Investigating Effectiveness of Boom Energy Recuperation Hydraulic Excavator using Intensifier and Accumulator

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Abstract

Hydraulic excavators are essential in construction and mining due to their high load-handling capacity and operational flexibility, but they suffer from low energy efficiency and high energy consumption. The present investigation proposes a modified hydraulic circuit aimed at enhancing energy regeneration by utilizing output from both working chambers of a three-chamber hydraulic cylinder during the boom-lowering phase. Unlike conventional systems, where fluid from one chamber is sent to the accumulator and the other is wasted into the reservoir, the proposed design directs fluid from both chambers to a hydraulic pressure intensifier, which boosts the pressure before storing it in an accumulator. This modification significantly increases the amount of energy that can be recovered and reused during boom lifting, thereby reducing support on the hydraulic pump and minimizing energy waste. Additionally, it lowers negative pressure at the pump inlet, reducing the risk of cavitation and extending pump life. Early simulation results using Automation Studio® Educational Version 6.0 demonstrate a notable improvement in energy recovery over traditional systems. The integration of a pressure boosting mechanism and redesigned flow path shows great potential for enhancing the performance and efficiency of hydraulic excavators, paving the way for more energy-efficient and sustainable solutions in heavy machinery operations.

Keywords: Hydraulic excavator; three-chamber cylinder; hydraulic accumulator; hydraulic intensifier

Introduction

In industries including mining, construction, demolition, and infrastructure projects, hydraulic excavators are important equipment [1, 2]. They are an essential asset on any site because of their versatility, which enables them to carry out a variety of tasks such soil compaction, grading, lifting, and excavating. Both linear and rotary motion are made possible by hydraulic actuators, which convert fluid pressure into mechanical force [3]. This enables operators to manipulate and precisely maneuver a variety of attachments [4].

The hydraulic boom is one of the essential parts for performing lifting and lowering operations. In general, it operates by hydraulic cylinders that actuate due to fluid delivered by a primary hydraulic pump. As expectations grow for faster, more energy-efficient and high-performing machines, the hydraulic efficiency of the boom system becomes increasingly important [5]. Despite the considerable progress in hydraulic engineering, inefficiencies remain that limit the full utilization of the energy.

Energy Loss in Conventional Hydraulic Setups

Although hydraulic systems are excellent at transmitting force, they are not inherently energy-efficient. A significant amount of energy is lost due to heat dissipation, internal leakage, and pressure drops across system components. A major source of energy wastage occurs during the boom's lowering movement. In typical configurations, only the fluid from the head-end chamber of the boom cylinder is directed to an accumulator for energy storage [6]. The fluid expelled from the rod-end chamber is usually diverted to the reservoir without any attempt to recover its energy.

This discharge process leads to considerable energy loss, especially considering how frequently boom lowering occurs during normal operations. The potential energy stored in the weight of the boom and arm, which could be harnessed, is instead dissipated. As a result, the system must rely entirely on the hydraulic pump to deliver fresh energy for lifting operations, increasing both energy demand and fuel consumption. These inefficiencies in hydraulic systems directly result in higher fuel use, especially since excavators primarily rely on diesel engines to drive hydraulic pumps. The more energy that goes enraptured, the more load is placed on the engine to compensate, driving up both fuel consumption and associated costs [7, 8].

The development of equipment that can capture and reuse energy contributes to the larger objectives of environmental sustainability. While operators and contractors benefit from reduced emissions and simpler understanding of regulatory requirements, manufacturers benefit from this change since it promotes the development of environmentally friendly technologies. The addition of energy recovery into hydraulic systems improves sustainability without compromising practicality or efficiency.

The objective of this research is to develop and evaluate a modified hydraulic circuit for boom lowering operations that ensures higher energy efficiency and improved system reliability. Specifically, the study aims to design a logical flow path that directs fluid from both chambers into the accumulator through a Hydraulic Pressure Intensifier (HPI), thereby enhancing the energy recuperation process. The integration of HPI will increase the pressure of fluid before entering the accumulator, enabling effective energy storage and utilization. Furthermore, the research focuses on minimizing back pressure in the pump during the lowering process to reduce cavitation risk and efficiency losses. By systematically analyzing and implementing these modifications, the study seeks to demonstrate an advanced hydraulic circuit capable of achieving greater energy savings compared to existing conventional designs.

Methodology

In Conventional double chamber cylinder (DCC) Hydraulic Circuit, a double acting cylinder along with 4/3 DCV, power pack and PRVs is used which is shown in figure 1 (a). With the help of DCVs fluid is guided either piston side or rod side chamber. Which causes extension or retraction accordingly? The main disadvantage of this cylinder is that During

Lowering high pressurized fluid is directed towards the sink. These results in wastage of huge energy & a huge negative pressure build in pump during lowering.

To overcome this new age technology actuator is proposed which is three chamber cylinders (Figure 1 (b)). Where one of the chambers is connected to accumulator so that during lowering process high pressurized fluid can be utilized to store energy.

As discussed earlier one chamber of three chamber cylinder (TCC) is connected to Accumulator. So that during lowering process some energy can be directed into accumulator. Which can later be used to lift the actuator during actuator raising process. Additionally, it reduces load on Pump & increases efficiency of system. Resistance offered by Accumulator also helps in reducing negative pressure in pump. Which increases pump life and pump efficiency and reduces power consumption.

This hydraulic circuit solves problem up to greater extent but there is still one problem associated with this hydraulic circuit is that during lowering process fluid from others chamber is still going into sink. It does not capture all energy which could have increase the circuit efficiency furthermore.

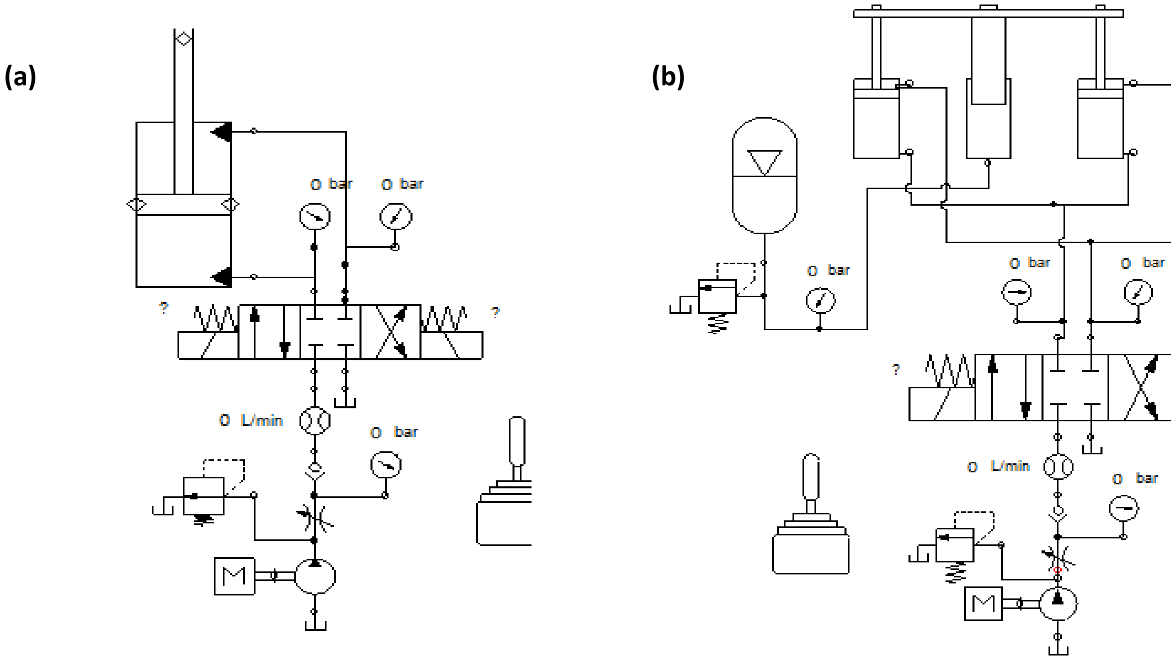

Fig. 1. Schematic of Proposed Hydraulic Circuit Diagram

The proposed hydraulic circuit is designed to enhance energy efficiency during the operation of the excavator boom by recovering energy from both return chambers of the three-chamber cylinder. Figure 2 depicts the hydraulic circuit diagram of the proposed hydraulic system for energy saving. Table 1 is showing the ON/OFF sequence of the different DCVs for various operations.

During the lowering motion of the boom, the fluid from both return chambers is first combined using DCVs 6 and 9, increasing the total volume fluid. This combined flow is then sent into a HPI. The HPI raises the pressure of the fluid to a level of 60 bar for storage in the accumulator. In this way we can store more amount of energy into accumulator. In the next lifting phase, the stored pressurized fluid is reused alongside the hydraulic pump output to raise the boom. This reduces the demand on the pump, resulting in lower energy consumption and improved overall system efficiency.

There are five different operations are possible with proposed hydraulic circuit. With different solenoids activating in different combination, each time a new logic is formed & it makes possible new operation.

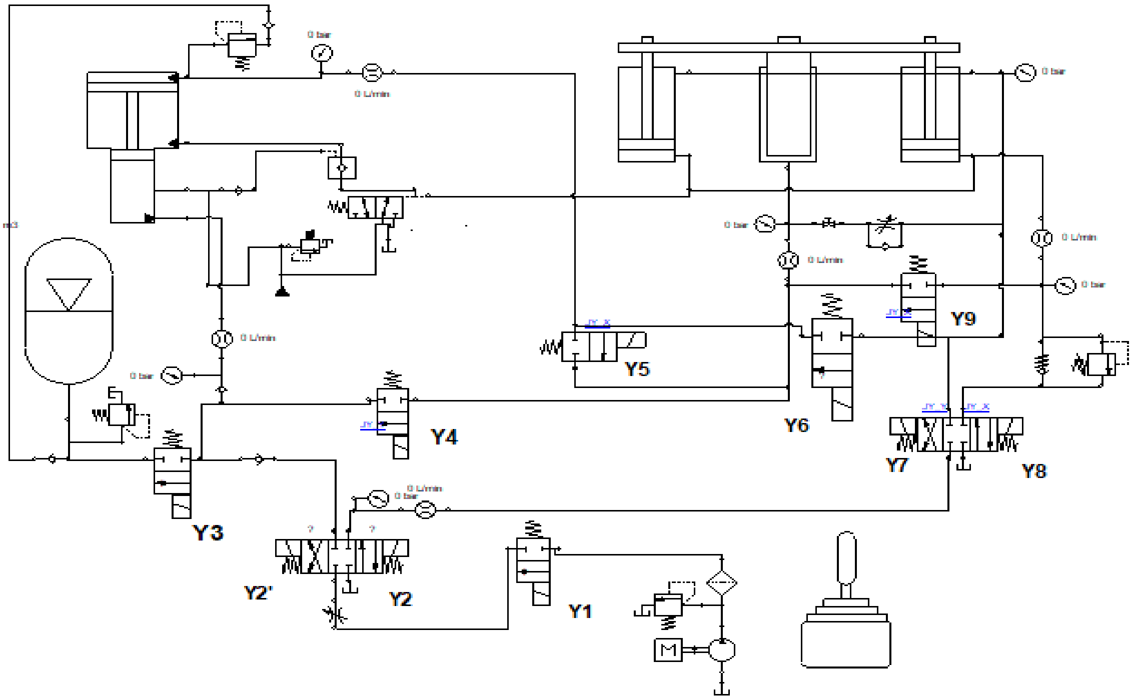

Fig. 2. Schematic of Proposed Hydraulic Circuit Diagram

Table 1: Solenoid excitation during different operations

S. No.	Description of Operations	Valve ON
1.	Charge Accumulator	Y1 , Y2, Y3
2.	Lowering To Accumulator	Y1, Y3, Y5, Y8, Y2
3.	Lowering To Tank	Y1, Y4, Y8, Y9, Y2
4.	Raising w/o Accumulator	Y1, Y6, Y7, Y9, Y2
5.	Raising with Accumulator	Y1, Ý3, Y4, Y6, Y7,Y2

The major components used in the simulation analysis and their parametric values are tabulated in Table 2.

Table 2. Components' Specification

Sr. No.	Components	Specifications	Value
1.	Positive displacement pump	Displacement Angular speed Flow rate	50 cm^3/rev 500 rpm 25 lpm
2.	Three chamber cylinders	Side piston dia. Central piston dia. Rod dia. Stroke length	45 mm 93 mm 10 mm 300 mm
3.	Hydraulic pressure intensifier	Large piston dia. Rear piston dia. Stroke length	90 mm 63 mm 150 mm
4.	Accumulator	Precharge pressure Volume Process	60 bar 2000 cm^3 adiabatic
5.	DCV	2/2 DCV 4/3 DCV	5 2
6.	Hoses	Dia.	20 mm

Results and Discussion

Comparison graph (Figure 3) shows the flow rate of accumulator of both hydraulic circuits. It is clear that during lowering process flow rate of modified TCC is less than Simple TCC till hydraulic pressure intensifier is lowering because HPI increase the pressure to twice but decrease the flow rate by half. But after HPI , flow rate of Modified TCC is greater than Simple TCC because now combine fluid from both the chamber is directly flowing in accumulator without use of HPI but simple TCC is directing only one chamber fluid into accumulator.

In hold and raising process Flow rate of the model is almost the same as both circuits utilizes accumulator to lift the actuator & accumulator is charged at almost same pressure. Pressure in accumulator of both the circuit starts from same position at 60 bar as it is the pre charge pressure. But if look closely at the end of lowering pressure of Modified TCC is little higher i.e. 70.25 bar and pressure of simple TCC is 69.45 bar (Figure 4). Volume Storage in Modified TCC at the end of lowering process is higher than Simple TCC. As fluid from both the chamber is directed into accumulator but in Simple TCC fluid from only one Chamber is going into Accumulator

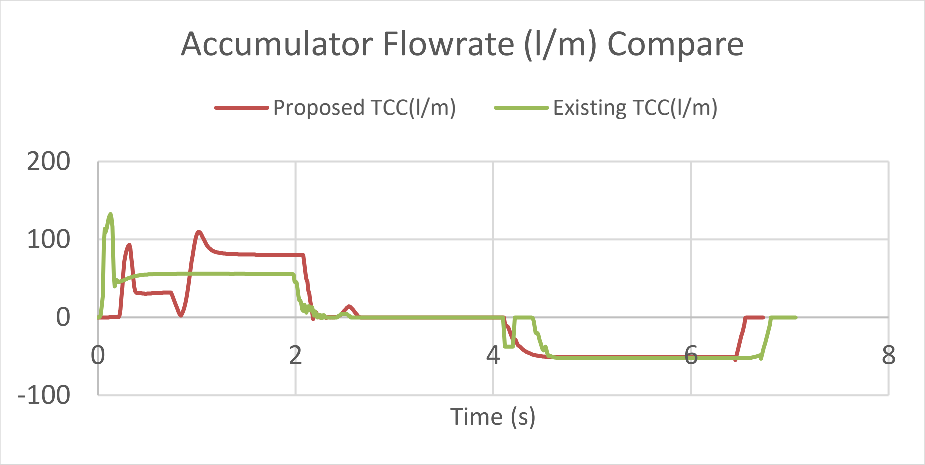

Fig. 3. Comparison of Flow rates of Accumulators

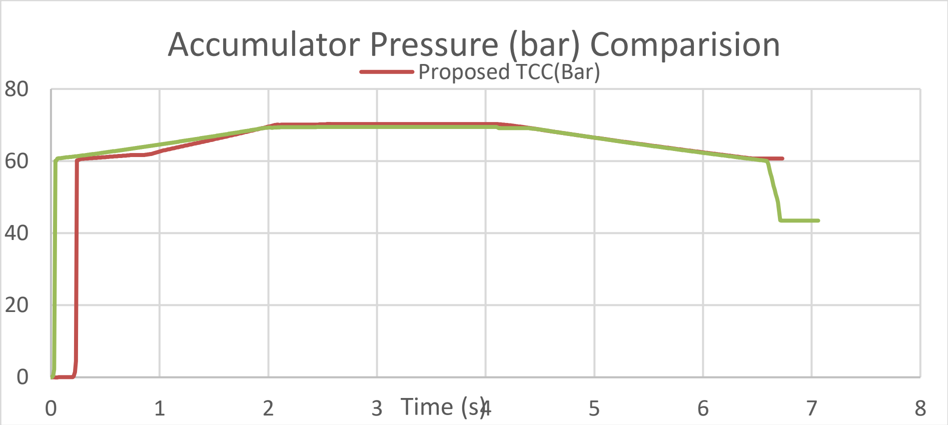

Fig. 4. Comparison of Pressures of Accumulators

1.1. Accumulator Energy comparison

The comparisons of energy storage in accumulator for the circuits are given in figure 5. Energy storage in accumulator in modified proposed circuit is clearly higher (13.68 kJ) than Simple TCC hydraulic circuit (12.66 kJ) as it stores high pressurized fluid from both chamber but Simple TCC stores high pressurized fluid from only one chamber. And during hold process both circuits maintain energy level of accumulator unchanged.

During raising energy of accumulator of both the circuit is reducing as they are supplying energy to lift the arm. Which helps to reduce load on pump. At the last of decay, it is clear that modified TCC stores more energy even after complete raising process.

The modified TCC hydraulic circuit receiving less energy till 1 second because of HPI as it is having huge mechanical losses. But later when fluid from both chamber is directly going into accumulator. Modified TCC Hydraulic circuit showing higher power or more energy receiving.

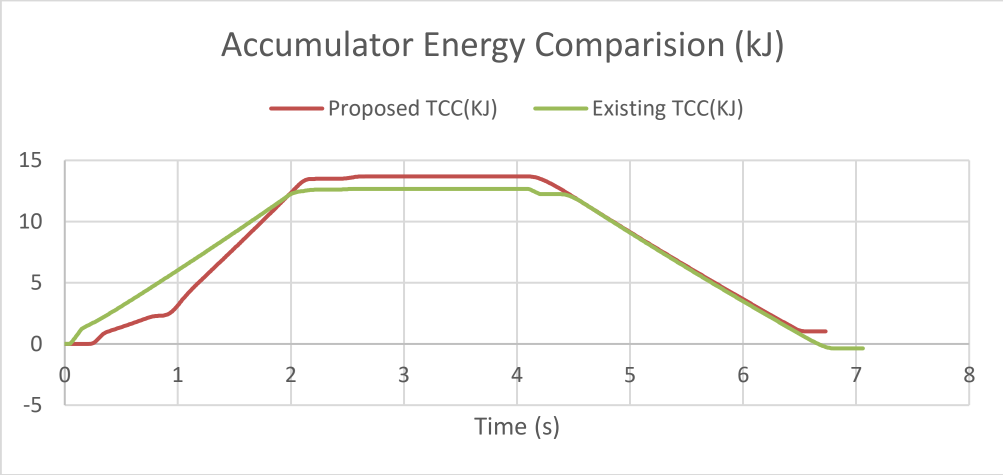

Fig. 5. Comparison of Energy of Accumulator

1.2. Pump Power comparison of Different Circuits

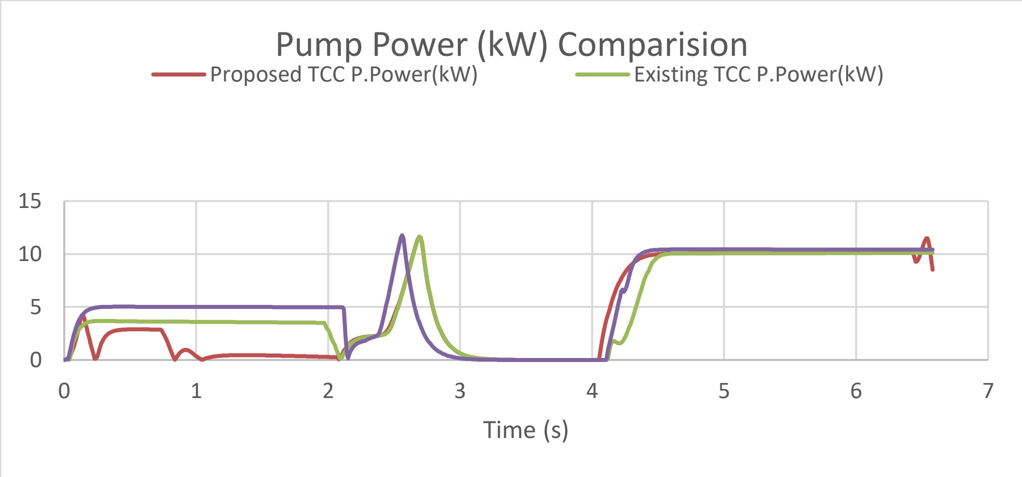

Fig. 6. Power comparison of Pump

Figure 6 is showing the comparison of pump energy during the application of both conventional as well as modified hydraulic circuits. During lowering process proposed modified hydraulic circuit consumes minimum power followed by Simple TCC and then Conventional DCC. During raising process modified TCC consumes very little less power than Simple TCC.

The final & most important comparison of this research which proves the importance of proposed modified TCC hydraulic circuit.

Here energy consumption by proposed modified TCC is 31.07 kJ, energy consumed by Simple TCC hydraulic circuit is 36.39 kJ & energy consumed by conventional DCC hydraulic circuit is 41.14 kJ. So, this proves that proposed modified TCC hydraulic circuit is more economical than other two hydraulic circuit.

Proposed Modified Hydraulic TCC hydraulic circuit consumes 17.12% less energy than Simple TCC Hydraulic Circuit & 32.41% less energy than Conventional DCC hydraulic circuit.

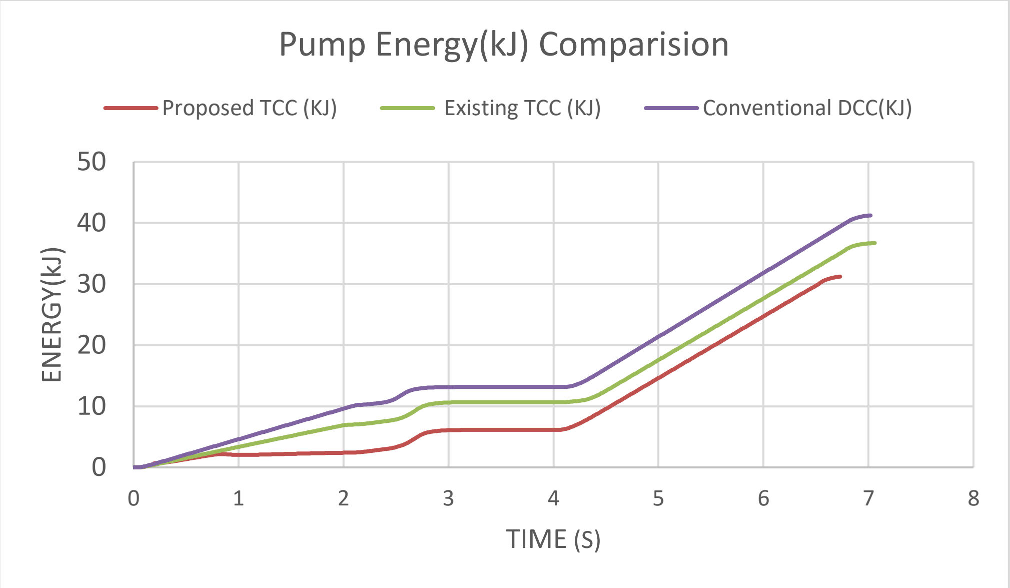

Fig. 42 Energy Comparison of Pump

Conclusion

In order to effectively recover and reuse the potential energy of a hydraulic excavator's boom, this study suggests an integrated drive and energy recuperation system that makes use of a three-chamber hydraulic cylinder and a hydraulic intensifier. These results are the finding of a comprehensive analysis.

- During whole process of lowering, hold and lifting the proposed innovative hydraulic circuit consume minimum energy as compared to existing TCC hydraulic circuit and then followed by conventional DCC hydraulic circuit. Which is 31.07 kJ, 36.39 kJ, 41.14 kJ respectively.
- Proposed hydraulic circuit consume 17.12% less energy during complete cycle as compared to existing TCC hydraulic circuit and 32.41% less energy as compared to conventional DCC hydraulic circuit.
- Proposed TCC Hydraulic Circuit can be used to charge the accumulator during idle time.

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