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INVESTIGATION OF VELOCITY MODES OF LIQUID FLOWS AROUND ELECTRIC MOTORS OF SUBMERSIBLE PUMPS

Abstract. Water supply and wastewater disposal are among the industries with intensive use of pumping equipment, the share of electricity consumed by pumps is more than 50% of the total energy consumption. One of the reasons for the decrease in technical and economic indicators of submersible pumping units is the failure of pump motors due to overheating during their operation. In this regard, the substantiation and development of methods of research and calculation of fluid flow parameters around the pump motor, is an urgent scientific and practical task. The aim of the work is to provide conditions of stable cooling of pump motors at which the temperature of electric motor windings will be within permissible limits. To achieve this goal, the task of developing a methodology for modelling the turbulent vortex fluid flow along the electric motor of a submersible pump is solved.

Key words: *: flow velocity, liquid, submersible pump, electric motor, hydrodynamics, design optimisation, efficiency of operation, productivity, energy losses, liquid flow.*

Суасты сорғыларының электр қозғалтқыштарының айналасындағы сұйықтық ағындарының жылдамдық режимдерін зерттеу

Аңдатпа. Сумен жабдықтау және су бұру сорғы жабдықтарын қарқынды пайдаланатын өнеркәсіп салаларына жатады, сорғылар тұтынатын электр энергиясының үлесі жалпы энергия тұтынудың 50%-дан астамын құрайды. Суасты сорғы қондырғылары жұмысының техникалық-экономикалық көрсеткіштерінің төмендеуінің себептерінің бірі сорғылардың Электр қозғалтқыштарының жұмыс процесінде қызып кетуіне байланысты істен шығуы болып табылады. Осыған байланысты сорғы қозғалтқышының айналасындағы сұйықтық ағынының параметрлерін зерттеу және есептеу әдістерін негіздеу және дамыту өзекті ғылыми және практикалық міндет болып табылады. Мақсатқа жету үшін суасты сорғысының электр қозғалтқышы бойымен сұйықтықтың турбулентті құйынды ағынын модельдеу әдісін әзірлеу міндеті шешілуде.

Түйінді сөздер: *дизайнды оңтайландыру, жұмыс тиімділігі, өнімділік, энергия шығыны, сұйықтық ағыны.*

Исследование скоростных режимов потоков жидкости вокруг электродвигателей погружных насосов

Аннотация. Водоснабжение и водоотведение относятся к отраслям промышленности с интенсивным использованием насосного оборудования, доля электроэнергии, потребляемой насосами, составляет более 50% от общего энергопотребления. Одной из причин снижения технико-экономических показателей работы погружных насосных установок является выход из строя электродвигателей насосов из-за перегрева в процессе их работы. В этой связи обоснование и развитие методов исследования и расчета параметров потока жидкости вокруг двигателя насоса является актуальной научной и практической задачей. Для достижения поставленной цели решается задача разработки методики моделирования турбулентного вихревого потока жидкости вдоль электродвигателя погружного насоса.

Ключевые слова: *скорость потока, жидкость, погружной насос, электродвигатель, гидродинамика, оптимизация конструкции, эффективность работы, производительность, течение жидкости.*

Introduction

The overall energy consumption in industries depends in no small measure on the performance of pumping equipment. The efficiency of a pumping station is often lower than the efficiency of the individual pumps installed in the station. The reason for the low energy efficiency is a mis-match in the operating characteristics of the equipment. To improve the efficiency of pumping plants, it is necessary to reduce the operating costs of the pumping equipment [1].

In an electric motor, during high efficiency operation, part of the electrical power input is used for heating. Heating the motor reduces its efficiency, which is often accompanied by power overruns. At the same time, cooling the motor increases the service life of the pump unit. Surface motors have a fan on the shaft, which cools the motor with air flow when the motor is switched on. Motors for borehole pumps have a different design, and they do not have a fan, but they also need to be cooled by any means during operation. When the motor is working in the well, usually the water temperature ranges from 8–14°C, and it is this water that will cool the motor [2]. Due to improper selection and operation of the pumping unit in some wells the motors are cooled normally, and in others they fail due to overheating. In surface motors, a fan creates sufficient airflow to extract the heat generated by the motor during operation. Similarly, well motors are cooled by the flow of the pumped fluid. A certain flow velocity around the pumping unit makes it possible to cool and operate the motors normally. In some cases, the fluid flow velocity along the submersible pump motor is not sufficient. In such cases, the liquid flow velocity can be en-sured by means of cooling shrouds. In addition, very often borehole pumps are used to supply water from tanks, cisterns or open ponds, where the use of cooling covers is man-datory. Manufacturers of borehole pumps specify in the technical data the minimum permissible liquid velocity for cooling the motor housing. Some manufacturers also specify the maximum operating time of the motor when the valve is closed [3].

Submersible pumps are used in demanding applications. They are constantly exposed to water pressure, vibration, high temperatures, abrasive particles, etc. Therefore, the pump units are manufactured with a large safety margin, but over time they develop various failures. The main failures of electric submersible pump units and their causes can be divided as follows:

1. Decrease in insulation resistance:

a. mechanical damage to the cable insulation when the submersible pump is lowered, due to violation of the rate of descent of the unit or presence of foreign objects in the well;

b. displacement of current carrying conductors of the ex-tension or main cable running to the check valve, due to poor installation during operation.

2. Infiltration of formation or purge fluid into the motor cavity, frontal part or outlet ends (non-tightness of mechanical seals, tightness failures in the places of current input or flange connection motor – waterproofing), due to vibration or atmospheric precipitation during installation.

3. Motor overheating due to violation of the cooling mode [4, 5].

The considered reasons of failure of electric motor of submersible pumps are connected mainly with its overheating.

Insufficient pump cooling occurs when a small diameter pump is installed in a well with too large a diameter or, even worse, in an open well [6]. When the well diameter is slightly larger than the pump, the water cools the motor housing, protecting it from overheating. It is recommended that the difference between the internal diameter of the borehole and the diameter of the pump should be at least 4 mm and not more than 100 mm. In addition, very often borehole pumps are used to supply water from tanks, cisterns or open ponds, where the use of cooling covers is mandatory. Cooling covers for submersible pumps allow a part of the pumped liquid or external liquid to circulate around the stator housing of the electric motor. In doing so, excess heat is absorbed by forced convection, providing effective cooling of the pump. They provide additional cooling of the motor when the pumped liquid is warm or the pumps have to run continuously. During the operation of a borehole pump, its service life is directly dependent on the cooling of the motor. Therefore, it is very important for the operation of a downhole pump to provide the necessary temperature and rational speed of the turbulent vortex fluid flow along the electric motor of the sub-mersible pump [7].

Research methods

In practice, the surface temperature of some modern pump motors can reach 90°C (194°F). At elevated temperatures, many materials begin to char and become conductive. All materials become brittle from prolonged exposure to elevated temperatures long before charring, easily break down and lose their insulating properties. This process is called thermal ageing [8, 9, 10].

In most modern designs of submersible pumps their water intake part is located above the electric motor. This technical solution ensures high pump performance, but under some conditions (installation of a narrow pump in a well with too large a diameter) it can lead to overheating of the electric motor.

When the electric motor is located above the water intake part of the pump, the entire pump unit is mounted in a casing so that the flowing water cools the electric motor. This solution leads to a reduction of the impeller diameter, which in turn reduces the pump performance.

Increase of productivity can be achieved in a similar way by increasing the speed of rotation of the motor, but increasing the speed of rotation of the electric motor will require an increase in the frequency of the power supply network more than 50 Hz, which in turn prevents the motor speed from exceeding 3000 rpm. Therefore, today the task of eliminating the processes of overheating of submersible pump motors is urgent and in demand [11]. The set task is achieved by the fact that a cooling casing is installed on the upper part of the suction pipe of a submersible pump. When entering the device, the liquid passes close to the motor part, thus increasing the speed of the liquid flow entering the pump, improving the cooling process of the electric motor (Fig. 1.).

It is recommended to install cooling hoods when the cooling of the electric motor is insufficient [12]. This increases the life of the motor. Cooling covers are recommended when:

- the borehole pump is subjected to high thermal loads due to e.g. asymmetrical current consumption, dry running, overloads, high ambient temperatures and poor cooling;

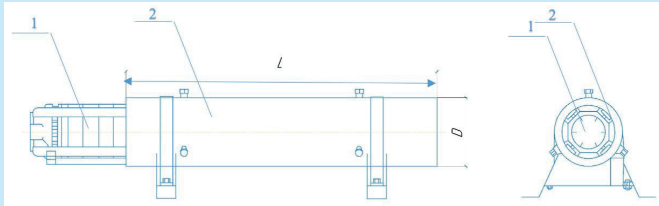


Figure 1. Schematic diagram of the pump unit cooling jack-et: *1 – pump; 2 – cooling jacket.*

Сурет 1. Сорғы қондырғысының салқындатқыш көйлегінің схемасы: *1 – сорғы; 2 – салқындатқыш көйлек.*

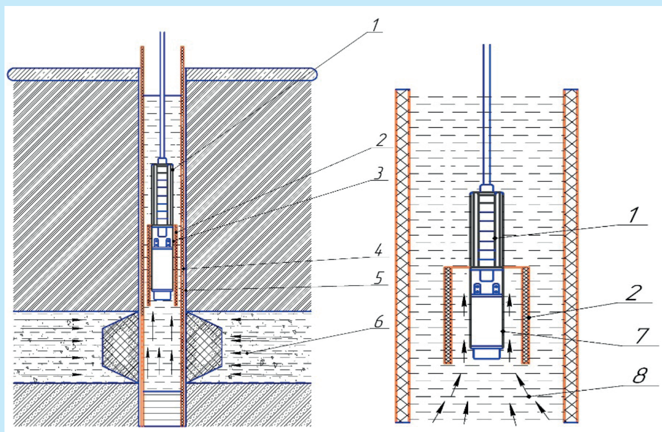
Рис. 1. Принципиальная схема рубашки охлаждения насосного агрегата: *1 – насос; 2 – охлаждающая рубашка.*

- the pump is pumping corrosive liquids, as the corrosion rate doubles when the temperature rises by 10°C.

The discussion of the results

Figure 2 shows the general view of the process well and the principle of operation of the cooling shroud in wells. The device consists of an electric submersible pump unit *(1)*, cooling shroud *(2)*, suction pipe of the submersible electric pump *(3)*, casing *(4)*, process well *(5)*, fluid bed *(6)*, motor part of the submersible pump *(7)* and fluid flow *(8)*. The cooling shroud is attached to the top of the suction pipe, with its length exceeding the length of the pump unit motor by 20–50 cm. A gap of 20–30 mm in diameter is left between the pump unit and the end of the blind pipe.

It is recommended to use a cooling jacket made of PVC material, as this type of material is low cost and lightweight



a) *b)*

Figure 2. General view of the process well: *a – scheme of installation of downhole submersible pump; b – principle of operation of submersible pump with cooling casing.*

Сурет 2. Технологиялық ұңғыманың жалпы түрі: *а – ұңғыма суасты сорғысын орнату схемасы; б – салқындатқыш қаптамасы бар суасты сорғысының жұмыс принципі.*

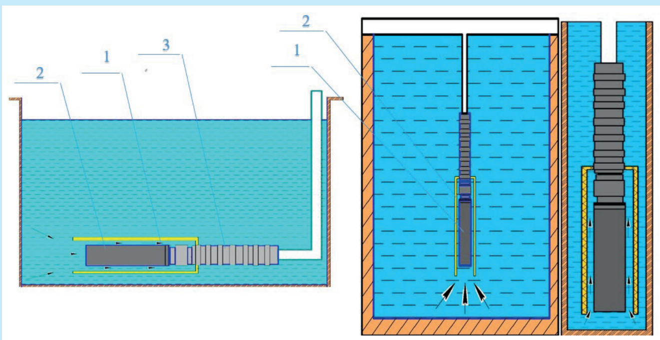
Рис. 2. Общий вид технологической скважины: *а – схема установки скважинного погружного насоса; б – принцип работы погружного насоса с охлаждающим кожухом.*

compared to a stainless steel sheet construction, making it more cost effective.

By using a suction cooling shroud, the motor operates at a reduced temperature and does not overheat during continuous operation. During pump shutdowns, the cooling jacket absorbs residual heat from the motor, thus preventing thermal effects. This prolongs the intervals between the necessary cleaning of the well from mineral crust.

Danger of localised heating of the pump motor, especially in horizontal pump installations and where several units are located close to each other. In such cases, cooling hoods should always be used on the suction side.

Examples of options for installing cooling covers on submersible pumps installed in open water bodies, cisterns, tanks, wells and boreholes with inlets above the suction inlets, where cooling of the submersible pump motor is only provided by free convection, are shown in Figure 3.



a) *b)*

Figure 3. Examples of installation of the cooling jacket for: *a – horizontal installation of the pump; b – vertical installation of the pump: 1 – electric motor; 2 – cooling jacket; 3 – pump.*

Сурет 3. Салқындатқыш күртешені орнату мысалдары: *а – сорғыны көлденең орнату; б – сорғыны тік орнату: 1 – электр қозғалтқышы; 2 – салқындатқыш күрте; 3 – сорғы.*

Рис. 3. Примеры установки рубашки охлаждения для: *а – горизонтальной установки насоса; б – вертикальной установки насоса: 1 – электродвигатель; 2 – рубашка охлаждения; 3 – насос.*

If the flow velocity of the pump motor is less than that specified in the equipment data sheet, the use of cooling covers is mandatory.

The following formula is used to calculate the cooling rate:

$$v = \frac{353 \cdot Q}{D^2 - d^2} \text{ [m/s]},$$

Q – flow rate (minimum pump capacity is required for calculation), m³/h;

D – nominal diameter of the well, mm;

d – nominal diameter of the electric motor, mm.

At carrying out mathematical calculations and experimental works we have chosen 2 types of technological wells (well diameter Dsk = 159 mm and Dsk = 195 mm), 2 types of submersible pumps (USK408/42 pump motor diameter Ddv = 93 mm and URN 6 25/14 pump motor diameter Ddv = 145 mm). As they are frequently used types of equipment at industrial enterprises. The results of the performed calculations are given in table 1.

Table 1

Types of submersible pumps

Кесте 1

Суасты сорғыларының түрлері

Таблица 1

Типы погружных насосов

Flow rate Q, m³/h	Well diameters Dsk, mm	Pump motor diameters Ddv, mm	Suggested diameters of cooling hoods, mm	Flow cooling velocities of motors, m/s
8	159	93	113	0,6
			123	0,43
			133	0,31
			143	0,23
			159	0,19
25	195	145	165	1,42
			170	1,12
			175	0,91
			180	0,77
			185	0,66
			195	0,51

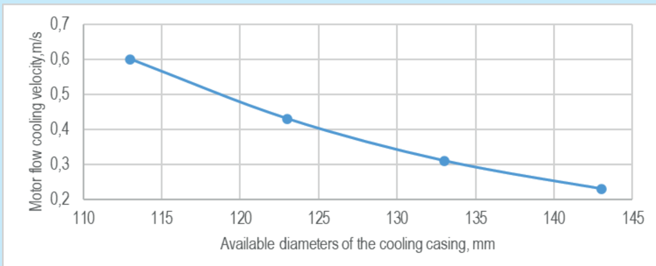


Figure 4. Dependence of change of flow cooling velocities on internal diameters of cooling casings (well diameter Dsk = 159 mm, pump motor diameter Ddv = 93 mm).

Сурет 4. Ағынның салқындату жылдамдығының өзгеруінің салқындатқыш қаптамалардың ішкі диаметрлеріне тәуелділігі (ұңғыманың диаметрі Вск = 159 мм, сорғының электр қозғалтқышының диаметрі Вдв = 93 мм).

Рис. 4. Зависимость изменения скоростей охлаждения потока от внутренних диаметров охлаждающих кожухов (диаметр скважины Dск = 159 мм, диаметр электродвигателя насоса Dдв = 93 мм).

The velocity of the liquid flow around the electric motor should be in the range from 0.15 to 3 m/s to ensure optimum operating conditions for the pump.

On the basis of the obtained data, studies were carried out by modelling the hydrodynamic processes during the operation of the submersible pump and the cooling shroud using the KOMPAS software package (Figure 6).

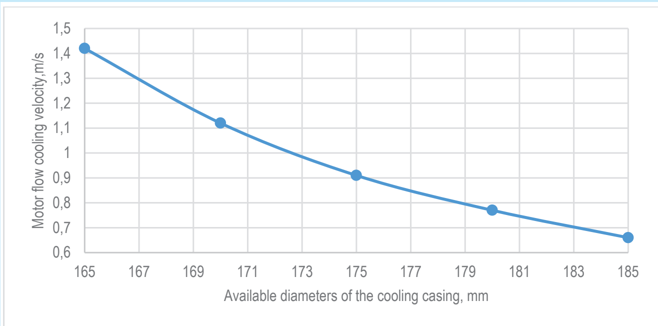
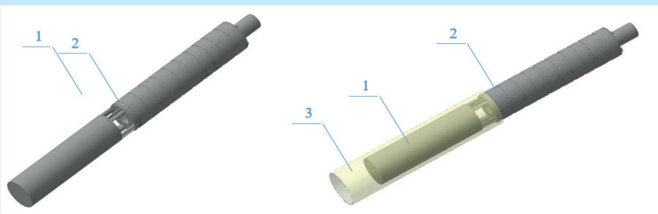


Figure 5. Dependence of flow cooling velocity variation on the internal diameter of the cooling casing (borehole diameter Dsk = 195 mm, pump motor diameter Ddv = 145 mm).
Сурет 5. Ағынның салқындату жылдамдығының өзгеруінің салқындатқыш корпустың ішкі диаметріне тәуелділігі (ұңғыма оқпанының диаметрі Вск = 195 мм, сорғы қозғалтқышының диаметрі Всв = 145 мм).
Рис. 5. Зависимость изменения скорости охлаждения потока от внутреннего диаметра охлаждающего кожуха (диаметр ствола скважины Dск = 195 мм, диаметр двигателя насоса Dдв = 145 мм).



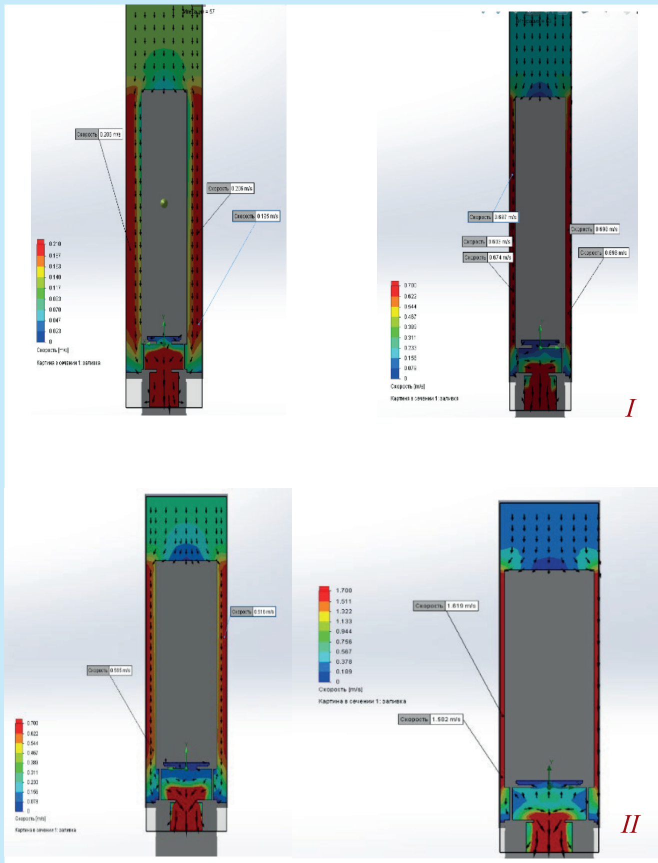
a) *b)*
Figure 6. Submersible electric pump: *a – general view of the submersible electric pump without cooling jacket; b – submersible electric pump with cooling jacket: 1 – electric motor; 2 – pump; 3 – cooling jacket.*
Сурет 6. Суасты электр сорғысы: *а – салқындатқыш жейдесіз суасты электр сорғысының жалпы көрінісі; б – салқындатқыш жейдесі бар суасты электр сорғысы: 1 – электр қозғалтқышы; 2 – сорғы; 3 – салқындатқыш жейде.*
Рис. 6. Погружной электронасос: *а – общий вид погружного электронасоса без рубашки охлаждения; б – погружной электронасос с рубашкой охлаждения: 1 – электродвигатель; 2 – насос; 3 – рубашка охлаждения.*

Experimental work to investigate the changes in the flow cooling rate using the recommended cooling shroud was carried out using SolidWorks software. The obtained results are shown in Figure 7.

Analysis of the results shown in the graphs indicates that in order for the motor to cool normally, it is necessary to provide a certain speed of the fluid flow around it. This velocity can be achieved by means of cooling shrouds.

Conclusion

To establish the technical and economic efficiency of using the results of research on the application of the recommended



a) *b)*
I – at borehole diameter Dsk = 159 mm, pump motor diameter Ddv = 93 mm; II – at borehole diameter Dsk = 195 mm, pump motor diameter Ddv = 145 mm; a – submersible electric pump without cooling casing; b – submersible electric pump with a cooling casing

Figure 7. Results of experimental work in SolidWorks software.
Сурет 7. SolidWorks бағдарламалық жасақтамасындағы эксперименттік жұмыстардың нәтижелері.
Рис. 7. Результаты экспериментальной работы в программе SolidWorks.

cooling device for submersible pump motors, the following calculations were made.

Annual power consumption of the used pumping equipment without application of the recommended cooling device of the submersible pump motor:

$$Wn_{oun\ op} = P_a \cdot EUR \cdot t = 7{,}4 \cdot 0{,}85 \cdot 8760 = 55100{,}4\ kW{\cdot}h/year,$$

where:

P_a – actual capacity of pumping equipment at pump capacity Qcr = 8 (m^3/hour);

EUR = 0.85 equipment utilization rate over time;

t = 8760 operating time of pumping equipment relative to the billing period, hour/year.

Annual electricity consumption when using the recommended cooling device for the submersible pump motor:

$$W_{prelim.ver} = P_a \cdot EUR \cdot t = 7 \cdot 0{,}85 \cdot 8760 = 52122\ kW{\cdot}h/year,$$

where:

P_a – actual capacity of pumping equipment at pump capacity Qcr = 8 (m^3/hour);

EUR = 0.85 equipment utilization rate over time;

t = 8760 operating time of pumping equipment relative to the billing period, hour/year.

The electrical resistance of conductors increases with in-creasing temperature and decreases with decreasing temperature. At very low temperatures, the resistance of some metals and alloys drops to zero (superconductivity). When heated, the vibrations of metal ions in the nodes of the metal lattice increase, so the free space for the movement of electrons becomes smaller. The electrons are more likely to be thrown back, so the value of current decreases and the value of resistance increases, from this we can conclude that, when the temperature of the motor increases, the power consumption of the submersible pumping equipment increases [4].

Energy saving by using a cooling device for the submersible pump motor:

$$\Delta W = W_{noun\ op} - W_{prelim.ver} = 55100{,}4 - 52122 = \\ = 2978{,}4\ kW{\cdot}h/year.$$

Calculated data and obtained performance indicators of pumping units at application of submersible pump motor cooling device are given in Tables 2, 3, 4, and changes of energy efficiency of submersible pump motor cooling device application by years of operation are shown in Fig. 8.

Table 2

Capital cost per submersible pump

Кесте 2

Суасты сорғысының күрделі шығындары

Таблица 2

Капитальные затраты на погружной насос

Expenses	Thousand dollars
Cost of the submersible pump motor cooling unit	350
Installation work (17%)	60
Delivery to (10%)	35
Total amount in dollars:	445
Total amount in tenge:	217 572

As a result of the conducted researches it has been established that it is expedient and economically reasonable to install cooling covers in case of: insufficient cooling; high ambient temperature; pumping of aggressive liquid; sludge (deposits on the electric motor). At the same time, the cooling cover provides a longer life of the electric motor by increasing the velocity of the fluid flow along the motor and contributes to increasing the energy efficiency of the pumping unit by 5–7%.

Table 3

Costs per submersible pump

Кесте 3

Бір суасты сорғысының құны

Таблица 3

Затраты на один погружной насос

Name	Units of measurement	Per 1 submersible pump
Annual electricity consumption of the pumping equipment in use		
Annual electricity consumption	kWh/year	55100,4
Cost of 1 kWh of electricity including VAT	Dollars/kWh	450
Cost of consumed electricity	million USD/ year	27,8
Annual electricity consumption by pumping equipment under the proposed variant		
Annual electricity consumption	kW·h/year	52122
Cost of 1 kWh of electricity including VAT	million Dollars/year	23,5
Electricity saving	million USD/ year	4,3

Table 4

Calculation of cumulative cash flow and equipment payback period

Кесте 4

Кумулятивтік ақша ағынын және жабдықтың өтелу мерзімін есептеу

Таблица 4

Расчет кумулятивного денежного потока и срока окупаемости оборудования

Indicators of economic efficiency	Unit	Years				
		2024	2025	2026	2027	2028
Operating cost variance	Mln. Dollars	4,3	4,3	4,3	4,3	4,3
Depreciation and amortisation	Mln. Dollars	-	0,9	0,9	0,9	0,9
Net profit	Mln. Dollars	4,3	3,4	3,4	3,4	3,4
Capital expenditure	Mln. Dollars	0,45	0,0	0,0	0,0	0,0
Net cash flow	Mln. Dollars	3,85	3,4	3,4	3,4	3,4
Cumulative cash flow	Mln. Dollars	3,85	7,25	10,65	14,05	17,45
Payback period	Year	2				

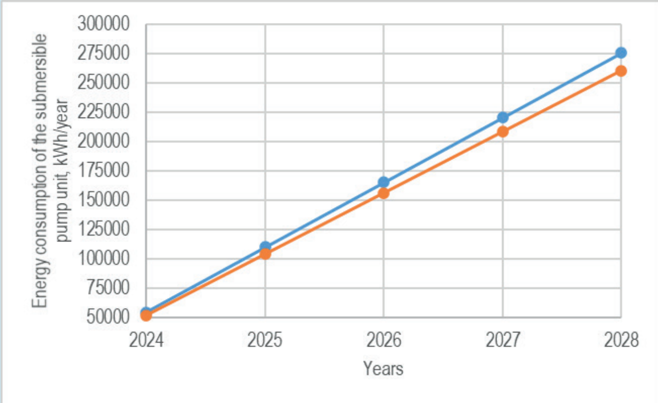


Figure 8. Change in energy efficiency of the application of the submersible pump motor cooler by year of operation.
Сурет 8. Пайдалану жылдары бойынша суасты сорғысының электр қозғалтқышының салқындатқышын қолданудың энергия тиімділігін өзгерту.
Рис. 8. Изменение энергоэффективности применения охладителя электродвигателя погружного насоса по годам эксплуатации.

Cooling casing is a space formed between the body of the cooling casing and the stator surface of the electric motor in which there is a singlephase, turbulent, vortex motion of the fluid flow along the electric motor with convective heat exchange.

It has been experimentally established that there are several main reasons for the equipment of additional cooling jacket (cooling shrouds): to ensure the required fluid flow velocity; to prevent the formation of deposits of components (iron, manganese, fluid salts, bacteria or minerals, etc.) in the well water and to ensure uniform cooling of the electric motor; to reduce the growth of corrosive activity of water by eliminating the increase in temperature of the electric motor; to absorb heat and prevent the thermal effect.

The results of numerical simulation and experimental work performed to investigate the changes in the flow cooling rate using the recommended cooling casing allowed to characterise in detail the velocity fields around the pump unit, to identify the features of the hydrodynamic behaviour of the system and to establish the dependence of the change in the flow cooling rate on the internal diameter of the cooling casing.

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