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SUBSTANTIATION OF THE METHOD FOR INCREASING THE EFFICIENCY AND RELIABILITY OF FLUID COUPLINGS IN MINE CONVEYOR DRIVES WHEN USING WATER EMULSIONS AS A OPERATING FLUID

ОБГРУНТУВАННЯ МЕТОДУ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТА НАДІЙНОСТІ ГІДРОМУФТ ПРИВОДІВ ШАХТНИХ КОНВЕЄРІВ ПРИ ЗАСТОСУВАННІ В ЯКОСТІ РОБОЧОЇ РІДИНИ ВОДНИХ ЕМУЛЬСІЙ

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Abstract. The article addresses the urgent problem of increasing the reliability and efficiency of constant-fill safety-start fluid couplings in the drives of underground scraper chain conveyors. An analysis of the use of various types of operating fluids is conducted in terms of ensuring fire safety and optimizing key operational characteristics. The study aims to establish regularities between the mechanical characteristics of fluid couplings and the concentration and properties of operating fluids—specifically, water-oil emulsions of the HFA-E type. The research was carried out through bench testing of a serial GPE345U fluid coupling at various fill volumes and concentrations of Solcenic Pl Plus emulsol. It has been experimentally proven that increasing the emulsol concentration in the operating fluid significantly improves mechanical characteristics during transient operating modes of the fluid coupling, while minimizing heat generation and excessive energy losses. The scientific novelty lies in identifying the deviations in the behavior of water-oil emulsions from the laws of classic Newtonian fluids within the flow passage of fluid couplings. The practical value of the results consists in justifying the feasibility of using a 10% HFA-E type emulsion as the operating fluid of a fluid coupling to significantly improve efficiency and durability indicators.

Keywords: hydrodynamic drive, constant-fill fluid coupling, mine scraper chain conveyor, mechanical characteristic, oil-in-water emulsion, HFA-E, operating fluid, concentration.

Introduction.

Hydrodynamic power transmissions have become widely used in the drives of belt and scraper mine conveyors [1]. During operation, the fluid coupling is a critical component that ensures their reliable performance.

In scraper conveyor drives (Fig. 1) with a power rating of 30–250 kW, it is technically viable to use constant-fill safety-start fluid couplings (closed-loop system), which provide the following functions:

– facilitated starting of conveyor electric motors under no-load and loaded conditions;

– maximum utilization of the electric motor's traction characteristics to start the conveyor in a loaded state;

– protection of the drive and the conveyor traction element against overloads by limiting the torque;

– load equalization between drives in multi-drive conveyors.

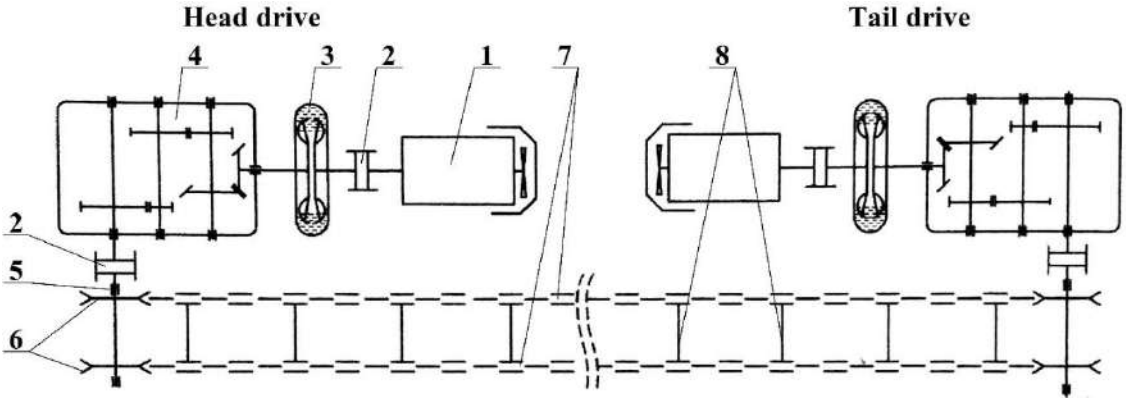


Fig. 1 Kinematic diagram of a scraper conveyor equipped with fluid couplings in the drives: 1 – electric motor; 2 – connecting coupling; 3 – fluid coupling; 4 – gear reducer; 5 – drive shaft; 6 – sprockets; 7 – drag chains; 8 – scrapers.

This type of fluid coupling features a relatively simple design, with only an internal operating fluid circulation loop and air cooling. In drives with a power output exceeding 250 kW, there arises a need for additional cooling of the operating fluid. This is achieved either by introducing an external circulation loop or by using fluid couplings with auxiliary chambers that increase the volume of the operating fluid, expand the cooling surface, and can provide a smoother, slower start. Both approaches lead to a more complex design and reduce the viability of using fluid couplings. In high-power drives, competing technical solutions are more frequently utilized, such as controlled drives with electromagnetic brakes [2], two-speed electric motors with flexible couplings, thyristor soft starters, variable frequency drives [3], and others [4].

Thus, along with their advantages and beneficial functions, fluid couplings also possess a number of fundamental drawbacks, such as high heat generation and energy losses, and therefore require improvement.

Literature Review.

The conducted analysis identified the following directions for improving the performance of hydrodynamic transmissions:

Increasing energy capacity.

This is aimed at reducing the mass and dimensions of the hydrodynamic transmission and the drive as a whole, which intends to lower equipment costs, reduce installation expenses, and expand the feasibility of using compact drives when mining thin coal seams. This can be achieved through:

Using high-density operating fluids (ρ). The torque that a hydrodynamic drive can transmit has a direct linear dependence on ρ [5, 15]. This follows from the formula for determining torque derived from the general similarity theory of turbomachines:

$$M = \lambda \cdot \rho \cdot D^5 \cdot \omega^2, \quad (1)$$

where λ is the torque coefficient, which accounts for the shape of the fluid coupling's flow passage and the viscosity of the operating fluid; ρ is the density; D is the active diameter (in the case of fluid couplings, the outer blades diameter); ω is the rotational speed.

Optimizing the viscosity-temperature parameters of operating fluids. This reduces friction losses during the circulation of the operating fluid during operation, increases transmission efficiency, lowers heat generation, and consequently enables the use of more compact transmissions for a given power and rotational speed.

Enhancing the heat dissipation capability and heat capacity of the fluid. This is aimed at maintaining operation within a specified temperature range (without overheating) due to the properties of the operating fluid, the design and materials of the main components, and the

presence of a cooling circuit.

Optimizing the geometry of the flow passage. This includes reducing the thickness of the impeller blades and the surface roughness of the flow passage.

Increasing reliability.

This is aimed at improving the operational performance indicators of both the fluid coupling itself and the drive as a whole, while maintaining all functional properties. This can be achieved through:

Reducing thermal stress during operation by means of the operations [5, 15].

Using operating fluids with high anti-corrosion and anti-friction properties to prevent the failure of transmission components.

Simplifying the design of hydrodynamic systems and reducing the mass and dimensions of rotating parts to lower dynamic loads.

Using operating fluids with a high boiling point and low saturated vapor pressure, which is crucially important for closed-circuit fluid couplings to prevent additional loads on the housing. Concurrently, preference should be given to fluids with a high flash point, and in the conditions of underground coal mines – to non-flammable, non-toxic, and environmentally safe fluids.

Reducing energy consumption in steady-state and transient conditions

It is technically expedient to bring the transmission efficiency as close to 100% as possible in steady-state (nominal) operating modes that do not require impeller slippage. Generally, these modes account for about 90% of the drive operation time. Therefore, increasing efficiency by even 1–3% yields significant energy savings, reduces the thermal load on all transmission elements, and enhances drive reliability.

However, the hydrodynamic method of torque transmission requires operating fluid circulation, which is only possible when slip occurs S>0. This means that using purely hydrodynamic methods, we can only approach an efficiency of 100%. Currently, the best-performing fluid couplings achieve an efficiency of 97–98% in nominal mode (with a nominal slip of S = 2…3%).

The efficiency of a fluid coupling can be increased by optimizing its design (the shape of the flow passage, the number and tilt angle of the blades, etc.), by altering the parameters of the operating fluid, or by a combination of both methods.

As an example, transitioning from the use of I-20A industrial oil to a water-oil emulsion (3% oil, 97% water) as the operating fluid increases the nominal efficiency from 96.1% to 97.7% without modifying the design of the 1GPE400U fluid coupling [2]. Given the nominal power of 55 kW transmitted by this fluid coupling, power losses under nominal load in this specific case decreased from 2.12 kW to 1.25 kW, while the heat flux causing the coupling to heat up was reduced by 40%.

A transmission efficiency of 100% can be achieved by mechanically locking the impellers during operation [6, 7]. This possibility derives from the friction torque component M_{FRIC} in the torque equation for a fluid coupling:

$$M = M_{HD} + M_{FRIC} + M_D - M_W \quad (2)$$

where M is the total torque transmitted by the fluid coupling; M_{HD} is the hydrodynamic component (torque transmission via the energy of operating fluid flows); M_{FRIC} is the torque transmitted by friction in bearings and seals, via internal fluid friction, or through locking elements (for couplings featuring a lockup system); M_D is the dynamic component during non-steady-state (transient) conditions due to the acceleration of the fluid coupling's driven rotating masses and the operating fluid (equals 0 under steady-state conditions without acceleration); M_W is the windage torque caused by the friction between the housing and the surrounding medium (air).

In practice, implementing a mechanical lockup requires a more complex fluid coupling

design and the integration of a control system. In most cases, this is impractical in terms of reliability, ease of maintenance, and manufacturing cost. Furthermore, during lockup, the fluid coupling loses several beneficial functions, such as protection against static and dynamic overloads, and load balancing between drives in multi-drive conveyors. Consequently, the use of impeller lockups in fluid coupling drives requires a cautious approach.

Locking the impellers or reducing slip can also be achieved by controlling the viscosity of the operating fluid—specifically, by transitioning from the "fluid coupling" mode (low viscosity, high circulation) to the "viscous coupling" mode (high viscosity, low or no circulation). The latter method remains under-researched but holds promise for the development and efficiency enhancement of hydrodynamic drives.

During transient operating modes (drive startup, overload operation), when slip can reach values from 5 to 100%, a large amount of energy is lost, converting into heat that warms up the operating fluid and the fluid coupling itself. Although such modes account for only about 10% of the drive operation time, their behavior significantly affects the operational reliability of both the fluid coupling itself and the drive as a whole.

Most scraper conveyor failures occur precisely during startup (especially when buried under coal), static overload, and dynamic overload during flight bar chain jamming. As a result, the temperature of the fluid coupling operating fluid rises, and under critical load and long duration, the thermal protection of the fluid coupling trips. According to data [2], in scraper conveyors equipped with fluid coupling drives, thermal protection tripping accounts for 14% of failures and 7.55% of downtime.

Recent studies on the failure distribution among main components during the operation of the TR-7A conveyor [8] are shown in Fig. 2.

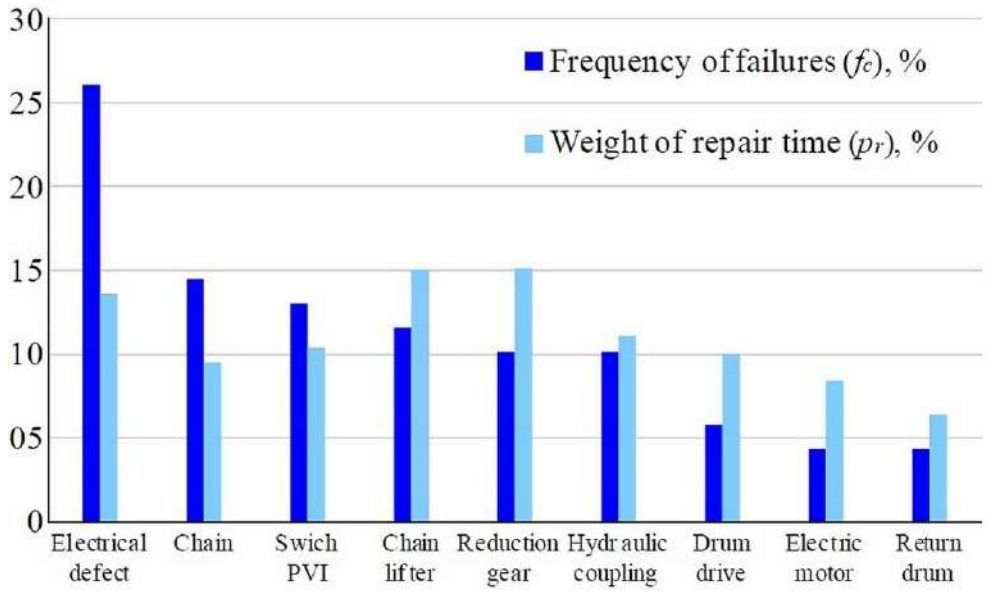


Fig. 2 Failure distribution for main components during the operation of the TR-7A conveyor.

The nature of the conveyor failure distribution indicates that fluid couplings account for approximately 10% of failures and 11% of time spent on restoration and repairs. Indirectly, the operation of the fluid coupling also influences the reliability of all listed components, including electrical equipment. Due to the cushioned motor startup, the cables and the electromagnetic starter experience high startup currents for a shorter duration, thanks to the starting and safety properties of the fluid coupling. That is, the correct operation of the fluid coupling can significantly increase the reliability of all conveyor components and reduce repair costs, both in terms of material and time.

Therefore, it is important to optimize the starting, acceleration, and static characteristics of fluid couplings. On one hand, this reduces wasted energy; on the other hand, it increases

the reliability and operational efficiency of the fluid coupling, electric motor, drive, and the machine (conveyor) as a whole. In the drive of a mine scraper conveyor, the joint operation of the fluid coupling and the induction motor must be considered. Figure 3 shows the superposition of their mechanical characteristics. The slip S is plotted along the abscissa axis (x-axis), and the torque M transmitted by the fluid coupling and the motor is plotted along the ordinate axis (y-axis).

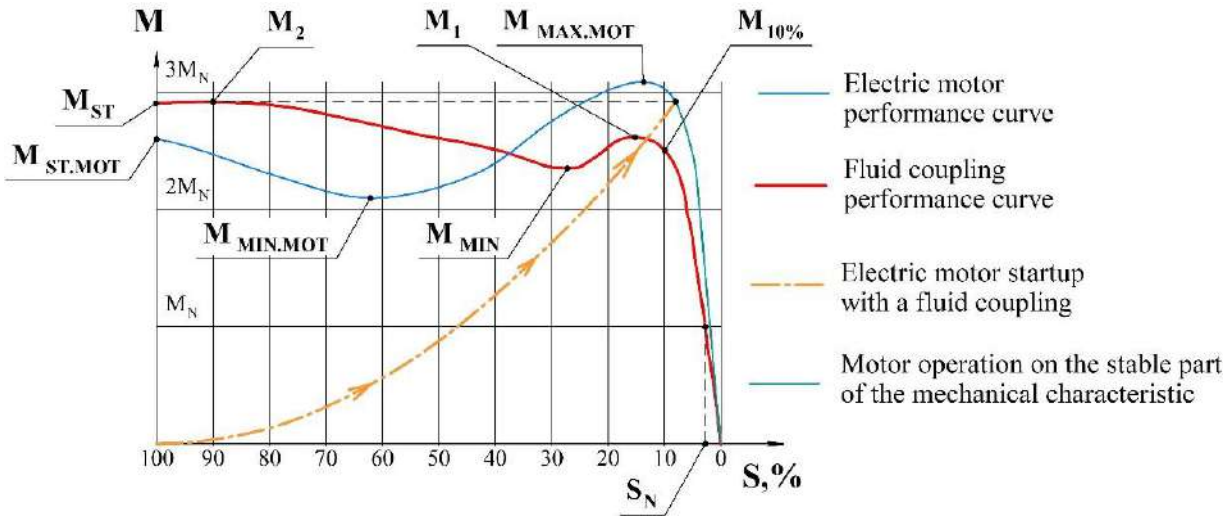


Fig. 3 Mechanical characteristics of the electric motor, fluid coupling, and their joint operation in the scraper conveyor drive.

Under a static load of an operating drive, the torque transmitted by the drive is determined by the fluid coupling, while the electric motor operates on the stable part of its mechanical characteristic, thereby being protected from overloads. This occurs due to the absence of a rigid connection between the driving shaft of the electric motor and the driven shaft of the gearbox – the fluid coupling separates the electric motor and the output part of the drive via a hydrodynamic method of torque transmission.

As the load increases, the slip S of the fluid coupling increases from the nominal value up to 100%, at which point the output shaft is braked (stalled condition). In this case, the electric motor operates under overload, but there is no stalling (drop-off) into the unstable part of its mechanical characteristic. Under these conditions, the motor's traction capabilities are fully utilized: the torque reaches values of 2…3 M_N (M_N is the nominal torque), and the current reaches values of 3…4 I_N (I_N is the nominal current).

At the moment of the drive startup, due to the slip S decreasing from 100% to the nominal value, the fluid coupling allows the motor to accelerate rapidly (up to 1 s) and pass the unstable part of the mechanical characteristic, where the currents reach 5.5…8.5 I_N. This provides protection for the electric motor during the starting mode.

To ensure protection of the electric motor and the drive against overloads on one hand, and to maximize the utilization of the motor's traction capabilities on the other, the mechanical characteristics of fluid couplings in scraper conveyor drives must meet the following requirements:

– The fluid coupling slip at nominal load, S_N , must be as low as possible and should not exceed 3%, which ensures minimum efficiency $\eta \geq 97\%$:

$$S_N \leq 3\ \%; \tag{3}$$

– The maximum torque values that the fluid coupling can transmit must range from 0.85 to 0.95 of the maximum torque $M_{MAX.MOT}$ that the electric motor can develop on the stable part of its mechanical characteristic:

$$M_{ST}, M_1 , M_2 = 0{,}85…0{,}95\ M_{MAX.MOT;} \tag{4}$$

– The starting torque of the fluid coupling, M_{ST}, must be equal to or higher than the maximum torques M_1 and M_2 of the fluid coupling's static characteristic. This is a necessary condition for damping self-excited oscillations during chain jamming, which was experimentally proven by A.V. Leusenko [2]:

$$M_{ST} \geq M_1 , M_2; \quad (5)$$

– To ensure the required rigidity of the stable section of the mechanical characteristic of the fluid coupling, the minimum values of the maximum torque M_1 and the torque $M_{10\%}$ at a slip S = 10% are standardized as follows:

$$M_1 \geq 2\ M_N; \quad (6)$$

$$M_{10\%} \geq 1{,}7\ M_N; \quad (7)$$

– To ensure uniform and efficient drive acceleration and to prevent long-term operation of the fluid coupling with high slip values during overload, the minimum torque M_{MIN} (the torque "dip") should be absent or is standardized by the following expression:

$$M_{MIN} \geq 2\ M_N; \quad (8)$$

– To protect the drive and the conveyor's flight bar chain assembly from dynamic loads (for example, during chain jamming), the maximum dynamic torque \(M_{dyn.c}\) transmitted by the fluid coupling during emergency stalling of its driven part must not exceed 3.5 M_N within a braking time of t = 0.5 s [3]:

$$M_{DYN} \leq 3.5\ M_N. \quad (9)$$

Summarizing all the considered aspects, three main directions for regulating and improving the characteristics of fluid couplings can be distinguished:

– Changes in the design and geometry of the flow passage;
– Selection of the optimal fluid coupling filling volume;
– Optimization of the operating fluid parameters.

The first direction (**design-based**) can be applied at the stages of development, manufacturing, and bench testing. This direction has been foundational for fundamental research ever since the inventor of hydrodynamic transmissions, Prof. Föttinger. Currently, the largest amount of research in this field is conducted by Voith (Germany). The general optimization of the modern design of safety-starting fluid couplings for mine scraper conveyors produced in Ukraine by the "Svitlo Shakhtarya" plant was carried out in the 1980s and 1990s, based on research from the Skochinsky Institute of Mining and the works of engineers from their own research laboratory: A.V. Leusenko, V.K. Gavrilenko, and V.Y. Kapshtyk. The general dependencies of mechanical characteristics on the number of blades, flow passage parameters, and other design variables are provided in [9].

The second direction (**filling volume optimization**) is used during the testing and fine-tuning phases to match the characteristics to specific operating conditions once the design and operating fluid type have been finalized. As a rule, safety-starting fluid couplings are filled with operating fluid to 65...90% of the total internal cavity volume. Higher filling values correspond to higher values of transmitted torque M and power N. The optimal filling volume, which maximizes the traction, safety, and starting capabilities of the fluid coupling, is approximately 88% of the internal cavity volume. By reducing the filling volume, the torque can be regulated from M_{MAX} down to $0{,}6M_{MAX}$. This method of selecting the optimal filling volume is used as an auxiliary tool during the final phase of pre-operational testing.

In our research, we examined the third path – **optimizing the composition of the operating fluid**, as it can improve the performance efficiency of both newly designed equipment and machinery already in operation. Design changes always require significant material costs, which are much higher than the cost of replacing the operating fluid. Practical experience with safety-starting fluid couplings has revealed that operating fluids significantly

affect both the mechanical characteristics of the couplings and their operational reliability. In our opinion, insufficient attention has been paid to this issue in previous studies. Therefore, it is crucial to establish the dependencies that will aid in selecting the optimal characteristics of the operating fluid.

We will examine the key requirements for operating fluids used in fluid couplings of coal mine conveyor drives.

Modern coal mine safety regulations [10, 11] require **the use of fire-resistant fluids only.** This requirement is due to the periodic discharge of overheated operating fluid when the thermal protection of fluid couplings is tripped. The tripping temperature of the protection system in modern fluid couplings ranges between +120...+150 °C, which is determined by the thermal stability of seal and bearing materials, as well as the allowable casing temperatures of +165...+170 °C upon contact with coal dust [12]. To prevent fires and explosions in Ukrainian mines, the use of mineral oils as operating fluids in hydraulic drives was discontinued in the 1970s. They were replaced by HFA-type oil-in-water emulsions consisting of water and emulsol in concentrations up to 20% (oil in water), which are completely non-flammable fluids (classified according to ISO 12922:2020 [13]). The transition to HFA-type fluids provided many advantages regarding their application in fluid couplings, but it also introduced certain technical difficulties compared to mineral oils. Below, we examine the criteria by comparing these two types of operating fluids.

HFA-type emulsions **must contain a package of anti-friction and anti-corrosion additives to compensate for the aggressive properties of water** toward metal parts and friction pairs. For the same purpose, in fluid couplings operating with emulsions, the bearings are lubricated with grease instead of the operating fluid and are equipped with additional seals. That is, bearing units in fluid couplings using mineral oils as operating fluids have a somewhat simpler design than those operating with HFA emulsions. The fluid couplings manufactured by the "Svitlo Shakhtarya" plant, which were used in this study, are adapted for operation with water emulsions; they feature two levels of protection (against overheating and overpressure) and are equipped with bearing units isolated from the operating fluid.

When selecting an operating fluid, it is necessary to ensure **compatibility with seal materials (elastomers).**

Operating fluids must have **low viscosity to reduce internal friction losses** and increase hydrodynamic efficiency during fluid coupling operation in the steady-state mode. In terms of this parameter, HFA-type emulsions have a major advantage over oils because they possess significantly lower viscosity and show less dependence of viscosity on temperature. It is worth noting that choosing the optimal viscosity of the operating fluid is a critical issue. As a result of our research, we obtained findings indicating more complex dependencies than those considered in classical sources (see below in the text).

In order to increase energy capacity, preference is given to fluids with **higher density**. HFA emulsions have a density 15...20% higher than mineral oils, which provides a corresponding gain in the torque and power that the fluid coupling can transmit.

During the operation of hydrodynamic transmissions in starting modes and during overloads under steady-state modes, a significant amount of heat is generated, which goes toward heating the operating fluid. To ensure the proper operation of the drive in these modes (without overheating), the operating fluid must effectively store thermal energy and dissipate it to the environment. It is most expedient to **use fluids with a higher specific heat capacity** (the ability to heat up less with the same amount of supplied heat) **and a higher thermal conductivity coefficient** (the ability to transfer heat within the fluid). HFA emulsions are twice as effective as oils in terms of specific heat capacity, and 4...5 times more effective in terms of heat transfer [14].

Operating fluids **must comply with environmental and sanitary standards and have the lowest possible cost**. Since HFA-type emulsions consist of more than 80% water, they have an advantage in these indicators not only over mineral oils but also over water-glycols

(HFC) and synthetic operating fluids (HFD), which can also be used in fluid couplings.

Table 1 presents a comparison of the performance indicators of various types of operating fluids for fluid couplings [5, 14, 15].

Table 1. Characteristics of operating fluids for fluid couplings

Parameter / fluid type (ISO 6743-4)	Mineral oils	HFA (oil in water)	HFB (water in oil)	HFC (water-glycol)	HFD-U (synthetic fluid)
Water content, %	—	≈ 95 (80 min)	40…60	35…45 (18–20 for HFC-E)	—
Fire resistance (minimum ignition temperature), °C	flam-mable	non-flammable	+650	+600	+400
Compliance with Section 3.1.1 of the 7th Luxembourg Report [11]	-	+	-	+	-
Fire resistance class according to Section 3.1.3 of the 7th Luxembourg Report [11]	H	A	E	B-C	G-H
Lubricating capacity	+++	+	+	++	+++
Kinematic viscosity at +60 °C, cSt	6…18	0,5…3	18…25	10…25	14…25
Density, kg/dm³	0,85…0,9	0,99…1 for HFA-E, 1…1,15 for HFA-S	0,92…1,05	1,07…1,14	0,91…0,93
Specific heat capacity relative to mineral oil	1	2,3	1,8	1,8	0,7
Thermal conductivity relative to mineral oil	1	4	5	2,5	0,9
Relative cost	1	0,5	0,5	3	6

As can be seen from the table, only HFA and HFC-type fluids fully comply with fire safety regulations. One of the leading manufacturers of hydrodynamic transmissions, "Voith Turbo" (Germany), recommends HFD-U class fluid as fire-resistant, considering it one of the primary options alongside HFA fluids [5, 16]. In essence, HFD-U fluid is a synthetic substitute for mineral oil [17] and can be used as a fire-resistant fluid in industrial gearboxes of mining equipment and in metallurgy. However, for fluid couplings operating in mines hazardous due to gas and coal dust, which are typical for Ukraine, the use of HFD-U fluid is impossible due to its non-compliance with safety regulations.

Based on an aggregate assessment of all factors, it is evident that HFA-type emulsions are the most expedient choice for hydrodynamic couplings under coal mine conditions. In the mines of Ukraine and Eastern European countries, the most widespread practice is the use of emulsions based on the Solcenic Pl Plus concentrate (manufactured by FUCHS Petrolub SE, Germany). The data were obtained from surveys of technical departments at mines in the Donets Coal Basin (Donbas) and from open internet sources (tender procurement, Prozorro) for the period from 2009 to 2025. In our research, we selected this operating fluid as the primary subject for analysis.

Research Methodology.

In the vast majority of studies focusing on the performance characteristics of fluid couplings, homogeneous liquids—such as mineral and synthetic oils, water, and even vegetable oils, which are considered an environmentally friendly alternative to petroleum-based oils [18]—have been used as operating fluids. However, the operating fluids currently used in the fluid couplings of coal mine scraper conveyor drives are emulsions, i.e., two-component liquids. Therefore, establishing relationships between fluid coupling characteristics and the composition and properties of HFA-type operating fluids represents an urgent contemporary problem addressed in this study.

In this work, a pilot study was conducted to trace the dependence of the torque transmitted by the fluid coupling on the concentration of the water emulsion. Water emulsions of the HFA-E type based on Solcenic Pl Plus concentrate (a mineral oil-based concentrate) were investigated. The concentration recommended by the manufacturer has changed over time. In the 2000s and 2010s, it was recommended to use a 0.5–2% emulsion; currently, Fuchs Lubricants Ukraine recommends using a 1.3–5% emulsion [19]. Practical experience demonstrates that saving on concentration compromises the operational reliability of mine hydraulics, and it is recommended to increase the concentration up to 5% [20]. In 2009, a survey of mechanical engineers at SE Sverdlovantratsit (Luhansk Oblast) revealed that increasing the emulsion concentration from 1.5% to 10% led to a 3.5-fold increase in the service life of fluid coupling seals. Consequently, it was decided to test the fluid couplings using operating fluids with the following volumetric content of concentrate in water: 1.5, 3, 5, and 10%.

The tests were performed on a GPE345U safety-start constant-filling fluid coupling using an STG110M test bench at the "Svitlo Shakhtarya" plant. The GPE345U fluid coupling has the following main technical specifications:

- Active diameter D = 345 мм;
- Internal cavity volume V = 6.26 dm^3 (l),
- Weight without motor half-coupling and flexible insert m = 32 kg;
- Total weight (including motor half-coupling and flexible insert) M = 46.5 kg;
- Rated power N_n = 22…30 kW at a motor rotational speed n_1 = 1480 rpm.

The design and operating principle of safety-start fluid couplings manufactured by the "Svitlo Shakhtarya" plant are discussed in detail in [2]. The installation layout of the GPE345U fluid coupling in conveyor drives and other machinery is shown in Fig. 4.

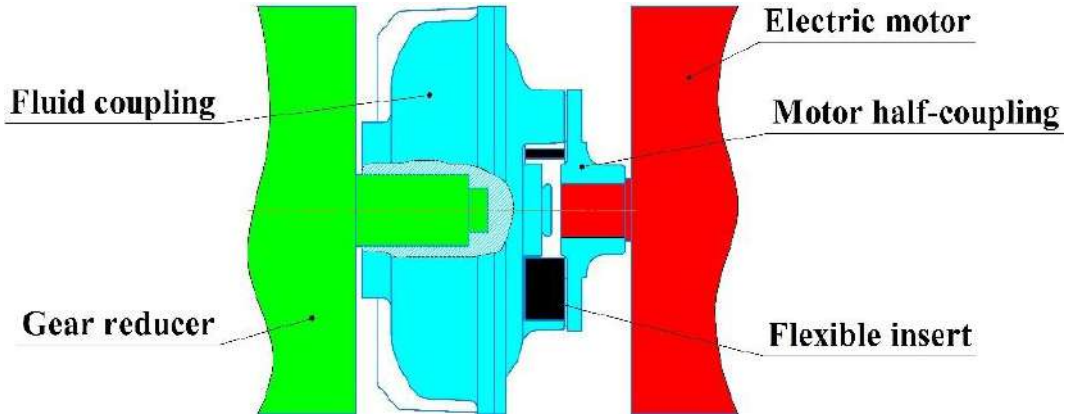


Fig. 4. Installation diagram of a fluid coupling in machine drives.

The mechanical characteristics were recorded at two different operating fluid fillings:

– 4.9 dm^3 (l), which constitutes 78% of the internal cavity volume and is used for operation with electric motors rated at N_n = 22 kW;

– 5.3 dm³ (l), which constitutes 85% of the internal cavity volume and is used for operation with electric motors rated at N_n = 30 kW.

Figures 5, 6, and 7 show the test bench for fluid couplings. The technical capabilities of the test bench allow for testing fluid couplings and electric motors with power ratings ranging from 11 to 500 kW. On the test bench, fluid coupling 4 is installed identically to its operational layout in machine drives (Fig. 4). The STG110M test bench measures the torque M and power N transmitted by the fluid coupling, as well as the rotational speeds of the driving part n_1 and the driven part n_2 (the pump and turbine impellers). The rotational speeds are measured by tachometers 10, which are mounted on the rear end of electric motor 1 (driving part) and on the shaft of mechanical brake 7 (driven part). Torque is measured using torque transducer shaft 5. One side of this shaft connects to the driven part of the fluid coupling, while the other side connects to transfer gearbox 6, which distributes the torque between brakes 7 and 8. The fluid coupling receives rotation from electric motor 1, which is mounted on support 2. Brakes apply the load while recording mechanical characteristics. Powder electromagnetic brakes 8 generate the load when recording static and start-up characteristics, as well as when determining slip S at fixed loads. Mechanical drum brake 7 applies emergency loads to simulate conveyor chain jamming within a braking time of $t \leq 0.5$ s [3]. Bench control (starting, setting the load level), speed monitoring, and load control are managed via control panel 9.

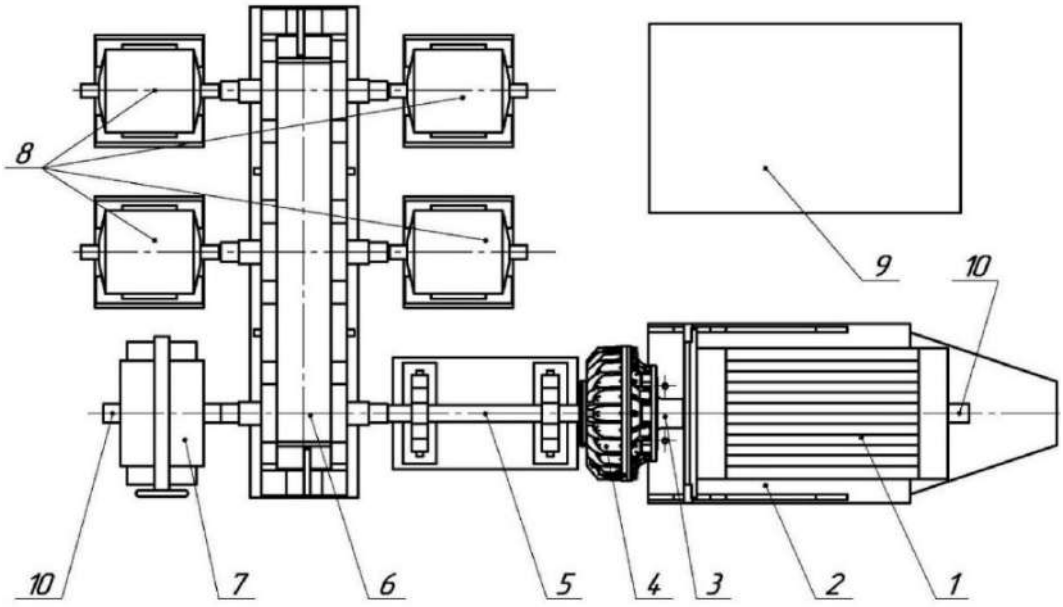


Fig. 5. Schematic diagram of the STG110M test bench for fluid coupling testing: 1 – electric motor, 2 – electric motor support (base); 3 – motor half-coupling (connecting coupling); 4 – fluid coupling under test; 5 – torque transducer shaft; 6 – transfer gearbox; 7 – mechanical drum brake; 8 – powder electromagnetic brakes; 9 – control panel; 10 – tachometers.

Rotational speeds are measured by two optical sensors (tachometers), which ensure a high response speed with an accuracy of ± 1 rpm. Their signals are sent to a computer to be recorded while capturing static, start-up (acceleration), locked-rotor (starting), and dynamic characteristics. They are also sent to the control panel to visualize rotational speeds under steady loads.

The torque measurement accuracy is at least ± 5 N·m. The torque transducer shaft transmits the signal to the computer for recording via Bluetooth wireless technology. Compared to the previously used contact-based data transmission via brushes, wireless technology reduces noise by an order of magnitude and improves measurement accuracy.

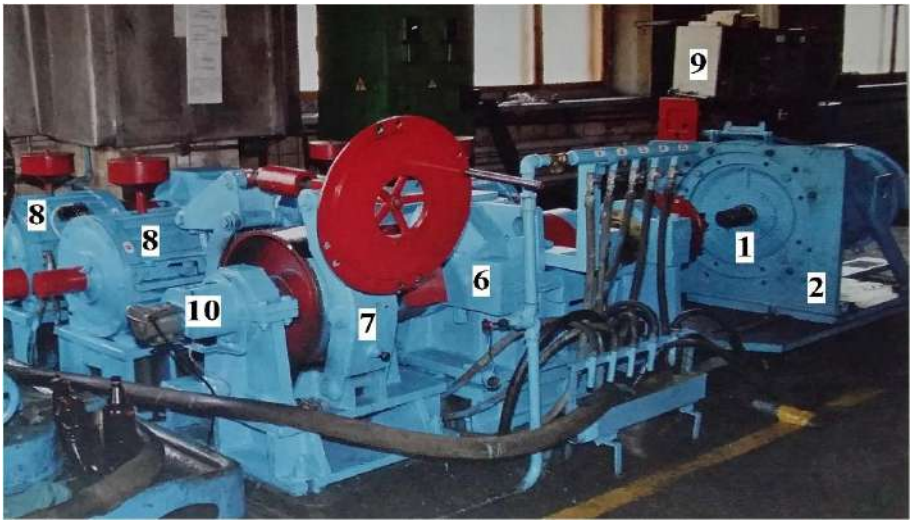


Fig. 6. General view of the STG110M test bench for fluid coupling testing.



Fig. 7. Mounting location of fluid couplings for testing on the STG110M test bench.

Load monitoring and visualization during the tests are performed using a wattmeter installed in the control panel. The wattmeter measures the active electrical power N_A consumed by the electric motor with an accuracy of ± 0.5 kW. When creating the required mechanical load level, the value of the active electrical power was determined based on the electric motor efficiency using the formula:

$$N_A = N_M / \eta, \quad (10)$$

where N_A is the active electrical power indicated by the wattmeter; N_M is the mechanical power developed by the electric motor; η is the electric motor efficiency.

During the tests, the following characteristics were recorded:

a) Start-up (acceleration) characteristics. The torque M, as well as the rotational speeds of the driving part n_1 and the driven part n_2, were recorded from the moment of start-up until the driven part reached its maximum speed under a specified load. The load was defined by the idle resistance torque of the powder brake with no voltage applied to it. The resistance torque in this case was 100…120 N·m, which accounted for approximately 80% of the nominal load at 22 kW and 60% at 30 kW.

b) Static characteristics. The driven part of the fluid coupling was gradually loaded from a minimum torque of 0,6…0,8 M_N up to the locked-shaft state, where the speed of the driven shaft $n_2 = 0$ (slip S = 100 %), while recording the rotational speeds and torque. The nominal rotational speed of the driving shaft was $n_1 = 1495$ rpm. To eliminate the influence of

the inertia of rotating masses on the torque readings, the load was increased smoothly, ensuring a braking time of 15...20 s. To construct the torque M versus slip S characteristic curve, the speed readings n_1 and n_2 were converted using formula (11):

$$S = \frac{\omega_1 - \omega_2}{\omega_1} \cdot 100\% = \frac{n_1 - n_2}{n_1} \cdot 100\%, \quad (11)$$

where ω_1 is the angular velocity of the fluid coupling driving part, rad/s; ω_2 is the angular velocity of the fluid coupling driven part, rad/s; n_1 is the rotational speed of the driving part, rpm; n_2 is the rotational speed of the driven part, rpm.

c) Locked-rotor (starting) characteristics. The test was performed by starting the system with a completely locked (braked) driven shaft while recording the starting (stall) torque M_{ST} – simulating the start-up of a conveyor drive under a coal blockage.

d) Dynamic characteristics. From the nominal rotational speed of the driven shaft, emergency braking was applied to bring it to a complete stop within 0.5 s, while recording the torque and rotational speeds. The maximum torque value is standardized and represents the dynamic torque M_{DYN}, which is used in structural strength calculations for drive components, the traction element, and conveyor housing parts.

e) Measurement of slip S_N at nominal load. The required load level was set using the powder brake: M_N = 142.5 N·m at N_N = 22 kW and M_N = 194 N·m at N_N = 30 kW. The speeds n_1 and n_2 were recorded. Slip S_N was calculated using formula (11). Oscillograms were recorded for all filling levels and concentrations. For static loading, they were converted into static characteristics, the general view and symbols of which are shown in Fig. 8.

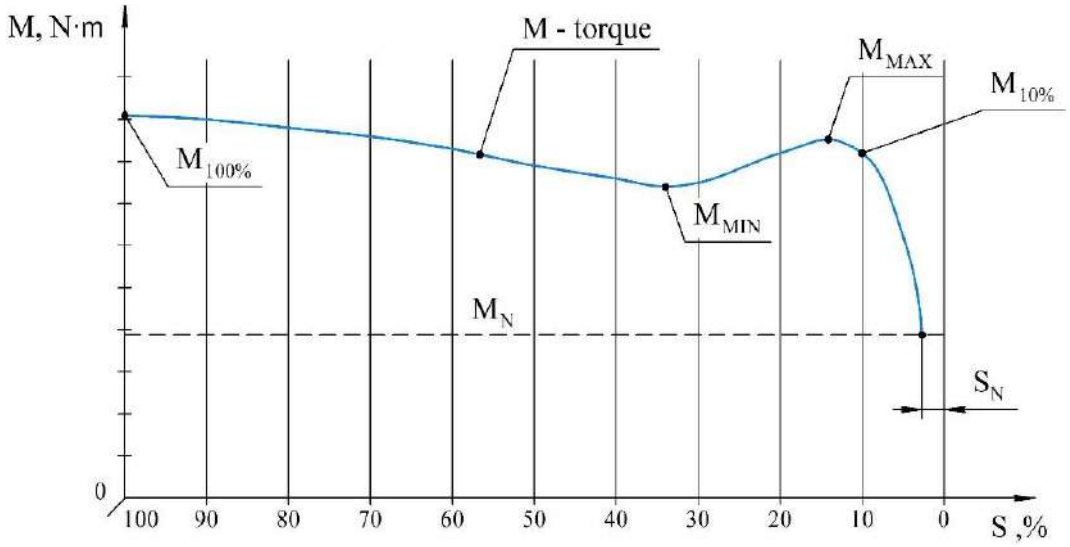


Fig. 8. Parameters of static characteristics and accepted notation.

Accepted notation in tables and figures:
S_N – nominal slip,
M_N – nominal torque,
$M_{10\%}$ – torque at S = 10 % slip,
M_{MAX} – maximum torque on the stable part of the mechanical (static) characteristic curve,
M_{MIN} – minimum torque on the unstable part of the mechanical (static) characteristic curve,
$M_{100\%}$ – torque at S = 100 % slip (with the driven part locked),
T_{ST} – run-up (acceleration) time of the driven part after switching on the electric motor,
M_{ST} – starting torque at S = 100 % slip (starting with a locked driven shaft),
M_{DYN} – maximum torque during emergency braking within 0.5 s.

Results.

For comparison, Fig. 9 shows the acceleration characteristics and static load at the same fluid filling of 5.3 dm³ under different emulsol concentrations: 1.5% (Fig. 9a) and 10% (Fig.9b).

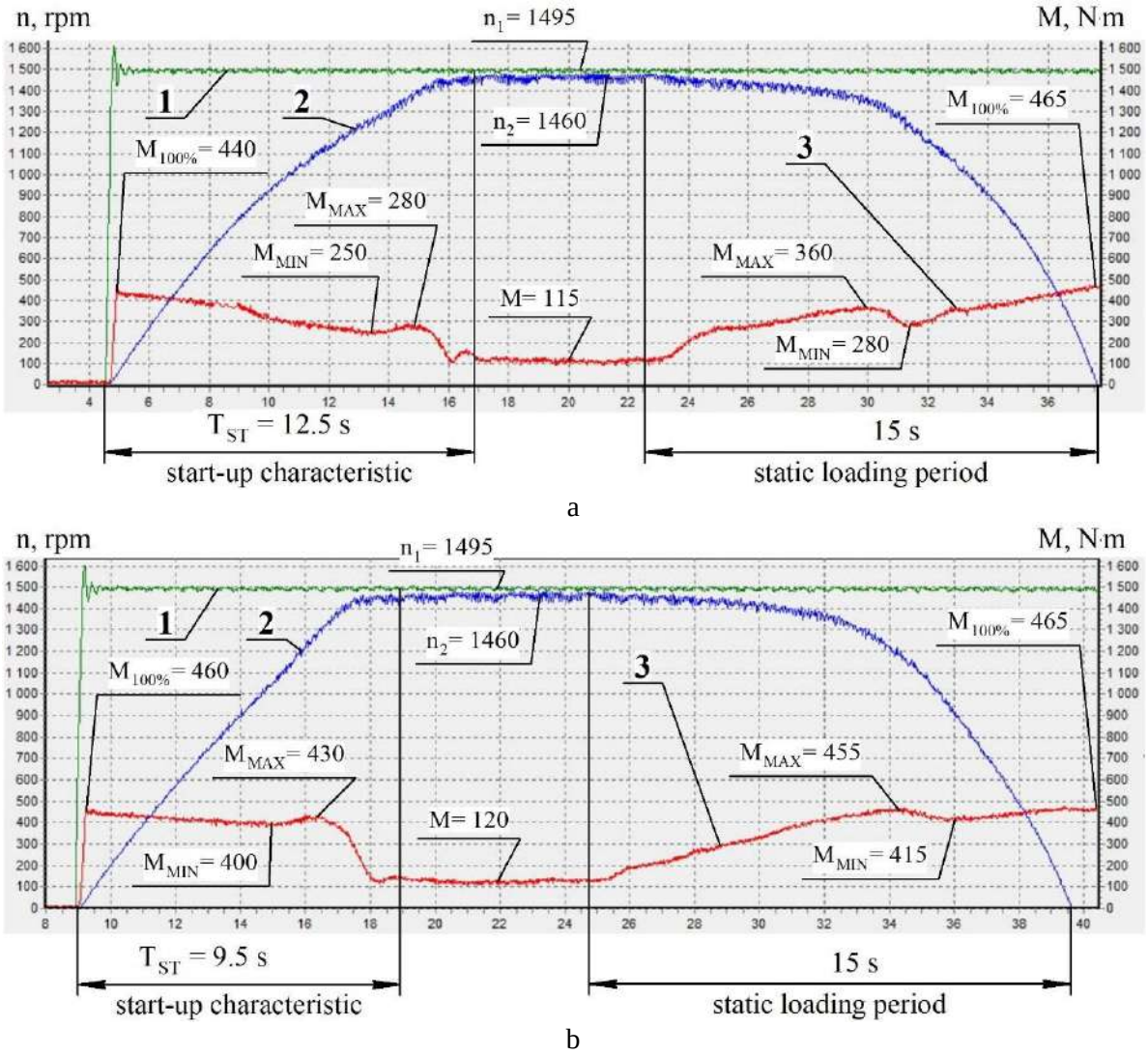


Fig. 9. Start-up characteristics and static loading of the fluid coupling GPE345U with a 5.3 dm³ (l) fluid fill at different emulsol concentrations: a – 1.5%; b – 10%: 1 – speed curve of the driving part n_1 (electric motor); 2 – speed curve of the driven part n_2 (gear reducer); 3 – torque curve M.

A lower emulsol concentration (Fig. 8a) corresponds to lower torque values. There is a noticeably large "dip" on the unstable part of the mechanical characteristic, along with a prolonged, inefficient run-up featuring a large torque drop and excessive fluid coupling operation time at high slip values (S). This can lead to increased heating of the operating fluid and the inability to start the conveyor under a coal overload. In contrast, at a 10% concentration (Fig. 8b), the start-up and static load curves exhibit no large drops or "dips" and meet the performance requirements for scraper conveyors.

A similar pattern is observed for both fluid fills (4.9 and 5.3 dm³) — as the concentration increases, the characteristics gradually approach more acceptable levels. For convenience of result analysis, all obtained data were plotted as overlaid static characteristics (Figs. 10, 11) and summarized in reference Tables 2 and 3.

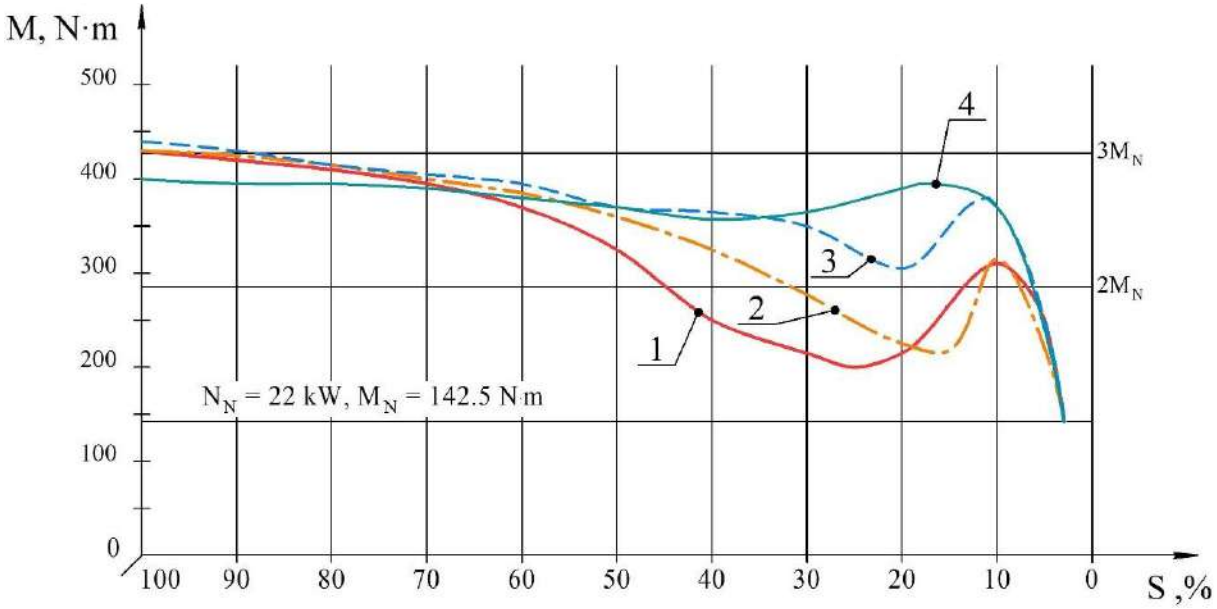


Fig. 10. Static characteristics of the fluid coupling GPE345U with a 4.9 dm³ (l) fluid fill at different emulsol concentrations: 1 – torque curve at 1.5% concentration; 2 – torque curve at 3% concentration; 3 – torque curve at 5% concentration; 4 – torque curve at 10% concentration.

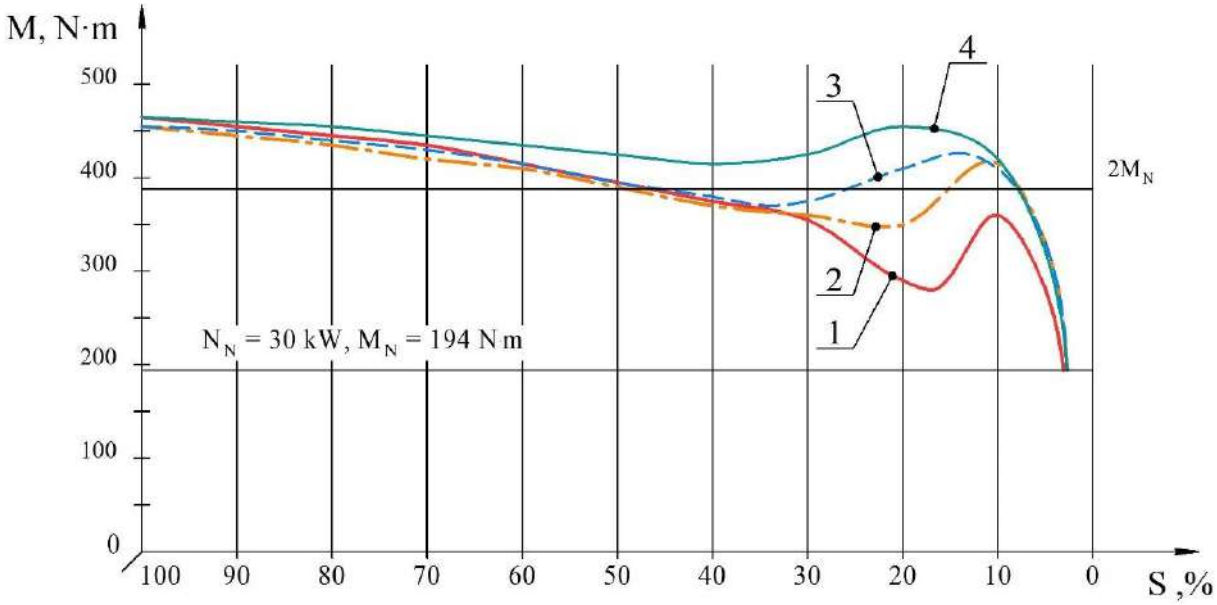


Fig. 11. Static characteristics of the fluid coupling GPE345U with a 5.3 dm³ (l) fluid fill at different emulsol concentrations: 1 – torque curve at 1.5% concentration; 2 – torque curve at 3% concentration; 3 – torque curve at 5% concentration; 4 – torque curve at 10% concentration.

In Tables 2 and 3, parameters that do not meet the performance requirements for scraper conveyor drives are highlighted in red. It is evident that operating fluid couplings with emulsions of 1.5...3% concentration fails to satisfy several criteria—see formulas (6), (7), and (8). Therefore, fluid coupling operation can be recommended with emulsions containing a Solcenic PL PLUS emulsol concentration of 5...10%.

The greatest deviations in the mechanical characteristics at low emulsol concentrations are associated with the occurrence of a "dip" on the unstable part of the mechanical characteristic at a slip of 10...40%. This is a negative phenomenon that leads to inefficient performance during transient modes–drive startup (especially under a coal overload) and operation with overloads.

Table 2. Mechanical characteristics of the fluid coupling GPE345U. Operating fluid: Solcenic PL PLUS water emulsion at concentrations of 1.5, 3, 5, and 10%. Fluid coupling fill volume: 4.9 dm³ (l). Nominal load: N_N = 22 kW, M_N = 142.5 N·m.

Concentration	S_N, %	$M_{10\%}$, N·m	M_{MAX}, N·m	M_{MIN}, N·m	$M_{100\%}$, N·m	T_{ST}, s	M_{ST}, N·m	M_{DYN}, N·m
1,5%	2,9	310 (2,18M_N)	310 (2,18M_N)	200 (1,4M_N)	430 (3,02M_N)	17	385 (2,7M_N)	490 (3,44M_N)
3%	2,9	250 (1,75M_N)	315 (2,21M_N)	215 (1,51M_N)	425 (2,98M_N)	16	385 (2,7M_N)	498 (3,5M_N)
5%	2,9	370 (2,6M_N)	380 (2,67M_N)	305 (2,14M_N)	440 (3,09M_N)	11	396 (2,78M_N)	500 (3,5M_N)
10%	3,0	370 (2,6M_N)	395 (2,77M_N)	357 (2,51M_N)	400 (2,81M_N)	11	390 (2,74M_N)	470 (3,3M_N)

Table 3. Mechanical characteristics of the fluid coupling GPE345U. Operating fluid: Solcenic PL PLUS water emulsion at concentrations of 1.5, 3, 5, and 10%. Fluid coupling fill volume: 5.3 dm³ (l). Nominal load: N_N = 30 kW, M_N = 194 N·m.

Concentration	S_N, %	$M_{10\%}$, N·m	M_{MAX}, N·m	M_{MIN}, N·m	$M_{100\%}$, N·m	T_{ST}, s	M_{ST}, N·m	M_{DYN}, N·m
1,5%	3,1	360 (1,86M_N)	360 (1,86M_N)	280 (1,44M_N)	465 (2,4M_N)	12,5	445 (2,29M_N)	538 (2,77M_N)
3%	2,7	415 (2,14M_N)	415 (2,14M_N)	347 (1,79M_N)	455 (2,35M_N)	11	435 (2,24M_N)	510 (2,63M_N)
5%	2,8	410 (2,11M_N)	425 (2,19M_N)	370 (1,91M_N)	455 (2,35M_N)	10,5	435 (2,24M_N)	528 (2,72M_N)
10%	2,7	425 (2,19M_N)	455 (2,35M_N)	415 (2,14M_N)	465 (2,4M_N)	9,5	450 (2,32M_N)	528 (2,72M_N)

The shape of the "dip" and the minimum torque M_{MIN} clearly depend on the emulsol concentration. At the same time, the highest quality mechanical characteristics, featuring small drops in torque M at a slip S = 10...100 %, were observed at high concentrations (curves 3 and 4). Run-up efficiency is indicated by the parameter T_{ST} (start-up time to nominal speed). Increasing the emulsion concentration from 1.5% to 10% reduces the start-up time by 25...35%. As noted previously, the startup was performed under a load of 0.6...0.8 M_N. Under real operating conditions with a nominal load, and even more so when starting a conveyor under overload, the start-up time, excess energy losses, and fluid coupling overheating will differ significantly across concentrations. This will crucially affect the conveyor's tractive characteristics and drive reliability. The parameter M_{MIN} serves as an indicator of the conveyor's capability to start under an overload. As the emulsol concentration in the operating fluid increases, it rises:

- with a 4.9 dm³ fill volume and N_N = 22 kW from 1,4M_N to 2,5M_N
- with a 5.3 dm³ fill volume and N_N = 30 kW from 1,44M_N to 2,14M_N

Based on the obtained data, the relationships between the mechanical characteristics and the operating fluid concentration have been plotted.

Fig. 12 shows that the torque values, especially during transient operating modes of the fluid coupling, are a function of both emulsion concentration and viscosity. A rather

unexpected result was that higher torque is achieved with emulsions of high concentration and viscosity. In classical sources, lower viscosity values should correspond to higher torque values due to lower internal friction losses. However, during our research, we obtained the opposite result.

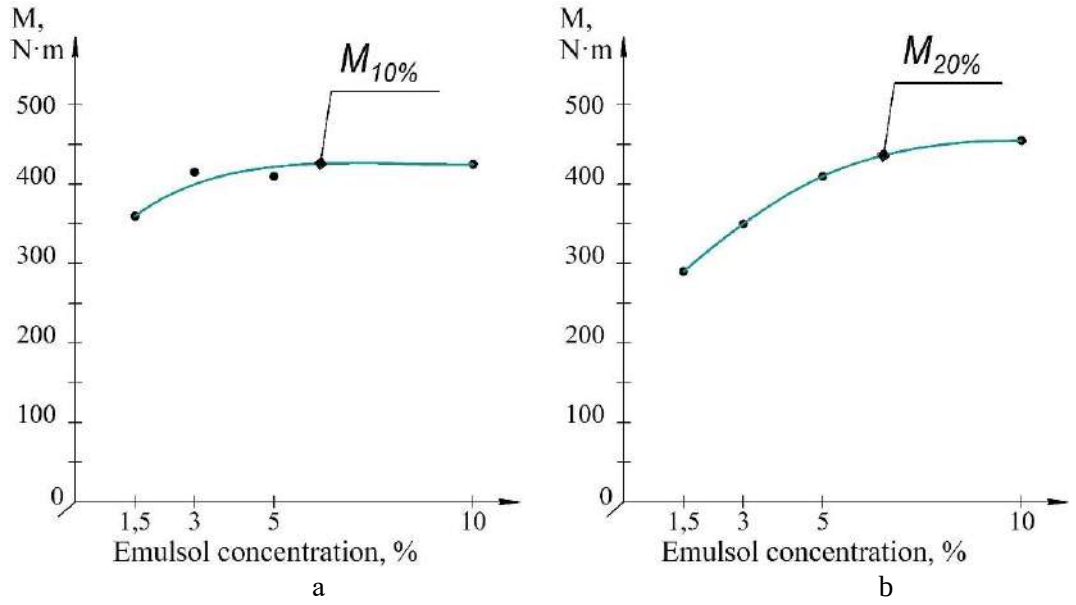


Fig. 12. Dependence of the torque transmitted by the fluid coupling (5.3 dm³ fluid fill) on the emulsol concentration: a – at 10% slip; b – at 20% slip.

This may be caused by several factors:

– easier discharge of the low-viscosity fluid into additional chambers, which are designed into the fluid coupling to limit torque [2, p. 187], at lower emulsol concentrations;

– deviation of HFA-E type emulsion properties from the classical properties of Newtonian fluids (according to [21], oil-in-water emulsions exhibit non-Newtonian properties at oil concentrations of 5...80%);

– the Toms effect [22], which states that polymer substances added to water reduce fluid friction against the walls, smooth out surface defects, and dampen turbulent pulsations in the fluid flow. These facts require verification and further research to develop a more accurate physical model of the processes occurring during fluid coupling operation with HFA-E type operating fluids.

Conclusions.

An analysis of prior research into improving power drives for mine conveyors indicates that the most promising and relevant approach to enhancing fluid coupling efficiency and reliability is the use of HFA-E type water emulsions as an operating fluid. This area remains insufficiently explored and requires a comprehensive set of studies aimed at investigating fluid coupling characteristics depending on the percentage composition of water emulsions.

Based on the mechanical characteristics of the GPE345U fluid coupling obtained during exploratory bench testing, it can be asserted that at an emulsion concentration of 10%, the fluid coupling operates with maximum efficiency according to the following parameters:

– maximum utilization of the electric motor's traction characteristics due to a high torque value M_{MAX} on the operating section of the mechanical characteristic;

– smooth acceleration of the conveyor chain, without oscillations, including startup under maximum load of the transported material;

– minimum heating of the operating fluid during startup due to the absence of a "dip" in the mechanical characteristic, which ultimately increases the operational reliability of the fluid coupling and reduces power consumption.

These findings show that using Solcenic PL PLUS emulsion as the operating fluid improves conveyor efficiency. Increasing the emulsol concentration from 1.5–5% (the standard for hydraulic roof supports) to 10% significantly boosts scraper conveyor performance and reliability.

Further research should focus on how viscosity, which depends on emulsol concentration, affects torque and slip across operating modes. Additionally, developing physical models and calculation methods for fluid coupling traction characteristics using HFA-E emulsions holds both scientific and practical value.

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ОБГРУНТУВАННЯ МЕТОДУ ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТА НАДІЙНОСТІ ГІДРОМУФТ ПРИВОДІВ ШАХТНИХ КОНВЕЄРІВ ПРИ ЗАСТОСУВАННІ В ЯКОСТІ РОБОЧОЇ РІДИНИ ВОДНИХ ЕМУЛЬСІЙ

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Анотація

Статтю присвячено актуальній інженерній проблемі підвищення надійності та експлуатаційної ефективності запобіжно-пускових гідромуфт з постійним заповненням, які використовуються у приводах шахтних скребкових конвеєрів. Проведено комплексний порівняльний аналіз різних робочих рідин для забезпечення вимог пожежної безпеки та оптимізації ключових експлуатаційних параметрів в умовах шахт, небезпечних за газом та вугільним пилом. Головною метою цього дослідження є встановлення закономірностей між механічними характеристиками гідромуфт та властивостями (концентрацією) водомасляних

емульсій класу HFA-E.

Експериментальні дослідження виконано на лабораторному випробувальному стенді з використанням серійної гідромуфти ГПЕ345У виробництва заводу «Світло шахтаря» (Україна). Методика випробувань передбачала оцінку роботи гідромуфти для двох різних об'ємів заповнення рідиною (78% та 85% від повного об'єму внутрішньої порожнини), що відповідає роботі у приводах з асинхронними електродвигунами потужністю 22 кВт та 30 кВт. Склад рідини варіювався за об'ємною концентрацією емульсолу Solcenic Pl Plus (виробництва FUCHS Petrolub SE, Німеччина) – 1,5%, 3%, 5% та 10%.

Експериментальні дані показали, що збільшення концентрації емульсолу суттєво покращує механічні характеристики під час критичних та перехідних режимів роботи, таких як запуск конвеєра та режимів перевантаження. Визначено, що вища концентрація емульсолу усуває падіння («провал») крутного моменту в цих режимах роботи, що призводить до мінімізації нагрівання рідини та марних втрат енергії, тим самим знижуючи ризик спрацьовування теплового захисту. Кількісно, перехід від 1,5% до 10% концентрації емульсії підвищує перевантажувальну здатність привода з 1,4...1,5M_H до 2,1...2,5M_H, що відповідає вимогам для приводів забійних скребкових конвеєрів.

Наукова новизна отриманих результатів полягає у виявленні реологічних відхилень від класичних законів ньютонівських рідин у поведінці водомасляних емульсій в проточній частині гідромуфти. Практична цінність результатів полягає в технічному обґрунтуванні використання 10%-ї емульсії типу HFA-E як оптимальної робочої рідини. Впровадження такої концентрації рідини економічно доцільне та забезпечує суттєве підвищення енергоефективності й довговічності як самої гідромуфти, так і всієї приводної системи шахтного скребкового конвеєра.

Ключові слова: гідродинамічний привід, гідромуфта постійного заповнення, шахтний скреперний ланцюговий конвеєр, механічна характеристика, масловодна емульсія, HFA-E, робоча рідина, концентрація.