

Optimization of Hydraulic System Operation in Agricultural Machinery for The Purpose of Reducing Energy Consumption

Veherinskyi Taras Ihorovych

Company's president Honix Express LLC and Fixrent Corp
Aurora IL, USA

Article Received: 27/11/2024, Article Accepted: 13/12/2024, Article Published: 31/12/2024

© 2024 Authors retain the copyright of their manuscripts, and all Open Access articles are disseminated under the terms of the [Creative Commons Attribution License 4.0 \(CC-BY\)](https://creativecommons.org/licenses/by/4.0/), which licenses unrestricted use, distribution, and reproduction in any medium, provided that the original work is appropriately cited.

ABSTRACT

The study examines the principal directions for enhancing hydraulic systems of agricultural machinery to increase their energy efficiency. The relevance of the work is driven by rising energy resource prices and tightening environmental requirements, which necessitate the implementation of resource-saving solutions in agro-industrial complexes. The objective of the research is to classify and analyze contemporary methods for improving the energy efficiency of hydraulic circuits in tractors and combines, including through the use of advanced components, intelligent control algorithms, and innovative technologies for repair and modernization. The methodological foundation comprised a review of scientific publications, synthesis of advanced practical experience, and a comparative investigation of various hydraulic system architectures. The results demonstrated that the application of Load-Sensing (LS) and electrohydraulic (EH) control systems can reduce fuel consumption depending on the operating mode. The economic and technological justification for employing progressive methods of restoring worn components is also shown, contributing to reduced operational costs and maintenance of the hydraulic system near its optimal performance. Based on the obtained data, a comprehensive approach has been formulated, envisaging the combination of installation of modern assemblies and precision restoration of components. The information presented in this work will be of interest to designers, service engineers, and managers of agricultural enterprises focused on improving production profitability and environmental sustainability.

KEYWORDS

hydraulic system, energy efficiency, agricultural machinery, Load-Sensing, electrohydraulic control, energy consumption reduction, component restoration, optimization, tractor, fuel consumption.

Introduction

The agro-industrial sector — one of the largest consumers of energy resources, with the greatest share of expenditures accounted for by diesel fuel for mobile agricultural machinery. According to reports by the International Energy Agency, agriculture accounts for approximately 5 % of global final energy consumption, and this figure is increasing due to the necessity to ensure food security with the growing world population [1]. In the energy expenditure structure of tractors and combines, hydraulic systems can absorb up to approximately 30 % of engine power under peak operating conditions [2]. Traditional open-center and fixed-displacement pump schemes are characterized by throttling losses: the excess portion of the working fluid not engaged in driving the actuators returns to the tank through a relief valve, causing unnecessary oil heating and, consequently, increased fuel consumption. There is a clear research-to-practice gap between theoretical developments of energy-efficient hydrocomponents and their systematic implementation at all stages of the equipment life cycle — from initial outfitting to subsequent modernization and maintenance. This

problem assumes particular significance in the context of ongoing electrification and hybridization of agricultural mobile machinery, since the efficiency of each unit, including the hydraulic one, directly affects range and load on the powertrain [3].

The objective of the study — to conduct an analysis and systematization of modern methods for improving the energy efficiency of hydraulic systems of tractors and combines, encompassing both the introduction of innovative components and control schemes, and practical technologies for adjustment and restoration of hydraulic circuits to reduce fuel consumption.

The scientific novelty lies in the proposal of an integrative approach that unites the theoretical principles of energy conservation through advanced hydrocomponents with practical methodologies for restoration and modernization of hydraulic units, which allows the formation of a holistic strategy for enhancing the operational efficiency of agricultural machinery throughout its entire life cycle.

The author's hypothesis is that a synergistic effect from the application of modern hydraulic systems with Load-Sensing technology in combination with precision restoration of worn components (hydraulic cylinders and pivot joints) will ensure a significant and long-term reduction in energy consumption compared to the implementation of each of these approaches separately.

Materials and methods

In modern studies on the optimization of hydraulic systems in agricultural machinery, several interrelated directions can be identified, reflecting both macro- and micro-level approaches to reducing energy consumption and increasing efficiency.

Firstly, at the global level, analysis of energy consumption in the agricultural sector is based on statistical data from international agencies and reviews of the energy intensity of major production systems. Thus, the International Energy Agency database provides information on the dynamics of energy use in agriculture and allows the identification of key growth points in energy consumption [1]. Based on these data, Kargwal R. et al. [2] conducted a comparative analysis of the energy efficiency of the largest production systems, emphasizing the significant share of mechanization in the overall energy balance and indicating the promise of optimizing machine drive systems.

The second direction is related to the electrification and hybridization of mobile hydraulic systems. Beltrami D. et al. [3] considered the current state and prospects of electrifying compact off-road machinery, noting the growing interest in fully electric and hybrid drives as a means of reducing emissions and the overall energy intensity of machines. Similar conclusions were drawn by Bertolin M., Vacca A. [11], who proposed a power-split hybrid transmission scheme for a mini-excavator that combines the advantages of hydraulic and electric drives, thereby providing smoother and more economical power distribution. Fresia P. et al. [12] additionally proposed an approach with a centralized power source and combined speed control, which in hybrid mobile hydraulic systems enables the reduction of energy losses by optimizing the operating points of pumps and electric motors.

The third major research block is devoted to the control and modeling of electro-hydraulic systems. The review by Wang L. et al. [4] covers current control methods for the electro-hydraulic implement of automated tractors, including adaptive and predictive algorithms aimed at maintaining optimal flow and pressure under variable load. Kumar S. et al. [5] presented a model, simulation, and experimental validation of flow through an electro-hydraulic hitch valve of an agricultural tractor, which made it possible to assess the influence of the valve's design parameters on the energy efficiency of the system in various operating modes. Zhu Z. et al. [6] demonstrated that a tractor with a mechano-electronic-hydraulic power unit is capable of significant fuel savings through coordinated control of the engine, pump, and distribution valves, especially when performing cyclic operations at low speeds. Another important approach is flow coupling technology, the review of which is presented in the work by Li R. et al. [7] the authors analyze methods for balancing supply and return flows in multi-pump systems, allowing the minimization of excess return losses and the improvement of the overall efficiency of the hydraulic system.

The fourth direction focuses on reducing friction losses and wear through the use of new materials and surface modifications. Skowrońska J., Kosucki A., Stawiński Ł. [9] examined modern materials for the main components of hydraulic cylinders and sealing systems, as well as surface modification methods (laser processing, plasma spraying, chemical hardening), which allow a significant reduction in metal-on-metal friction and an extension of seal service life. Concurrently, Hu H. et al. [10] investigated wear-resistant ceramic coatings applied by

liquid thermal spraying, which exhibit high adhesion and resistance to abrasive wear under aggressive hydraulic environments.

Finally, the condition of the working fluid plays an important role. The analysis of the causes and consequences of its contamination, presented in the InvexOil resource, shows that the presence of abrasive and corrosive particles significantly increases internal leakage and friction, directly leading to increased energy consumption of the hydraulic system [13].

An additional review of the materials and presentations of the 13th International Colloquium on Fluid Power (13th IFK 2022) expands the understanding of the latest laboratory and field research in small hydraulic drives, new types of pumps, and control systems, confirming the relevance of the aforementioned directions [8].

Despite the considerable number of studies, contradictions can be noted in the assessments of the effectiveness of various control methods: some authors report substantial reductions in energy consumption with the implementation of predictive control algorithms [4], whereas experimental data [5] indicate a more restrained effect under real field conditions. Similarly, works on hybrid systems [3, 11] differ in their assessments of implementation complexity and payback. The questions of the impact of working fluid degradation on energy losses in the long term, as well as the integration of multicomponent approaches (control, materials, fluid quality) into a single optimization model for real operating conditions, remain the least explored.

Results and Discussion

In scientific research modern approaches to improving the efficiency of hydraulic systems of agricultural machinery are conventionally combined into two main directions: implementation of energy-rationalization elements and advanced control systems, as well as use of progressive methods of maintenance, repair and modernization. The systematic combination of these measures ensures a reduction in energy consumption and an increase in the operational productivity of machines. In traditional hydraulic circuits with a constant-displacement pump the main source of losses is throttling of the excess fluid flow. Since the pump continuously delivers the maximum volume of oil the unused portion is dumped through a flow regulator or relief valve back into the reservoir causing fluid overheating and increased load on the engine. A radical solution has been provided by load-sensitive systems (Load-Sensing, LS). Their operating principle is based on the fact that the variable-displacement pump supplies to the circuit only the flow rate and pressure required by the actuator at each specific moment. Thanks to the feedback line (LS-line) a signal of the maximum load pressure is sent to the pump controller which maintains the pressure in the delivery line at a value exceeding the load pressure by a set differential (Δp usually 1.5–2.5 MPa) thereby minimizing throttling losses in the directional control valve [6, 7].

Comparative analysis confirms the clear advantages of LS-systems in operations that do not require peak hydraulic forces — for example during transport or when working with light mounted implements — fuel savings reach 20–25 % compared to open-center systems [11]. **Figure 1** presents comparative data on the fuel consumption of a 150 hp tractor with OC and LS hydraulic systems when performing various typical operations

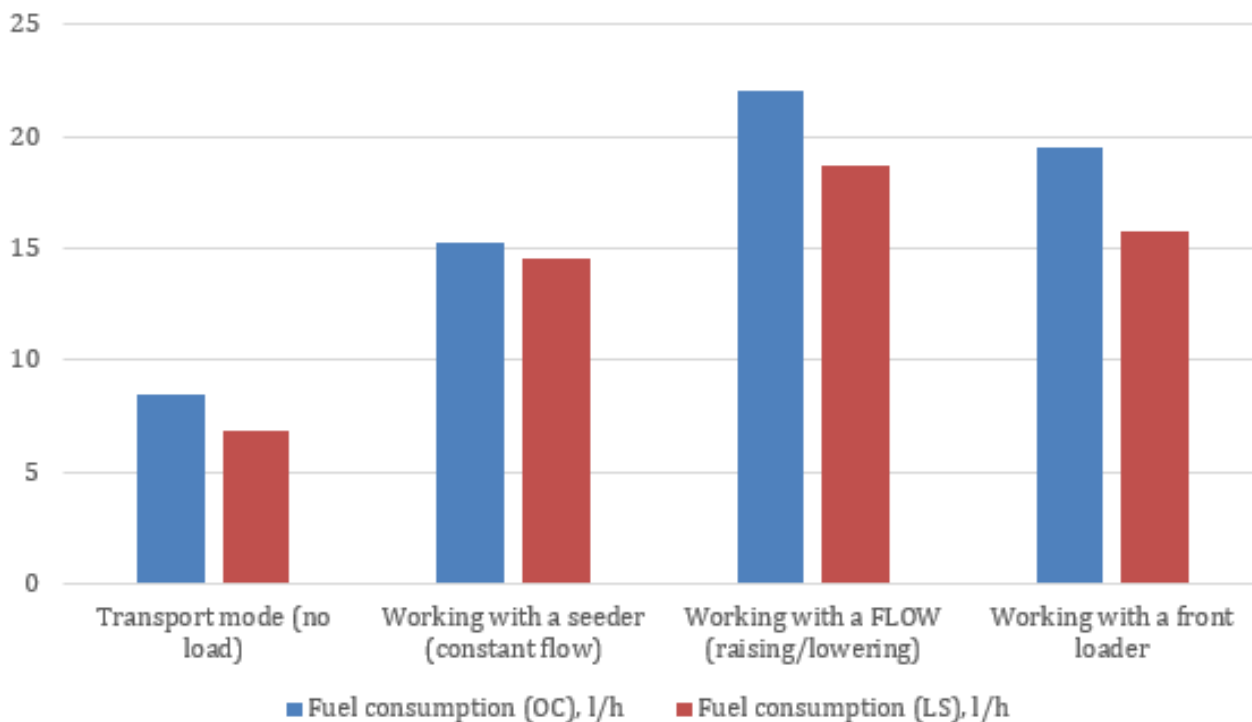


Fig. 1. Comparative hourly fuel consumption of a tractor with OC and LS systems (compiled by the author based on [3, 5, 8, 11]).

According to the data shown in Fig. 1, the greatest energy-saving effect of LS-systems is observed under variable load conditions with frequent shutdowns of the hydraulic section (for example, during loader operation or in transport mode), where savings in the range of 19–23 % are achieved. Even under conditions of relatively stable flow (when continuous rotation of the fan hydraulic motor is required, as in the case of seeder operation), a noticeable reduction in losses is noted due

to the absence of excess fluid supply.

The next stage in the development of such schemes was the introduction of electrohydraulic (EH) control systems providing proportional flow modulation. They enable smooth regulation of actuator speeds via an onboard controller over a digital bus (for example, CAN-bus), opening up extensive possibilities for automation and optimization of technological processes. Thus, the system can automatically reduce the speed of the working mechanism when approaching a limit position, eliminating hydraulic shocks, or maintain a specified soil cultivation depth regardless of changes in its compaction.

One striking example of a deep modernization with the implementation of EH-technologies is the project based on the Caterpillar CAT-320D crawler excavator. In its original configuration, the machine was supplied with a conventional hydraulic system for digging operations. During the upgrade, a two-circuit proportional hydraulic scheme was integrated and a medium-pressure line was introduced, which required replacement of the hydraulic distributor, laying of additional hydraulic lines, a complete reconfiguration of the control system, and adaptation of the controller software. As a result, the excavator gained the capability to operate with complex demolition attachments (hydraulic shears with rotator, breaker hammers), which expanded its functionality and increased its market value by 15–20 %.

Targeted improvement of the hydraulic system demonstrates not only increased productivity but also improved energy efficiency: the introduction of proportional control ensures delivery of power to the actuator with high precision and metering, surpassing traditional on/off solutions in this parameter [12].

Over time, even finely tuned hydraulic units lose their original characteristics due to natural wear. As a result, worn seals and working surfaces of pumps, valves, and cylinders contribute to internal leakage of working fluid

from the high-pressure zone to the low-pressure zone, where energy is irreversibly lost as heat. As the rods and sleeves of hydraulic cylinders wear, friction force increases, requiring additional power expenditure. Destruction of pivots—links, pins, and bushings—leads to clearances that impair positioning accuracy and cause impact loads capable of adversely affecting the entire system.

Turnkey replacement of worn components often proves economically impractical and is accompanied by long equipment downtimes while awaiting spare parts delivery. As an alternative, a method of precision restoration of assemblies is employed. The practice of FixRent, a company specializing in repair and restoration of construction machinery, confirms the high efficiency of this approach: the focus is on restoring the bearing seats of boom, arm, and bucket pivots. Holes hardened by wear, work-hardening, and indentations lose their nominal tolerances, making it impossible to install

standard pins and bushings. Mobile overlay-boring units allow machining of the worn seat, automatic metal overlay, and subsequent finish boring to the original size directly on the machine, without disassembly of major units [7, 9].

Particularly noteworthy is the developed technology for restoring cast-iron swing frames for JCB and CAT backhoe loader and other similar machines: with the cost of a new part around € 5000 and delivery time up to 1.5 months, low-current overlay welding followed by mechanical processing allows the part to be returned to service in three days, reducing the client’s costs by approximately € 4000 and radically shortening downtime—a key metric for commercial machinery. A schematic cycle of wear and restoration of the pivot joint is shown in Figure 2.

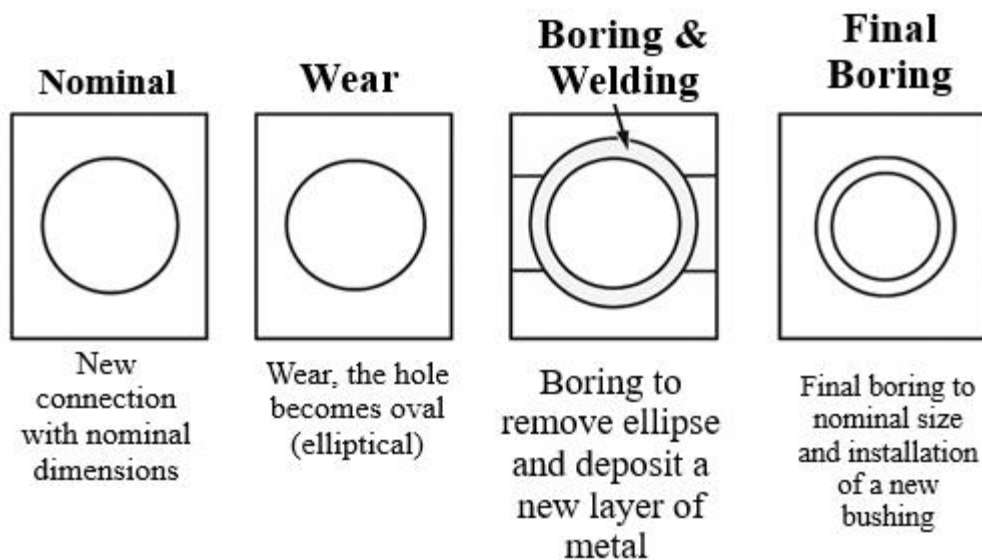


Fig. 2. Stages of wear and restoration of the landing hole of the hinge joint (compiled by the author based on [8, 9, 10])

Similar methods find application in the restoration of hydraulic cylinders. Using the example of the repair of Komatsu PC8000 excavator hydraulic cylinders, a set of technological operations has been developed, including rod straightening, pointwise removal of the worn chrome layer and subsequent deposition of a new coating composed of high-strength materials (including those of ceramic origin). Simultaneously, a complete replacement of the liners is carried out employing high-precision welding, after which the weld seams are inspected by

ultrasonic flaw-detection control.

The hydraulic cylinder restored according to the

described methodology demonstrates parameters comparable to those of new units, while the costs of its restoration are lower than the cost of procuring the original part. Preservation of hermetic integrity and reduction of internal friction in the hydraulic cylinder directly increase the overall coefficient of performance of the system, eliminating energy losses due to micro-

leakages and overheating [13].

Table 1, compiled on the basis of production experience.

Economic and time benefits of the proposed approach are evident and are confirmed by the results presented in

Table 1. Comparative effectiveness of component restoration and replacement methods (compiled by the author based on [4, 8, 13]).

Method	Cost, € (approx.)	Completion time	Impact on energy efficiency
Beckhoe loaders Swing frames (JCB, CAT)			
Replacement	5000	30–45 days	Restoration up to 100%
Restoration	1000	3 days	Restoration up to 98–100%
Boom hydraulic cylinder (medium class)			
Replacement	3500	14–30 days	Restoration up to 100%
Restoration	1200	4–5 days	Restoration up to 98–100%
Hinge connection bore			
Component replacement (boom)	>10000	>60 days	Restoration up to 100%
Restoration	500–800	1–2 days	Elimination of backlash, reduction of impact loads

Therefore, precision restoration functions not simply as a method of spare parts economy but as a strategic management mechanism enabling the hydraulic system to maintain a highly optimized level of energy efficiency. The obtained data confirm the initial hypothesis that the combination of advanced units and innovative methods of their service restoration generates a synergistic effect maximally reducing energy expenditure in the long term.

Conclusion

Within the framework of the conducted analysis, a systematization of the key directions for improving hydraulic systems of agricultural machinery aimed at

reducing energy consumption was performed. It was found that achieving an optimal level of energy efficiency is possible only through the integration of modern hydrocomponents and multilevel control strategies with advanced maintenance and restoration methods.

The transition from outdated open-center hydraulic systems to load-sensing hardware solutions, as well as to hybrid electrohydraulic schemes, is considered a determining factor in reducing energy consumption. Empirical data demonstrate that during operations with variable hydraulic pressure, fuel savings can reach 20–25 %, which directly increases machine profitability.

Investments in the modernization of the existing machinery fleet through the implementation of advanced hydraulic components, exemplified by the CAT-320D excavator, demonstrate economic feasibility: such measures expand the functional capabilities of machines while simultaneously increasing their energy efficiency.

Maintaining high hydro-system performance throughout the entire equipment lifecycle requires the application of precision restoration technologies for worn assemblies. Overlay welding followed by boring, the application of wear-resistant coatings, and hydraulic cylinder repair methods reduce both financial and temporal costs compared to full component replacement and minimize energy losses due to internal leaks and increased friction.

The developed comprehensive approach, combining component modernization and precision restoration technologies, ensures a synergistic effect: the new energy-efficient system retains its declared performance only with proper technical support, and the restoration procedures allow assemblies to be maintained in conditions close to peak, providing long-term reduction of operating expenses.

Prospective directions for further research include the creation of predictive diagnostic systems based on telemetry data for forecasting hydrocomponent wear, as well as deeper integration of hydraulic systems with electric and hybrid power units to achieve even higher energy efficiency indicators.

References

1. International Energy Agency. (n.d.). Data and statistics. Retrieved from: <https://www.iea.org/data-and-statistics> (date accessed: January 18, 2024).
2. Kargwal, R., Yadvika, Kumar, A., Garg, M. K., & Chanakaewsomboon, I. (2022). A review on global energy use patterns in major crop production systems. *Environmental Science: Advances*, 1(5), 662–679. <https://doi.org/10.1039/D2VA00126H>
3. Beltrami, D., Iora, P., Tribioli, L., & Uberti, S. (2021). Electrification of compact off-highway vehicles—Overview of the current state of the art and trends. *Energies*, 14(17), 5565. <https://doi.org/10.3390/en14175565>
4. Wang, L., Wang, Y., Dai, D., Wang, X., & Wang, S. M. (2021). Review of electro-hydraulic hitch system control method of automated tractors. *International Journal of Agricultural and Biological Engineering*, 14(3), 1–11. <https://doi.org/10.25165/j.ijabe.20211403.6175>
5. Kumar, S., Tewari, V. K., Bharti, C. K., & Ranjan, A. (2021). Modeling, simulation and experimental validation of flow rate of electro-hydraulic hitch control valve of agricultural tractor. *Flow Measurement and Instrumentation*, 82, 102070. <https://doi.org/10.1016/j.flowmeasinst.2021.102070>
6. Zhu, Z., Yang, Y., Wang, D., Cai, Y., & Lai, L. (2022). Energy saving performance of agricultural tractor equipped with mechanic-electronic-hydraulic powertrain system. *Agriculture*, 12(3), 436. <https://doi.org/10.3390/agriculture12030436>
7. Li, R., Sun, Q., Ding, X., Zhang, Y., Yuan, W., & Wu, T. (2022). Review of flow-matching technology for hydraulic systems. *Processes*, 10(12), 2482. <https://doi.org/10.3390/pr10122482>
8. RWTH Aachen University, Institute for Fluid Power Drives and Systems. (n.d.). 13th IFK 2022. Retrieved from: <https://www.ifas.rwth-aachen.de/cms/ifas/das-institut/internationales-fluidtechnisches-kolloqu/vergangene-ifks/~wfiaw/13-ifk/?lidx=1> (date accessed: February 21, 2024).
9. Skowrońska, J., Kosucki, A., & Stawiński, Ł. (2021). Overview of materials used for the basic elements of hydraulic actuators and sealing systems and their surfaces modification methods. *Materials*, 14(6), 1422. <https://doi.org/10.3390/ma14061422>
10. Hu, H., Mao, L., Yin, S., Liao, H., & Zhang, C. (2022). Wear-resistant ceramic coatings deposited by liquid thermal spraying. *Ceramics International*, 48(22), 33245–33255. <https://doi.org/10.1016/j.ceramint.2022.07.267>
11. Bertolin, M., & Vacca, A. (2022). A power-split hybrid transmission to drive conventional hydraulic valve controlled architectures in off-road vehicles: The case of a mini-excavator. *JFPS International Journal of Fluid Power System*, 15(2), 62–70. <https://doi.org/10.5739/jfpsij.15.62>
12. Fresia, P., Rundo, M., Padovani, D., & Altare, G. (2022). Combined speed control and centralized power supply for hybrid energy-efficient mobile hydraulics. *Automation in Construction*, 140,

104337.

<https://doi.org/10.1016/j.autcon.2022.104337>

- 13.** Parker Hannifin Corporation. (n.d.). The handbook of hydraulic filtration. Retrieved from:
<https://www.parker.com/content/dam/Parker-com/Literature/EMHFF/Miscellaneous/HTM-5.pdf>
(date accessed: March 12, 2024).