented design overcomes problems with water leakages.

3.6 Pressure sustainability to the returning pulses

The hydraulic hammer sustainability becomes more important in terms of water hydraulics and special applications.

The water hydraulics is a promising area of industrial hydraulics. Water hydraulic systems are environmentally-friendly and have no fire risk.

Special applications such as mining equipment are widely utilized in industrial applications. Oil-based hydraulic components are prohibited in mining due to the threat of inflaming. A special water mixture is in use for hydraulic instruments and equipment. Axial piston pumps and vane pumps successfully operate with such kind of fluids, but they provide no resistance to the hydraulic hammer caused, for example, by loading the hydraulic system with a boring machine. Gear pumps and motors cope with the returning pulses of pressure, but they can't afford stable operation with water mixtures.

The presenting pump and motor is capable of working on the water mixture as a fluid and is resistant to returning pulses of pressure. It is obvious from Figure 1 that the slide valves never move relative to the rotor under the pressure, since they are stiffly fixed in the channels of the rotor by semicircular recesses (shown on Figure 1). The hydraulic forces don't act on the cam slot or another parts and components of the pump, which may be corrupted by pressure, thus the only parts of the pump being undergo the hydraulic load, are slide valves, rotor and bearings of the rotor and input shaft. These parts may be easily manufactured stiff and rigid.

3.7 Manufacturability and easy service

The design of the developed pump is obvious. Cylindrical shape of the slide valves and their fixation in the rotor in case of displacement endures the requirements for cleanliness of the channels in the rotor and the slide valves by themselves. It also simplifies assembling and disassembling the pump. The most critical parameters of manufacturing are the gaps between the elements of sliding seals and wear-resistance.

All sliding seals operating under the load have flat sliding surfaces and the components are mutually movable in order to compensate wear and heating irregularities.

As a result, the most important operation of the seals adjustment is a flat milling of the rotor's ends, also the end seals. This operation has no particular difficulties during industrial manufacturing.

Mutual axial mobility of all the elements, being in a loaded joint sliding connection (rotor and slide valves from one hand and partitions with end seals from the other) partly compensates the total wearing and endures requirements for special hard surface treatment.

Thus, the expenses of introduction of the pump in the industry would be no more then those of the vane or axial piston pumps.

3.8 Applications

Industrial and mobile applications of the presented pump are at least of the same diversity as for axial-piston and vane pumps and motors. The pump has similar parameters such as maximal and average pressure, top speed, applicable working fluids, etc. The range of available speeds is up to 5000 rpm, pressure is limited by 42 MPa, at that, the stability of the displacement and the noise level are better then those of the vane pumps.

There are no restrictions on the types of the working fluids—both water and water mixtures are possible.

Another branch of promising applications is the batcher-pumps for aggressively corroding fluids. The combination of stability of the flow with acceptance of plastic components permits to produce precise batcher systems for any applications in chemical, pharmaceutical and food industry.

Some of the areas of possible applications are not so obvious, as mentioned above. The aerospace industry is one of the examples. This area feels lack of the fuel pumps steadily and precisely feeding the fuel to the turbine or another consumer. Developers use special means of elimination of the fluid pulsations in the fuel lines. Such fuel pumps cost up to dozens of thousands dollars and are implemented as massive and heavy devices, while the weight and the dimensions are the crucial parameters of aerospace industry. Our development doesn't need to be accompanied with any additional systems, since that, low weights and small expenses may be easily reached.

Market of the vane and axial piston pumps is broad enough. The total production of the axial piston and vane pumps on the US market reached the level of 2 million items with a total cost of 1 billion USD in 2000. This value slightly reduced by 2002.

We suppose that in a particular industry using axial piston and vane pumps the presented system is supposed to work well and its advantages are obvious:

- Precision and speed of hydro-mechanical control systems will grow

- Reliability of the hydraulic systems will be increased due to low pulsations, damaging pipes and joints
- The overall noise emissions from the hydraulic systems will reduce
- Areas of utilization will spread on account of resistance to hydraulic hammer

4 CONCLUSIONS

The pump presented in the article combines all the advantages of the vane and axial piston pumps and motors, but also has doubtless enhancements in comparison to modern pumps—low noise levels, absence of displacement pulsations and the technological simplicity leading to quick installation for production. The design of the machine opens opportunities for the wide gamma of polymers and composite materials promising successful operation with water and non traditional working fluids.

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