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Fuel-Saving Solution for Forklifts Using Hydraulic Energy Storage and Regeneration Device Cluster Additionally Installed

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ABSTRACT

Forklifts are indispensable vehicles in warehouse logistics work. Large forklifts have a common configuration that uses a combustion engine to create energy to drive the machine's hydraulic system. Due to the characteristics of diesel engines, a large amount of energy is wasted and harmful gases are emitted every day. Especially with millions of older-generation forklifts and construction machines being used in developing countries, the above problem is even more serious while immediately replacing them with new generation machines is impossible. To solve this, the solution is to design and manufacture an additional device cluster to save fuel and reduce emissions. It is both economically and environmentally viable with the right technology. This article proposes the structure and working principle of an additional hydraulic device cluster to increase the working efficiency of the above types of forklifts. Based on building a mathematical model of the mechanical-hydraulic system during the lowering and lifting processes when applying the solution, the main parameters of the process were surveyed. The solution applied on a 3.5 tons forklift shows that the renewable energy percentage in one lowering and lifting cycle is 65.5%. The amount of diesel saved in a year is 2057 liters, corresponding to the one of CO_2, CH_4 and N_2O emissions removed by 5.55 tons, 223 grams and 326 grams, respectively. The proposed device cluster installation is easy with older-generation forklifts and can also be applied in the production of new forklifts.

Keywords: energy storage, forklift, fuel-saving, hydraulic system, renewable energy, sustainable development goals.

INTRODUCTION

Research on energy efficiency use, advanced fossil fuel technology, and emergency measures to respond to climate change are two of the urgent contents in the world's sustainable development goals. Machines and equipment serving the industrial and construction industries are actively researched and applied solutions to save energy, reduce fuel consumption, and reduce harmful gas emissions by researchers and machine manufacturers around the world. In 2007, [1] introduced Komatsu's 4 – wheel hybrid electric forklift model, with a lifting capacity of 1.5 tons and using batteries to store excess energy. Energy savings up to 20% while reducing CO_2 emissions by 20%. Similarly, Mitsubishi also developed a hybrid forklift line driven by an internal combustion engine and using batteries to store energy. Fuel efficiency increases by up to 39% [2]. In 2015, Lonnie R. Oxley's invention also presented a hybrid electric forklift model [3]. For big machines and equipment, research directions focus on developing hybrid technologies to achieve the required capacity, maximum fuel efficiency, and reduced emissions. The first is the development of energy regeneration systems through a generator – electric battery/accumulator – electric motor as in [4–7]. In [4], the energy recovery effectiveness from the lifting and lowering process of the heavy excavator is analyzed. In [5], the hybrid excavator structure and its working characteristics are analyzed. Based on that, the control strategies are proposed, including the constant working point, dual working point, and dynamic working point of the engine. The authors in [6] systematically analyze the power transmission system performance of the hydraulic excavator and compare the performance between the parallel configuration and conventional ones based on excavators 5 tons. In terms of both performance and cost, the parallel drivetrain is the best configuration for hybrid excavators. Regarding evaluation and comparison with using batteries and combining with pressure tanks to store energy, the potential energy recovery efficiency of the excavator boom lifting process is 41% and 17%, respectively [7]. The second is to develop batteries/accumulators and energy storage systems to meet machine capacity, such as battery systems with sufficient capacity to serve effective work for forklifts [8–11]. The third is to develop an energy regeneration system through hydraulic accumulators and motors. Research [12] uses a parallel hydraulic system to regenerate and reuse energy while operating the wheel loader. The power controller according to the logic threshold approach method is built to control dynamic switching between different operating modes. Finally, there is a combination of electric batteries/accumulators with a hydraulic accumulator and renewable energy source control strategies. This direction is currently very developed. Some typical publications can be mentioned as [13–16]. In [13] both hydraulic and electric accumulators are used to store energy from the energy recovery system on the excavator and combine with a strategy controlling the limited recovery time of the renewable energy. The result is that 39% of the total potential energy is regenerated. The authors in [14] design a controller according to an improved logic threshold approach in energy management for a power-splitting electric vehicle system. By combining the internal combustion engine's performance map and optimal torque curve with the battery's state of charge, the controller helps manage the internal combustion engine in its peak performance zone. Fuel consumption and engine system performance are improved. The work [15] studies the control strategy and parameters comparison of the power transmission system for hybrid hydraulic excavators. The working loads of the excavator 20 tons are measured and analyzed. Dynamic programming algorithms are used to control various system parameters. Genetic algorithms are used to obtain optimal energy consumption parameters. Simulation results show that the machine's performance is improved by 8.80% compared to traditional excavators. Research [16] proposes a new potential energy recovery system using a hydraulic accumulator and valve-motor-generator for hybrid hydraulic excavators. The results demonstrate that the dynamic performance of the system is close to that of the throttle control system.

The general configuration of big construction machines in general and big forklifts in particular is to use a combustion engine and hydraulic transmission. Although there are many studies aimed at developing new fuels to replace fossil fuels [17, 18] and improving the performance of compression ignition engines [19, 20], today a large number of these machines are still using traditional fossil fuels (especially diesel) with a quite low engine's efficiency. The amount of energy generated by burning fuel that is converted into useful energy to serve the actuator is very small. In research [21], it was shown that the percentage of useful energy only accounts for 6.7% of the overall one. Thus, the most effective way to regenerate and use the energy obtained is to regenerate hydraulic energy from the actuator and use that energy directly without converting or storing it to convert it to other forms of energy (hydraulic-electric-hydraulic).

Currently, the current situation in developing countries is that many older-generation forklifts are used for construction, loading and unloading in warehouses, factories, and ports. Large fuel consumption and gas emissions cause serious environmental pollution. It is impossible to immediately replace all of them with machines with better technology. Meanwhile, to meet the development of technical and logistics infrastructure, the need to use them is increasing rapidly.

To solve the problem of large fossil fuel consumption and emissions for these machines, this work proposes a solution to install an additional hydraulic device cluster into the hydraulic system of older-generation machines to turn them into new-generation machines. Regenerated energy from the potential energy of the lifted object is recovered into a hydraulic accumulator during the lowering process and directly reused that hydraulic energy flow for the lifting process. The article describes the proposed fuel-saving solution. To analyze the working process and evaluate its effectiveness, the research establishes a model of mechanical-hydraulic system dynamics during the lifting and lowering processes when applying this solution; implements the numerical simulation; analyzes system operating parameters; and determines the amount of energy saved corresponding to the amount of fuel saved and of harmful emission reduction. Finally, the evaluations and conclusions are drawn based on the results of the solution application to a specific forklift model.

PROPOSING SOLUTIONS TO REGENERATE AND USE ENERGY EFFECTIVELY

Requirements for the proposed solution

The requirements for the proposed solution include the following points:

- renewable energy is in the form of hydraulic oil flow energy and is used directly for the system. It should not convert renewable energy into electricity and vice versa;
- store renewable energy and use it for activities that require large amounts of energy;
- do not use large servo valves, maximize the use of existing equipment on the machine and minimize additional equipment;
- connection operations and installation of the additional device cluster shall be simplified;
- although the system works to save energy, the system shall ensure the safety functions;
- ensure the original functions of the machine;
- reasonable price so the solution can be widely applied.

Structure of the proposed hydraulic system

The hydraulic and control circuit for the proposed fuel-saving solution by regenerating and using energy efficiently is shown in Figure 1. The added equipment group includes the elements

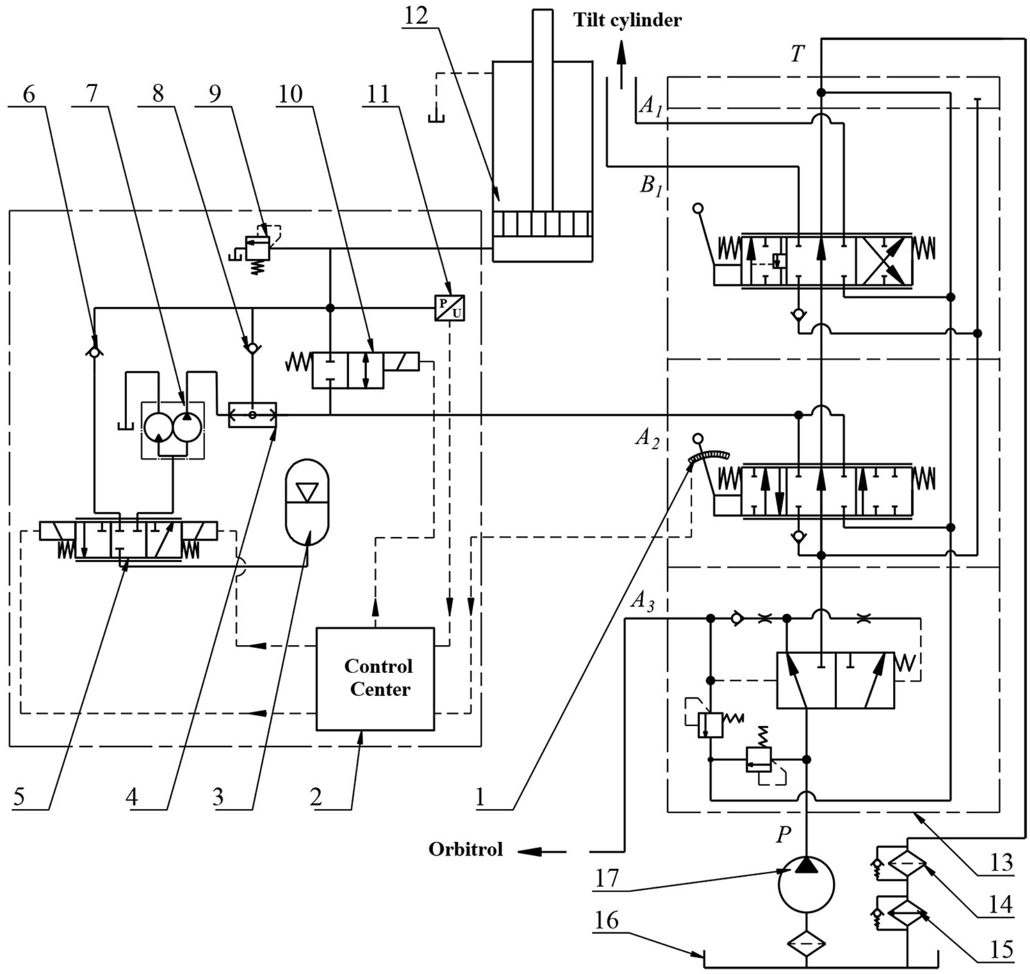

Figure 1. Hydraulic circuit to regenerate energy and use it for forklift: 1 – position sensor; 2 – central controller; 3 – hydraulic accumulator; 4 – or valve; 5 – proportional control valve 3/3; 6 and 8 – check valve; 7 – pressure amplifier; 9 – safety valve, 10 – directional control valve 2/2, 11 – pressure sensor, 12 – lifting cylinder, 13 – control valve block, 14 – oil filter, 15 – cooler, 16 – oil tank, 17 – fixed hydraulic pump

numbered 1 to 11. The remaining elements belong to the original machine. The lifting valve joystick has a minor modification compared to it on the original machine. When controlling it in the lifting direction, it moves through two zones. The joystick moves in the first zone, the lifting valve is not been affected to change to the lifting state. Otherwise, when it moves in the remaining zone, the lifting valve works. The position sensor is installed in the first and the lowering zones.

Work principle of the system during the lowering process

Pressure sensor 11 provides information about oil pressure in the lifting cylinder to the central controller. When the pressure is large enough combined with the position sensor signal created by controlling the lifting valve to lower the piston, valve 5 is controlled to switch to the charging state. The oil flows from lifting cylinder 12 through check valve 6, then through valve 5, and into hydraulic accumulator 3. The opening of valve 5 is proportional to the displacement of the lifting valve joystick. This lowering process is one of regenerating energy from the potential energy of the forks, the lifting frame, and the lifting object to become hydraulic energy and store it in the accumulator. In case it is necessary to quickly lower the piston, valve 10 is controlled to cause the oil to pass through the lifting valve and return to the oil tank as in the normal working mode of the machine. When the oil pressure in the cylinder is not high enough (such as lowering the fork without a lifting object), it is impossible to charge the oil to the accumulator, the central controller controls valve 10 to let the oil flow to the oil tank.

Work principle of the system during the lifting process

The position sensor provides the signal that is generated by the displacement of the lifting valve joystick in the lifting direction (in the first zone) to the central controller. Valve 5 is controlled to switch to the oil discharge state. The valve's opening is proportional to the joystick displacement. The boundary between two zones in the lift direction corresponds to the maximum opening of valve 5. The oil from hydraulic accumulator 3 discharges through valve 5, through pressure amplifier 7 (pressure increases according to the amplification factor), through valve 4, then through valve 8, and into the lifting cylinder 12. The object is lifted and the oil pressure in the cylinder gradually decreases. When the lifting object tends to stop, the operator continues to control the joystick in the second zone to pump oil into the cylinder as in the machine's original mode (the oil is no longer discharged from the accumulator).

ESTABLISHMENT OF MECHANICAL-HYDRAULIC SYSTEM MODEL

Dynamics of lifting and lowering process

Applied assumptions

The following assumptions are used in the computational model and simulation:

- the value of the elastic modulus of oil and pipes is independent of system pressure and is an extremely large constant;
- energy loss in hydraulic systems is due to pressure loss when oil passes through hydraulic elements;
- pressure loss when oil flows through the pipe is ignored;
- the process of charging and discharging gas from an accumulator is an adiabatic one.

Lowering process

The lowering process of the piston is the one of charging oil into the hydraulic accumulator. The piston and the lifting object move downward with acceleration. The Equation of their motion during this process is

$$(m_c + m_n)g - F_f - pA = (m_c + m_n)\ddot{x} \tag{1}$$

where: m_c – mass of the fork, lifting frame and piston (kg), m_n – mass of the lifting object (kg), g – acceleration of gravity, F_f – friction force (N), p – hydraulic oil pressure in the cylinder (N/m^2), A – area of the piston (m^2), $\ddot{x}$ – acceleration of the lowering process, (m/s^2).

The friction force that resists the piston's movement is determined as follows [22].

$$F_f = (10^5 + 0.02p)A \tag{2}$$

The pressure difference between the inlet and outlet of valve 5 is

$$\Delta p_x = p - \Delta p_{cv} - p_a \tag{3}$$

where: Δp_{cv} – pressure loss at valve 6, and p_a – hydraulic oil pressure in the accumulator.

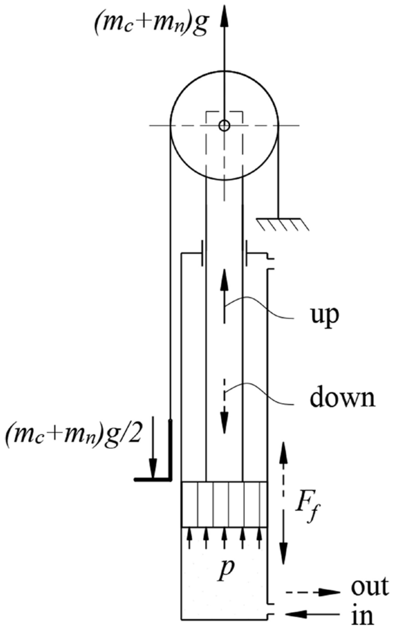

Figure 2. Mechanical model during lifting and lowering processes

The flow rate through valve 5 depends on the pressure drop which is the pressure difference between the inlet and outlet ports and the corresponding nominal flow. The following Equation shows the details of this.

$$Q_x = Q^*_{Nom} \cdot \sqrt{\frac{\Delta p_x}{\Delta p_{Nom}}}, \tag{4}$$

where: Δp_{Nom} – pressure drop when the flow rate is nominal, and the command signal is maximum, $\Delta p_{Nom} = 5 \cdot 10^5$ Pa; and Q^*_{Nom} – flow rate depending on the command signal.

Flow rate Q^*_{Nom} is determined as follows:

$$Q^*_{Nom} = Q_{Nom} f(u) \tag{5}$$

where: u – a variable that characterizes the joystick position, and Q_{Nom} – the nominal flow rate corresponding to the maximum opening position of the joystick.

Flow rate Q_x is also calculated through piston velocity $\dot{x}$ as follows:

$$Q_x = 2A\dot{x} \tag{6}$$

Substituting (5) and (6) into (4), one has

$$\Delta p_x = \left(\frac{2A\dot{x}}{Q_{Nom} f(u)} \right)^2 \Delta p_{Nom} \tag{7}$$

The process of compressing gas in the accumulator is an adiabatic one, so

$$p^*_a V_a{}^n = p^*_1 V^n_1 \tag{8}$$

where: p^*_1, V_1 – absolute pressure and volume of the gas in the accumulator at the beginning of the charging process, V_a – volume of the gas in the accumulator corresponds to absolute pressure p^*_a, and n – adiabatic index.

The gas volume V_a is determined through the displacement of piston x and the volume V_1 as follows:

$$V_a = V_1 - 2Ax \tag{9}$$

Substituting (9) into (8), the absolute gas pressure value p^*_a is

$$p^*_a = p^*_1 \left(\frac{V_1}{V_1 - 2Ax} \right)^n \tag{10}$$

Continue substituting (10) and (7) into (3), one has

$$p = \left(\frac{2A\dot{x}}{f(u) Q_{Nom}} \right)^2 \Delta p_{Nom} + p^*_1 \left(\frac{V_1}{V_1 - 2Ax} \right)^n + \Delta p_{cv} - 10^5 \tag{11}$$

Substituting (2) and (11) into (1), the piston's acceleration during the lowering process is

$$\ddot{x} = g - \frac{A}{m_c + m_n} \left[-2 \cdot 10^3 + 1.02 \left(\frac{2A\dot{x}}{f(u) Q_{Nom}} \right)^2 \Delta p_{Nom} + \right.$$
$$\left. + 1.02 p^*_1 \left(\frac{V_1}{V_1 - 2Ax} \right)^n + 1.02 \Delta p_{cv} \right] \tag{12}$$

Lifting process

Here, only the piston lifting process is considered due to the hydraulic power source provided by the accumulator. The motion Equation of the piston during lifting is as follows.

$$pA - (10^5 + 0.02p)A - (m_c + m_n)g = (m_c + m_n)\ddot{x} \tag{13}$$

The oil pressure in the cylinder is determined by

$$p = k\eta_a (p_a - \Delta p_x) - \Delta p_{cv} - \Delta p_{or} \tag{14}$$

where: k – amplification factor of the hydraulic pressure amplifier; η_a – performance coefficient of the hydraulic pressure amplifier, and Δp_{or} – pressure loss at valve 4.

Performing the same as above, the absolute gas pressure in the accumulator is determined

$$p^*_a = p^*_2 \left(\frac{V_2}{V_2 + 2Axk} \right)^n \tag{15}$$

where: p^*_2, V_2 – absolute pressure and volume of the gas in the accumulator at the beginning of the discharging process.

The pressure drop at the valve 5 in this process is

$$\Delta p_x = \left(\frac{2A\dot{x}}{Q_{Nom} f(u)} \right)^2 \Delta p_{Nom} \tag{16}$$

Substituting (15) and (16) into (14) and then into (13), the acceleration of the piston in the lifting motion is specified as follows.

$$\ddot{x} = \frac{0.98k\eta_a A}{(m_c + m_n)} \left[\frac{p_2^* V_2^n}{(V_2 + 2Axk)^n} - \left(\frac{2Ak\dot{x}}{Q_{Nom} f(u)} \right)^2 \Delta p_{Nom} - \right.$$

$$\left. - \frac{\Delta p_{cv} + \Delta p_{or}}{k\eta_a} - \frac{10^5}{0.98k\eta_a} - 10^5 \right] - g \tag{17}$$

Amount of renewable energy and save fuel

The energy stored into the hydraulic accumulator is the compression gas energy increased when compressed from the initial pressure p^*_1 to the final pressure of the charging process p^*_2.

$$E_n = \frac{V_1 \left(p_1^* \right)^{1/n}}{n} \int_{p_1^*}^{p_2^*} p^{-1/n} dp \tag{18}$$

$$E_n = \frac{V_1 \left(p_1^* \right)^{1/n}}{n-1} \left[\left(p_2^* \right)^{(n-1)/n} - \left(p_1^* \right)^{(n-1)/n} \right] \tag{19}$$

The useful energy released from the accumulator in one lifting and lowering cycle is

$$E_x = (m_c + m_n) g h_x \tag{20}$$

where: h_x – the height of the object lifted by the hydraulic energy supplied by the accumulator.

The amount of fuel saved during one lifting and lowering cycle of the forklift is

$$m_{ck} = \frac{E_x}{\eta_c H_t} \tag{21}$$

where: η_c – overall performance coefficient of the internal combustion engine and transmission system, η_c = 6.7% [21]; and H_t – heat capacity of diesel fuel, $H_t = 43 \cdot 10^6$ J/kg [23].

The mass of fuel saved in a year is

$$m_{1y} = c_h h_d d_y m_{ck} \tag{22}$$

where: c_h – number of lifting and lowering cycle per hour, h_d – number of working hours of the machine per day; and d_y – number of working days in a year.

The amount of CO_2 emissions removed by applying this fuel-saving solution can be determined by

$$m_{CO2} = \frac{k_{CO2} m_{1y}}{\gamma_{diesel}} \tag{23}$$

where: k_{CO_2} – CO_2 emission coefficient, k_{CO_2} = 2697.5 kg/m^3 [24]; and γ_{diesel} – density of diesel, γ_{diesel} = 830 kg/m^3.

Similarly, the amount of other harmful emissions such as CH_4 and N_2O removed can also be found based on fuel savings.

APPLYING THE SOLUTION ON THE 3.5 TONS FORKLIFT

The charging and discharging processes of the accumulator correspond to the process of lowering and lifting ones of the piston in the lifting cylinder. The consideration of dynamic parameters and hydraulic flow parameters to evaluate the compatibility between additional equipment and the forklift's existing hydraulic system and also to evaluate the effectiveness of energy saving is necessary. Corresponding to that is evaluating the effectiveness of fuel savings and CO_2 emission reduction when applying the proposed solution on a specific forklift.

Investigating the piston lowering process according to Equation (12) with specific parameters determined from the ones of the 3.5 tons forklift - a common forklift configuration and ones of the hydraulic accumulator as shown in Table 1. The initial conditions include t = 0 s, x = 0 m, and $\dot{x}$ = 0 m/s.

Similar to the lowering process, the parameters for the investigation of the lifting process (discharging the hydraulic from the accumulator) according to Equation (17) are shown in Table 2, and the initial conditions consist of t = 0 s, x = 0 m, and $\dot{x}$ = 0 m/s.

Programming to investigate the above problems in Matlab software with three control modes of the joystick shown in Figure 2 and the characteristic curve of valve 5 shown in [25]. The results obtained are graphs of the piston displacements in Figure 3 and Figure 4, the piston velocities in Figure 5 and Figure 6, the charging oil flow rate into the accumulator in Figure 7, the discharging one from the accumulator in Figure 8, and the

Table 1. Parameters for investigating the piston lowering process

m_c (kg)	m_n (kg)	n	A (m²)	Δp_{or} (N/m²)	Q_{Nom} (m³/s)	p_1^* (N/m²)	V_1 (m³)
250	3500	1.4	2.826×10^{-3}	2×10^{5}	58.3×10^{-5}	5.86×10^{6}	20×10^{-3}

Table 2. Parameters for investigating the piston lifting process

m_c (kg)	m_n (kg)	n	k	A (m²)	Δp_{or} (N/m²)	Δp_{cv} (N/m²)	Q_{Nom} (m³/s)	p_2^* (N/m²)	V_2 (m³)
250	3500	1.4	2.42	2.826×10^{-3}	2×10^{5}	2×10^{5}	58.3×10^{-5}	12.68×10^{6}	11.55×10^{-3}

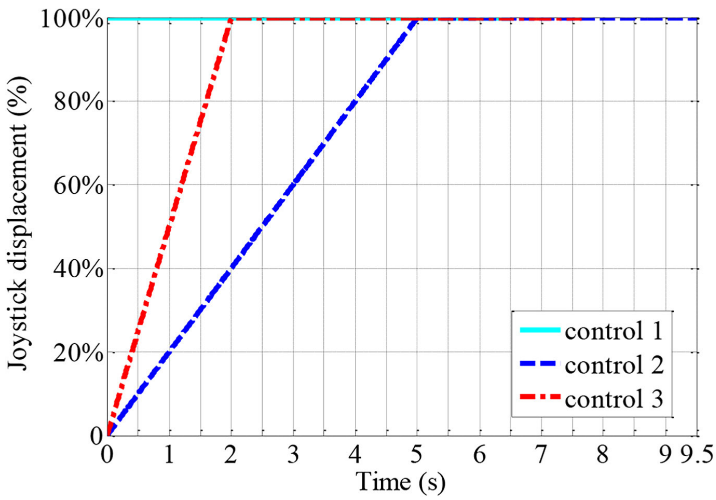

Figure 3. Joystick control modes

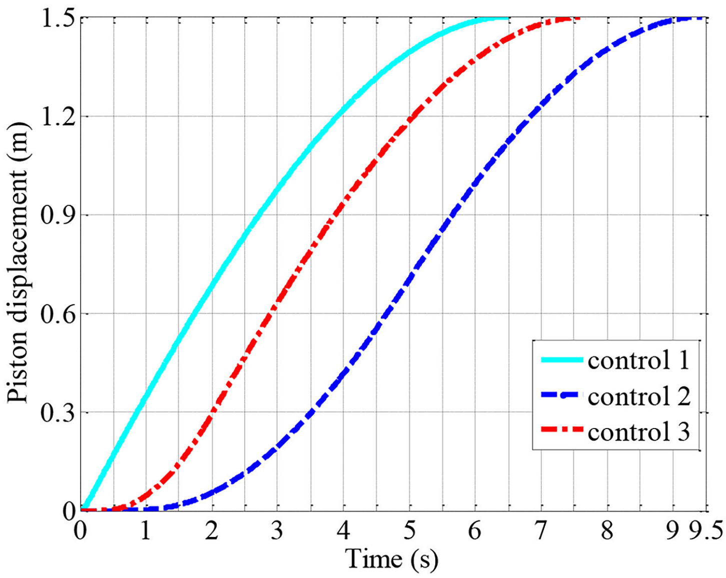

Figure 4. Displacement of the piston during the lowring process

absolute pressure of the gas in the accumulator during both processes in Figures 9 and 10.

From the above results, it can be seen that the lifting and lowering speeds depend on the joystick control modes. The lifting speed increases rapidly when the joystick is suddenly controlled (corresponding to the mode of control 1). During lifting control, this control mode should be avoided. The values of the kinematic parameters and hydraulic flow parameters in modes of control 1 and 2

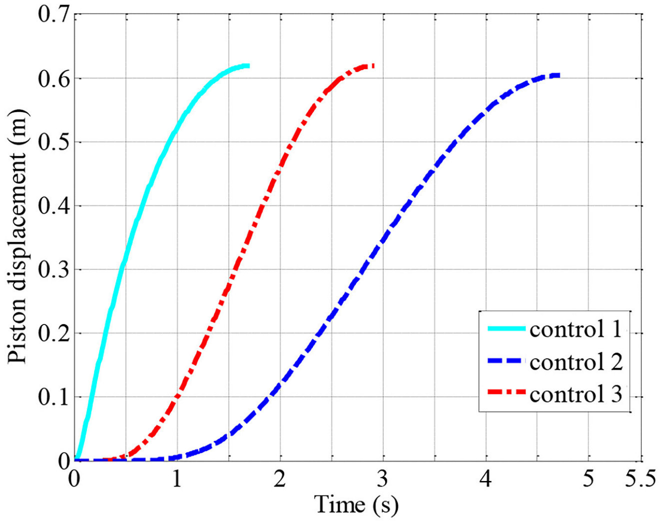

Figure 5. Displacement of the piston during the lifting process

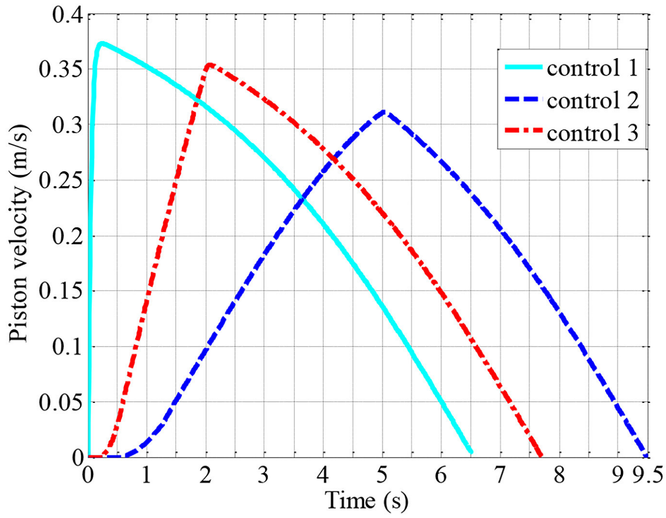

Figure 6. Velocity of the piston during the lowring process

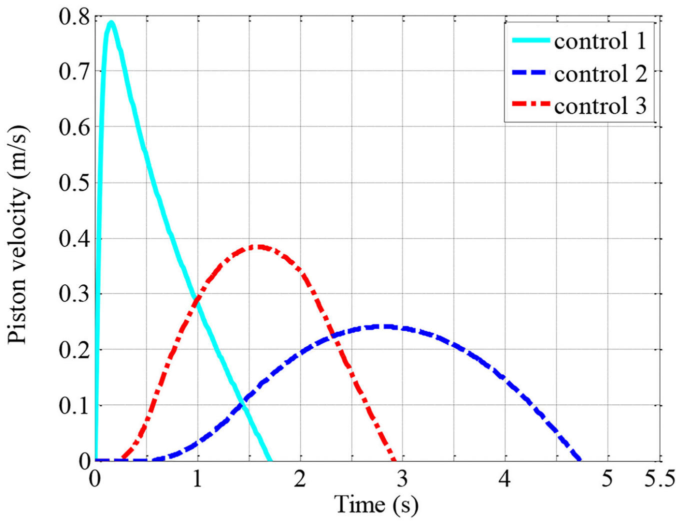

Figure 7. Velocity of the piston during the lifting process

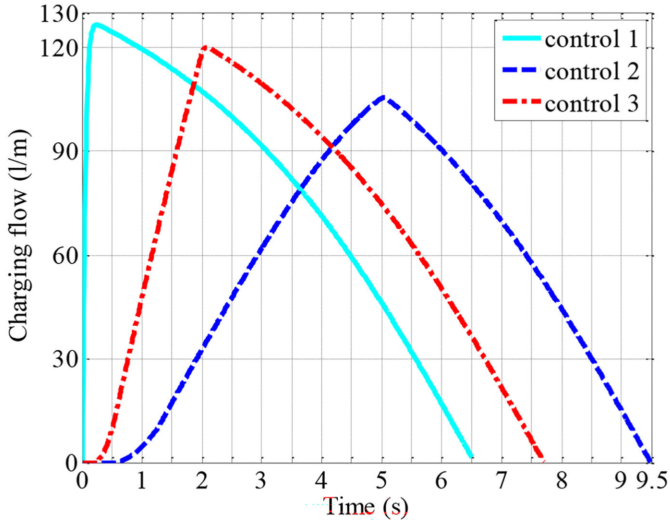

Figure 8. Charging oil flow rate into the accumulator during the lowring process

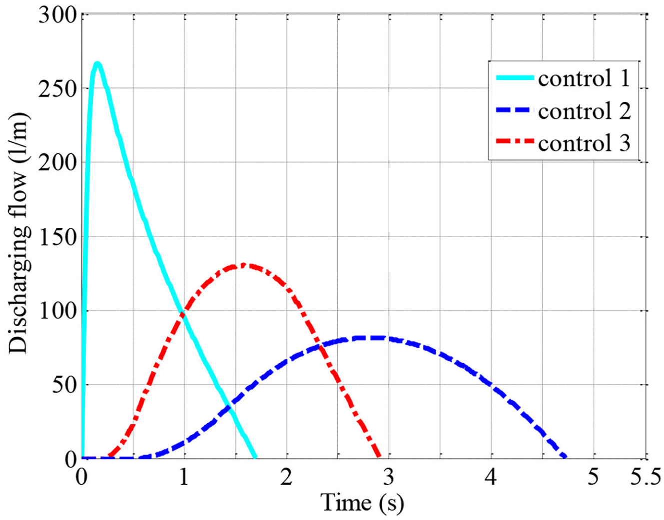

Figure 9. Discharging oil flow rate from the accumulator during the lifting process

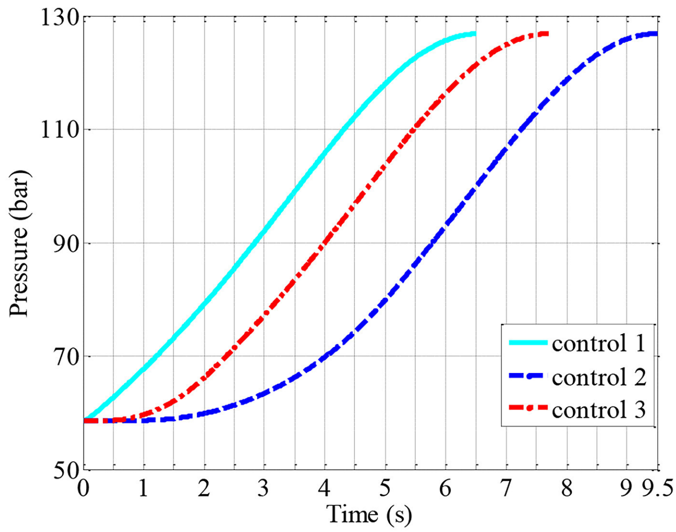

Figure 10. Absolute pressure of the gas in the accumulator during the lowring process

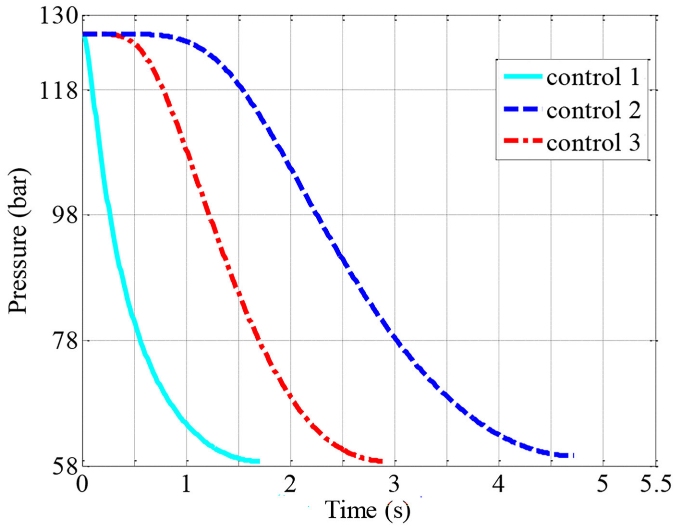

Figure 11. Absolute pressure of the gas in the accumulator during the lifting process

Table 3. Parameters for determining the efficiency of energy and fuel savings

p_1^* (N/m²)	V_1 (m³)	p_2^* (N/m²)	n	η_c	H_t (J/kg)	k_{CO2} (kg/m³)	γ_{diesel} (kg/m³)
5.86×10^6	12.7×10^{-3}	12.68×10^6	1.4	0.067	43×10^6	2697.5	830

Table 4. Efficiency of energy and fuel savings

Stored energy into the hydraulic accumulator in one lifting and lowering cycle	72296 J
Percentage of renewable energy in one lifting and lowering cycle	65.5%
Renewable energy is used usefully in one lifting and lowering cycle	45543 J
Percentage of renewable energy used usefully in one lifting and lowering cycle	41.3%
Amount of fuel saved in one lifting and lowering cycle	15.8×10^{-3} kg
Amount of fuel saved in one year (45 cycles/hour, 8 hours/day, and 300 days/year)	1707 kg (2057 liters)
Amount of CO_2 removed in one year	5549 kg
Amount of CH_4 removed in one year	223×10^{-3} kg
Amount of N_2O removed in one year	326×10^{-3} kg

are more consistent with the values of the ones on the forklift. They can be adjusted by adjusting the joystick movement speed and setting the initial values of the added system. The amount of renewable energy, fuel saved, and the toxic emissions removed are calculated with the parameters in Table 3. The results are obtained in Table 4.

The results have shown that the amount of renewable, stored, and beneficially used energy is large. The percentages of energy recovered during one lifting and lowering cycle and energy usefully used exceed 65% and 41%. The economic benefit obtained after each year with one machine operating is a significant number (exceeding 2000 liters of diesel reduced). It contributes to the motivation to invest in upgrading old-generation forklifts. More specifically, the benefits of environmental protection are more evident when a large amount of harmful emissions are eliminated.

CONCLUSIONS

The study has proposed a solution to install an additional hydraulic device cluster into the existing forklift hydraulic system to recover excess energy into an accumulator during the lowering process and directly reuse the hydraulics energy flow for the lifting process.

The work shows a significant effect in terms of fuel savings when applying the proposed solution on the forklift with a lifting capacity of 3.5

tons, specifically saving 2057 liters of diesel per year and eliminating 5549 kg of CO_2, 223×10^{-3} kg of CH_4, and 326×10^{-3} kg of N_2O.

Adjusting the lifting and lowering speed can be done by controlling the joystick and setting the initial pressure of the hydraulic accumulator. The solution is very efficient because the energy is regenerated and used in the same form (no loss due to conversion from hydraulic energy to electrical energy and vice versa; no costs for electrical motors and generators). Millions of older-generation forklifts are utilized while still ensuring fuel economy and minimizing harmful gas emissions.

It is feasible to install the proposed device cluster on older-generation forklifts to convert them into hybrid forklifts. It can also be applied to the production of new forklifts and machines with similar configurations and lifting process such as excavators, wheel loaders, etc.

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REFERENCES

1. Yoshida M., Tsukamoto Y., Matsuda T., Dougan Y., Ueno K. Introducing Electric-powered Forklift Truck "New ARION Series". Komatsu Technical Report 2007, 53(195), 1–6. https://www.komatsu.jp/en/company/tech-innovation/report/pdf/159-06_E.pdf (Accessed: 05.02.2024).
2. Ogawa K., Futahashi K., Teshima T., Akahane F. Development of the world's first engine/ battery hybrid forklift truck. Mitsubishi Heavy Industries Technical Review 2010, 47(1), 46–50. https://www.mhi.co.jp/technology/review/pdf/e471/e471046.pdf (Accessed: 07.02.2024).
3. Oxley L.R. Hybrid Forklift Truck. US Patent Application Publication, Pub. No. US 2015/0122584 A1, 2015.
4. Minav T., Laurila L., Pyrhönen J. Energy Recovery efficiency comparison in an electro-hydraulic forklift and in a diesel hybrid heavy forwarder. In: International Symposium on Power Electronics, Electrical Drives, Automation and Motion. Pisa, Italy, June 2010. https://doi.org/10.1109/SPEEDAM.2010.5542232
5. Xiao Q., Wang Q., Zhang Y. Control strategies of power system in hybrid hydraulic excavator. Automation in Construction 2008, 17(4), 361–367. https://doi.org/10.1016/j.autcon.2007.05.014
6. Wang D., Gua C., Pan S., Zhang M., Lin X. Performance analysis of hydraulic excavator powertrain hybridization. Automation in Construction 2009, 18(3), 249–257. https://doi.org/10.1016/j.autcon.2008.10.001
7. Lin T., Wang Q., Hu B., Gong W. Research on the energy regeneration systems for hydraulic excavators. Automation in Construction 2010, 19(8), 1016–1026. https://doi.org/10.1016/j.autcon.2010.08.002
8. Keränen T.M., Karimäki H., Viitakangas J., Vallet J., Ihonen J., Hyötylä P., Uusalo H., Tingelöf T. Development of integrated fuel cell hybrid power source for electric forklift. Journal of Power Sources 2011, 196(21), 9058–9068. https://doi.org/10.1016/j.jpowsour.2011.01.025
9. Hosseinzadeh E., Rokni M., Advani S., Prasad A. Performance simulation and analysis of a fuel cell/battery hybrid forklift truck. International Journal of Hydrogen Energy 2013, 38(11), 4241–4249. https://doi.org/10.1016/j.ijhydene.2013.01.168
10. Minaw T., Virtanen A., Laurila L., Pyrhoenen J. Storage of energy recovered from an industrial forklift. Automation in Construction 2012, 22, 506–515. https://doi.org/10.1016/j.autcon.2011.11.010
11. Shin M.-H., Eom T.-H., Park Y.-H., Won C.-Y. Design and control of fuel cell-battery hybrid system for forklift. In: IEEE Transportation Electrification Conference and Expo. Busan, Korea, 584–589, June 2016. https://doi.org/10.1109/ITEC-AP.2016.7513020
12. Hui S., Junqing J. Research on the system configuration and energy control strategy for parallel hydraulic hybrid loader. Automation in Construction 2010, 19(2), 213–220. https://doi.org/10.1016/j.autcon.2009.10.006
13. Lin T., Huang W., Ren H., Fu S., Liu Q. New compound energy regeneration system and control strategy for hybrid hydraulic excavators. Automation in Construction 2016, 68, 11–20. https://doi.org/10.1016/j.autcon.2016.03.016
14. Fu Z., Wang B., Song X., Liu L., Wang X. Power-split hybrid electric vehicle energy management based on improved logic threshold approach. Mathematical Problems in Engineering 2013, 2013(11), 1–9. https://doi.org/10.1155/2013/840648
15. Chen Q., Lin T., Ren H. Parameters optimization and control strategy of power train systems in hybrid hydraulic excavators. Mechatronics 2018, 56, 16–25. https://doi.org/10.1016/j.mechatronics.2018.10.003
16. Chen Q., Lin T., Ren H., Fu S. Novel potential energy regeneration systems for hybrid hydraulic excavators. Mathematics and Computers in Simulation 2019, 163, 130–145. https://doi.org/10.1016/j.matcom.2019.02.017
17. Žvirblis T., Hunicz J., Matijošius J., Rimkus A.,

Kilikevičius A., Gęca M. Improving diesel engine reliability using an optimal prognostic model to predict diesel engine emissions and performance using pure diesel and hydrogenated vegetable oil. Eksploatacja i Niezawodność – Maintenance and Reliability 2023, 25(4), 174358. https://doi.org/10.17531/ein/174358

18. Caban J., Gniecka A., Holeša L. Alternative fuels for diesel engines. Adv. Sci. Technol. Res. J. 2013, 7(20), 70–74. https://doi.org/10.5604/20804075.1073063
19. Caban J., Droździel P., Ignaciuk P., Kordos P. The impact of changing the fuel dose on chosen parameters of the diesel engine start-up process. Transport Problems 2019, 14(4), 51–62. https://doi.org/10.20858/tp.2019.14.4.5
20. Hoang A.T., and Pham V.V. A study on a solution to reduce emissions by using hydrogen as an alternative fuel for a diesel engine integrated exhaust gas recirculation. AIP Conference Proceedings 2020, 2235, 020035. https://doi.org/10.1063/5.0007492
21. Hijikata S., Weishaar P., Leifeld R., Schmitz K. Experimental evaluation of system efficiency for a hydraulic hybrid architecture of excavators. MM Science Journal 2018, 2455–2459. https://doi.org/10.17973/MMSJ.2018_10_201836
22. Bak M.K. and Hansen M.R. Analysis of offshore knuckle boom crane - part one: modeling and parameter identification. Modeling, Identification and Control 2013, 34(4), 157–174. https://doi.org/10.4173/mic.2013.4.1
23. Wickert J., Lewis K. An Introduction to Mechanical Engineering. Cengage Learning, USA, 2017.
24. U.S. Environmental Protection Agency. Emission Factors for Greenhouse Gas Inventories. https://www.epa.gov/system/files/documents/2023-03/ghg_emission_factors_hub.pdf, 2023. (Accessed: 05.02.2024).
25. Nguyen V.T. Anti-vibration control of turntable ladders by a steel rope-hydraulic control system. Eng. Technol. Appl. Sci. Res. 2023, 13(2), 10389–10394. https://doi.org/10.48084/etasr.5642