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Improved System Efficiency through Drained Case Operation of Axial Piston Units

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Abstract

This article presents a drained case approach for axial piston units in mobile hydraulics to minimize splashing (churning) losses and enhance system efficiency. Utilizing a Venturi valve and existing flushing flows, the system evacuates an oil-air mixture from the motor housing without additional energy input. Experimental validation demonstrated evacuation times of 30–55 seconds and significant reduction in power loss. The solution is applicable with slightly modified standard hydraulic components and supports significant energy savings and lower operating costs in agricultural machinery.

Keywords: Hydraulic efficiency, axial piston units, splashing losses, mobile hydraulics, energy savings.

1. Introduction

The demand for increased efficiency and reduced CO_2 emissions in mobile machinery, such as self-propelled agricultural machines, has enabled innovation in hydraulic drive technology. Hydraulic drive technology is applied in open-circuit and closed-circuit arrangement to distribute the engine power throughout the machine and towards the point of power consumption. Some modern agricultural machinery – like the JAGUAR 1000 series in Figure 1 – makes significant use of this hydraulic power distribution.

Figure 1. JAGUAR 1000 - Hydraulic system and power distribution

The cylinder-based work functions are supplied by the constant pressure hydraulics (CPH system) which is an open-circuit system which is supplied by a variable work pump at constant 205 bar pressure level. High-power motor-based work functions are implemented as closed-circuit hydrostatic transmission. In total, 4 closed-circuit hydrostatic transmissions are utilized on the JAGUAR 1000 – the ground drive and the feeder drive as well as the variable header drives 1 and 2. Axial piston hydrostatic pumps and motors – in swash plate and bent axis design – are integral to the implementation of closed-circuit transmission due to their reliability, robustness, and power density. Improvements in these critical components can lead to significant cost savings and environmental benefits which will help hydrostatic drives to compete in the market with electric alternatives.

However, splashing losses caused by the rotation of the internal components (rotational kit) in the oil-filled housings remain a significant source of inefficiency [1, 2]. Reducing power losses will prevent substantial heat dissipation into the oil and simplify the thermal management on the mobile machine. Draining the oil from the case of the hydrostatic components significantly reduces the power loss and is referred to as drained case operation at CLAAS. This paper examines the innovative system solution for drained case operation and minimized hydro-mechanical power losses in mobile machines as introduced to the market at Agritechnica 2025.

2. Fundamentals of Hydrostatic Transmissions

Hydrostatic pumps and motors are components which are design to convert mechanical power into hydrostatic power (pump) and back to mechanical power (motor). The hydrostatic transmission (HST) in Figure 2 combines pump (1) and motor (2) into a closed-circuit system that provides an infinitely variable ratio from the pump input shaft towards the motor output shaft. This closed circuit must be pre-charged via the charge pump (3), filter (5), relief (4) and charge valves (6) to reduce air content in the oil and thereby increase the stiffness of the drive. Heated oil is flushed from the system into the cooler (9) via flushing (7) and purge valve (8). High pressure relief valves (10) protect the system against overload. Due to the dual high-pressure lines, the HST can be operated in four quadrants – forwards, reverse, uphill, and downhill.

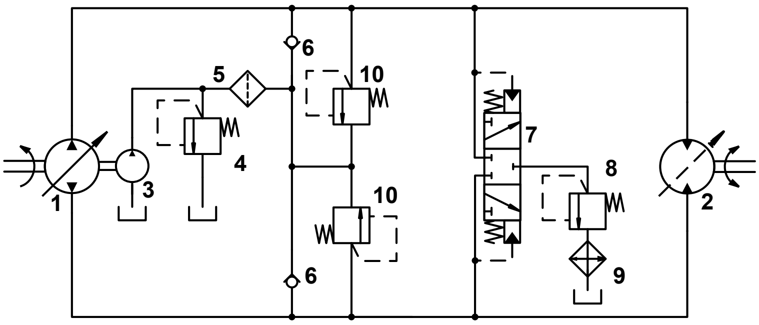

Figure 2. Hydrostatic transmission in closed-circuit system [3, 4]

Most of the hydraulic flow constantly circulates inside the closed-circuit system to transmit the hydraulic power from the pump to the motor. Consequently, the required exchange volume in the hydraulic tank is reduced and it can be designed smaller.

Axial piston units (pumps & motors) are complex components that are developed for efficient conversion of mechanical into hydraulic energy and vice versa. In mobile machinery the power of the Diesel engine is converted into hydraulic flow and pressure by the hydraulic pump. The hydraulic power is converted back to mechanical power and motion by the hydraulic motor. Axial piston units operate on the principle of axial movement, in which pistons slide dynamically within cylindrical bores, driven by a swash plate (pump) or by a bent axis (motor).

Losses in hydrostatic units are differentiated in volumetric and hydro-mechanical losses. While volumetric losses impact the flow of the hydrostatic unit, hydro-mechanical losses impact the torque. Splashing losses are caused by the rotation of the internal kit of the hydrostatic unit in the oil-filled housing (see Figure 3, left) and are considered part of the hydro-mechanical losses. These losses are strongly dependent on the rotational speed of the hydrostatic unit und reach significant values. Due to higher speed levels of hydrostatic motors, the splashing losses in hydrostatic motors are generally higher. Draining the oil from the housing (Figure 3, right) prevents the splashing and thereby eliminates the splashing losses in the hydrostatic unit.

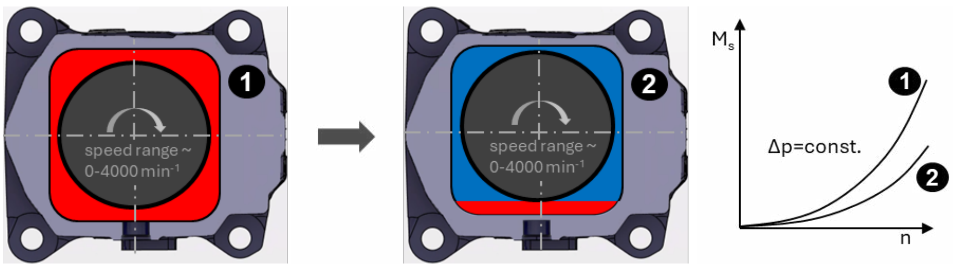

Figure 3. Sectional view of hydrostatic unit with full (1) and drained (2) housing

The introduced benefits of drained case operation are well known to the industry since many years [5]. The component suppliers can develop the hydrostatic units to allow drained case operation, but the OEM must develop a system solution around this hydrostatic unit to get drained case operation started. With the introduced system solution, the benefits of drained case operation outweigh the additional system cost.

In 2025, Grimme presented the outcome of a real-life study of drained case operation on a self-propelled beet harvester. The four motors of the hydrostatic ground drive are drained from oil by air from the compressed air system of the machine. There was no negative effect identified on the components or the hydrostatic system and the expected savings from test stand measurements were reproduced in real life on a real machine [6].

3. Development Objectives and Technical Challenges

During the development of the JAGUAR 1000 series, new hydraulic functions had to be considered in the thermal management of the machine. It became obvious that drained case operation had to be implemented to control the losses in the hydraulic system. Further development of the serial solution for drained case operation on the CLAAS SCORPION telehandler allowed for reduction on the power losses.

Summary of the key requirements during the development:

- Integration into compact, cost-sensitive mobile hydraulic system
- Minimize splashing losses in standard hydrostatic components during field and road operation (close collaboration with supplier required)
- Leverage existing flushing flows in the Venturi nozzle to avoid additional power consumption
- Rapid and complete evacuation of the motor housing during operation
- Effective de-aeration of the evacuated oil to prevent cavitation and maintain lubrication in the hydrostatic units
- Compatibility with supplier specifications (e.g. temperature, pressure limits)

The following paragraphs will describe the implementation of the drained case solution in the CLAAS JAGUAR series.

4. Drained Case Operation

Drained case operation minimizes splashing losses and leads to a more efficient machine operation. By implementing a suction and ventilation system, the hydrostatic unit can continuously drain fluid from the housing. Reduced thermal load on the system reduces the power needs for cooling of the hydraulic fluid.

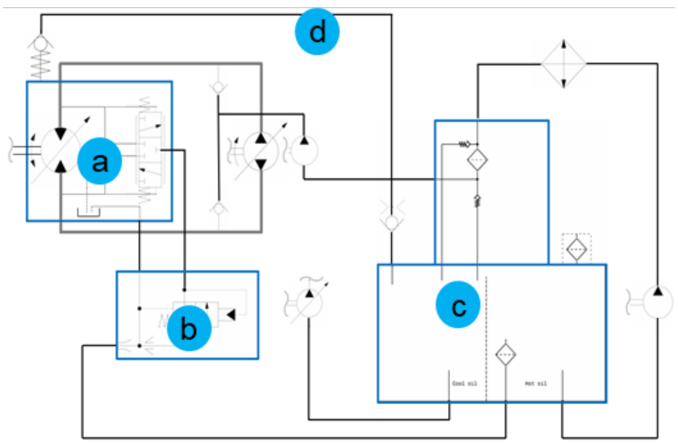

Figure 4. Conceptual schematic of the system solution for drained case operation

4.1. System Layout and Key Components

The system solution for drained case operation is introduced as a conceptual schematic in Figure 4. It becomes obvious that drained case operation cannot be supplied by a single supply, however it must be introduced by the OEM as system integrator.

The key components of the drained case system solution (see Figure 4):

- Hydrostatic motor (a) – Transforms hydrostatic to mechanical power in the closed-circuit transmission and is the source of splashing losses in standard design.
- Venturi nozzle (b) – Utilizes the loop flushing flow from the closed-circuit hydrostatic transmission as driving force for the suction from the hydrostatic motor.
- Hydraulic tank and filter system (c) – Separates the air from the hydraulic oil and allows for additional volume from drained hydrostatic motor.
- Ventilation system (d) – Essential for continuous suction of oil-air mixture from the hydrostatic motor.

A robust system solution requires an optimized alignment of components and performance parameters. The interaction between the different machine parts must be analyzed carefully and the required adjustments to the system must be carried out with care. The decision was taken that the Venturi principle shall be used to implement the drained case feature.

4.2. Hydrostatic Motor

The hydrostatic motor is an essential part of the closed-loop hydrostatic transmission and transforms the hydrostatic power into mechanical power which can be utilized in the ground drive or the header drive of the JAGUAR 1000. This main functionality remains intact, but the motor requires some adjustments to allow drained case operation.

The Venturi principle which was selected as the driving force for the evacuation of the housing requires a driving hydraulic flow as the power input to the nozzle. With the loop flushing in the hydrostatic motor, this driving force is already existing in the hardware of the hydrostatic motor. However, this flow must be re-routed from the motor housing to an external port to be connected to the Venturi nozzle.

Adjustments to the hardware and the operation conditions of the hydrostatic motor can only be realized in close cooperation with its supplier. For the initial implementation of the drained case operation, the HMV swash-plate variable motors from LHY were modified to fit the requirements – as single and dual variant. In particular, the motor also had to be prepared to be robust in drained case operation.

The following modifications to the HMV were necessary:

- Re-routing of loop flushing flow to an external port as input to the Venturi nozzle
- Evacuation port at the bottom of the unit (mounting position of Venturi nozzle)
- External flushing supply for the main bearings of the hydrostatic unit

Besides these modifications, test runs for the hydrostatic units were necessary to confirm temperature levels in drained case operation that lead to sufficient viscosity and lubrication in the key tribological interfaces. Figure 5 introduces a cut-away view of the hydrostatic motor which provides an impression of the rotating parts of the hydrostatic kit in the hydrostatic motor.

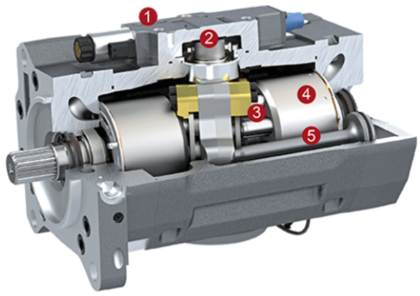

Figure 5. HMV swash-plate variable motor from LHY [7, 8]

4.3. Venturi Valve

The Venturi valve utilizes the Bernoulli effect to generate a suction effect from the loop-flushing flow which is leveraged to evacuate the hydrostatic units. Thereby enabling the evacuation without any additional energy input.

The Bernoulli effect states that the local pressure p_2 of a fluid decreases from the static pressure p_1 as the speed of this fluid increases from v_1 to the accelerated speed v_2. Purposefully increasing the speed of a fluid – e.g. by means of a nozzle – creates suction which is the working principle behind jet pumps. This effect is also well known in pump or valve design and can lead to cavitation as fast jets of fluid occur.

Accordingly, the pressure drop in the suction pressure p_2 versus the pressure in the driving flow p_1 is dependent on the speed of the fluid before (v_1) an after the nozzle (v_2) according to equation 4.1.

$$p_2 = p_1 - \frac{\rho}{2} \cdot (v_2^2 - v_1^2) \qquad (4.1)$$

With the continuity assumption for the hydraulic flow

$$v_1 \cdot A_1 = v_2 \cdot A_2 \qquad (4.2)$$

and the calculation of a round area

$$A = \frac{\pi}{4} \cdot d^2 \qquad (4.3)$$

the dependency on the diameter of the nozzle (d2) versus the diameter of the inlet of the Venturi valve (d1) becomes visible in equation 4.4.

$$p_2 = p_1 - \frac{\rho}{2} \cdot v_1^2 \cdot \left(\frac{d_1^4}{d_2^4} - 1\right) \qquad (4.4)$$

The effect of suction starts as soon as the suction pressure drops below the pressure in the housing of the hydrostatic unit. These assumptions are only valid for ideal, unobstructed, and frictionless flow which cannot be guaranteed in real life applications. Nevertheless, this is the basis for the development of the Venturi nozzle in the CLAAS application.

Figure 6 presents a schematic with the key characteristics of the Venturi valve which consists of the jet nozzle, the intake nozzle, the mixing chamber, and the diffusor. The main design parameters that were developed and confirmed by real experiments are labelled in the schematic. Another critical parameter is the flow rate and pressure in the driving flow from the loop-flushing valve of the hydrostatic motor.

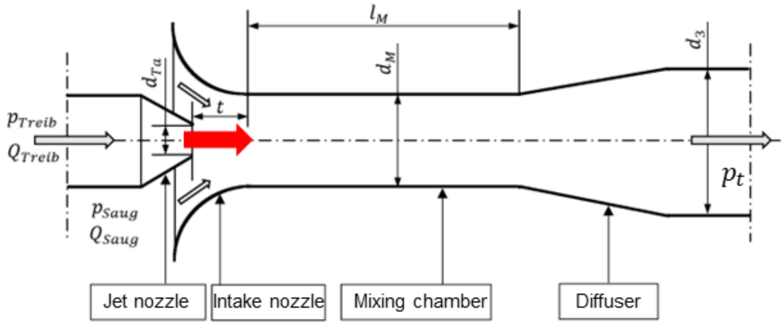

Figure 6. Schematic of the Venturi nozzle applied in the CLAAS Venturi valve

The key advancement in the presented system solution is the utilization of the existing loop flushing flow as the driving force for the suction effect – an efficiency improvement versus existing solutions in the market.

4.4. Hydraulic Tank and Filter System

The hydraulic tank serves as the reservoir for the pendulum volume of the hydraulic system which includes the volume resulting from draining the housings of the hydraulic motors. In the hydraulic system of the JAGUAR 1000, the tank is essential for filtration, thermal separation, as well as the de-aeration of the hydraulic fluid. Figure 7 shows a cut-away view of the tank (left) and the results of the CFD simulation that was performed to optimize the tank design.

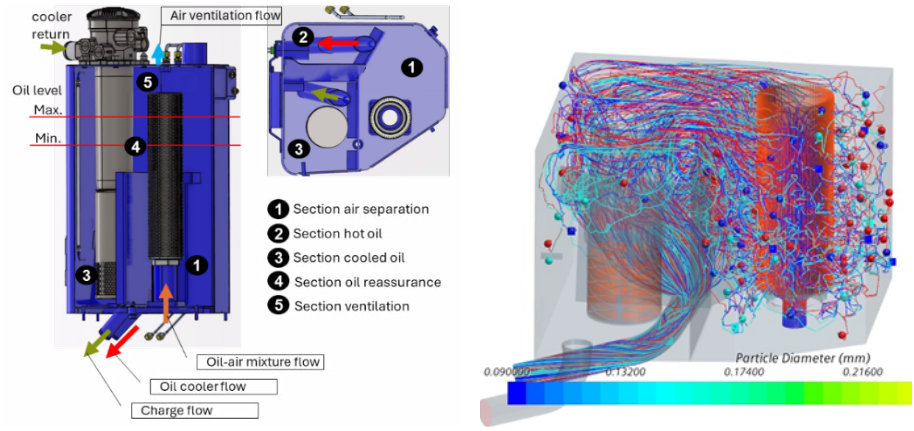

Figure 7. Desing of the hydraulic tank and visualization of CFD simulation

The drained oil-air mixture from the motor housings enters the hydraulic tank through the air separation element which the oil flow passes from bottom to the top in section 1 for the air separation. After transition to the “hot oil” section 2 the oil it pumped through the oil cooler and returns into the tank via the filter element into the “cooled and cleaned oil” section 3. From this section, the flows for charging of the closed-circuit systems and the work hydraulics are taken. The connection port to the ventilation system (5) is in the cover plate on the top of the hydraulic tank. This port is kept free of oil to guarantee circulation of air in all operation conditions.

The design of the hydraulic tank was optimized for thermal management and de-aeration by means of CLAAS internal CFD simulations. The target for the de-aeration of the oil in the application is volumetric air content of less than 1%.

4.5. Ventilation System

When thinking about the drained-case solution, the need for the ventilation system of the motor housings is not obvious. For the continuous and fast suction of an oil-air mixture from the motor housings, the system must feed air back to the housings. In figure 8 this Venturi valve is mounted to the bottom drain port of the housing while the ventilation port is in the top of the housing.

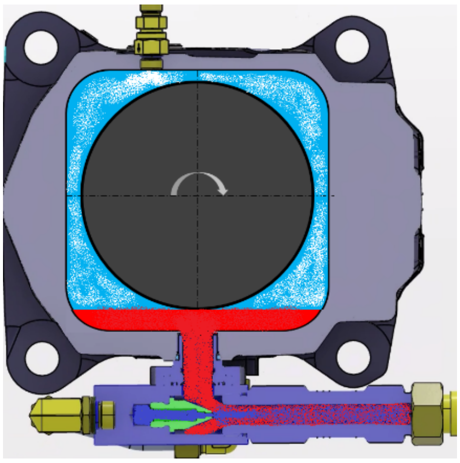

Figure 8. Cross section of drain motor with ventilation (top) and Venturi valve (bottom)

The illustration in figure 9 visualizes the ventilation system, the essential air circuit for the successful drained-case operation. The flow of air through the top port in the cover plate of the hydraulic tank is restricted by a check valve and a restricting orifice. With this restriction, the pressure level in the motor housings can be kept lower.

There is another pre-loaded check valve (0,2 bar) in the top of the motor housing to prevent any oil from entering the ventilation system. When oil enters the ventilation system, draining the motor housings is significantly delayed.

The oil-air mixture is drained from the motor housings by means of the loop-flushing flow for the closed-circuit hydrostatic transmission. The purge valve, included in the Venturi valve, secures the minimum pressure level on the low-pressure side of the closed-circuit system. The air is fed back to the hydraulic tank as oil-air mixture and is separated again in the separation element.

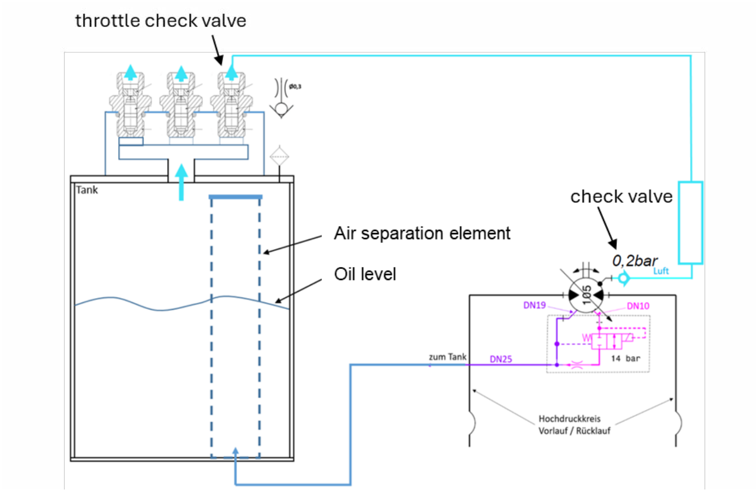

Figure 9. Illustration of the ventilation system for a single motor

The ventilation system is closed towards the environment to keep water, dust and other particles away from the hydraulic system.

5. System Integration in Mobile Machinery

The integration of the system for drained-case operation into a self-propelled forage harvester – or similar mobile machinery – requires careful design modification across various mechanical and hydraulic components. The interaction between these different machine parts – including pumps, motors, filters, and tank – must be analysed thoroughly before actions can be taken.

The introduced solution for drained-case operation is purely hydro-mechanical and does not require any electric actuation. Evacuation of the housings is initiated solely by the loop-flushing flow which starts as soon as sufficient pressure difference is build-up in the hydrostatic transmission. Temperature sensors and software is introduced only as monitoring system to prevent the operation outside of specified limits.

The various modifications to components require close collaboration with the respective suppliers of hydrostatic components, tanks, valves, and filtration system. The additional hydraulic lines of the ventilation system are the only modification which is visible for the outside. This modification requires additional design space on the machine and causes some additional system cost.

The assessment of the operating conditions of the machine is essential to determine the main sources for the heat load on the hydraulic system in critical situations. The data from telematics systems which is available today helps to identify the peaks loads on the cooling system. This way, the required modification and the additional system cost can be balances against other counter measures. Thoughtful introduction of the drained-case operation can lead to a competitive advantage in terms of efficiency and machine performance.

6. Validation and Testing

Validation and extensive testing are critical to confirm the operational integrity and functionality of the system solution for drained-case operation. On the one hand, the system must fulfil the performance requirements. On the other hand, the system must be safe and reliable. Precise data acquisition for monitoring of pressures, speeds, temperatures, and fluid flows provided valuable insights into system performance.

For many years, the optimization of the Venturi nozzle was researched and implemented on development machines in the CLAAS hydraulics workshop. The main objective was the utilization of the loop-flushing flow as the driving force. Only this way, the benefits of drained case operation could lead to the required loss reductions on system level.

As mentioned before, the collaboration with our suppliers was essential for the success of the market introduction. The hydraulic motors had to be reliable in drained-case operation at high rotational speeds and pressure loads. Design modifications were confirmed in extensive test series which lead to the approval of the new CLAAS operation conditions. Some temperature thresholds in the monitoring system had to be adjusted based on the created experiences.

Machine level integration tests of the drained-case solution were necessary to confirm that the modifications had no negative impact on machine operation. For the ground drive, which is very relevant for the customer experience, a standard test series was executed with accelerations, decelerations, load changes, reversals, forwards and reverse driving. Finally, the system got approval for serial introduction.

During the testing, it was confirmed that an evacuation time of 30 to 55 seconds was reached by the system. Based on the dynamics in the thermal behaviour of a mobile machine, this duration is considered as “rapid”. Especially when considering the absence of any additional power consumption for the evacuation.

Additionally, the targeted savings in power loss of 5 to 10 kW per hydraulic motor were confirmed during the testing on machine level. This confirmed two things at once. The evacuation of the motor housing was complete and the expected savings from test stands could be reproduced in real machine operation.

Measurements of the volumetric air content in the oil behind the tank element for air separation confirmed a consistent value below 1%. The experience with this value and the required threshold for reliable machine operation was very limited at CLAAS and our suppliers. However, based on long-term validation runs on development machines it was concluded that the existing system design is well suited for the CLAAS lifetime requirement.

This final validation and testing also confirmed that the original development targets were achieved and fulfilled.

7. Conclusion and Future Steps

This paper has described the transformation approach for reducing the power loss of a system with hydrostatic transmissions by means of a system solution for drained-case operation. The operation of the drained-case system is based on the Venturi effect. High velocity loop-flushing flow through the Venturi nozzle creates a low-pressure zone which is sucking an oil-air mixture from the motor housing into the hydraulic tank. The air is fully separated from the oil in the tank and a volumetric air content below 1% is maintained. The results which were obtained in the testing and validation phase confirm the effectiveness of the drained-case operation in significantly reducing the hydraulic losses.

The drained case system demonstrated:

- Significant reduction in splashing losses in hydrostatic components
- Utilization of the existing loop-flushing flow which additional power consumption
- Reliable operation across all tested speed and load conditions
- Compatibility with standard hydraulic components and CLAAS machine system

As a conclusion it can be stated that drained-case operation of axial piston units offers a practical and effective method for improving the efficiency of hydraulic transmissions. It is particularly applicable for self-propelled agricultural machinery where space, cooling capacity, and cost constraints are critical.

The achieved savings in power loss of 5 to 10 kW per hydrostatic component (dependent on operation conditions) are sufficient to compensate for the additional system cost. Additional system cost is mainly created by the Venturi valve, the ventilation system, and the air separation element in the hydraulic tank. Reduced power loss translates directly into higher productivity of the agricultural machine and lower operational cost for the machine operator.

As the markets continue to focus on efficiency and fuel consumption, the assessment of power losses will be very relevant for future improvements on system level. The drained-case operation can be one contribution to the benefit of hydrostatic transmissions in the competition with alternative drive technologies.

Future work will focus on expanding the compatibility with various hydraulic components and exploring application in additional CLAAS machines. Efficiency modelling and evaluation of historic data for machine operation will support the introduction of drained-case operation to other machines and functions.

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