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Innovative solution of hybrid hydraulic fire wood splitting machine

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Abstract Hybrid powertrains have already proven themselves as viable solutions for reducing fuel consumption while maintaining the same operating performance of conventional ones, which is achieved by using an additional energy source in combination with energy recuperation. Many forestry machinery and tools which are intended for field use are hydraulics-based and powered by tractors or skidders. These tools may also be hybridized by incorporating a properly-sized hydraulic accumulator. This paper proposes an innovative solution of hydraulic fire wood splitting machine which uses a hydraulic accumulator in order to increase its efficiency. A simple model of conventional and hybridized machine is developed and presented in this paper. The model is then simulated over a defined operating cycle with realistic loads. Simulation results show that hybrid structure may improve the splitting performance with lower power requirements. Finally, the conventional and hybridized machine performances are compared and discussed.

Keywords: • forestry machinery • firewood splitting machine • hybridization • hydraulics • tractor attachment •

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1   Introduction

Wood is an important natural resource and one of the few renewable energy sources. It predominates in everyday life, and it would be difficult to enumerate its many applications. For instance, almost all home furniture is made of wood [1]. However, one of the first things that is associated with wood is the solid fuel (biomass) used for firewood. Heating with biomass, especially wood, is one of the most sought-after types of heating in small-scale residential objects. Due to the higher costs of electricity and gas, this traditional type of fuel is also considered by people living in single-family homes (e.g. cottages), especially in the countryside. As we are witnessing climate changes taking place, primarily caused by harmful gases from combustion of non-renewable energy sources (oil and gas), increasing emphasis is being placed on residential heating impact on ecology. In that sense, wood is also accepted as the most widespread renewable source of energy in the form of biomass [2].

In recent years, great emphasis has also been placed on hybrid and electric powertrains in road vehicles, given the advantages this has regarding the reduction of fuel consumption and harmful gas emissions and, thus, on preserving the environment. Hybrid vehicles are a complex system which use two or more different on-board energy sources [3]. Lately, forestry vehicles have been also increasingly equipped with hybrid electric power-trains [4,5,6] in order to provide significant gains in fuel economy, and also to facilitate measurable reductions in greenhouse gases emissions.

This leads to many open questions, such as whether hydraulics-based forestry tools which are intended for field use and powered by tractors or skidders could also be hybridized by using a properly-sized hydraulic accumulator. This paper investigates one possible solution of hydraulic fire wood splitting machine which uses a hydraulic accumulator in order to increase its efficiency. A simple model of conventional and hybridized machine is developed and presented and then simulated over a defined operating cycle with realistic loads.

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2   Firewood splitting machine models

A firewood splitting machine is a device used to produce logs that are suiTable for firewood, with recommended lengths typically between 20 and 100 cm, depending on the construction of the splitter. There is a wide variety of wood splitting machines on the market today, however, this paper deals only with the hydraulic one, powered by mechanical power from a tractor or a skidder.

2.1   Classical model

Within the classical system, force wood splitting is realized through a hydraulic cylinder driven by the flow of hydraulic oil, which is provided by a hydraulic pump. The hydraulic pump is driven by a tractor via a power take-off (PTO) shaft. Table 1 below lists the data for several vertical hydraulic tractor splitters and their specifications which are used as a basis for model development.

Table 1: Technical specifications of vertical hydraulic powered firewood splitting machines

	Krpan CV 18 K PRO [7]	Uniforest TITANIUM 18 [8]	Lancman STX 17 [9]	Robust R16 [10]	Zanon SVTK 16 [11]
F [kN]	170	160	170	160	160
P [kW]	25	21	22,7	25	22
x [mm]	972	1100	1100	1100	1000
t_2 [s]	3,1	4,2	3,33	4,57	-
t_3 [s]	6,3	6,5	8,33	-	-
t_1 [s]	3,2	4,2	5	5,71	-

The hydraulic wood splitting machine which will be primarily used for splitting pieces of wood one meter or less in length with a force of up to 160 kN (~ 16 tons) is selected for analysis in this paper. Due to possible errors when cutting the log to length, it is ensured that the log slightly longer than 100 cm fits under the splitter axe. Therefore, it was chosen that the height from the base to the top

of the axe is 105 cm (1050 mm). The selected splitting force of 16 t is the mean splitting force declared by the renowned manufacturers of splitters and forestry equipment, as indicated in Table 1. Based on the catalogue data [7-11], the reference splitting time at the high speed t_2 is 3 - 4 s, at the low speed t_3 is 6 - 8 s, and the return time of the axe to the initial position t_1 is 3 - 5 s. Looking at the travel speeds of 1000 mm, the high speed is 0.25-0.33 m/s, the low speed 0.14-0.17 m/s, and the return speed 0.2-0.33 m/s. According to the catalogue data [7-11], the oil flow in the system is 50-70 l/min and the pressure in the system is 200-250 bar. In order to avoid oil overheating issues, it would be convenient to have a relatively large volume of oil in the tank, i.e. between 25 and 35 L. The maximum PTO speed is 540 rpm. Figure 1 shows the hydraulic diagram of a splitter consisting of a hydraulic cylinder, a pump, a directional control valve, a filter, a non-return spring-loaded valve, a relief valve, and a fluid reservoir. Of course, in addition to all these components, hydraulic pipes and the fluid (oil) itself are also needed.
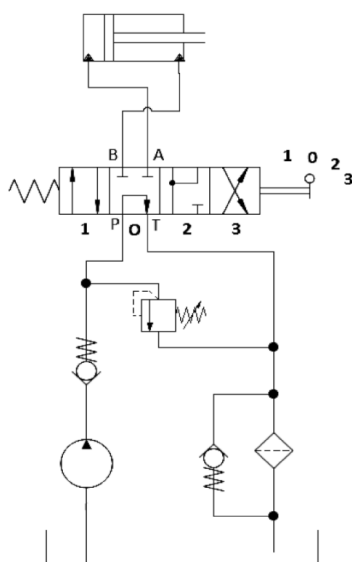
Figure 1: Hydraulics scheme of classical system.

The maximum force F of the cylinder that needs to be achieved to split the wood in this case is 160 kN. Wood splitters usually work at pressures between 200 and 250 bar, so the lower value of the working pressure p of 200 bar was chosen in this calculation as a kind of worst-case scenario. From the above data, the diameter d_{min} of the piston can be determined as follows:

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$$d_{\min} = \sqrt{\frac{4F}{\pi p}} \tag{1}$$

Based on the calculated minimum piston diameter of cylinder $d_{\min}$, the first larger standard piston diameter is selected from a suiTable catalogue (Table 2, [12]). The usual double-acting hydraulic cylinder (i.e. the so-called "differential cylinder"), has two connections (for hydraulic hoses) that allow the cylinder to move linearly to one side or the other.

Table 2: Technical specifications of cylinder

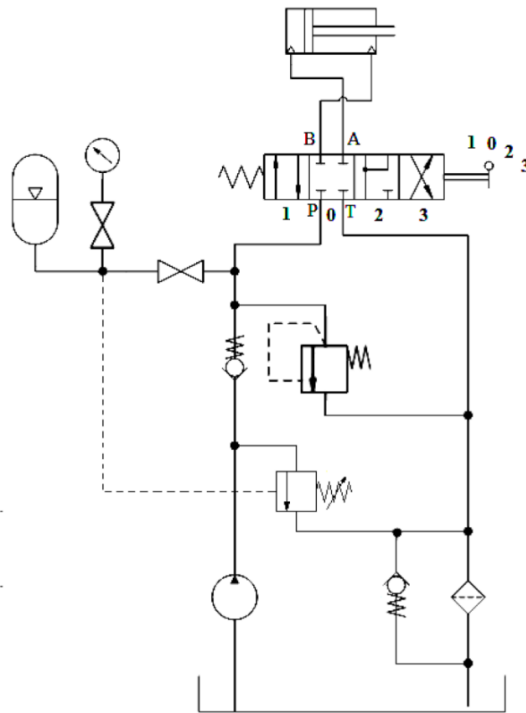| Hydraulic cylinder (100/60-1050)	
p_{max}	250 bar
$F+$ (250 bar)	190 kN
$F-$ (250 bar)	120 kN
x_{max}	1050 mm
v_{max}	500 mm/s
d	100 mm

Note that, due to the different ratio of the surface area of the compressed oil at different sides of the piston, the piston also has different pulling and contracting forces. Moreover, due to the different volume of oil on both sides of the cylinder, the piston speed is different for different movement directions, i.e. the piston moves faster from one side to another compared to movement in the opposite direction. In particular, when the cylinder is "pulled out", the oil acts on the entire surface of the piston, in which case the cylinder command a greater force and moves at a lower speed. When the surface of the piston is smaller, the piston moves faster in that direction and therefore the cylinder overcomes less force. The ultimate goal is to have favourable time of lowering the axe between 6 and 8 s (see t_3 in Table 1). Although the cylinder is able to move even faster (achieving traverse time of just 2.1 s), this requires a much larger fluid flow (and a larger pump), which leads to higher component costs. On the other hand, the axe should not move too slowly in order to avoid unnecessary loss of time and decreased productivity. Therefore, the required fluid flow Q for movement can be calculated as:

$$Q = \frac{vd^2\pi}{4\eta_{vol}}$$

(2)

where d is piston diameter and η_{vol} is volumetric efficiency of the system (η_{vol} = 0.95 is chosen in this paper). An adequate pump volume V_p of 32 cm³ is determined to satisfy required fluid flow at the pump operating speed of 2000 rpm [12, 13]. Please note that there is also a quick-stroke cylinder position on the direction valve (see position 2 in Figure 1) that can be used for higher cylinder pull-out speeds, but only at lower loads.

2.2   Hybrid model

A hydraulic accumulator has been added to the classic hydraulic fire wood splitter system to increase its efficiency and productivity, and, consequently, the hybrid system now possesses two energy sources (mechanical and hydraulic) through hybridisation. The hydraulics scheme, showing the location of the hydraulic accumulator, is shown in Figure 2. In addition to the hydraulic accumulator, a manometer, a shut-off valve and a valve for relieving the pressure of the accumulator have also been added to the system.

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Figure 2: Hydraulics scheme of hybrid system.

Figure 3 shows the operating cycle of a cylinder that cyclically repeats the operating strokes. The durations of individual work cycles were measured in real life [13], and the arithmetic mean was taken from several measurements. One working cycle lasts a total of 29 s. It should be noted that in the analysis the first few working cycles during system warm-up and startup of the working machine (tractor) are not taken into account due to them having significantly longer durations compared to steady-state operating regimes.
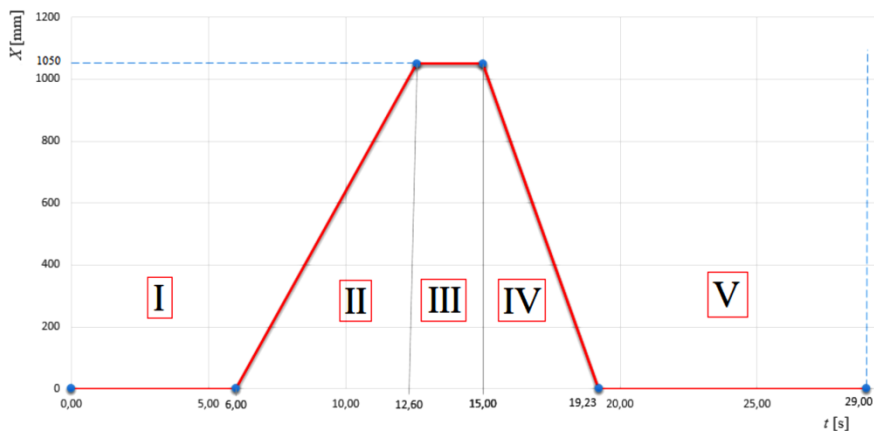

Figure 3: One duty cycle.

It can be seen that one operating cycle consists of 5 parts. The first (I) part is the preparation of wood, i.e. taking the log and placing it on the work surface. This takes 6 s and during this time both the cylinder and the axe are in their initial position ($x = 0$ mm). By holding the log on the splitter and pressing the lever downwards, the second (II) part begins, which represents the movement of the cylinder and the axe downwards, and the splitting of the wood begins. In this phase, the axe begins to enter the log which is already positioned on the splitter. With a log 100 cm long (the usual length), the stroke of the axe is 1050 mm, and this phase takes 6.6 s to complete. Afterwards, in the third (III) phase the lever is moved to the neutral position wherein the cylinder holds the final outward position for 2.4 s. During this phase it is sometimes necessary to manually separate the wood if it does not crack completely, but this does not frequently occur. Immediately after switching the lever upwards, the fourth (IV) phase is initiated, where the cylinder moves up to its initial position ($x = 0$ mm). The time required to return the cylinder is 4.23 s. Finally, in the fifth (V) phase logs are removed from the splitter, and are carried by a worker to their intended place

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and arranged in a row. The whole process takes 14 s and the cylinder is at a standstill at the end of stage V (stands in the initial position), and the hydraulic pump is constant switched on, giving flow throughout. Figure 4 shows a flow diagram of the time that the pump must achieve to move the cylinder.
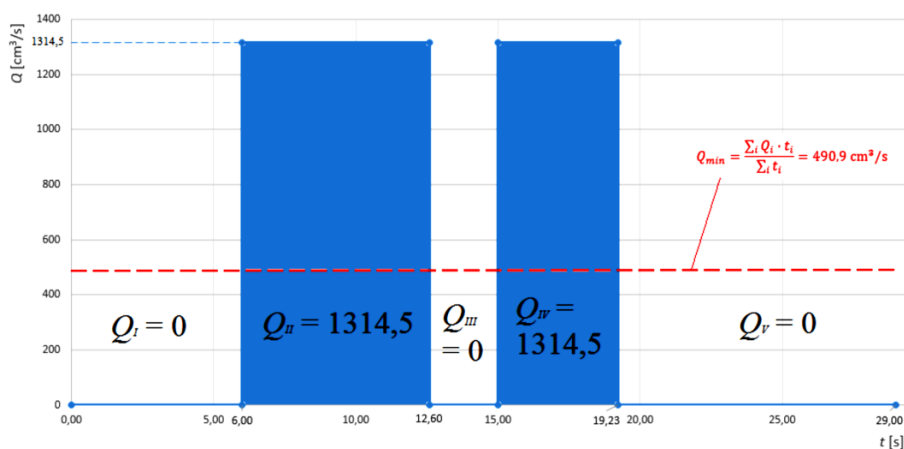

Figure 4: Required fluid flow for cylinder movement.

Figure 4 shows that parts I, III and V do not require fluid flow, i.e. the cylinder does not move in these phases, meaning that the hydraulic pump flow is not necessary. It is seen that the pump must operate only in phases II and IV. This is inefficient, as most of the time the pump provides a flow that is not actually needed by the system. When needed, the hydraulic oil flow is quite large, which means that a large hydraulic pump is needed for that purpose. The red dashed line in the diagram represents the pump flow Q_{min} which is determined as mean value for one duty cycle (490.9 cm³/s, or 29.45 l/min). If the required flow were distributed over the total time of one operating cycle, the required flow is almost three times lower compared to the peak flow. Therefore a smaller pump would be sufficient for that purpose.

Figure 5 shows a comparison of the volume provided by the average flow Q_{min} and the volume required for the entire operating cycle over time. The volume ΔV represents the part that needs to be compensated from the hydraulic accumulator. For dimensioning the hydraulic accumulator, the maximum ΔV is taken, which can be read from the diagram in Figure 5, and amounts to $\Delta V_{IV} =$ 886 cm³. Data related to the hydraulic accumulator are as follows: charging

pressure $p_0 = 80$ bar, operating pressure in the system $p_1 = 200$ bar and maximum pressure $p_2 = 320$ bar. The volume of the hydraulic accumulator for the adiabatic process with the charge of the accumulator with nitrogen ($n = \varkappa = 1.4$) was defined according to the following expression:

$$V_a = \frac{\Delta V}{\left[\left(\frac{p_0}{p_1}\right)^{\frac{1}{n}} - \left(\frac{p_0}{p_2}\right)^{\frac{1}{n}}\right]} \tag{3}$$

Therefore, the required volume of the hydraulic accumulator is 5.98 L, which has been rounded up to 6 L for further analysis. Such hydraulic accumulators can be found on the market and meet the required specifications.
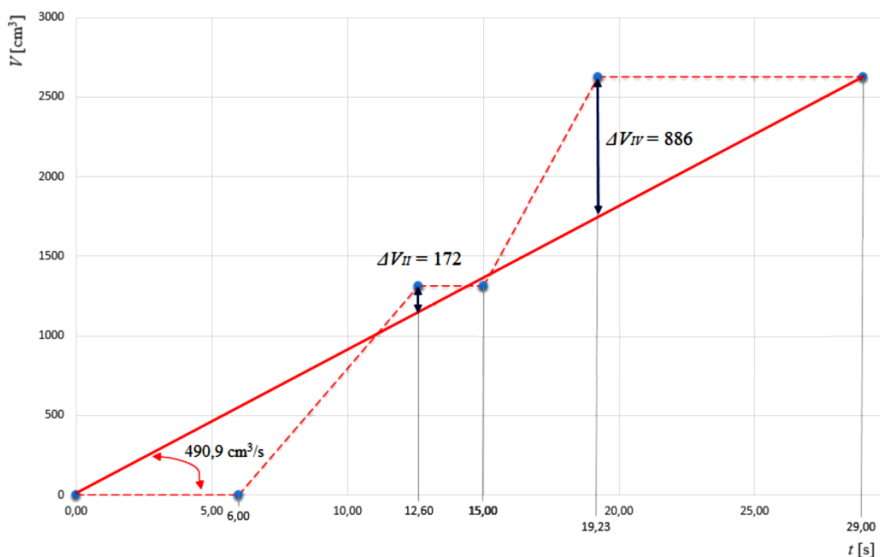

Figure 5: Required fluid flow for cylinder movement.

3   Simulation results

The previously analysed typical operating cycle of a classic hydraulic system for normal stroke scanario is simulated in FluidSIM environment. The results of this simulation scenario, including all five phases of piston operation (presented in Figure 3) are shown in Figure 6. The exact position of the cylinder in time can

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be seen, which approximately corresponds to the previously drawn diagram in Figure 3. It can be clearly seen how long it takes for the cylinder to move out, returns inside, and how long it actually stands in place and moves. Below the position diagram is a diagram of the speed of movement of the cylinder.
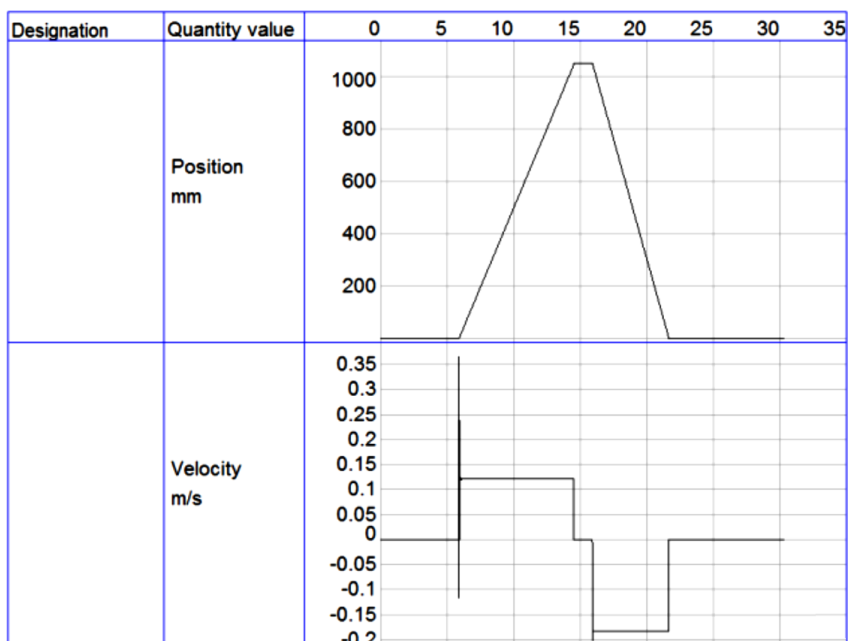
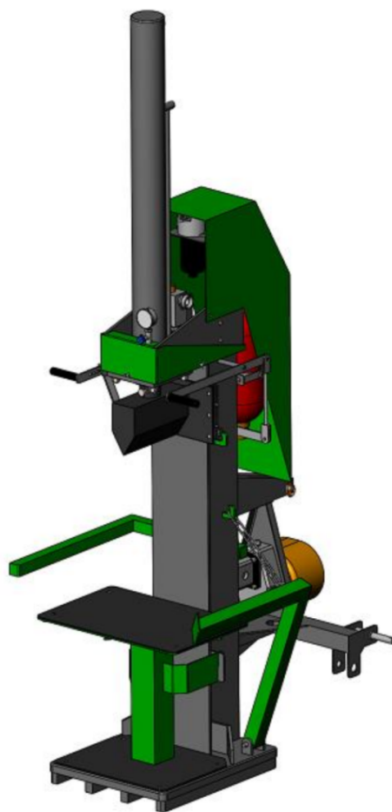**Figure 6: Simulation results of cylinder movement.**

The simulation results of the splitter operation using the computer program FluidSIM are given further and are compared with calculations. The simulation results show how the designed hydraulic system works and confirm that both the classical and the hybridised system meet the predefined requirements. The final results are presented in a Table 3, comparing these two systems in terms of analytical calculations and simulations in the FluidSIM program. The differences between analytical calculations and simulation results are primarily due to the fact that simple mathematical models used for steady-state analysis do not take into account some real physical phenomena such as friction, elasticity and fluid compressibility, and piston motion dynamics. In this case the cylinder is set to overcome the friction between steel and wood, however, given the friction factor offered, the question is how well this factor corresponds to real values. In addition, not all required parameters within the components were known, so

some required values were assumed, which could greatly affect the final simulation results. Furthermore, some parameters have been simplified in the FluidSIM software tool also, and it is therefore not possible to enter the exact characteristics of the hydraulic components from the catalogue (e.g. proper filter characteristics). The quality of the obtained results largely depends on details of the developed scheme, but also on the selected components. Due to the idealization of the system and lack of information on all parameters, certain deviations in results can be expected from the actual application. However, in the particular case these discrepancies between the results obtained by the simulation model and the analytical calculations are pretty negligible.

Table 3: Comparison of classical and hybridised system [13]

	CALCULATION		SIMULATION	
	Classical system	**Hybridised system**	**Classical system**	**Hybridised system**
v **[m/s]**	0.122	0.159	0.12	0.15
t_2 **[s]**	8.6	6.6	8.8	6.9
t_3 **[s]**	3.09	2.39	3.1	2.44
t_1 **[s]**	5.51	4.23	5.8	4.4
V_p **[cm³]**	32	16	32	16
Q **[l/min]**	57.49	30.4	57.16	30.39
n **[rpm]**	2057	2052	2057	2052
P **[kW]**	20	10	-	-
V_a **[l]**	0	6	0	6

The design solution of the hybridized hydraulic splitter is shown in Figure 7 and more details on structural calculations can be found in reference [13].

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Figure 7: 3D CAD model of hybridised firewood splitting machine [13].

4   Conclusion

The paper proposes the concept of a hydraulic machine for splitting firewood that uses a hydraulic accumulator to increase its efficiency. The hydraulics were chosen due to their high power density, i.e. they enable the transmission of large forces with relatively small devices and elements and straightforward conversion of hydraulic energy into mechanical work. Moreover, based on the proposed splitter implementation, a very simple realization of linear motion of the axe is possible. The hydraulics are also characterized by favourable dynamics, i.e. low inertia of the moving parts, with extremely simple overload protection by means of a pressure relief valve. In addition, hydraulic oil as a liquid medium (fluid),

which ensures favourable lubrication and heat conduction (cooling). The addition of a hydraulic accumulator is a novelty in this group of machines.

The splitting time of the wood (log) itself is very short compared to the remainder of the working cycle, i.e. significant part of the work cycle time is spent on placing log on the splitter and removing the split wood. In the classical system, the speed of the cylinder depends on the flow of the pump, while in the hybrid system, using a hydraulic accumulator, the operating speed is higher due to the added flow and pressure from the accumulator. In addition, it is possible to use the main pump rated for lower fluid flow, and, thus, a lower input power is needed from the tractor to drive the system. In other words, the use of a hydraulic accumulator allows the system of equal force and higher splitting speed to be permanently driven by a smaller tractor (lower power drive).

It is expected that a hybrid splitter system using a hydraulic accumulator would only be slightly more expensive than the conventional system. However, the the cylinder speed is increased and the splitting times are shortened by using the hybridised system, whereas a pump of smaller volume is needed, which results in less required power. Therefore, lower fuel consumption of the tractor during operation can be expected if hybrid solution is used. Economic viability is more emphasised in lower-power tractors, which are cheaper than their higher-power counterparts.

However, despite all of its advantages, hydraulics also have some disadvantages. Among the most significant is that hydraulic elements are highly expensive. In addition, there is a slightly greater need for maintenance because due to impurities and wear of components, there is a possibility of increased friction and possible losses due to fluid leakage, which leads to a decrease in efficiency. The environmental component is also questionable due to increased noise, potential fluid leakage into the environment and fire hazards.

Acknowledgments

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