

This paper reports a study into the possibility of using the chassis of combine-harvesters as a mobile energy device. The operational requirements for mobile energy technological devices for general purposes have been developed.

The traction-coupling characteristics of the combine-harvester with an adapter that increases traction force have been investigated.

The theoretical dependences have been derived of the motion speed, the power on a hook, the specific fuel consumption, as well as a factor of loading the wheels of the driven axle, on the traction force on the hook of an energy-technological device.

It is noted that the use of the controlled axle with drive wheels reduces the slippage of the engines of the energy technological device. At the engine slippage level of up to 16 % an energy device, equipped with a driven axle with drive wheels, generates a traction force on the hook of up to 40 kN. Under the conditions of driving the axle by the hydraulic transmission mainline, the motion speed of an energy device decreases by 17.9 %, 28.5 %, 35.9 %, and 49.0 %, respectively, on gears I, II, III, and IV of the drive axle gearbox.

The power on the energy device's hook is increased due to the corresponding increase in traction effort: on gear III, at a traction effort within 35–40 kN, the capacity on the hook is 68–75 kW. Under these conditions, the specific fuel consumption is 430–460 g/kWh at the device's motion speed within 1.9–1.95 m/s.

The limits for changing the load factor on the wheels of the driven axle (not less than 0.2) have been determined, at which the requirements for control over an energy device are met.

The specific fuel consumption (540–580 g/kWh) by a combine-harvester with a throughput capacity of 9–11 kg/s has been established, when using it as an energy technological device for general purposes at a motion speed of 1.7–2.1 m/s and a traction effort on the hook of 24–33 kN

Keywords: combine-harvester, energy technological device, operational requirements, traction-coupling properties, adapter

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DEVELOPMENT OF OPERATIONAL REQUIREMENTS FOR SELF-PROPELLED COMBINE-HARVESTERS WITH THE CAPABILITIES OF MOBILE ENERGY DEVICES

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1. Introduction

The principle of modular-block design of machines and various technical assemblies is known and widely used in the industries involving the application of machines. This is carried

out in order to build universal mobile energy devices (UMED). These means execute numerous technological operations employing the variable modules installed in them.

In agriculture, one of the designs of the modular-block type is a combine-harvester. It consists of a powerful self-pro-

pelled energy device containing the chassis, engine, hydraulic system, cabin, automated control system. An energy device hosts variable modules for harvesting various crops: corn, sunflower, legumes, soybeans, lupin, rape, cereals, sorghum, herb seeds, etc. In addition, for harvesting grain by different technologies, reaping machines are used of the appropriate capture width, as well as pickers and tools for the non-grain part of the crop (shredder, accumulator, roller).

However, despite a rather large degree of the universalization of the energy device for a combine-harvester, this modular-block structure has a significant disadvantage – the total utilization over the year does not exceed three months. The seasonality of agricultural work imposes restrictions on the utilization of agricultural machinery during the year. This also applies to fodder- and beetroot-harvesting combines. The most attractive solution to this issue is the construction of universal traction-type energy devices. These tools should be easily adjusted to a set of variable modular-block structures. The use of energy devices with interchangeable modular-block structures would make it possible to execute the entire volume of operations relating to the cultivation and harvesting of grain crops, corn, sugar beet, to cargo-transporting operations and fertilization. Ultimately, this could improve efficiency and reduce the cost of production.

The above proposals to use, in the off-season, combine-harvesters as universal energy devices also include the following. An analysis of the principles of control and the structure of combine-harvesters and energy devices has established the universality of approaches to their synthesis. The high level of unification also characterizes their transmissions. Based on the above, it is a relevant issue to systematically coordinate the possible production of combine-harvesters and energy devices for general purposes under the same technological conditions at the same production facilities.

2. Literature review and problem statement

Discussions of and research into the priorities in the production of mono combine-harvesters or universal, multi-functional energy devices began at the end of the last century [1]. Given the technical level of the marked period in the development of the sectors of the national economy, engineering, chemical, electronic industry, no desired results were achieved. Several variants of self-propelled chassis were built to be subsequently used as vehicles. Such solutions were substantiated because the transportation of cargoes during agricultural operation accounts for about 70–80 % of all costs of the production process [2]. Over the years, this scientific and practical problem was further advanced. This is confirmed by the Terra-Trac TT350 energy device made by HORSCH (Germany), designed for the application of liquid mineral and organic fertilizers. These productive units were developed on the basis of motor transport modules. They were mostly used in the U.S. and Europe [3].

The volume of studies into the issues of universalization and increasing the utilization of powerful energy devices, fodder- and beet-grain harvesting modules to them, has been significantly reduced recently. This is largely caused by the lack of innovative design solutions, the difficulties of implementing, at the modern technical level, the components of the modules of modular-block systems. The results of work relating to the construction of universal mobile energy devices (UMED) and modular-block complexes (MBC) were

implemented in the form of the XERION UMED made by CLAAS (Germany) [4], the GITRAC 300 MBC made by GILLES (Belgium), etc.

Noteworthy are those design solutions, according to which the threshing and separating device of the grain harvesting module is located immediately behind the reaping part, across the movement of the threshing unit. The disabling of the conventional technological tract in the combine-harvester KZR-10 Polesie-Rotor has made it possible to build the grain harvesting complex KZR-10 (Belarus) based on the Polesie-250 UMED («Gomsilmash»). The throughput capacity of such a complex is up to 12 kg/s, the productivity of grain threshing is up to 30 t/h; direct costs for grain harvesting are less by 2.5 times compared to the corresponding indicators for the combine-harvester Don-1500. However, the modular-block systems built by the Gomsilmash design bureau were not effective enough, so the production of KZR-10 was eventually suspended.

At the modern level of the technical-technological support to grain production systems, combine-harvesting technologies are fundamentally the most progressive. They make it possible to obtain a product (cereals) directly in the field, and the product itself is characterized by the convenience of transportation and the efficiency of post-harvest processing [6]. Therefore, specialists at leading combine-building companies of the world, in agrotechnical science, and at relevant design organizations direct their efforts to improve combine-harvesters and other technical means for the implementation of mainly combine technology of grain harvesting [7, 8].

Study [9] suggests an approach to solving the issue of the development of tractor energy engineering and agricultural machinery through the implementation of four steps. Those include the construction of the Machine System based on a new type of tractors; the introduction of a system to devise the agrotechnical (output) requirements by those enterprises (firms) that build new agricultural machinery. Implementation of the third step involves the protection of consumer interests by strengthening the system of conformity control of the developed equipment to the declared agrotechnical requirements. The fourth step implies the coordination of research aimed at the construction of new equipment. However, the authors disregarded issues of the possible production of combine-harvesters and tractors at the industrial facilities of the same machine-building enterprise.

Study [10] reports the results of the development of new equipment, which differs in that the authors took into consideration the requirements for the ecophilic properties of the tire. Meeting this requirement makes it possible to maximize the permissible level of pressure of tractor wheels on the ground, taking into consideration the maximum load-bearing capacity of the wheel tires. The practical effectiveness of the new approach was confirmed using an example of determining the possibility and level of ballasting of a particular wheeled tractor, which operates as part of an arable assembly. However, the authors disregarded issues relating to the operational requirements for self-propelled combine-harvesters with the capabilities of mobile energy devices.

The authors of study [11] developed a dynamic model of the combine-harvester's frame as a solid body with 7 degrees of freedom. Comparing the independent modal frequency of the frame chassis and threshing with the frequency of the combine-harvester's frame, it was proved that the constant modal frequency of the loaded combine-harvester is directly related to the independent modal frequency of the chassis frame and

threshing. The vibration reaction of the combine-harvester's frame under the influence of several sources can serve as a guideline for further improvements of the combine-harvester's frame, taking into consideration its possible use as an energy device.

Study [12] describes a system for identifying a new model of the tractor thrust dynamics at higher speeds of its movement. The authors defined the limitations for a tractor driver (operator) when neglecting these dynamics, which can lead to deterioration of tractor handling at the band frequencies required for precise control at greater speeds. However, they disregarded issues of operational requirements for the combine-harvester as a universal energy device. The highlighted information does not apply to the tasks of the work and is not mentioned in the subsequent text of the article.

The monitoring of various ways to improve the productivity of agricultural machinery under conditions of the development of intelligent agricultural production showed [13] that conventional directions of increasing the concentration of energy, the size of working elements, and the movement speed had almost reached their resource capabilities. The power of already existing machines is not fully utilized due to the influence of the human factor. The study established a real possibility of creating an automated control and regulation system. If the operator is excluded, it is possible to improve the efficiency of a machine from 10 to 50 percent depending on its type. Some recommendations on the structure of priorities of automatic devices are given and the basic principles for understanding intelligent combine-harvesters are formulated. However, the authors disregarded an issue relating to the universalization of combine-harvesters.

The increase in the scientific and technical level of industry has rendered more relevance to the issue of constructing universal energy devices, which are saturated with the following properties:

- the reliability and durability of work and maintenance;
- the possibility to operatively, with an acceptable level of difficulty, convert one modular-block structure to another;
- maximum annual operating load (an increase, compared to an existing one, by 2.5–3.0 times);
- a sufficient volume of free zones due to successful design and technological solutions: multi-positioning location of the cab, free space in the inter-axle zone and around the cabin, the side position of the engine, etc.

Numerous literary data of assembling combine-harvesters with peelers, seeders, straw presses, roller harvesters, forklifts, snowmobiles indicate the possibility of their application for operations that are inappropriate to a combine-harvester [14, 15]. It is appropriate to pay attention to the possibility of using the chassis of combine-harvesters (both with and without working bodies) as a mobile energy device. Under such conditions, it is used as a tractor to execute agrotechnological operations in farming [16]. This feature leaves hope for increasing the level of universalization and unification of not only the components of the combine-harvester and tractor, built on the basis of the combine-harvester's chassis but also the unification of the production technologies of these machines [17].

3. The aim and objectives of the study

The aim of this study is to devise operational requirements for self-propelled combine-harvesters with the capabilities of mobile energy devices for general purposes. Such solutions would make it possible to improve the efficiency of

crop production, the level of universalization and unification of the components of combine-harvesters and energy devices built on the basis of the combine-harvester's chassis.

To accomplish the aim, the following tasks have been set:

- to define and elucidate the components of operational requirements for agricultural processors (combine-harvesters with the capabilities of an energy device), their technical and technological characteristics;
- to theoretically investigate the loading of the wheels of an energy technological device, which ensures meeting its handling requirements;
- to establish the impact of engine slippage on a traction effort, as well as the movement speed of an energy device with a driven axle when it is driven by the mainline of hydraulic transmission;
- to establish the impact of a traction effort on the power value on the hook of an energy device at its motion speed within 1.9–1.95 m/s;
- to determine the specific fuel consumption by the combine-harvester with a throughput capacity of 9–11 kg/s as an energy technological device at a motion speed of 1.7–2.1 m/s.

4. Materials and methods to study the operational requirements for self-propelled combine-harvesters with the capabilities of mobile energy devices

A combine-harvester is a self-propelled grain-harvesting machine that executes consistently, as a continuous sequence, and simultaneously a series of technological operations. They include cutting the plant, feeding it to the threshing unit, threshing grain from spikelets, separating it from the heap and other impurities, transporting clean grain into the hopper, and mechanical discharge from it, laying waste after the work of the combine-harvester on the ground.

The main requirements for combine-harvesters are regulated by DSTU 7454:2013 «Combine-harvesters. General technical requirements» and ISO/DIS 8210 Equipment for harvesting – Combine-harvesters – Test procedure and performance assessment. International ISO standards are also required. The basic technological parameters are the rated performance and the throughput of combine-harvesters.

The base of an energy technological device is a combine-harvester thresher with a sloping chamber and a trailer device, which is assembled, when harvesting crops, with reaping units, roller pickers, trailers-diggers, etc.

To perform the functions non-inherent in the combine-harvester, that is, to supplement it with agricultural machines and tools, its structure is complemented with certain systems. These systems make it possible to attach devices in the form of removable adapters: frontal, rear, attachable adapters to increase traction effort, adapters to reduce the specific pressure on the ground with an attachable device, adapters to reduce the specific pressure on the ground with an attached device and a steering mechanism.

Operational requirements for an agricultural processor (a combine-harvester with operational capabilities of a mobile energy device) have been determined by generalizing relevant requirements for combine-harvesters and tractors (the hybrid requirements for an agricultural processor).

The basic operational requirements for an agricultural processor are divided into four groups:

- the requirements that determine the technical and economic indicators, in particular, productivity and efficiency;

- the requirements inherent in an agricultural processor as a mobile machine;
- the requirements of a general technical nature;
- special requirements that characterize the adaptability of an agricultural processor to meeting the special conditions of its operation.

The performance of an agricultural processor depends on the area treated by the assembly with appropriate agricultural machines per unit of time, provided that the specified performance indicators are maintained.

The efficiency of an agricultural processor is defined by the cost of operations performed and depends on the amount of fuel consumption, lubricants, and their cost, wage costs, maintenance and repairs, depreciation, and a series of other costs.

Among the groups of requirements inherent in mobile machines, the handling, maneuverability, and safety of movement are especially important for an agricultural processor. The ability to meet these requirements depends heavily on the structural features of the machine, its turnability, stability, braking properties, etc.

The most important, in terms of the general technical requirements for an agricultural processor, is the strength and durability, ease of maintenance and repair.

Among the special operational requirements, we highlight the considered agrotechnical requirements, which determine the adaptability of the agricultural processor to the technological requirements for agricultural production.

The basics of the theory of ensuring operational requirements for the agricultural processor are developed on the basis of the appropriate mechanic and mathematical models, which account for the static, kinematic, and dynamic features of it [18].

Underlying the theory of ensuring operational requirements for an agricultural processor is the generalized requirements for tractors and combine-harvesters.

The analytical study of the structure, kinematics, and dynamics of new energy devices and assemblies on their basis was conducted using the methods of theoretical mechanics. The experimental study involved combine-harvesters with a throughput capacity of 9–11 kg/s.

We determined the traction characteristics of the agricultural processor in accordance with GOST 26025-83 and ISO 789-9:2018 Agricultural tractors – Test procedures – Part 9: Power tests for drawbar.

To calculate the technical and operational indicators of MTA (machine-tractor assemblies) based on the agricultural processor, we applied the experimental and theoretical methods to determine the static normal reactions of the wheels of the combine-harvester to the supporting surface. To this end, we measured the reactions of the supports installed under the beam of the combine-harvester's axle at a certain distance from the flange connections of the onboard reducers. In the combine-harvester, placed on the horizontal plot, we alternately (left or right), with the help of jacks, raised the beam of the axle until the hanging of wheels, and placed one side on a rigid support. On the other side of the beam, we placed a jack with a compression dynamometer mounted on it. The jack set the beam to a horizontal position and recorded the micromanometer indicator readings.

Based on the results of our measurements and calculations, we determined the values of the pressure force of the wheels of the combine-harvester KZS-9-1 «Slavutych» to the supporting surface in the statistics, which are: front left wheel – 43.7 kN, front right – 42.6 kN, rear left – 26.8 kN, rear right – 27.4 kN.

The power that can be transferred to the wheeled engines of combine-harvesters is limited to the parameters of the hydrostatic transmission units (the axial plunger pump and motor). The combine-harvesters KZS-9-1 «Slavutych», «Skif 230», made at TOV NVP «Kherson Machine-Building Plant» (KhMZ), are equipped with hydraulic assemblies, the type of GST-112. These units are produced under the license from the company «Sauer-Sundstrand» by AT «Hydrosila». The maximal working volume of the pump GST-112 is 110.8 cm³, the maximum feed is 391.6 l/min, the maximum pressure is 42 MPa. The John Deere's S550 combine-harvesters are equipped with the model 64 hydraulic assemblies made by Eaton Corporation. The maximal working volume of the 64-model pump is 105.5 cm³, the maximum feed is 375 l/min, the maximum pressure is 41.5 MPa. Given the weight of the above combine-harvesters of about 14 tons, one should expect similar traction characteristics.

5. Development of the basic provisions of operational requirements for an agricultural processor (combine-harvester with the capabilities of a mobile energy device)

For an energy technological device to execute operations inappropriate to combine-harvesters, it must meet certain operational requirements set for the tractors for general purposes.

The basic operational requirements are:

- engine power and the power used for the thrust of agricultural machines and to drive their working bodies into operation;
- the range of working motion speeds;
- the fuel consumption per hour of operation;
- the maneuverability and stability of movement;
- the convenience of assembly and maintenance;
- the reliability and durability of basic parts and assembly units and their reparability;
- the degree of unification of assembly units with other tractors, self-propelled chassis, and combine-harvesters.

The requirements are aimed at ensuring the high productivity of an energy device; they must be met in conjunction with the agrotechnical requirements.

We highlight the agrotechnical requirements for agricultural energy devices for general purposes:

- ensuring the movement of machines on any surface;
- observance of the required ranges of a traction effort and a movement speed, as well as maneuverability;
- the minimal harmful effects of the running part on the soil;
- high-quality execution of technological processes.

The quantitative characteristics of the basic agrotechnical requirements are as follows:

- the slippage of engines in the tracked energy devices and in the wheeled energy devices with two and four drive wheels should be no more than 3, 14, and 16 %, respectively;
- the permissible pressure of engines on the ground is no more than 45 kPa for tracked machines and 110 kPa for wheeled machines;
- the ground clearance (the shortest distance vertically from the supporting surface to the elements of a tractor's structure) should be at least 36 cm for tracked tractors and 47 cm under the rear axle for universal tillage tractors;
- the agrotechnical clearance (the vertical distance from the supporting surface to the least distant elements of a tractor's structure above the line of crops) should equal 40–55 cm for the main low-stem crops (potatoes, beets, etc.), and

65–75 cm (with a portal design of the frame) for high-stem crops (corn, sunflower, etc.);

- the protective zone (the distance horizontally from the middle of the row to the edge of the wheel or the caterpillar of the tractor; it depends on the phase of plant development and the type of treatment) under the conditions of cultivation crops should equal 12–15 cm (minimum);

- the track and overall dimensions of an energy device should provide for the mutual structural link to the assembled agricultural machines;

- the smallest turning radius of an energy device should equal 3–4.5 m for the wheeled universal tillage tractors, 6.5–7.5 m for the wheeled tractors for general purposes, and 2–2.5 m for the tracked machines;

- protective devices against rollover, inclinometer, and a system that signals the reaching of the inclination angle that is the limit in terms of stability.

5.1. Studying the traction and coupling indicators of a combine-harvester with the capabilities of a mobile energy device for general purposes

The performance of a machine-tractor assembly (MTA) depends on a series of factors. The basic ones include the following: the traction and coupling characteristics of an energy device, engine power, operational mass, power on the hook and on the drive of the working bodies of agricultural machines, traction and complete efficiency, traction efforts on the hook, motion speed, etc.

There is a dependence between the operational weight of an energy device and the traction effort on the hook:

$$F_H = G \cdot \lambda_p \cdot \varphi_H, \tag{1}$$

where G is the operating weight of an energy technological device, N; F_H is the traction effort on the hook of an energy device, N; λ_p is the load factor on the engines of an energy device during its uniform movement with a traction effort on the hook; φ_H is the coefficient of usable utilization of the adhesion of engines (for wheeled, 0.4; for tracked, 0.5).

We have established dependences (2) of the value of load factors on the wheels of the drive λ_1 and the driven λ_2 axles of an energy device on the basic parameters. These include: the wheel (longitudinal) base L , the distance from the center of gravity to the axis of the drive wheels of the device l , the moment of resistance to the rolling of the driven M_{R1} and drive M_{R2} wheels, the traction resistance of the machine assembled with an energy device F_H , the angle of inclination to the surface of the field in the longitudinal plane of the smooth traction resistance of the assembled machine γ , the vertical coordinate of the traction effort application point h_H .

$$\begin{aligned} \lambda_2 &= \frac{L-l}{L} - \frac{M_{R2} + M_{R1} + F_H \cdot h_H}{G \cdot L} = \\ &= \lambda_{c2} - \frac{M_{R2} + M_{R1} + F_H \cdot h_H}{G \cdot L}, \end{aligned} \tag{2}$$

$$\begin{aligned} \lambda_1 &= \frac{l}{L} + \frac{M_{R2} + M_{R1} + F_H \cdot (h_H + L \cdot \text{tg}\gamma)}{G \cdot L} = \\ &= \lambda_{c2} + \frac{M_{R2} + M_{R1} + F_H \cdot (h_H + L \cdot \text{tg}\gamma)}{G \cdot L}. \end{aligned} \tag{3}$$

Analyzing dependences (2), (3), we note that the redistribution of loads acting on the wheels of the drive and driven axles of an energy technological device is largely affected by

the value of traction resistance, generated by the assembled agricultural machine. With an increase in the traction resistance, the value of the load factor on the wheels of the drive axle λ_2 will decrease, which can cause deterioration of the adhesion characteristics of an energy technological device.

To build the traction characteristic, we calculated the external speed characteristic of the engine in the combine-harvester KZS-9-1 «Slavutych». Note that a characteristic feature of the combine-harvester’s transmission is that the rated power of its engine is 20 % higher than the maximum capacity of the pump in the hydro-volume transmission GST-112. Therefore, we calculated only the right-hand side of the speed characteristic of the engine of an energy device (SMD-31A) [19].

The calculation of engine performance indicators during the movement of an energy device was carried out at idling on different gears and values of the parameter of regulation of the pump in a hydro-volume transmission.

The value of the traction effort on the hook of an energy device was determined from the following dependence:

$$F_H = \frac{i \cdot \eta_{TP}}{r_2} \cdot M - G \cdot f, \tag{4}$$

and apparent speed

$$v = \left(1 - \frac{\delta}{100}\right) \cdot \omega \cdot \frac{r_2 \cdot i_H}{i}, \tag{5}$$

where δ is the slippage of engines, %; f is the coefficient of resistance to rolling; i is the transfer ratio of the transmission on the corresponding gear; i_H is the parameter of regulation of the pump in a hydro-volume transmission; r_2 is the rolling range of the drive wheels, m; η_{TP} is the efficiency of the transmission of an energy technological device.

Based on the results of our calculations, we derived the indicators of traction characteristics for the combine-harvester KZS-9-1 «Slavutych». This combine-harvester can be used as an energy device provided it is operated on different transmissions and different values of the parameter of regulation of the pump in a hydro-volume transmission when driving on the stubble of grain crops (Fig. 1). Solid lines show the indicators of traction characteristics for the combine-harvester at the value of regulation parameter $i_H=1$, dashed lined – $i_H=0.75$.

Analyzing the dependences (Fig. 1), we note that the combine-harvester KZS-9-1 «Slavutych», when used as an energy device, will provide a traction effort within 25–32 kN. Under these conditions, the specific fuel consumption on gear II of the combine-harvester in this range would equal 530–560 g/kWh, and the power on the hook would equal 50–62 kW at an MTA’s motion speed of 1.8–2.0 m/s.

Taking into consideration the structural features of the combine-harvester KZS-9-1 «Slavutych» (the motor-propulsion unit arrangement in the tail part of the combine-harvester), in the absence of a reaping machine, there is significant unloading of the front drive wheel and loading of the rear axle of the combine-harvester. Under these conditions, the load factor on the engines of an energy device would equal $\lambda_p=0.56$ –0.59. The increase in the specific fuel consumption is also due to the use of a full flow hydro-volume transmission, which, under certain modes, reduces the total efficiency of the transmission of an energy device by 10–15 %.

It is noted that the increase in the efficiency of using a combine-harvester as an energy device is due to the increase in the load factors on the engines.

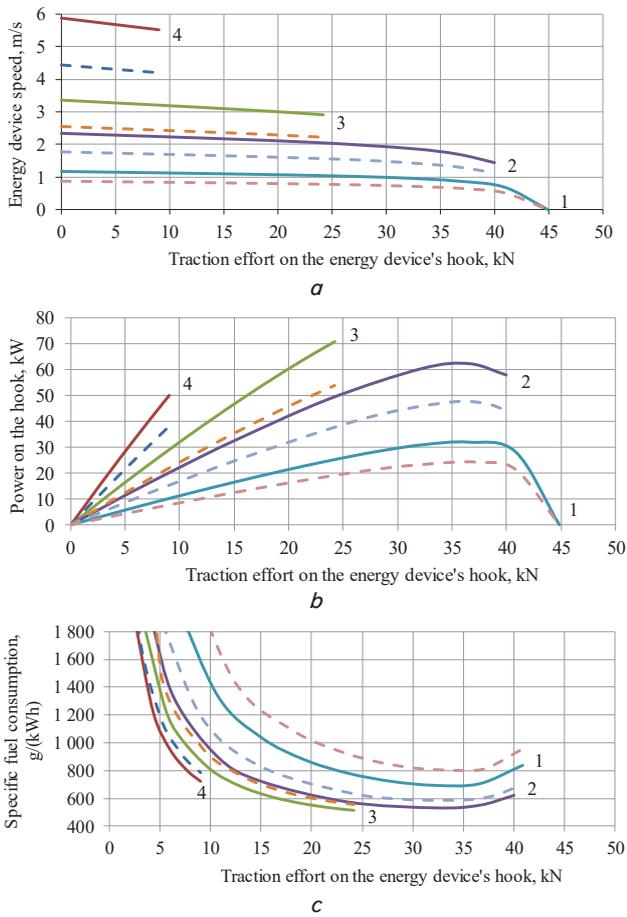


Fig. 1. Dependence of the impact of the traction effort on the hook of the combine-harvester KZS-9-1 «Slavutych» as an energy device on the technical-economic indicators: *a* – motion speed; *b* – power on the hook; *c* – specific fuel consumption; 1, 2, 3, 4 – gears in the transmission of the drive axle

To operate under severe conditions on waterlogged soils, especially when harvesting rice, the designs of four-wheel drive combine-harvesters are used. In the combine-harvesters of this type, the drive of the wheels of the driven axle is carried out by the high-torque rotor-piston hydraulic motors.

We have established the dependences to determine the frequency of rotation of the shafts of hydraulic motors of the driven and drive wheels (6), (7) of an energy device, the torques of the driven and drive axles (8), acquired from the shaft of the hydraulic motor, which depend on its working volume and the pressure of working fluid in the system, as well as a traction effort on the hook of an energy device with the drive driven axle (9):

$$n_{M2} = \frac{\left(1 - \frac{\delta_1}{100}\right) \cdot r_1 \cdot i}{\left(1 - \frac{\delta_2}{100}\right) \cdot r_2} \cdot n_{M1}; \quad (6)$$

$$n_{M1} = \frac{i_H \cdot V_{OP} \cdot n_H}{2 \cdot V_{OM1} + V_{OM2} \cdot \frac{\left(1 - \frac{\delta_1}{100}\right) \cdot r_1 \cdot i}{\left(1 - \frac{\delta_2}{100}\right) \cdot r_2}}; \quad (7)$$

$$M_{K1} = \frac{V_{OM1} \cdot \Delta p \cdot \eta_{MM1}}{\pi};$$

$$M_{K2} = \frac{V_{OM2} \cdot \Delta p \cdot \eta_{MM2} \cdot \eta_{TP} \cdot i}{2 \cdot \pi}; \quad (8)$$

$$F_H = \frac{M_{K1}}{r_1} + \frac{M_{K2}}{r_2} - G \cdot f, \quad (9)$$

where V_{OP} , V_{OM1} , V_{OM2} are the working (structural) volumes of the pump, hydraulic motors of the wheel drives of the driven and drive axles, respectively, cm^3/rev ; n_P , n_{M1} , n_{M2} is the frequency of rotation of the shafts of the pump and hydraulic motors, respectively, min^{-1} ; δ_1 , δ_2 is the slippage of wheels of the driven and drive axles, %; r_1 , r_2 are the rolling radii of the wheels of the driven and drive axles, m.

Based on the results of our calculations, we have built the traction characteristic of the combine-harvester KZS-9-1 «Slavutych», equipped with a driven axle with drive wheels. The specified combine-harvester can be used as an energy device (Fig. 2) under the conditions of its operation on different gears and values of the parameters of regulation of the pump in a hydro-volume transmission when driving over the stubble of grain crops (the value of the regulation parameter is $i_H=1$).

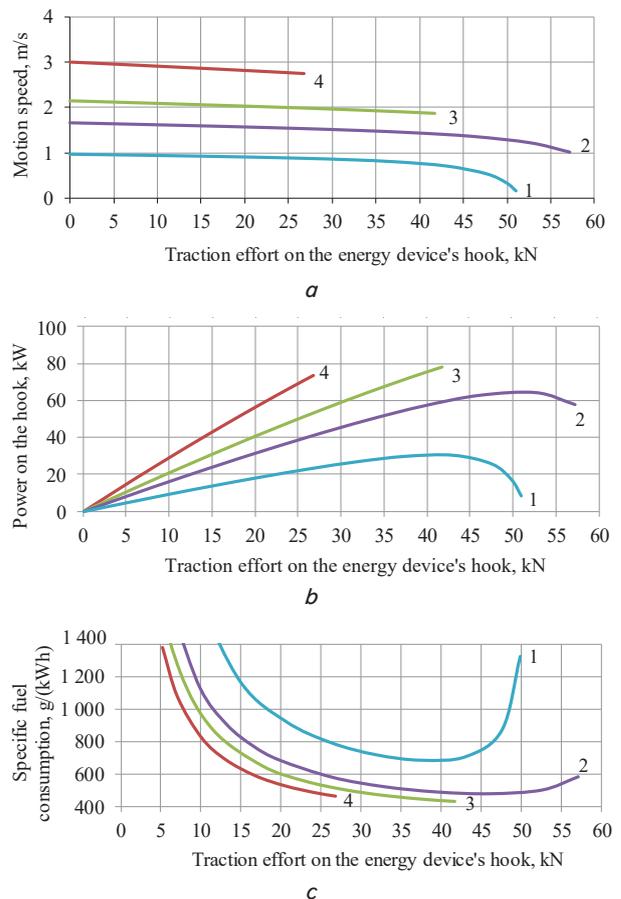


Fig. 2. Dependence of the impact of the traction effort on the hook of the combine-harvester with a throughput capacity of 9–11 kg/s (an energy device), equipped with a driven axle with drive wheels, on the technical-economic indicators: *a* – motion speed; *b* – power on the hook; *c* – specific fuel consumption; 1, 2, 3, 4 – gears of transmission in the drive axle gearbox

Analyzing the dependences in Fig. 2, we note that the use of a driven axle with drive wheels reduces the slippage of an energy technological device. At the level of slippage of engines of up to 16 %, a combine-harvester, equipped with a driven axle with drive wheels, develops a traction effort on the hook of up to 40 kN.

However, the use of a driven axle with drive wheels, if it is driven by the mainline of the combine-harvester’s hydro-volume transmission, leads to a decrease in the movement speed of the combine-harvester. This decrease amounts to 17.9 %, 28.5 %, 35.9 %, and 49.0 %, respectively on gears I, II, III, and IV of the gearbox of the drive axle of the combine-harvester.

The power on an energy device’s hook is increased due to the corresponding increase in the traction effort: at gear III, at the traction effort within 35–40 kN, the power on the hook is 68–75 kW. Under these conditions, the specific fuel consumption is 430–460 g/kWh at the motion speed of the device within 1.9–1.95 m/s.

5. 3. Studying the traction and coupling indicators of a combine-harvester with an adapter that increases traction effort

We used, as an adapter that increases the traction effort, an axle of the drive wheels with a box of variable gears, an axial plunger hydraulic motor, onboard reducers, and wheels, unified with the drive axle of the combine-harvester.

The schematic of forces acting on the energy device with an adapter is shown in Fig. 3.

The maximum value of the normal dynamic reaction of the wheel of the drive axle of the energy device, interacting with the soil surface, is observed if the contact of the adapter’s wheel with the soil is lost. Under such conditions, at $R_{Y3}=0$:

$$R_{Y2MAX} = \frac{G \cdot (L-l) + G_A \cdot (L+l_1) + M_{R1} + M_{R2} + F_H \cdot h_H + F_H \cdot \text{tg}\gamma \cdot (L+L_1)}{L},$$

$$R_{Y1} = \frac{G \cdot l - G_A \cdot l_1 - M_{R1} - M_{R2} - F_H \cdot h_H - F_H \cdot \text{tg}\gamma \cdot L_1}{L}, \tag{10}$$

and at $R_{Y2}=0$:

$$R_{Y3MAX} = \frac{G \cdot (L-l) + G_A \cdot (L+l_1) + M_{R1} + M_{R3} + F_H \cdot h_H + F_H \cdot \text{tg}\gamma \cdot (L+L_1)}{L+L_1}, \tag{11}$$

where R_{Y3} is the normal dynamic reaction of the adapter’s wheel interacting with the soil surface, at the increased traction effort of the energy technological device, N .

Analyzing dependences (10), (11), we note that the use of the reversible movement of the combine-harvester with an adapter would ensure the redistribution of the normal dynamic reactions, making it possible to additionally load the drive wheels and increase its traction and coupling properties.

We have established the dependence of the load factor (12) on the wheels of the driven axle on the weight of the adapter G_A and the weight of the energy device G , the wheel (longitudinal) base L , the distance from the direction of action of the gravity force of the adapter to the axis of the drive wheels of the device l_1 , the moments of resistance to the rolling of the driven M_{R1} and drive M_{R2} wheels, the traction resistance of the machine, assembled with an energy device, F_H , the vertical coordinate of the traction effort application point h_H , the distance between the axis of the adapter and the axle of the combine-harvester L_1 , the inclination angle to the surface of the field in the longitudinal plane of the equivalent traction resistance of the assembled machine γ , which defines the limits of change in the load factor on the wheels of the driven axle (not less than 0.2), at which it is possible to meet the handling requirements of an energy device.

$$\lambda_1 = \lambda_{c1} - \frac{G_A \cdot l_1 + M_{R1} + M_{R2} + F_H \cdot h_H + F_H \cdot \text{tg}\gamma \cdot L_1}{G \cdot L} \geq 0.2. \tag{12}$$

The structure of an energy technological device includes the unified axles and hydraulic assemblies of the combine-harvester and adapter, as well as an automated control system. This system allows the redistribution of pressure on the soil between the drive axles (the conditions $R_{Y2}=R_{Y3}$ and $R_{X2}=R_{X3}$ are met). The specified conditions are satisfied by maintaining a certain effort by the two-way hydraulic cylinders that lift the combine-harvester’s header. The calculation diagram of the required effort is shown in Fig. 4.

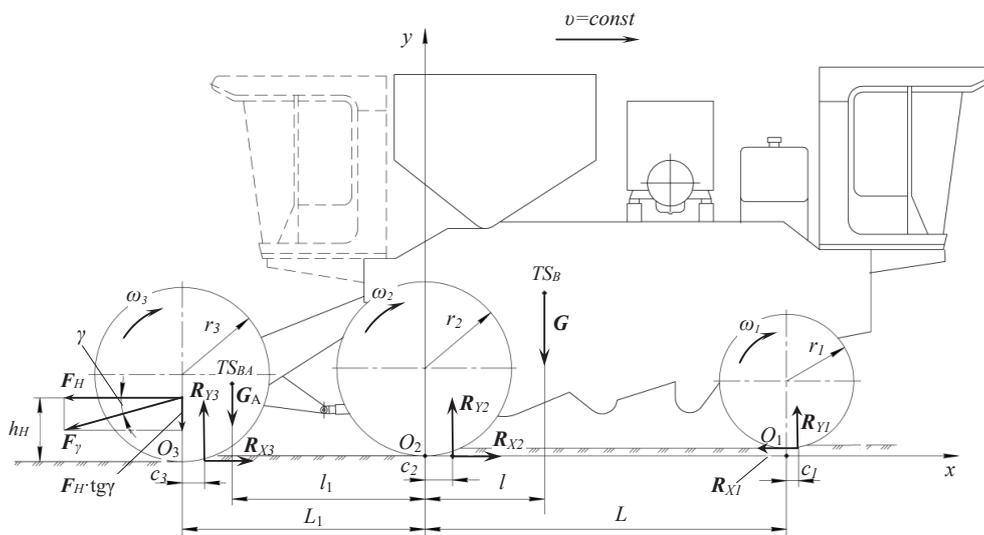


Fig. 3. Schematic of forces acting on the energy device with an adapter to increase the traction effort, in the longitudinal plane at a uniform movement

We have built the principal scheme of the volumetric regulation of a hydro-volume transmission of the energy technological device with an adjustable pump and a hydraulic motor (Fig. 6). The scheme was developed in conjunction with the automated torque adjustment system on the output shaft of the hydraulic motor, which responds to the corresponding fluctuations in the traction resistance values of the agricultural machine. Due to such actions, the ICE operation of an energy device under the modes of the rated power is made possible. Automatic force control of the transmission reduces the specific fuel consumption by MTA if it is used as a traction energy device for general purposes.

The developed principle diagram of an Agricultural processor (a combine-harvester with the possibilities of a mobile energy device for general purposes) is shown in Fig. 7.

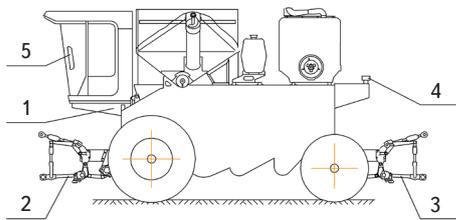


Fig. 7. Diagram of the energy technological device «Agricultural processor»: 1 – mobile thresher; 2 – front-facing attachment; 3 – rear attachment; 4 – camcorder; 5 – monitor

The structure of the unified front and rear attachments was developed. The front-facing attachment is designed as a replaceable adapter installed instead of the combine-harvester's inclined chamber. The rear attachment is unified with the front one and includes an additional cross beam while the mounting elements are unified with the front panels of the threshing machine. The drive of the power take-off shaft is enabled through the wedge-shaped transmissions from the upper counter-drive shaft of the combine-harvester.

We have designed the structure and started the production of the prototype adapters that increase a traction effort and reduce the specific pressure on the soil.

The adapter for increasing the traction effort of an energy technological device is based on the axle with wheels, onboard reducers, variable gearbox, and an adjustable hydraulic motor, unified with the drive axle of the combine-harvester. To drive the wheels of the adapter, the energy technological device may include an axial-plunger pump with a drive from the ICE pulley and the system of main lines with connecting fittings.

To ensure the reverse movement of an energy technological device, it is possible to re-arrange (reverse) the cabin or use two unified cabins.

The energy technological device is equipped with the systems of an automated engine loading control and the uniform pressure distribution between the drive axles of the energy device and adapter. Implementation of reversals at the ends of runs is carried out with the adapter's axle raised.

6. Discussion of the study results aimed at devising operational requirements for an agricultural processor (a combine-harvester with the operational capabilities of a mobile energy device)

Based on the results of our study, the operational requirements for an agricultural processor (a combine-harvester

with the operational capabilities of a mobile energy device) have been developed. It is necessary to note certain limitations regarding their use. They relate to the alignment of operational requirements for the energy and technological means with the relevant requirements for the tractors for general purposes. Given this, it becomes possible for an agricultural processor to execute a significant number of technological operations in farming at a suitable level of technological and economic efficiency.

We have investigated the traction and coupling characteristics of the combine-harvester with an adapter that increases the traction effort. The dependence (Fig. 1) has been derived of the impact of a traction effort on the hook, as well as the dependence (Fig. 2) of the impact of a traction effort on the hook of a combine-harvester with a throughput capacity of 9–11 kg/s (an energy device), equipped with a driven axle with drive wheels, on the technical-economic indicators (motion speed, power on the hook, specific fuel consumption). Analyzing Fig. 1, we note the prospects for the use of the combine-harvester as an energy device provided it is operated on different gears and different values of the parameter of regulation of the pump of a hydro-volume transmission when driving over the stubble of grain crops. Analyzing the dependences of Fig. 2, we note that the use of a driven axle with drive wheels reduces the slippage of engines in the energy technological device. The use of a driven axle with drive wheels, provided it is driven by the mainline of the hydro-volume transmission in a combine-harvester, leads to a decrease in the movement speed of the combine-harvester.

We have derived the theoretical dependences of the motion speed, the power on the hook, the specific fuel consumption, and the load factor on the wheels of the driven axle, on the traction effort on the hook of the energy technological device. Analyzing dependences (10), (11), we note that the use of the reversible movement of the combine-harvester with the adapter would ensure the redistribution of the normal dynamic reactions, making it possible to additionally load the drive wheels and increase its traction and coupling properties. The dependence (12) was established, which made it possible to determine the limits of changing the load factor on the wheels of the driven axle (not less than 0.2), at which the handling requirements for an energy device are met.

We have determined the specific fuel consumption by the combine-harvester with a throughput capacity of 9–11 kg/s as an energy technological device at the unit's motion speed of 1.7–2.1 m/s. It is noted that if the traction effort is reduced on the energy device's hook on gear II from 35 kN to 25 kN, the load on ICE decreases by 82 % to 61 %, and, when reducing the traction effort on gear III from 25 kN to 10 kN – by 87 % to 53 %, respectively.

It is noted that the value of the normal reaction of the soil to the wheels of the adapter and the effort on the hydraulic cylinders' rods are increased in proportion to the growth in the traction effort on the hook of the agricultural processor. The load factor on the wheels of its driven axle decreases from 0.297 to 0.200 if the traction effort on the hook increases from 0 to 70 kN.

Significant scientific and applied results of this research include the developed principal diagram of the volumetric regulation of the hydro-volume transmission of an energy technological device with the adjustable pump and hydraulic motor. In combination with the system of automated adjustment of torque on the output shaft of the hydraulic motor, they respond to the corresponding fluctuations in the

traction resistance values of the agricultural machine. Due to such actions, the operation of the energy device's ICE under the modes of the rated power is made possible. Automated force control of the transmission reduces the specific fuel consumption by MTA if it is used as a traction energy device for general purposes.

Most mobile capacities in farming account for tractors and combine-harvesters. Moreover, in terms of the structure, similar transmission, and the principles of motion control, they are almost the same. By the principle of assembling with technological machines and tools, they are also the same. Under these conditions, natural expectations are the feasibility of making combine-harvesters and tractors at the production facilities of the same machine-building enterprise. This gives hope for the high efficiency of their manufacture and operation.

The devised operational requirements for mobile energy technological devices for general purposes (agricultural processors) are the scientific and methodological basis for further research. The theoretical and experimental studies might prove useful. A limited volume of experimental research can be explained by objective economic conditions of work execution, by the limited financial and material-technical resources.

7. Conclusions

1. We have devised operational requirements for mobile energy technological devices for general purposes (agricultural processors), which has made it possible to substantiate the structural and functional scheme of the combine-harvester (an agricultural processor) with the possibilities of a mobile energy device, and the scheme of the volumetric regulation of the hydro-volume transmission of an energy technological device with the adjustable pump and hydraulic

motor in combination with the system of an automated adjustment of torque on the output shaft of the hydraulic motor.

2. The theoretical dependences have been derived of the motion speed, power on the hook, specific fuel consumption, and the load factor on the wheels of the driven axle on the traction effort on the hook of an energy technological device. The limits of changing the load factor on the wheels of the driven axle (not less than 0.2) have been defined, at which the requirements for handling the energy device are met.

3. It is noted that the use of a driven axle with drive wheels reduces the slippage of engines in an energy technological device. At the level of slippage of the engines of up to 16 %, the energy device, equipped with a driven axle with drive wheels, develops a traction effort on the hook of up to 40 kN. The use of a driven axle with drive wheels, provided it is driven by the mainline of the hydro-volume transmission of the energy device, leads to a decrease in the speed of its movement by 17.9 %, 28.5 %, 35.9 %, and 49.0 % respectively, on gears I, I, II, III, and IV of the gearbox of the drive axle.

4. We have established an increase in the power on the energy device's hook due to the corresponding increase in the traction effort. Thus, at an effort within 35–40 kN on gear III, the power on the hook is 68–75 kW. Under these conditions, the specific fuel consumption is 430–460 g/kWh at the motion speed of the device within 1.9–1.95 m/s.

5. It has been established that when using a combine-harvester with a throughput capacity of 9–11 kg/s as an energy technological device, the specific fuel consumption by MTA on its basis is 540–580 g/kWh at the unit's motion speed of 1.7–2.1 m/s and a traction effort on the hook of 24–33 kN. If the traction effort is reduced on the hook of the energy device on gear II from 35 kN to 25 kN, the loading of ICE decreases from 82 % to 61 %, and, when reducing the traction effort on gear III from 25 kN to 10 kN, from 87 % to 53 %, respectively.

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