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Research and Optimization of Designs of External Gear Pumps

Berg A.S.[1], Reshetnikova O.S.[1*], Krasnov A.O.[1]

Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan
*corresponding author

Annotation. Gear hydraulic machines are a type of volumetric hydraulic machines that are widely used in various industries. Their main purpose is to convert mechanical rotational energy into hydraulic energy (pumps) or vice versa (hydraulic motors). The performance of gear hydraulic machines depends on tribological properties such as hardness, wear resistance, strength, viscosity, surface roughness, lubricity. This article discusses the problems of gear pumps, namely their tribological properties associated with designs and materials of manufacture. There are several basic designs of gear pumps, each of which has its own characteristics, advantages and disadvantages. They ensure stable operation of systems that require fluid transfer with constant flow and pressure. However, their performance characteristics largely depend on the tribological properties of working elements such as gears, bearings and sealing devices. Wear and damage to these elements can significantly reduce the efficiency of the pump, lead to its breakdown or increased energy consumption. Various designs of gear pumps are considered, their characteristics, operating principles, liquid flows, advantages and disadvantages of various pump designs are studied.

Key words: gear pumps, design, characteristics, fluid flow, tribological properties

Introduction

Tribological properties of gear pumps refer to the characteristics associated with friction, wear and lubrication in mechanisms that ensure their durability, operating efficiency and reliability. These properties are especially important for gear pumps, as they operate at high pressures and are often subject to intense friction between working parts.

Table 1. Factors influencing tribological properties and methods of their improvement

Factors Affecting Tribological Properties	Description	Reasons	Methods of increasing
Friction	Resistance to movement between surfaces. In gears, it occurs when they interact.	Reduced friction improves efficiency, reduces overheating and wear.	Use of lubricants, improvement of surface treatment, coatings.
Wear	Resistance of materials to damage during prolonged contact.	Minimizing wear increases service life and stabilizes pump operation.	Use of wear-resistant materials, improvement of surface quality.
Lubrication	Friction protection using liquid or solid lubricants.	Proper lubrication reduces friction and wear, improving operating efficiency.	Use of synthetic oils, additives, nanomaterials for coating.
Service life	The time during which the pump operates efficiently without significant breakdowns.	Improving tribological properties extends service life and reduces repair costs.	Improving the quality of lubrication and coating, optimizing operating conditions.
Efficiency (Coefficient of Performance)	Pump efficiency, the ratio of useful work to energy expenditure.	Reducing friction and wear improves efficiency, reducing energy loss and increasing productivity.	Reduced friction and increased precision in machining of working parts.
Resistance to loads	The ability of the pump to operate under high pressure and loads.	Improved tribological properties help the pump operate under extreme conditions.	Use of stronger materials, improved lubrication and coating.
Leaks	Fluid loss through gaps between teeth and other parts of the pump.	Reducing leaks improves operating stability and productivity.	Elimination of design defects, improvement of tightness and accuracy.
Performance stability	Maintaining stable pump operation without significant fluctuations in efficiency.	Improving tribological properties contributes to stable and efficient operation.	Use of improved lubricants, improved surface treatment of teeth.

The factors influencing tribological properties in this study are friction, leakage and performance stability.

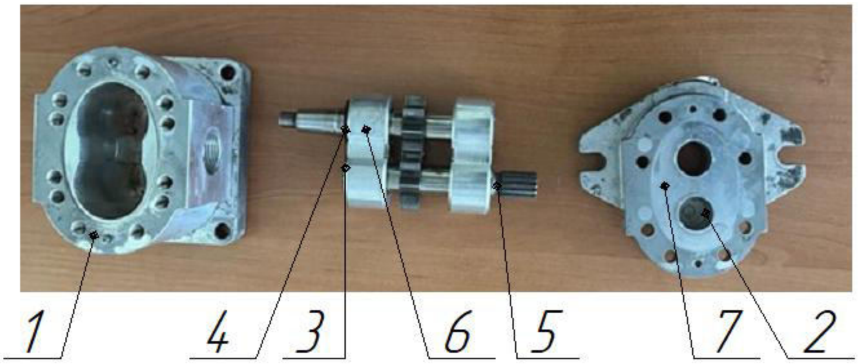
Gear pumps are widely used in many industries due to their reliability, simplicity of design, compactness and efficiency [1, 2]. Gear pumps are positive displacement pumps. Gear pumps are typically used to pump high viscosity liquids: fuel oils, petroleum, lubricating oils, paints, acids and alkalis, alcohols and solvents, the rotation is transmitted by the driving gear [3 – 6]. The rotation of the driven gear is produced by contact with the driving gear, the liquid is transported from the suction side to the discharge side of the pump (from the inlet channel to the outlet channel) [7]. A gear pump moves liquid by repeatedly enclosing a fixed volume in interconnected gears, transmitting it mechanically to ensure a smooth, pulse-free flow proportional to the rotation speed of its gears [8]. In this case, tight contact is formed between the teeth, as a result of which the reverse transfer of liquid from the discharge cavity to the suction cavity is impossible.

The choice of the object of study is determined by the following factors:

– these units have a set of basic parts and components that is very common in mechanical engineering practice, namely: shafts, gears, bearing supports, friction units (Figure 1);

– gear pumps are characterized by a wide range of operating modes, which means a large variety of different combinations of loads on the machine parts of the unit, up to the maximum possible;

– the practice of operating gear pumps in the CIS countries and abroad, as well as the analysis of foreign and domestic literary publications, shows that they experience premature failures.



1 - housing; 2 - bearing supports; 3 - seals; 4 - thrust bearings; 5 - driving pinion shaft; 6 - driven pinion shaft; 7 - housing cover.

Fig. 1. - Typical design components of gear pump

Reliability and durability of units are primarily determined by the loaded state of their constituent structural elements, parts, and assemblies. At present, methods for calculating the loaded state of parts and assemblies for various purposes have been developed quite deeply and are supported by a wide range of normative and technical documentation, including: GOSTs, industry standards, methods, etc., allowing you to set the required service life for most units and mechanisms containing typical machine parts: shafts, gears, bearing supports, friction units, etc..

1. Methodology

Gear pumps are mechanisms consisting of two gears in engagement, placed in a tightly enclosing housing. The pump operates on the principle of transferring liquid by working chambers from the suction cavity to the opposite discharge cavity and then squeezing the liquid out of the working chambers of the displacer.

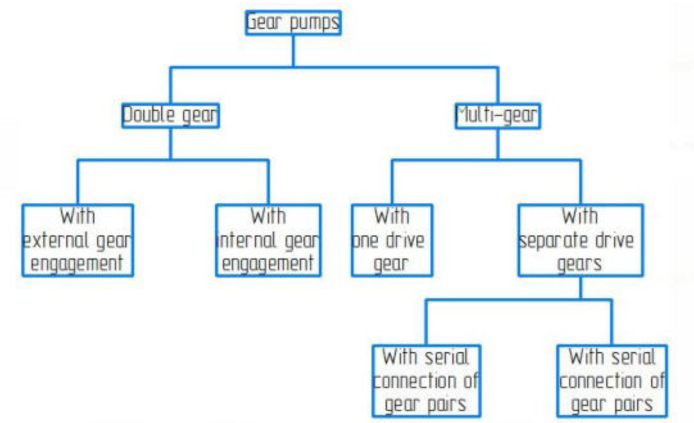
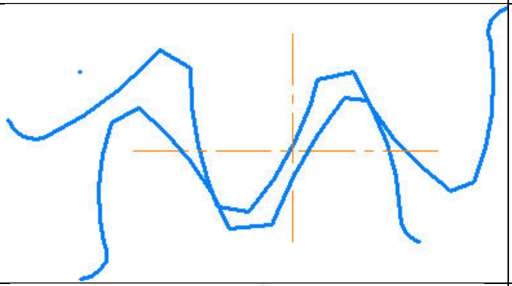
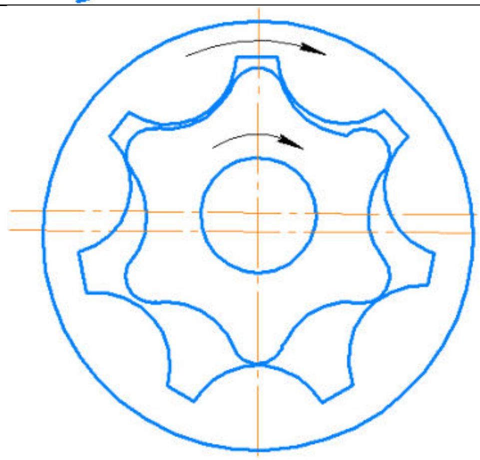
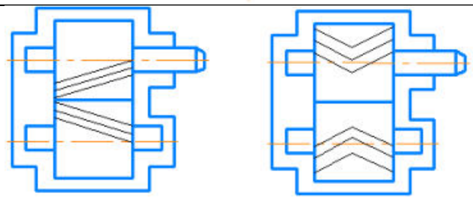


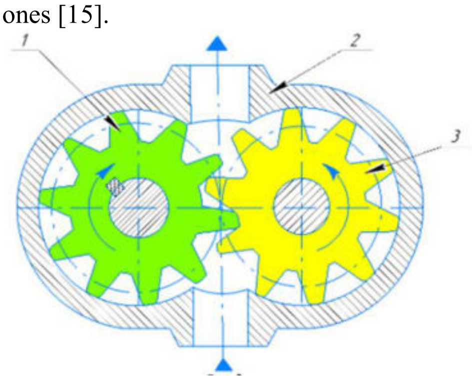
Fig. 2. - Classification of gear pumps

In gear pumps, the working chamber is the cavity between adjacent gear teeth, and the displacer is the gear tooth. Depending on the need, the following designs of gear pumps are used, each of which has its own characteristics, advantages and disadvantages (Figure 2, Table 2).

Table 2. Types of gear pump designs, their advantages and disadvantages.

Pump type	Scheme	Advantages	Flaws
External Gear Pumps: These pumps use two counter-rotating gears to pump fluid, which is trapped between the gear teeth and transferred through the pump body.		Simple design, high reliability, wide range of liquids	Not suitable for use with liquids containing solid particles as they may cause wear on gears. Require precision manufacturing to ensure stable operation. Limited in pressure range (usually no more than 20-30 bar).
Internal Gear Pumps: One of the gear elements (internal gear) is placed inside the outer gear, and the fluid is captured between the teeth and transferred through the pump. This is a type of design where the gears are not driven in one axis, which helps reduce flow pulsations.		– High stability of outlet pressure and low flow pulsations. – Higher working pressure than external gears. – Higher flow density and greater productivity.	- More complex and expensive design. – High demands on the precision of gear manufacturing. – Reduced durability when working with contaminated liquids.
Hexagonal Tooth Pumps: These pumps have gears with teeth that are angled (hexagonal teeth). This reduces flow pulsations and improves power transmission.		Reduced flow pulsations. Higher efficiency and less friction than conventional gear pumps. Suitable for working with viscous liquids.	Complex design and high demands on manufacturing precision. May require more expensive materials for durability. There may be problems with tightness.

There are several designs of gear pumps. External gear pumps come in various configurations, distinguished by the number and arrangement of gears. Some designs feature two (Figure 3), three, or four gears in a line, while others have three or four gears surrounding a central drive gear [14]. This simplifies production, maintenance and repair. Such designs provide a high efficiency due to minimal friction losses. They can work with various types of liquids, including viscous and abrasive ones [15].



1 - driving gear; 2 - housing; 3 - driven gear (displacer)

Fig. 3 - Design of a gear pump with two external gears [14]

There are also diagrams of gear pumps with three gears located on one axis (Figure 4).

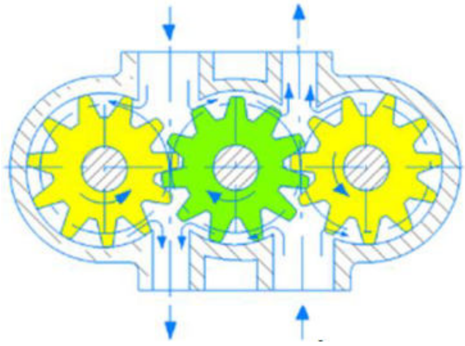
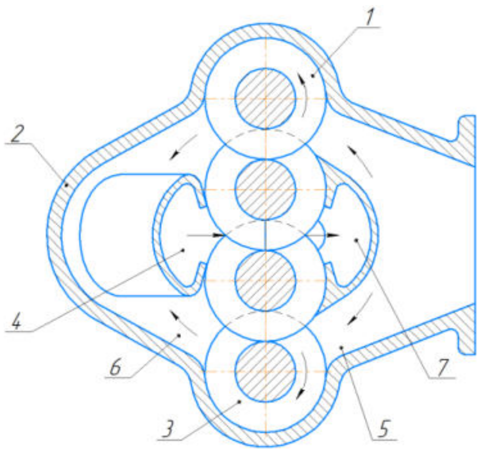


Fig. 4. - Three-gear pump with external gearing [14]

Gear pumps with external engagement and three gears are advisable to use in hydraulic drives where it is necessary to have two hydraulic lines with independent pressure, since this pump has two inlet and outlet openings, that is, one pump can provide the necessary fluid flow in two circuits at once [15].

There are designs with 4 gears located on one axis (Figure 5). Such a design increases the amount of energy that the pump consumes to pump a certain volume of liquid.



1 – drive gear; 2 – housing; 3 – plane; 4, 5 – suction channels; 6, 7 – discharge channels

Fig. 5. - Four-gear pump with external engagement with gears on one axis [9]

There are also known designs with six gear wheels, three on each driven and drive shaft (Figure 6). In such a pump, several gears are located on one drive shaft, each of which rotates the driven gear on the drive shaft. The suction and discharge lines of such pumps are usually separated, but can also be combined in a special design. Multistage pumps are used to increase the pressure or feed the unit.

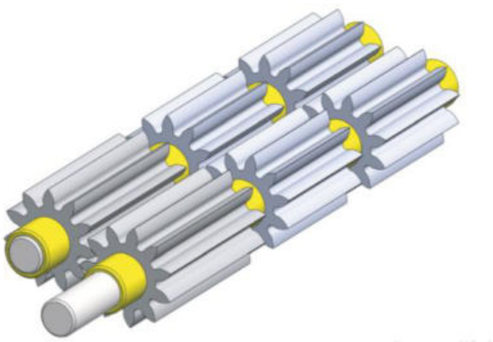


Fig. 6. - Driven and driven shaft of the pump under consideration of multistage gear pumps with external engagement [10]

To increase pressure, gear pairs are installed in series, to increase productivity (feed) - in parallel. By installing the second stage in series, we can almost double the pressure at the pump outlet. However, this will lead to a decrease in the efficiency of the machine, since the feed of each previous stage must be greater than the required feed of the subsequent stage to ensure a reliable supply of power. To get rid of excess liquid at the outlet of each stage, an overflow valve is used.

To increase productivity, multi-gear pumps with three or more gears placed around a central axis are used.

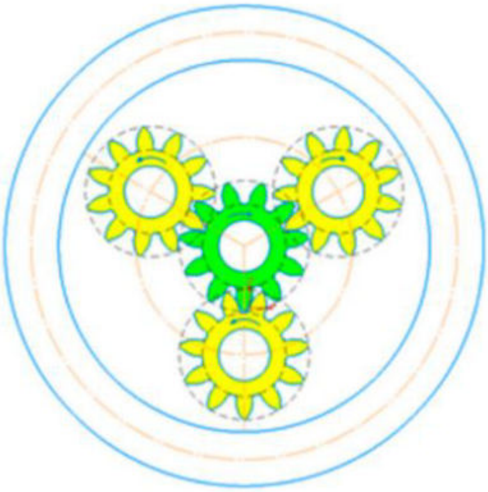


Fig. 7. - Multi-gear pump located around a central axis [11]

Another common type of pump is centrifugal pumps due to their simple design, high performance and ability to pump large volumes of liquid. However, like any mechanism, they have their drawbacks: sensitivity to cavitation, low efficiency, etc. Table 3 shows comparative characteristics of the use of a gear pump.

Table 3. Comparative characteristics of a gear pump and a centrifugal pump.

Characteristic	Centrifugal pump	Gear pump
Operating principle	Transfer of energy to a liquid by centrifugal forces	Movement of liquid by engagement of gears
Performance	High at high costs	High at low cost
Pressure	Low and medium	High
Pulsations	Tall	Low
Efficiency	Depends on the operating mode	High
Self-priming	No	Limited
Viscosity of the pumped liquid	Low and medium	Tall
Dimensions	Big ones	Compact

In order to improve tribological properties, a new design of a multi-gear pump with 3 or more driven gears placed around the central axis is proposed.

Pressure pulsation during fluid delivery is an integral characteristic of a gear pump with external engagement [12]. Flow pulsation, i.e. delivery occurs in portions equal to the volume of the chambers. The trapped volume, which they try to get rid of using the unloading grooves of the follower drive and other things, leads to sharp pressure drops in the tooth engagement zone. Pressure surges generate increased noise and vibration [13]. Flow pulsation can be represented graphically (Figure 8).

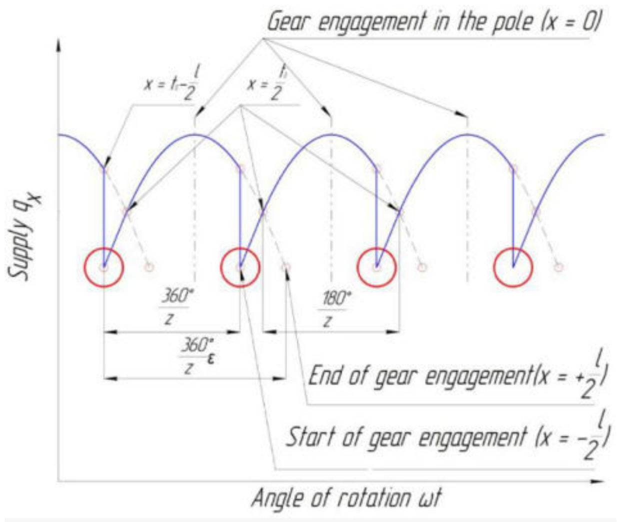
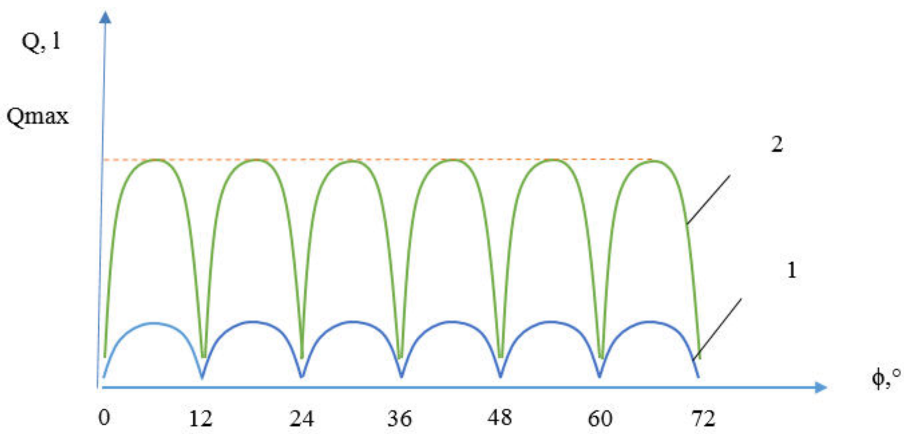


Fig. 8. - Flow pulsation graph [15, 16]

The study will examine the kinematic systems of multi-gear pumps, which is the main axis of this proposal, as well as its idea. The basis for the final optimization of the prototype and the creation of a useful mathematical apparatus from the industrial point of view, capable of accurately selecting pumps for given output parameters, will be the shape of the tooth and the dimensions of the pump parts.

2. Results and Discussions

During the research work, the parameters selected will be such parameters as the shape of the tooth and the dimensions of the pump parts, which will form the basis for the final optimization of the prototype and the creation of a useful mathematical apparatus from the industrial point of view, capable of accurately selecting pumps for the specified output parameters. The distribution of the same stresses that are used in the classic gear pump will allow the use of less critical materials or the application of greater forces, which will further popularize these designs.



1 – supply of fluid for engagement 1; 2 – supply of fluid for engagement 1

Fig. 9. - Fluid flow pulsation graph

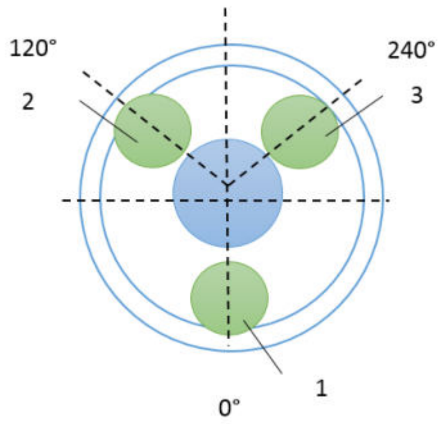
As can be seen from the graph (Figure 9), the feedgear pump is uneven, since simultaneously volumes (equal to the volume of the depressions) are forced into the system, limited by the parameters of the teeth and the housing.

It is known that the reduction of pressure unevenness depends on the number of gear teeth and the angle of engagement of the teeth. The greater the number of teeth, the less the unevenness of the feed, but the less the feed itself, which is undesirable.

The number of teeth of the drive gear was taken to be z1 = 30. Then $\phi = 360/30 = 12°$ is the angle of rotation of the tooth at which the displacement of the moved volume of liquid by the cavity of the tooth occurs.

- for three driven gears the offset of the axes is equal to:

$\alpha = \phi/3 = 12°/3 = 4°$. Consequently, the axes of the driven gears are shifted by angles of 4° and 8°, respectively (Figures 10, 11).



1, 2, 3 – driven gears

Fig. 10. - 4 gear pump

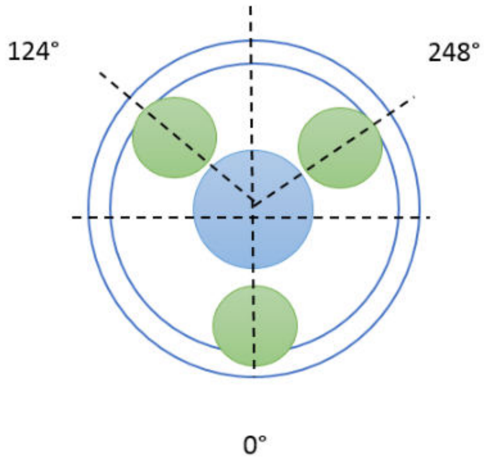


Fig. 11. - 4-x gear pump with offset driven gear axes

Advantages of the three-gear pump design:

- in such a design, the load on each of the gears is distributed more evenly. In a classic two-gear pump, the entire load falls on two gears (driven and leading), which can lead to their rapid wear. When adding a third gear, the load is distributed between three teeth, which reduces the mechanical stress on each of them;

- the presence of three driven gears increases the number of working cycles per unit of time. This can increase the pump's productivity, as the number of captured and pumped portions of liquid per one shaft revolution increases. For pumps designed for high volumes of pumped liquids, this significantly increases the efficiency of operation;

- pumps with three driven gears distribute the fluid flow more evenly, which reduces pressure pulsations. Pulsations can cause additional vibrations and noise, as well as unpredictable system behavior, which is important for precise or sensitive installations;

- the load is distributed evenly and the teeth contact is more even, the pump will wear out more slowly than a pump with fewer driven gears. This extends the life of the unit, which is important in heavy-duty applications such as oil or chemical fluid pumps;

- three-gear driven pumps are less likely to experience sudden pressure surges and, as a result, have reduced vibration and noise, especially at high speeds. This makes them more suitable for applications where low noise levels are required.

By using multiple driven gears, fluid flow parameters can be controlled more precisely, which is especially important for precision systems such as hydraulic and lubrication systems where it is important to maintain stable pressure and fluid flow.

Another important issue when designing a gear pump is the correct choice of material, which significantly affects the durability, efficiency and cost of the equipment. The optimal material must have a set of properties that ensure reliable operation of the pump under specific operating conditions.

Basic requirements for materials for pump housings:

– the material must be resistant to the effects of the pumped liquid (water, acids, alkalis, etc.);

- the housing must withstand internal pressure and mechanical loads.
– the material must be resistant to abrasive wear, especially when pumping solids;
– good thermal conductivity facilitates heat removal from the working parts of the pump;
– the material should be easy to process using traditional methods (casting, machining).

Table 4 presents standard materials of construction for gear pumps.

Table 4. Standard materials for gear pump construction.

Material	Example of construction	Advantages and disadvantages
Cast iron	 [17]	– Widely used due to its low cost and good casting properties. – Has sufficient strength and corrosion resistance in fresh water and neutral environments. – Not recommended for aggressive environments.
Steel	 [18]	– Used for the production of pump bodies operating in more aggressive environments or at high pressures. – Alloy steels have increased strength, corrosion resistance and wear resistance.
Bronze	 [19]	Used for pump bodies handling sea water or other aggressive media. – Has high corrosion resistance and good antifriction properties.
Brass	 [20]	It is used for the production of small pumps and parts requiring high corrosion resistance.
Polymer materials	 [21]	Used for the production of chemical pump bodies and pumps for the food industry. They have high corrosion resistance, are lightweight and low cost.

An analysis of standard materials for gear pump designs and previously conducted studies [21] showed that the use of aluminum will reduce the weight of a multi-gear pump without reducing the strength properties of the structure.

On the chart Figure 12 It is clear that the greatest weight reduction (16%) is observed in polycarbonate, followed by aluminum with 14% and cast iron with 12%. Although polycarbonate shows the greatest weight savings, the choice of material should take into account not only this parameter, but also other factors such as strength, manufacturability and cost. Aluminum, as the optimal material for the manufacture of pump parts, is proposed based on the best balance between weight and strength, as well as taking into account the technological aspects of production.

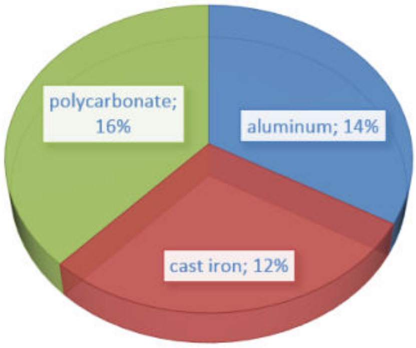


Fig. 12. - Histogram of the dependence of weight change depending on the selected material

This graph highlights the importance of material selection and design optimization to achieve lighter, more efficient pumps [11, 22 - 24].

Conclusions

An analysis of gear pump designs and possible materials for their manufacture showed that the design of a gear pump with three driven gears around a central axis is a structurally improved version of a classic gear pump. This solution allows for increased productivity, reduced pulsation, reduced wear and extended service life of the device, and also ensures more stable and uniform operation of the system. Such pumps are especially effective in cases where high productivity and durability are required, as well as reduced vibration and noise. This makes them suitable for use in more complex and demanding operating conditions. Further, a study and modeling aimed at the tooth profile and fluid flow in the pump will also be carried out. The use of aluminum for the design of a multi-gear pump will reduce the weight of the structure, material consumption and, as a result, economic costs.

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Information of the authors

Berg Alexandra Sergeevna, PhD, assistant, Abylkas Saginov Karaganda Technical University
e-mail: kibeko_1995@mail.ru

Reshetnikova Olga Stasisovna, doctor PhD, senior lecturer, Abylkas Saginov Karaganda Technical University
e-mail: olga.reshetnikova.80@mail.ru

Krasnov Alexandr Olegovich, Master's student, Abylkas Saginov Karaganda Technical University
e-mail: alexandr.kr.05.07.01@gmail.com