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Energy regeneration from the boom cylinder of a hydraulic excavator using a hydraulic accumulator

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Abstract: This paper introduces the design of a Single Accumulator Energy Recovery System (SAERS) aimed at enhancing the energy efficiency of the boom cylinders in hydraulic excavators. The SAERS concept is developed from a thorough analysis of existing regeneration structures and is formulated through a set of governing equations that describe its hydraulic behaviors. Field measurements from an operational excavator provide representative pressure-flow data used to calibrate the model. The simulation model of the SAERS, built in Amesim software, is then employed to evaluate its performance under two typical duty modes. Results indicate that, compared to the conventional boom system, the SAERS reduces hydraulic energy consumption of pump by approximately 13% in Eco mode and increases the boom-lifting speed by up to 30% in Power mode, while maintaining controllability. These findings demonstrate the retrofit potential of SAERS as a practical solution toward greener and more energy-efficient construction equipment.

Keywords: energy regeneration, boom energy recovery, hydraulic excavator, accumulator.

1. Introduction

The global demand for construction machinery, especially large-scale excavators employed in mining operations, has experienced steady growth. Recent reports indicate that the construction equipment market, valued at approximately 151.46 billion USD in 2017, is expected to reach 227 billion USD by 2025 [1]. Furthermore, this market is projected to grow substantially, reaching approximately 13.9 trillion USD by 2037, primarily driven by significant expansion in China, the United States, and India [2]. This rapid increase in excavator utilization has concurrently led to significant increases in fuel

consumption and pollutant emissions. Consequently, improving energy efficiency and reducing fuel usage have emerged as critical priorities in the development of environmentally sustainable construction machinery.

In hydraulic excavators, gravitational potential energy is generated when the boom moves downward. This energy is subsequently converted into hydraulic pressure within the piston chambers and can be reused during the upward movement of the boom cylinders, thereby significantly enhancing the operational efficiency of the excavator. In recent years, scientific studies have been conducted to develop energy recovery

techniques for hydraulic excavators [3, 4]. Various energy recovery strategies incorporating storage components such as batteries, supercapacitors, and hydraulic accumulators have been introduced [5–8]. These proposed energy recovery systems have demonstrated substantial potential in decreasing energy consumption, lowering operational expenses, and mitigating environmental impacts [9–11]. T. Lin et al. [12] developed a hybrid energy recovery architecture integrating both electrical storage units and hydraulic accumulators to enhance system performance. L. Xia et al. [13] developed a transmission system that utilized a three-chamber cylinder, in which the larger chamber was directly connected to a hydraulic accumulator to convert, store, and reuse the gravitational potential energy generated during the boom's downward motion. Similarly, L. Ge et al. [14] used a hydraulic accumulator to recover the gravitational potential energy of the boom, achieving a recovery efficiency of approximately 76%. L. Li et al. [15] demonstrated significant advantages of hydraulic accumulators, including compactness, rapid dynamic response, operational stability, and cost-effectiveness. Nevertheless, the study also highlighted the necessity of integrating electro-hydraulic components to further enhance the overall energy recovery efficiency of excavators. J. Zhu et al. [16] proposed an energy regeneration system for hybrid hydraulic excavators, in which a hydraulic accumulator was used to store energy during the lowering phase of the boom. The stored energy was subsequently used to power the hydraulic motor during the boom's upward movement. Although the aforementioned methods are effective, several limitations remain. The incorporation of additional cylinders for energy regeneration may limit the stroke of the boom. The use of multi-chamber cylinders can lead to buckling instability of the piston rod and an increase in the overall cylinder size. Moreover, the bidirectional conversion between hydraulic and electrical

energy may reduce overall energy recovery efficiency due to system losses. The relationship between accumulator parameters and the regeneration process has not been investigated in some studies. Furthermore, the proposed systems are often inherently complex, resulting in high initial investment costs and greater maintenance and repair challenges. The purpose of this paper is to develop and evaluate a Single Accumulator Energy Recovery System (SAERS) for hydraulic excavators. The SAERS is modelled in the Amesim software based on practical signals obtained from an actual excavator. Simulation results reveal that the SAERS can reduce the energy requirement by approximately 13% in Eco mode and increase the lifting velocity by about 30% in Power mode.

2. Design of Single Accumulator Energy Recovery System

2.1. Proposed system configuration

The proposed SAERS is shown in Fig. 1, in which a hydraulic accumulator is connected to the piston chamber of the boom cylinder. During the downward motion of the boom, the potential energy is converted and stored in the accumulator. The stored energy is subsequently utilized during the upward motion of the boom. This mechanism significantly reduces the flow rate of the hydraulic pump, thereby lowering overall energy consumption. The directional valve (AC valve) is used to precisely control the charging and discharging processes of the accumulator, ensuring optimal efficiency. In this system, one cylinder is controlled by the hydraulic pump, while the other one is actuated by the hydraulic accumulator. In practice, the pump and the accumulator exhibit different operating characteristics. Specifically, the accumulator undergoes significant pressure variations during a boom lifting lowering cycle. However, by appropriately selecting the accumulator parameters and coordinating the control signals of the main valve and the accumulator valve, the

disparity in the operating characteristics of these two hydraulic components can be substantially minimized. Moreover, the two cylinders are rigidly connected through the boom structure; therefore,

their operating behavior is still governed by the system's main control valve. This ensures that the system can recover energy without compromising control over its dynamic characteristics.

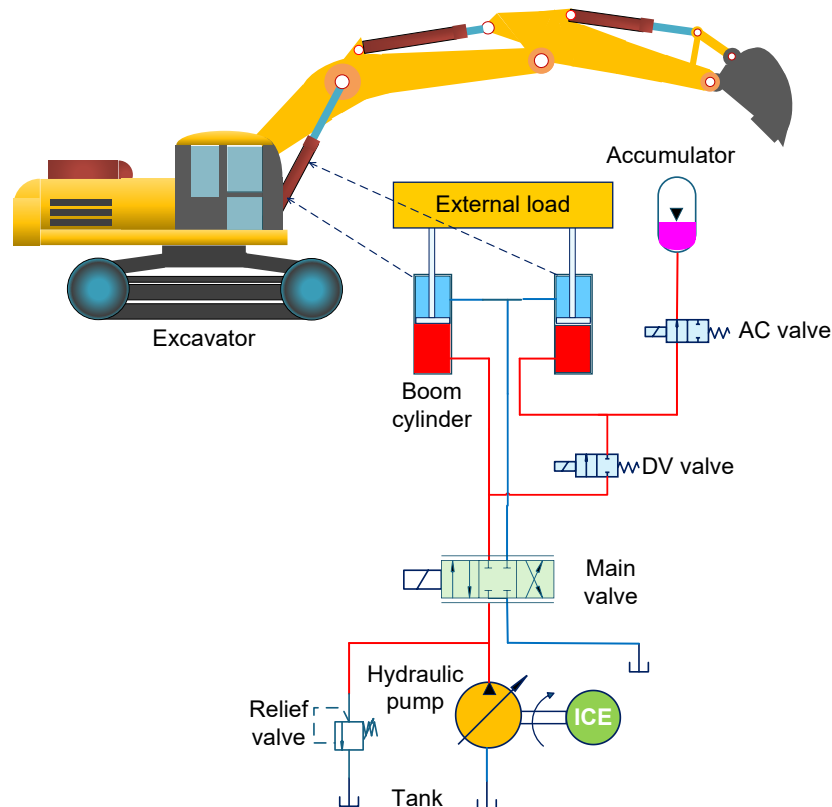


Fig. 1. Configuration of the SAERS

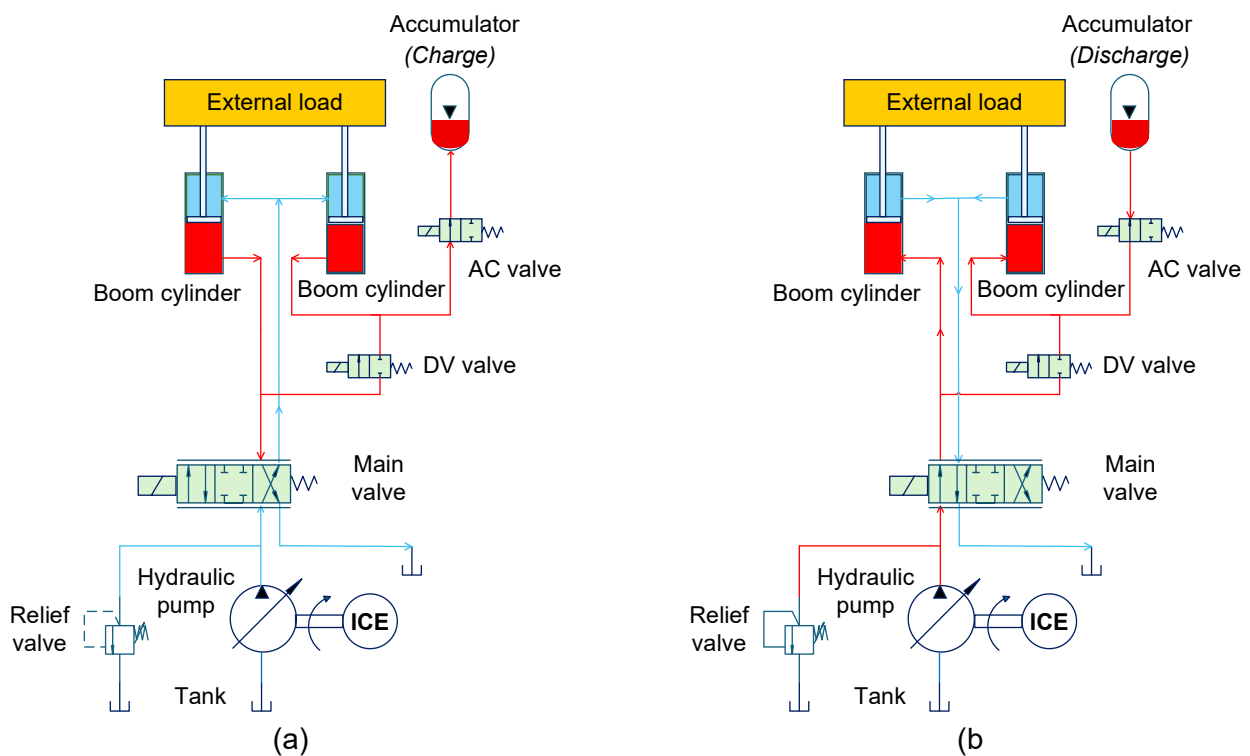


Fig. 2. Working principle of the SAERS (a) Energy recovery; (b) Energy reuse

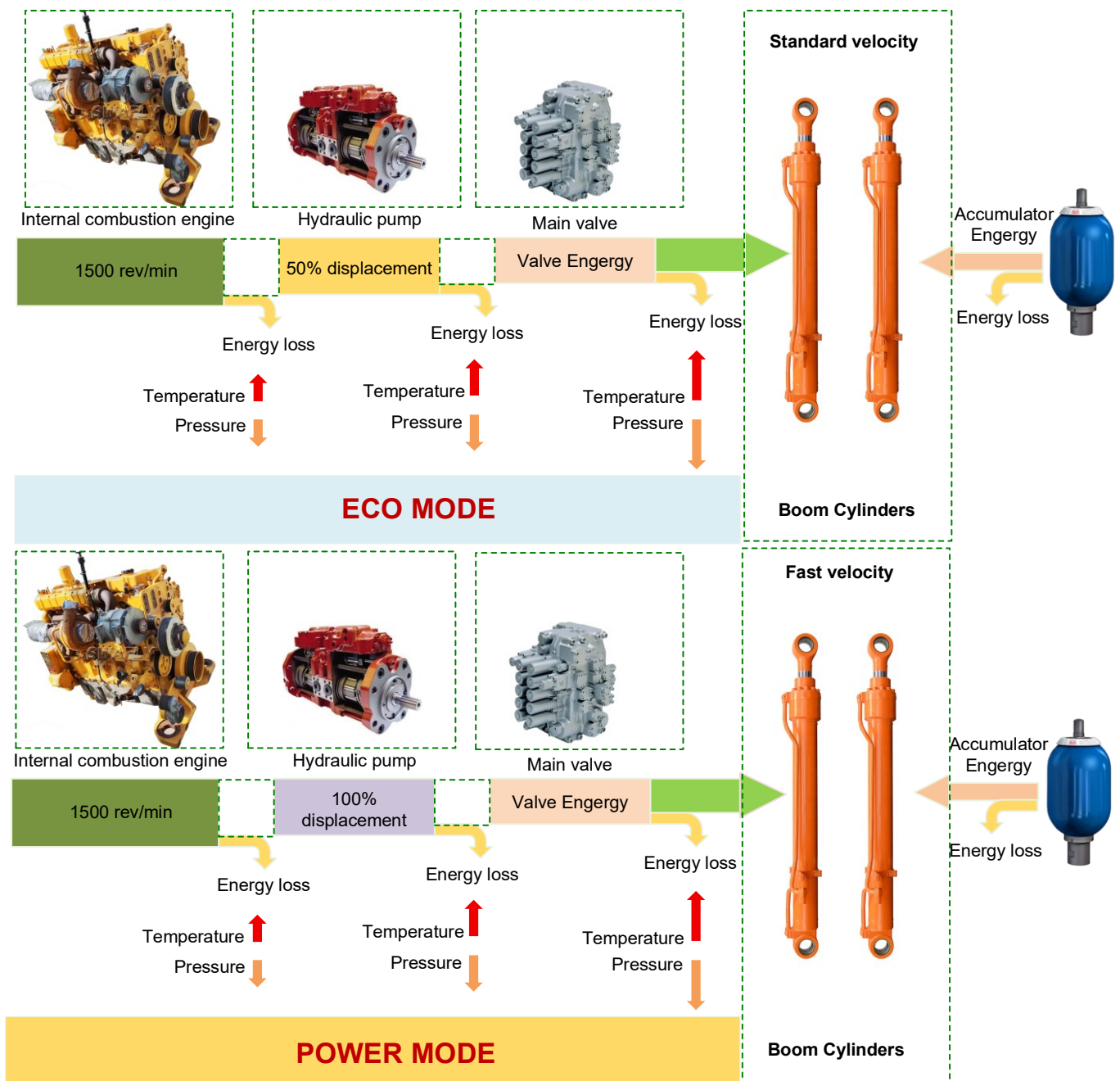


Fig. 3. Eco mode and Power mode of SAERS

2.2. Working principle of SAERS

During the first upward displacement of the piston, the AC valve is closed, while the DV valve is open. Hydraulic oil is directed to both the piston and rod chambers of the boom cylinders through the main valve. During this phase, the hydraulic accumulator remains inactive.

The energy recovery process is shown in Fig. 2(a). When the piston moves down, the AC valve is opened to allow hydraulic fluid to flow into the accumulator, while the DV valve is closed to

prevent the fluid from returning to the tank. As the fluid flows into the accumulator, the gas in the accumulator is compressed, resulting in a gradual increase in gas pressure. Based on the operating principle of a hydraulic accumulator, it is assumed that the pressure of oil equals the pressure of gas. Consequently, the pressure of oil inside the accumulator is increased until the piston reaches the end of its downward stroke.

The energy reuse process takes place during the lifting process of the boom, as shown in Fig.

2(b). The piston chamber, which does not connect with the accumulator, receives energy from the main pump. The chamber that connects with the accumulator gets the stored energy of the hydraulic accumulator. In this process, the AC valve is opened and the DV valve is closed. Since one piston is driven by the accumulator, the hydraulic pump in the proposed circuit only drives the other piston. As a result, the flow rate of the main pump can be reduced by nearly 30% compared to the conventional system. This leads to a lower energy consumption in the SAERS (Eco mode). If the main pump delivers the same flow rate as the original circuit, the lifting velocity of the boom in the SAERS is significantly increased (Power mode), as shown in Fig. 3.

3. Mathematical modelling of SAERS

3.1. SAERS model

An actuator is used to convert the hydraulic pressure into the linear movement of the piston of the cylinder. The amount of output power depends on the flow rate, the different pressures across the actuator, and its overall efficiency. The double-acting cylinders are commonly used to drive the boom of an excavator. They consist of main elements such as the barrel, the piston, and the rod. The static thrust developed by a hydraulic cylinder is the product of the pressure and area [17].

$$F_{\text{forward}} = p_1 \left(\frac{\pi D^2}{4} \right) - p_2 \left(\frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) \quad (1)$$

$$F_{\text{retract}} = p_2 \left(\frac{\pi D^2}{4} - \frac{\pi d^2}{4} \right) - p_1 \left(\frac{\pi D^2}{4} \right) \quad (2)$$

When dealing with dynamic systems, factors such as load inertia, seal friction, and load resistance must be considered when determining the dynamic thrust. As an initial estimate, the dynamic thrust can be assumed to be around 90% of the static thrust. Seal friction is influenced by the design of both the seal and the cylinder, and most cylinder manufacturers do not provide exact data on the pressure needed to overcome this friction.

For estimation, a breakout pressure of approximately 5 bar is commonly used. This value tends to decrease once the piston begins moving. Additionally, the pressure required to overcome seal friction generally decreases as the cylinder bore increases and also depends on the specific seal design. [17].

In any hydraulic circuit, the pump is driven by an engine to create a flow of working oil. For excavators, positive displacement pumps are commonly used because of their high flow rate and high power [17].

$$Q_{\text{theoretical}} = D_p \times n_p \quad (3)$$

where D_p is displacement per revolution; n_p is the number of revolutions per minute, $Q_{\text{theoretical}}$ is the theoretical flow rate of the pump

The actual pump delivery will be less than the theoretical delivery owing to internal leakage and slippage

$$\frac{Q_{\text{actual}}}{Q_{\text{theoretical}}} = \eta_v \quad (4)$$

where η_v is volumetric efficiency, Q_{actual} is the actual flow rate of the pump

The mechanical efficiency of a hydraulic pump can be expressed as

$$\eta_t = \frac{D_p \times p_p}{2\pi \times T_p} \quad (5)$$

where p_p is the pressure drop across the ports of the pump; T_p is the average driving torque of the pump

Overall pump efficiency can be determined

$$\eta_o = \frac{Q_p}{n_p \times D_p} \times \frac{D_p \times p_p}{2\pi \times T_p} = \eta_v \times \eta_t \quad (6)$$

The accumulator is a key component that regenerates the potential energy of the boom. The expression of this accumulator can be expressed according to [18]

$$p_s - p_a = \frac{1}{A_a} \left(m_a \times \frac{dq_a}{dt} + B_a \times q_a \right) \quad (7)$$

where p_s is the pressure of the system, p_a denotes the pressure in the accumulator, q_a is the flow rate

of the accumulator, A_a is the oil chamber area of the accumulator, m_a is the mass of the oil in the accumulator, and B_a is the viscous damping coefficient. By using the Boyle-Marriott gas law, we can obtain the important expressions.

$$p_0 \times V_0^n = p_a \times V_a^n \quad (8)$$

$$E_a = \int_{V_{a1}}^{V_{a2}} p_a \times dV_a = \int_{V_{a1}}^{V_{a2}} p_0 \times \left(\frac{V_0}{V_a} \right)^n \times dV_a \quad (9)$$

where E_a denotes the energy of the accumulator, V_{a1} and V_{a2} are the volumes of gas chambers at the beginning and the end states, p_a and V_a are the pressure and volume of gas at any moment, and p_0

and V_0 are the pre-charge pressure and initial volume of gas, respectively.

3.2. Simulation model of the SAERS

Fig. 4 and Fig. 5 illustrate the data collection process. The necessary data includes engine speed, flow rate, hydraulic pump pressure, and the control signal of the main valve. All data are measured using the excavator's on-board sensors. This data is subsequently used as inputs of the Amesim simulation model, as shown in Fig. 6. The working parameters of the hydraulic components used in the simulation are listed in Table 1.

4. Results and Discussion

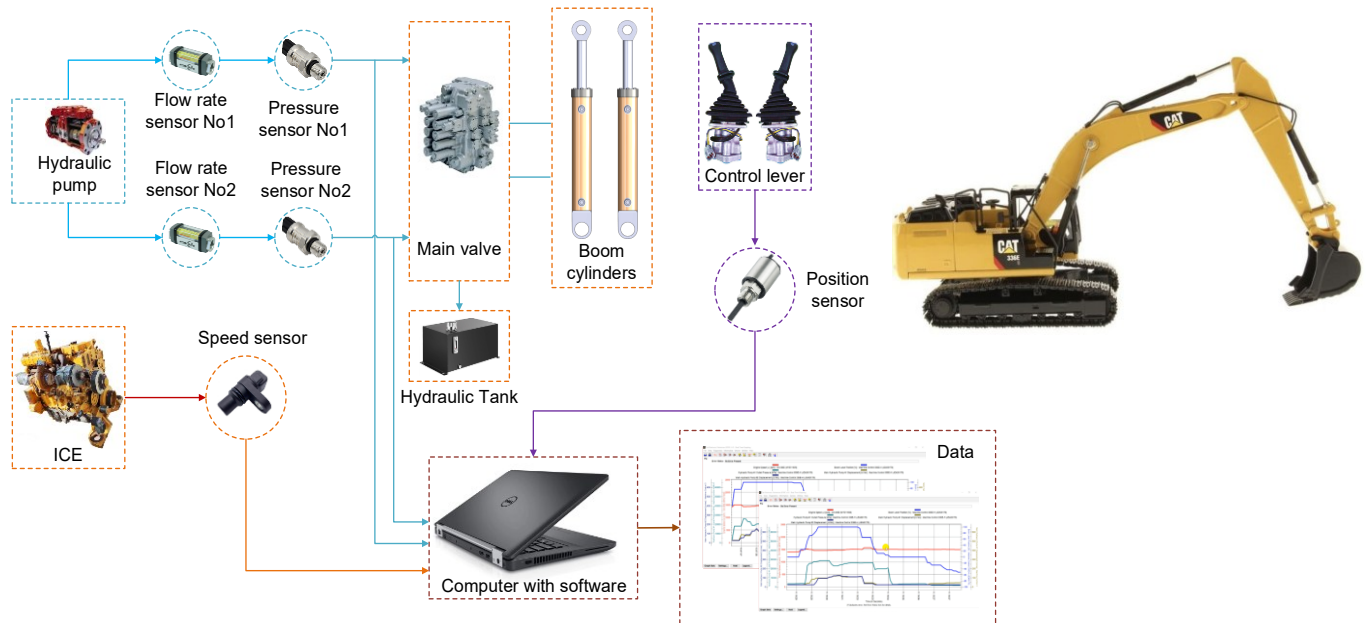


Fig. 4. Outline of signals of the hydraulic excavator



Fig. 5. Data collection process of the excavator

Fig. 7 shows the piston displacements of the boom cylinders in two systems. A full working cycle takes approximately 15 seconds to complete. The pistons reach a maximum stroke of approximately

0.8 m and then stop at the rod-end positions. Subsequently, they initiate their return stroke. Finally, the pistons remain fully retracted at the head-end positions. In the conventional system,

the displacement is linear, whereas in the proposed system, it is a nonlinear. This reflects the influence of the hydraulic accumulator, although this

influence is relatively small. The stroke limit values are not affected by the integration of the hydraulic accumulator.

Table 1. Working parameters of hydraulic elements used for simulation

Elements	Parameters	Values	Unit
Oil	Fluid type	Elementary	-
	Temperature	40	°C
	Density	850	kg/m ³
	Bulk modulus	17,000	bar
Hydraulic pump	Maximum displacement	250	cc/rev
	Speed	1500	rev/min
	Volumetric efficiency	0.92	-
	Mechanical efficiency	0.96	-
Hydraulic boom cylinder	Piston diameter	147	mm
	Rod diameter	105	mm
	Length of stroke	0.8	m
Pressure valve	Cracking pressure	350	bar
	Flow rate pressure gradient	100	L/min/bar
AC and DV valve	Control current	40	mA
	Flow rate at maximum opening	500	L/min
Main valve	Valve rated current	40	mA
	Flow rate at maximum opening	500	L/min
Accumulator	Accumulator volume	29	Lit
	Gas pre-charge pressure	110	bar

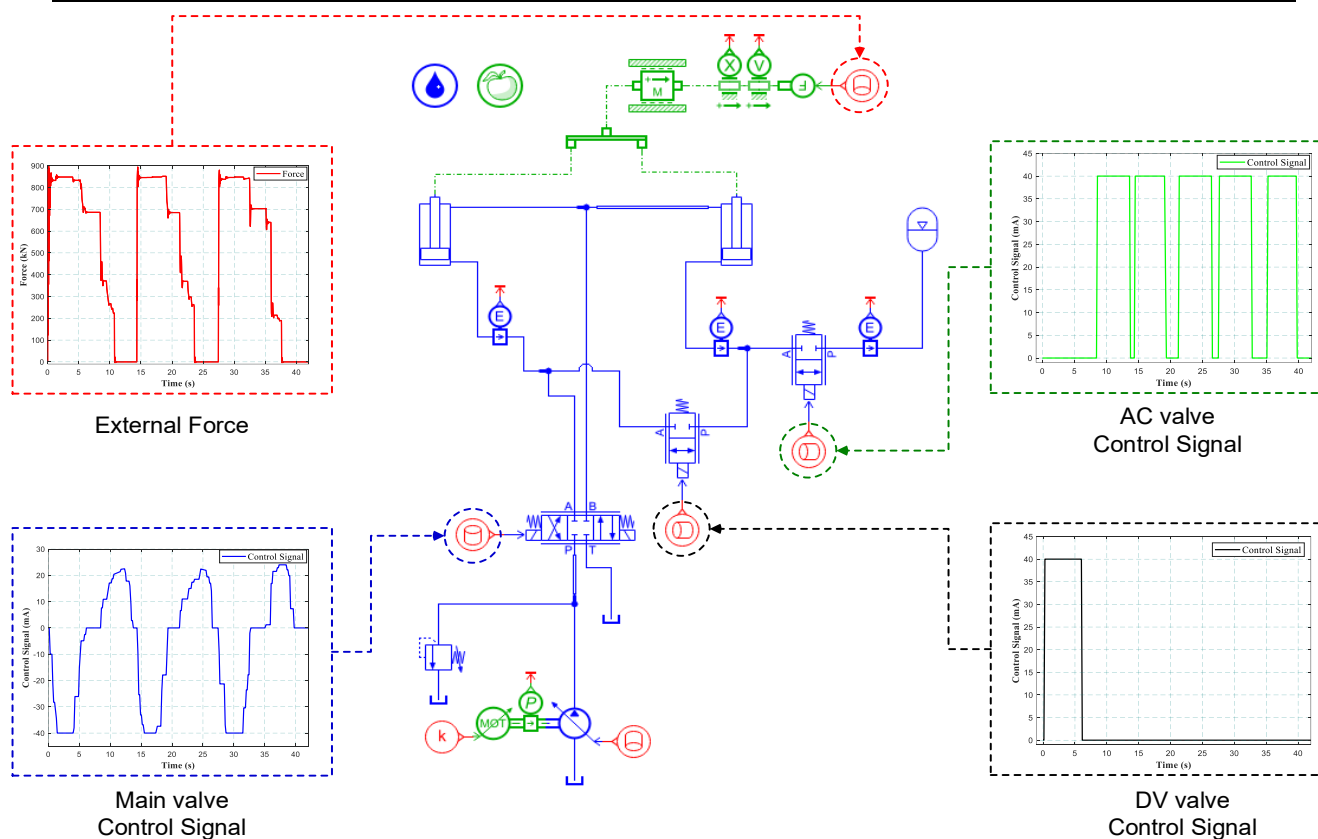


Fig. 6. Simulation model of SAERS in Amesim software

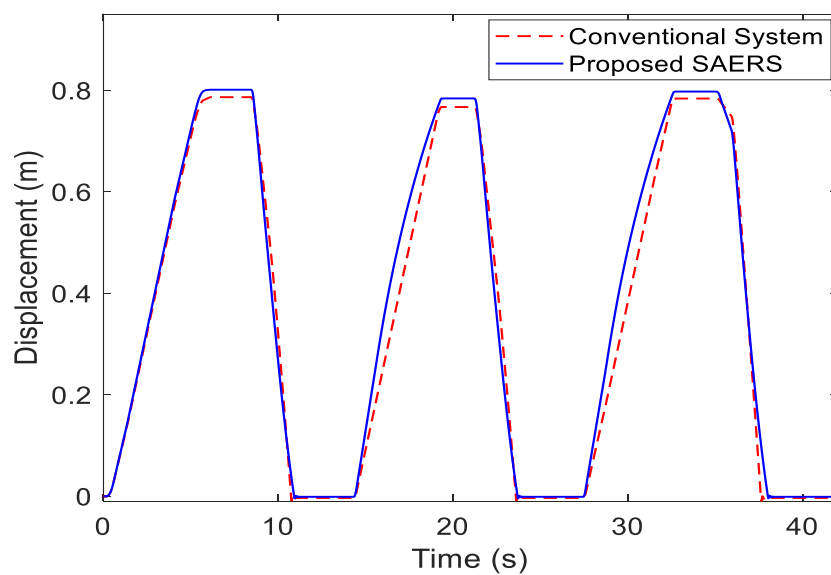


Fig. 7. Displacements of pistons

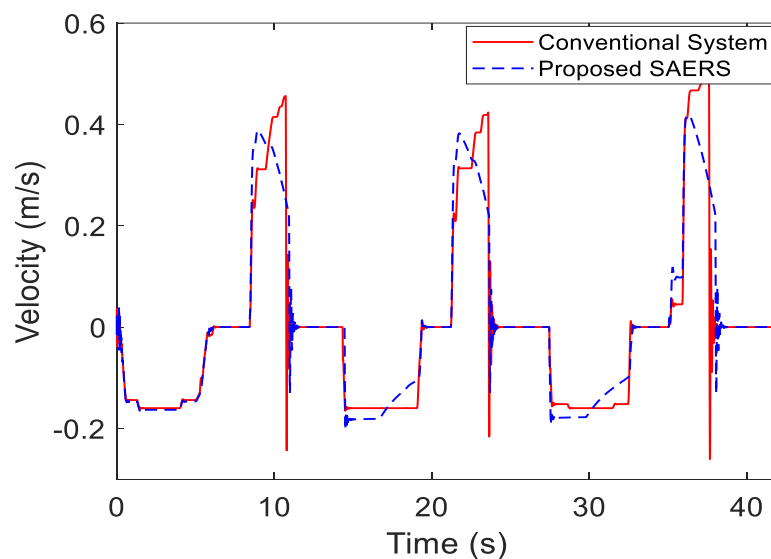


Fig. 8. Velocities boom cylinders

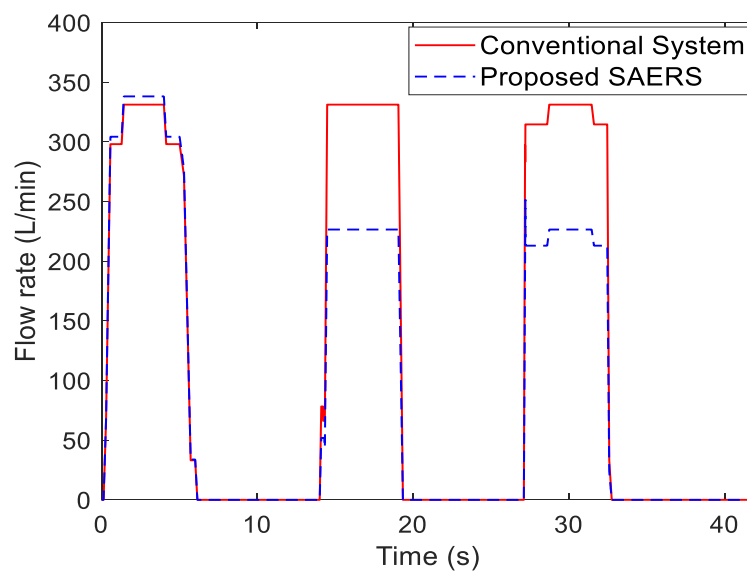


Fig. 9. Flow rates of hydraulic pumps

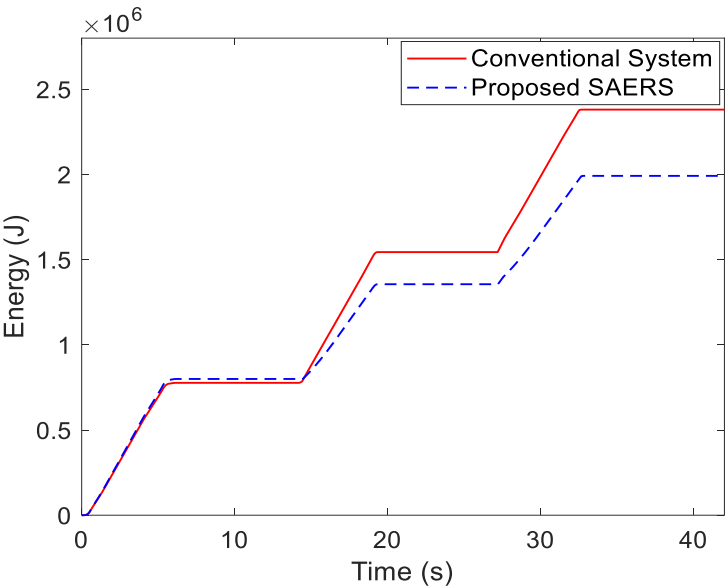


Fig. 10. Energy consumption of hydraulic pumps

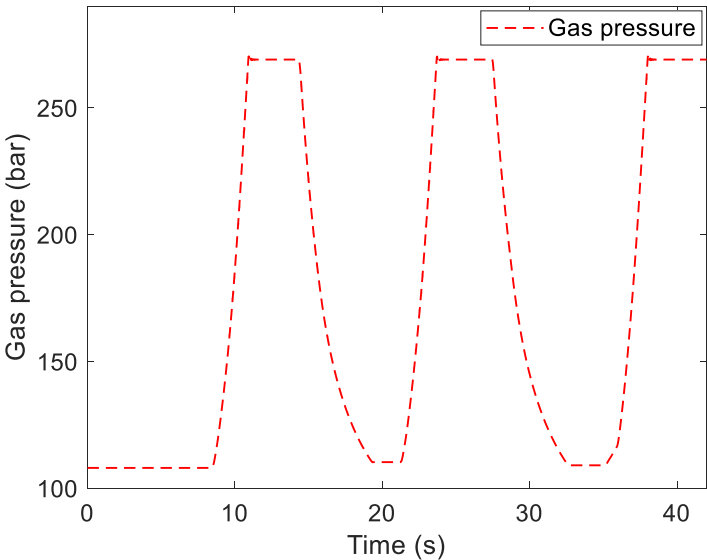


Fig. 11. Gas pressure variation

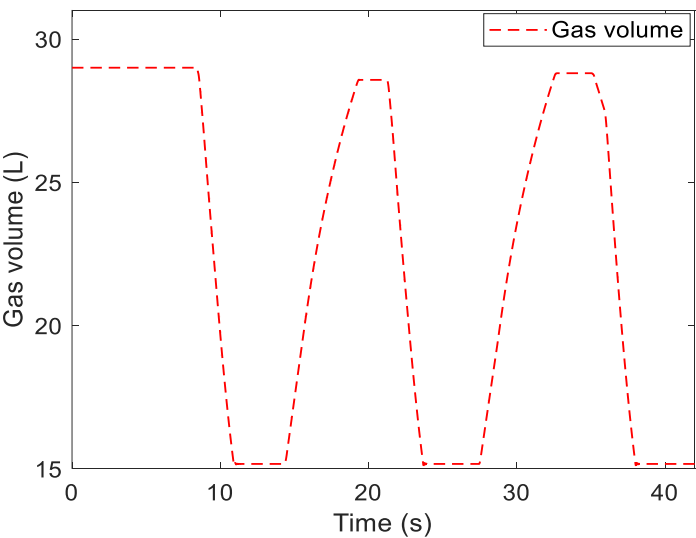


Fig. 12. Gas volume variation

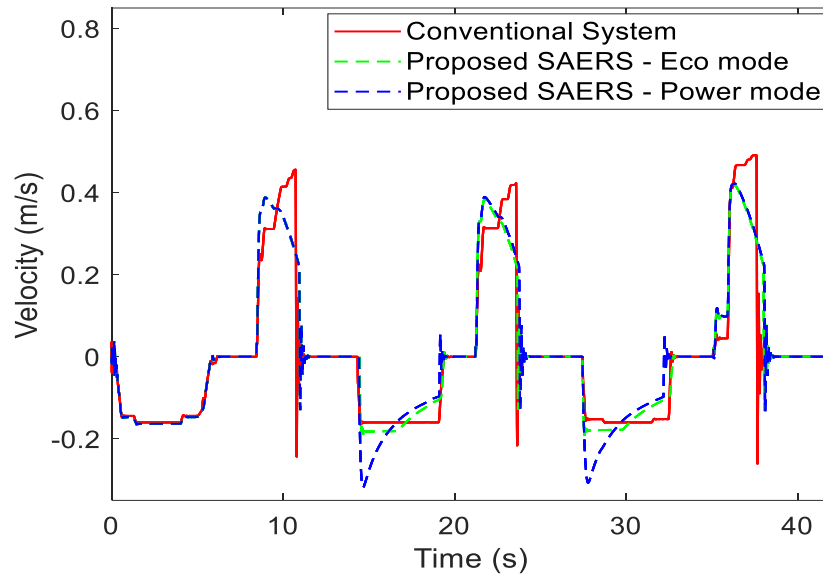


Fig. 13. Comparison of boom-cylinder velocities

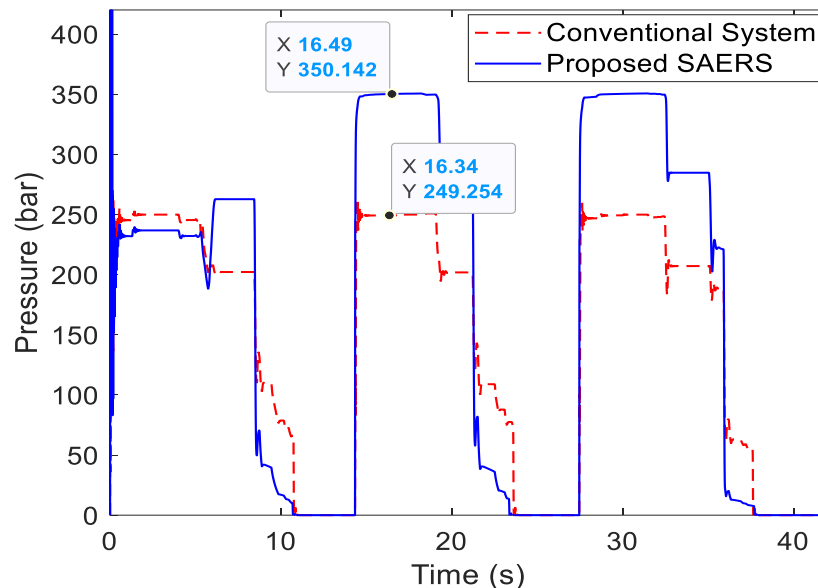


Fig. 14. Comparison of boom-cylinder pressures

Fig. 8 shows the velocities comparison of the pistons of the boom cylinders between the two systems. The positive values represent the downward velocities of the pistons, while the negative values correspond to the upward velocities. During the first upward displacement, both systems have the same velocity, as the hydraulic accumulator has not yet been activated. However, in the subsequent working cycles, there are differences in velocities between two systems. During the boom lowering process, the piston velocity in the proposed circuit is lower than that in the conventional circuit, because of the gradual

pressure increment of oil in the hydraulic accumulator during this process, which creates resistance to the outflow of oil from the piston chamber. During the boom lifting process, the piston velocity in the conventional system remains nearly constant, whereas in the proposed system, it gradually decreases. This decrement results from the declining pressure in the hydraulic accumulator during the process. Despite the differences in the piston velocities, the average velocities of the pistons in two systems are comparable. The velocity comparison results indicate that the hydraulic accumulator slightly reduces the boom

velocity. Nevertheless, the reduction is negligible and no sudden fluctuations in piston velocity are observed. Consequently, the dynamic characteristics of the hydraulic cylinder are preserved.

Fig. 9 shows the oil flow rates of the hydraulic pumps in the two systems. In the conventional system, the boom cylinders are driven by the hydraulic pump. Meanwhile, the hydraulic pump only drives one cylinder and the other cylinder connected to the hydraulic accumulator. During the first working cycle, when the hydraulic accumulator has not yet been utilized, the flow rate values of the hydraulic pumps in both systems are the same. The oil flow rate gradually rises to approximately 340 L/min during the boom lifting process and subsequently decreases to its minimum value during the boom lowering process. However, when the hydraulic accumulator is incorporated, the main pump flow rate in the proposed system reaches only approximately 240 L/min. This value is about 70% of that in the conventional system. In other words, the proposed system reduces the required main pump flow rate by nearly 30%.

Fig. 10 shows the energy consumptions of hydraulic pumps in two systems. In the hydraulic systems, the power consumption of a pump is determined by the product of the pressure differential across the pump and its flow rate, while accounting for the pump efficiencies. In the proposed system, the output flow rate reduction of the hydraulic pump, as shown in Fig. 9 leads to a corresponding decrease in hydraulic pump power requirement. This power reduction directly leads to the lower energy consumption of the pump. As shown in Fig. 10, after each working cycle, the energy consumption of the hydraulic pump in the proposed system is reduced by approximately 13%. The reduction in pump energy consumption not only lowers the operating cost but also reduces exhaust emissions from the internal combustion engine that drives the pump.

Fig. 11 shows the variation of gas pressure in

the accumulator. During the first working cycle, the accumulator pressure remains constant at approximately 100 bar, because the hydraulic accumulator has not yet been employed. However, in subsequent working cycles, the gas pressure inside the hydraulic accumulator fluctuates due to the piston's motion. As the piston moves downward, the gas pressure gradually increases; conversely, during the upward stroke, it decreases. This behavior is consistent with the operating principle of the hydraulic accumulator. The maximum gas pressure in the hydraulic accumulator reaches a peak value of approximately 280 bar. The increase in gas pressure corresponds to the energy recovery process. The gravitational potential energy of the boom is converted into energy stored in the hydraulic accumulator. Whereas the decrease in gas pressure represents the release of the stored energy of the hydraulic accumulator.

Fig. 12 shows the volume variation of the gas in the accumulator. The initial volume of the hydraulic accumulator is approximately 28 L. As the piston moves downward, the gas volume inside the accumulator decreases, reaching a minimum value of around 15 L. The decrease in gas volume corresponds to the energy recovery process, while the increase in gas volume represents the reuse of the energy of the hydraulic accumulator. Furthermore, the volume variation reflects the nonlinear characteristics of the hydraulic accumulator during operation.

Fig. 13 shows the comparison of the velocities of the pistons of the boom cylinders. The graph shows a significant difference in the upward velocity of the pistons. A comparison of piston velocities between the conventional system and the Eco mode of the proposed system was previously analyzed and shown in Fig. 8. This graph only focuses on the differences between Eco mode and Power mode. In Eco mode, the flow rate of the main pump is reduced to 30% of that in the conventional system, as shown in Fig. 9. In

contrast, in Power mode, the hydraulic pump delivers a flow rate comparable to that of the conventional system. As a result, during the boom lifting process, the piston velocity increases by approximately 30% compared to that in Eco mode. This result is consistent with the analysis presented in Fig. 9.

Fig. 14 shows a comparison of the pressures of the piston chambers before and after using the hydraulic accumulator. As shown in Fig. 14, the pressure in the proposed system is about 40% higher than that of the original system. However, the pressure variation pattern remains unchanged, and no significant oscillations occur. In practice, the bushings at the connection between the cylinder and the boom will wear due to the uneven loads on the two sides of the cylinder. However, the significantly improved productivity can offset the relatively low cost required for the periodic replacement of these bushings.

5. Conclusions

This paper has designed, modeled, and numerically validated the Single Accumulator Energy Recovery system for the boom circuit of hydraulic excavators. Beginning with a critical review of existing regeneration structures, the SAERS concept established the governing hydraulic-gas equations and calibrated the resulting model with pressure and oil flow data collected from a real excavator. The simulation mode was implemented in the Amesim software and exercised under representative Eco mode and Power mode duty cycles. The results indicate that SAERS lowers boom circuit hydraulic energy demand by about 13% in Eco mode while simultaneously boosting boom-lifting velocity by roughly 30% in Power mode, gains achieved without sacrificing controllability. The close agreement between simulated and measured transients confirms the fidelity of the model and supports the feasibility of SAERS as a retrofit solution. Overall, the proposed system offers a practical, cost-effective pathway toward more

energy-efficient and productive earth-moving equipment, warranting prototype development and field trials in future work. The proposed system has been validated through numerical simulations. In future work, it will be experimentally evaluated on a real excavator.

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Declaration of Generative AI

During the preparation of this work, the authors used ChatGPT-OpenAI in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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