DESIGN AND EVALUATION OF AN ENERGY REGENERATION SYSTEM FOR A HYDRAULIC SINGLE-BUCKET EXCAVATOR USING HYDRAULIC ACCUMULATOR

THIẾT KẾ VÀ ĐÁNH GIÁ HỆ THỐNG TÁI TẠO NĂNG LƯỢNG CHO MÁY ĐÀO MỘT GẦU SỬ DỤNG TÍCH ÁP THỦY LỰC

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Abstract - Hydraulic single bucket excavators are widely used in construction, mining and material production, but consume a lot of fuel and emit harmful exhaust gases. This paper proposes an energy recovery system using hydraulic accumulator to improve energy efficiency. In the system configuration, the accumulator and control valve are connected to the piston chamber of the boom drive cylinder. When the boom is lowered, the potential energy is recovered and stored in the accumulator, and then reused during the boom raising process, which reduces the energy consumption of the entire system. Important parameters such as the initial volume and pressure of the accumulator are investigated to select the optimal value. The system is built and simulated using Amesim software, showing the ability to significantly reduce the power consumption of the main pump, proving the feasibility and effectiveness of the solution.

Key words - Energy recovery; hydraulic accumulator; hydraulic hybrid excavator; energy recovery efficiency.

Tóm tắt - Máy đào một gầu truyền động thủy lực được ứng dụng rộng rãi trong xây dựng, khai thác và sản xuất vật liệu, nhưng tiêu thụ nhiều nhiên liệu và phát thải khí xả gây hại môi trường. Bài báo này đề xuất một hệ thống tái tạo năng lượng sử dụng tích áp thủy lực nhằm nâng cao hiệu quả năng lượng. Trong cấu hình hệ thống, tích áp và van điều khiển được nối với khoang piston của xylanh dẫn động cần. Khi hạ cần, năng lượng thế năng được thu hồi và lưu trữ trong tích áp, sau đó tái sử dụng trong quá trình nâng cần, giúp giảm tiêu thụ năng lượng của toàn hệ thống. Các thông số quan trọng như thể tích và áp suất ban đầu của tích áp được khảo sát để lựa chọn giá trị tối ưu. Hệ thống được xây dựng và mô phỏng bằng phần mềm Amesim, cho thấy khả năng giảm đáng kể công suất tiêu thụ của bơm chính, chứng minh tính khả thi và hiệu quả của giải pháp.

Từ khóa - Thu hồi năng lượng; tích áp thủy lực; máy xúc hybrid thủy lực; hiệu suất thu hồi năng lượng.

1. Introduction

The number of construction machines, especially hydraulic excavators used in construction, mining, and material production, is increasing rapidly. According to research and forecasts, by 2025, the global construction machinery market is expected to reach 227 billion USD, compared to 151.46 billion USD in 2017 [1]. This number is intended to climb to 13.9 trillion USD by 2037, driven by significant growth in the Chinese, US, and Indian markets [2]. With the rapid increase in quantity, issues related to energy crises and pollution caused by excavators have become increasingly severe. Therefore, reducing fuel consumption and improving operational efficiency are top priorities in the development of new-generation excavators.

In hydraulic excavators, when the boom is lowered, the potential energy of the working components (boom, arm, bucket) is converted into pressure inside the piston chamber of the boom cylinder. This energy can be recovered and reused during the boom-lifting process. In recent years, research has focused on developing energy regeneration technologies for hydraulic excavators to harness this energy source [3, 4]. In energy regeneration studies, energy storage devices such as batteries, supercapacitors, and hydraulic accumulators (ACC) are commonly used [5-9]. Energy regeneration systems help reduce fuel consumption, operating costs, and minimize environmental impacts during excavator operation [10-12]. T. Lin *et al.* proposed an energy regeneration system that combines the advantages of electrical storage and ACCs [13]. L. Xia *et al.* proposed an integrated drive system with energy regeneration using a three-chamber hydraulic cylinder, in which one chamber is directly connected to an ACC to recover and reuse the boom's potential energy; this system reduces energy consumption by over 50% during boom lifting [14]. L. Ge *et al.* utilized an ACC to recover energy from the boom-lowering operation of an excavator, achieving an energy recovery efficiency of approximately 76% [15]. Z. Li *et al.* proposed an electro-hydraulic drive system in which the ACC is connected to the piston chamber of the boom cylinder to recover energy, resulting in about a 70% reduction in energy consumption during boom lifting [2]. L. Li *et al.* demonstrated that ACCs offer advantages such as compact size, fast response, stable operation, and low cost; however, to further improve efficiency, it is necessary to integrate electro-hydraulic systems into the boom energy regeneration system [16].

J. Zhu *et al.* proposed an energy regeneration system for the boom system of a hybrid hydraulic excavator, where the ACC is used to recover energy during boom lowering and then used to drive a hydraulic motor to assist in boom lifting [17]. From the above analyses, it can be seen that ACCs are commonly used in hydraulic energy regeneration systems for the boom drive mechanism of excavators. Although these studies have achieved high efficiency, there are still some drawbacks: adding extra cylinders for energy regeneration limits the boom-lowering movement; the use of three-chamber cylinders leads to piston rod instability and increases geometric size; converting between hydraulic pressure and electrical energy reduces energy regeneration efficiency due to system losses. The parameters of the ACC have not been visually described in relation to the original system. Moreover, complex systems result in high initial investment costs and difficulties in maintenance and repair.

This paper proposed an energy regeneration system for the boom cylinder of a hydraulic excavator. In this system, an ACC and a control valve were directly connected to the piston chamber of the cylinder. The advantages of this system include a simple structure, compact ACC size, minimized losses through control valves, and easy installation on excavators. The initial volume and pre-charge pressure of the ACC were investigated to design the most suitable drive circuit for operating conditions. Simulation results using Amesim software demonstrated that the proposed system operated efficiently under the specified conditions.

2. Design of the hydraulic boom drive system integrated with energy regeneration for single-bucket excavators

2.1. Development of the hydraulic energy recovery system

This paper proposes an energy recovery system applied to the boom cylinder of a hydraulic excavator, as described in Figure 1.

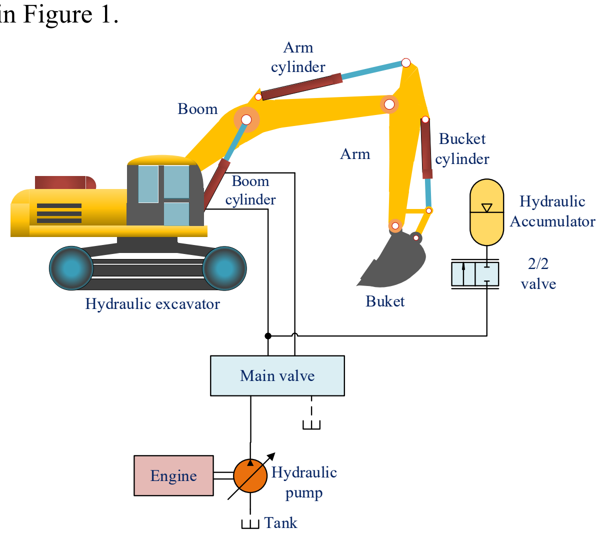


Figure 1. *Structure of the proposed system*

The energy recovery principle of the system is illustrated in Figure 2. In traditional hydraulic circuits, high-pressure oil in the piston chamber during boom lowering is discharged directly to the tank, resulting in wasted recoverable energy. Therefore, in this paper, the hydraulic valve DV1 and the ACC are placed on the oil outlet line of the piston chamber. When the piston moves downward, the potential energy of the working components is converted into hydraulic oil pressure in the piston chamber. Next, the oil passes through valve DV1 into the oil chamber of the ACC. The piston's downward speed is controlled by valve DV1 and the parameters of the ACC. Thus, the potential energy of the working components is recovered by the ACC.

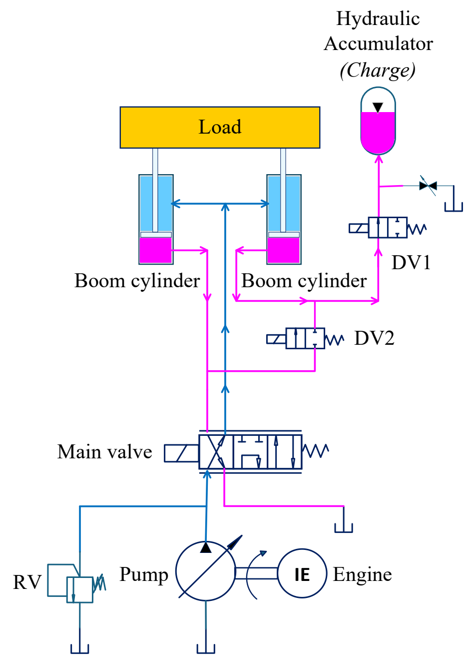


Figure 2. *Principe of Energy Recovery*

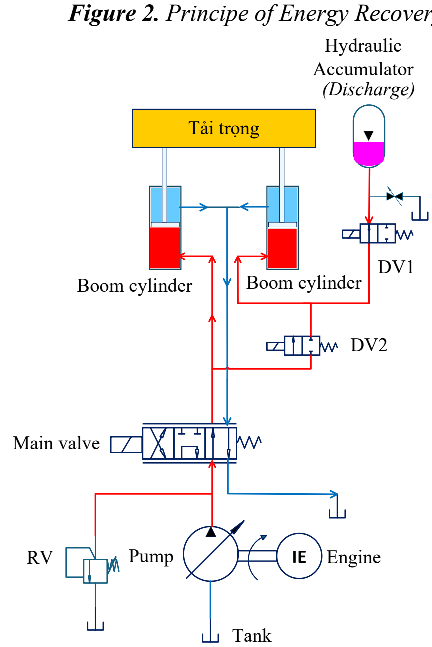


Figure 3. *Principe of Energy Reuse*

The principle of energy reuse is illustrated in Figure 3. During boom lifting, high-pressure oil from the ACC passes through valve DV1 into the piston chamber of the right cylinder. The stored energy is released from the ACC to assist the pump during the boom-lifting process. With the support of this regenerated energy, the hydraulic pump only needs to supply flow to the left cylinder. Thus, the proposed system reduces the pump flow requirement.

In the case of ACC replacement or when high operational accuracy is required, DV1 is closed and DV2 is opened, returning the system to its original state without the energy regeneration circuit. Therefore, the system can operate in both energy regeneration mode and original mode.

2.2. Calculation basis

Based on the proposed configuration, the mathematical formulas used to describe the system are as follows.

2.2.1. Hydraulic cylinder's calculation

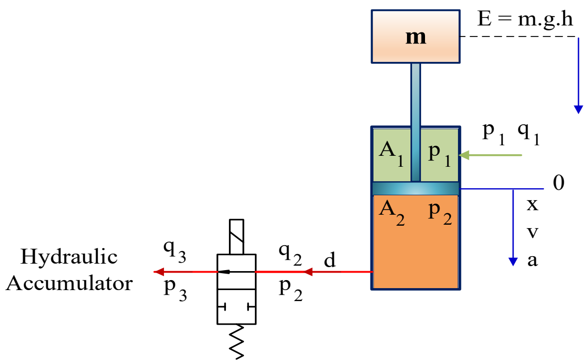


Figure 4. *Cylinder Working Priciple*

- The equation describing the motion of the working components:

$$m.a = mg + p_1A_1 - p_2A_2 - F_f \quad (1)$$

- The oil pressure in the piston chamber is determined by:

$$p_2 = \frac{m(g-a) + p_1A_1 - F_f}{A_2} \quad (2)$$

- The oil flow rate out of the piston chamber is determined by:

$$q_2 = q_1 + (A_2 - A_1).v \quad (3)$$

where, m is the equivalent mass, a is acceleration, v is velocity, p_1 is the oil pressure in the rod chamber, p_2 is the oil pressure in the piston chamber, F_f is the total resistance force, A_1 is the area of the rod chamber, A_2 is the area of the piston chamber.

2.2.2. Pipeline's calculation

Assuming laminar flow, the pressure loss is calculated as [18]:

$$\Delta p = \frac{32.\mu.l.v}{d^2} \quad (4)$$

where, Δp is the pressure loss between the two ends of the pipe, v is the average flow velocity, d is the pipe diameter, l is the pipe length, μ is the dynamic viscosity of the fluid.

This relationship is valid for Reynolds numbers (Re) up to 1200. Re values between 1200 and 2500 indicate transitional flow, where the flow becomes turbulent. For Re greater than 2500, the flow is fully turbulent.

$$Re = \frac{v.d.\rho}{\mu} \quad (5)$$

where, ρ is the fluid density.

For turbulent flow, the pressure loss is calculated as [18]:

$$\Delta p = \frac{4.f.l.\rho.v^2}{2.d} \quad (6)$$

where, f is the pipe friction factor, determined experimentally.

$$\Delta p = \frac{f.l.\rho.v^2}{2.d} \quad (7)$$

2.2.3. Mathematical formulas for the hydraulic accumulator

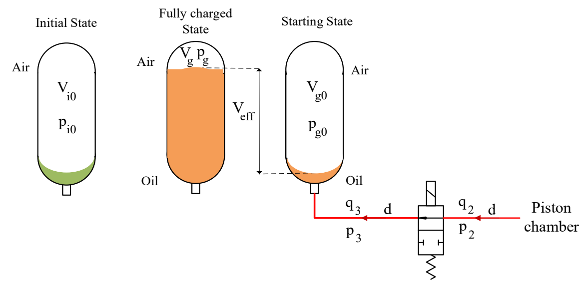


Figure 5. *Accumulator Working Principe*

During energy recovery, the gas pressure and volume inside the ACC follow the law presented in [18]:

$$p_{i0}V_{i0}^{\lambda} = p_{g0}V_{g0}^{\lambda} = p_gV_g^{\lambda} \quad (8)$$

where, λ is the coefficient, V_{i0} is the initial gas volume, p_{i0} is the initial pre-charge pressure, V_{g0}, p_{g0} are the gas volume and pressure at the moment the piston starts to move down, V_g, p_g are the gas volume and pressure at the moment the piston finishes moving down.

The effective oil volume V_{eff} in the ACC is calculated by:

$$V_{eff} = V_{g0} - V_g \quad (9)$$

The relationship between the oil flow into the ACC and the flow out of the valve is:

$$q_3 = \frac{dV_{eff}}{dt} \quad (10)$$

Neglecting flow losses through the valve (assuming the accumulator is directly connected to the piston chamber) and oil compressibility, the input and output flows of the valve are equal. The flow q_3 can be calculated based on the piston displacement as:

$$q_3 = A_2.v = \frac{dx}{dt} \quad (11)$$

where, x is the piston displacement.

From equation (10) we have:

$$V_{eff} = \int_0^t q_3.dt \quad (12)$$

From equations (9) and (12) we have:

$$V_g = V_{g0} - V_{eff} \quad (13)$$

From equations (8), (12), and (13) we obtain:

$$p_g = p_{g0}.\left(\frac{V_{g0}}{V_{g0} - \int_0^t q_3.dt}\right) \quad (14)$$

Equation (14) shows the relationship between the gas pressure in the ACC and the actual oil flow charged into the ACC during energy recovery.

From equation (8), the initial gas volume is determined as:

$$V_{g0} = V_{i0} \cdot \left(\frac{p_{i0}}{p_{g0}} \right)^{\frac{1}{\lambda}} \tag{15}$$

The recovered energy in the accumulator, Eth, is determined by:

$$E_{th} = \int_{V_{g0}}^{V_g} p.dV \tag{16}$$

From equations (8) and (16), the recovered energy can be expressed as:

$$E_{th} = \frac{p_{g0} V_{g0}}{\lambda - 1} \left[\left(\frac{V_g}{V_{g0}} \right)^{1-\lambda} - 1 \right] \tag{17}$$

Also, from equations (8) and (9), the effective volume can be determined as:

$$V_{eff} = V_{i0} \cdot \left[\left(\frac{p_{i0}}{p_{g0}} \right)^{\frac{1}{\lambda}} - \left(\frac{p_{i0}}{p_g} \right)^{\frac{1}{\lambda}} \right] \tag{18}$$

The recoverable energy from the system E_{pot} is the potential energy of the equivalent mass *m*, calculated by:

$$E_{pot} = m.g.h \tag{19}$$

where, *m* is the equivalent mass, *g* is the gravitational acceleration, *h* is the displacement distance.

The energy recovery ratio is calculated by:

$$\varepsilon = \frac{E_{th}}{E_{pot}}.100\% \tag{20}$$

3. Simulation and analysis of the model using amesim

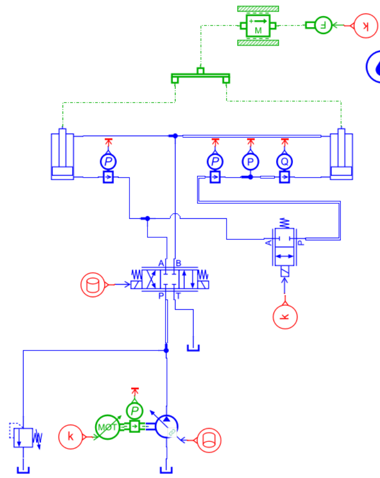
To select appropriate operating parameters for the ACC and to demonstrate the effectiveness of the proposed system, a simulation model was developed using Amesim software. This software has been used in many scientific studies published in reputable journals [2, 13, 19, 20]. In this study, the input parameters for the simulation model were referenced from [20] and are shown in Table 1. In addition, other parameters in the proposed circuit were calculated based on the formulas in Section 2.2. The hydraulic accumulator parameters are varied as shown in Table 2.

Table 1. *Parameters of traditional system*

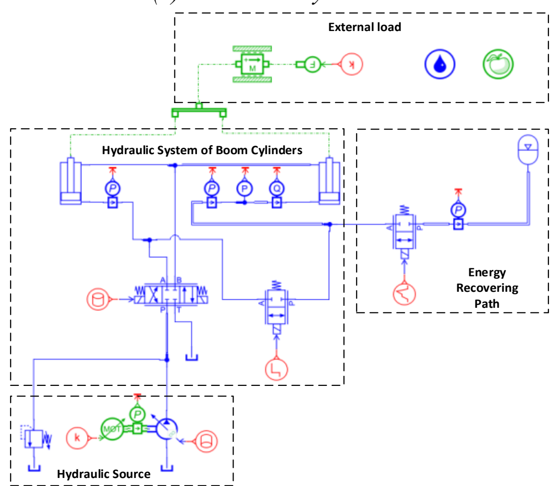
Components	Parameter	Value	Units
Hydraulic oil	Oil	Elementary	-
	Temperature	40	degC
	Density	850	kg/m³
	Bulk modulus	17000	bar
Mas	m	3000	kg
External force	F	10000	N
Hydraulic pump	Maxumum displacement	25	cc/rev
	Mechanical efficiency	0.96	-
	Volumetric efficency	0.92	-
	Speed	2000	rpm
Hydraulic cylinder	Piston diameter	55	mm
	Piston rod diameter	30	mm
	Stroke	0.45	m
Main valve	Current	40	mA
	Maximum flow rate	60	L/min
2/2 valve	Initial state	1	-
	Maximum flow rate	25	L/min
Relief valve	Cracking pressure	240	bar

Table 2. *Parameters of Hydraulic accumulator (ACC)*

Components	Parameter	Value	Unit
Accumulator	Initial volume	1-3	L
	Initial pressure	5-25	bar



(a) Traditional System



(b) Proposed System

Figure 6. *Simulation Model in AMEsim*

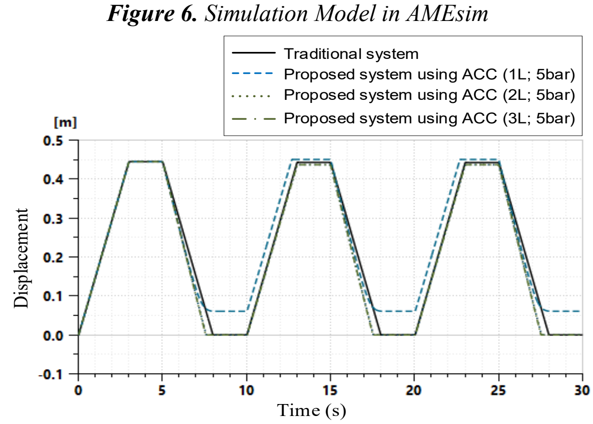


Figure 7. *Piston Displacement Comparison*

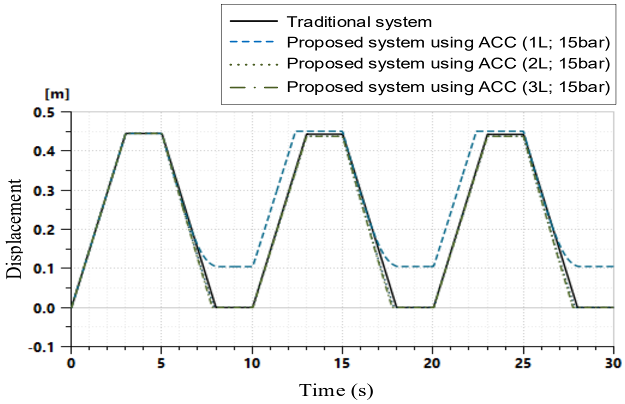


Figure 8. *Piston displacement comparison*

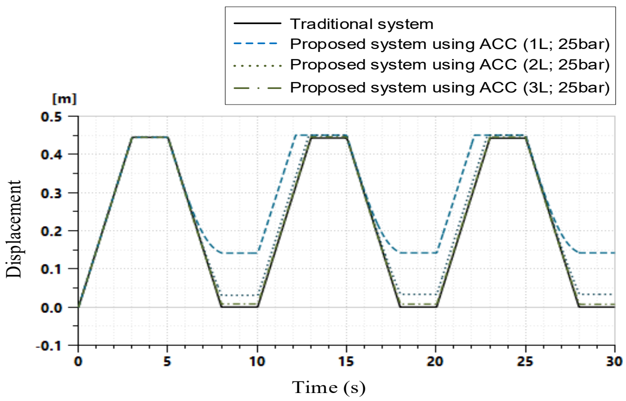


Figure 9. *Piston displacement comparison*

From the graphs in Figures 7, 8, and 9, it can be seen that the piston stroke varies with the volume and initial pressure of the ACC. With a 1L ACC, when the initial pressure increases from 5 to 25 bar, the piston cannot move to the end of its working stroke. Thus, a 1L ACC is not suitable for the specified conditions of the hydraulic system. With a 2L ACC, the appropriate initial pressure is 15 bar. For a 3L ACC, the suitable initial pressure is 25 bar. With appropriate volume and initial pressure matching the working conditions, the piston in the proposed system will move equivalently to that in the original system.

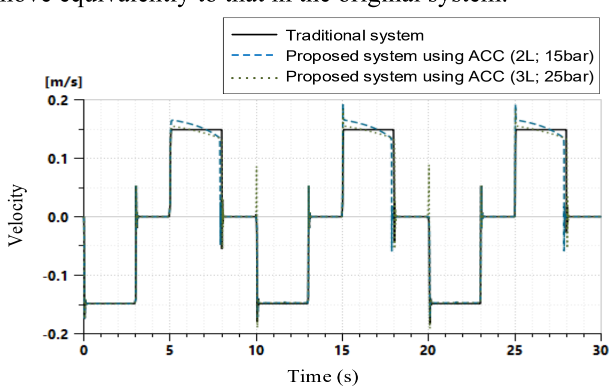


Figure 10. *Piston velocity comparison*

Figure 10 shows a comparison of piston operating velocity according to the volume and pressure of the ACC. The graph shows that the velocities during both upward and downward movements reach approximately 0.15 m/s. The graph also indicates some resistance during the piston's downward stroke due to the ACC connected to the cylinder outlet; however, this resistance is negligible.

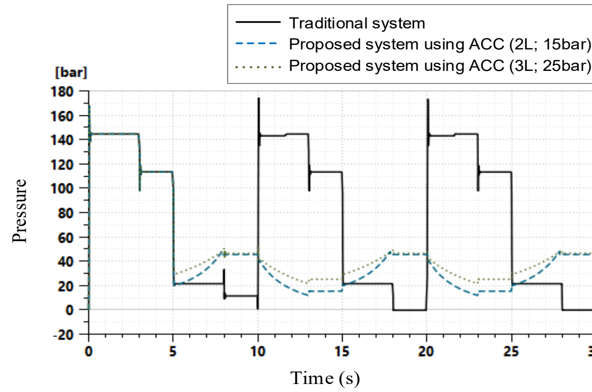


Figure 11. *Pressure comparison of piston chamber with ACC*

From Figure 11, it can be seen that, since the cylinder is driven only by the ACC, the operating pressure of this cylinder in the proposed circuit is significantly lower than that in the original circuit, although the flow supplied to the cylinder remains adequate.

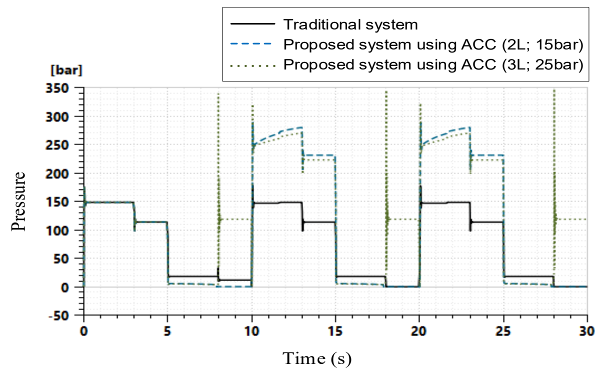


Figure 12. *Pressure comparison of piston chamber without ACC*

Figure 12 shows a comparison of the pressure in the piston chamber not connected to the ACC. The graph indicates that this piston bears a higher load in the proposed circuit. This is due to the pressure reduction in the piston chamber of the cylinder connected to the ACC.

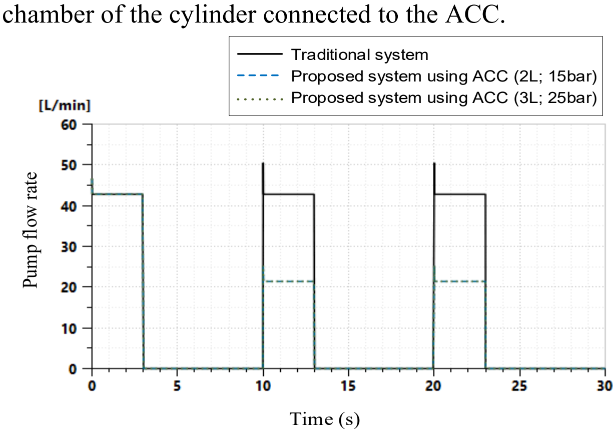


Figure 13. *Pump flow rate comparison*

Since the hydraulic pump only supplies flow to one side of the cylinder, the pump flow rate in the proposed circuit is reduced by about 50% compared to the original circuit, as shown in Figure 13.

The comparison of hydraulic pump power is shown in Figure 14. The graph shows that the power in the proposed circuit is lower than that in the original circuit. This demonstrates that the proposed system can recover energy during the boom-lowering process and reuse this energy during boom lifting. This operating principle helps the system consume less energy and operate more efficiently than systems without energy regeneration. The power difference when using an accumulator (2L, 15 bar) is not significantly different from using an accumulator (3L, 25 bar).

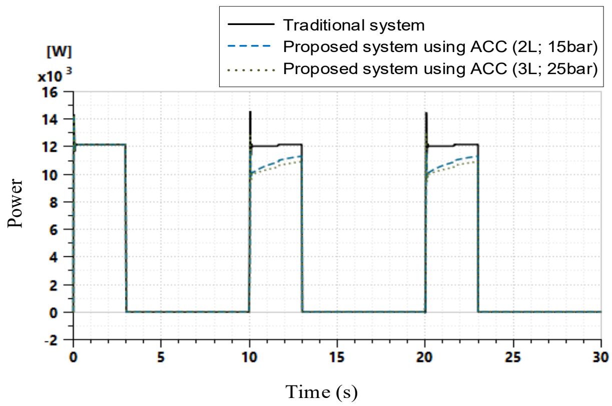


Figure 14. *Driving power comparison*

From the simulation comparison results, it can be seen that under the selected operating conditions, the proposed hydraulic circuit operates most efficiently when using a 2L ACC with an initial pressure of 15 bar.

4. Conclusions and recommendations

This paper has proposed an energy regeneration system using an ACC to address the fuel consumption issue of hydraulic single-bucket excavators. The energy from the boom-lowering process is recovered, stored, and reused thanks to the ACC and control valve. In addition, factors affecting the energy recovery process, such as the volume and initial pressure of the ACC, were also investigated to select the most suitable operating parameters. Simulation results using Amesim software have demonstrated that the proposed system operates efficiently under the given conditions. However, the pressure difference between the piston chambers in the proposed circuit leads to uneven loads on the two boom drive cylinders. This causes wear of the cylinder bearings and bushings during operation. Moreover, energy recovery on only one side of the cylinder results in a modest reduction in pump drive power. Therefore, energy regeneration on both piston sides of the boom cylinder is the research direction for the group in the future. An experimental model will also be developed to validate the simulation results.

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