



# Energy recovery and utilization system of excavator boom based on flow regeneration and balance theory

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Received: 14 February 2019 / Accepted: 2 December 2019 / Published online: 10 December 2019  
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## Abstract

To meet the tighter emission standard of the diesel engine and save energy, various energy recovery and utilization systems (ERUSs) of excavator boom began to be applied. In this paper, a new ERUS of excavator boom was proposed and designed for a 20-ton traditional excavator (TE) based on flow regeneration and balance theory. In the new ERUS, partial potential energy of excavator boom can be utilized directly, and other partial potential energy of excavator boom is accumulated and released within only one hydraulic–hydraulic circuit. When the models of working device and working device with the new ERUS were built and simulated by AMEsim software based on proportion integration differentiation control strategy and the typical working cycle of TE, it can be seen that the new ERUS can meet the working requirement. Calculating and analyzing the influences of main parameters on the energy saving efficiency of the new ERUS, the optimal parameters are achieved. Then, the performance of new ERUS with optimal parameters is analyzed, some conclusion achieved that the potential energy utilization rates of boom is 20.1%, 24.9 L oil is regenerated, and 37.8 L oil and 41.6% energy are saved.

**Keywords** Excavator boom · Flow regeneration · Balance theory · Potential energy recovery and utilization

## 1 Introduction

Driven by the cylinders, the working device of TE, which is mainly composed of boom, arm, bucket and cylinders, carries out the work of digging, loading and unloading. During the operation process, supporting the other parts of the working device, driven by the boom cylinder, the boom moves up and down frequently to cooperate with arm and bucket to complete the work, and a large amount of potential energy is dissipated as heat. According to the literature [1], this energy consumption accounts for more than 15% of the total consumption of the TE.

With the stricter emission standard for off-road diesel engine released, the ERUS of excavator boom has been paid more attention by academic and industry. At present, various ERUSs of excavator boom have been proposed, such as hydraulic [2–4], electrical [5–7], flow regeneration [8] and balance theory [9, 10] ERUS. The hydraulic ERUS accumulates and releases the liquid energy with hydraulic accumulator (HA) during the process of the boom falling and rising and has been used by Caterpillar [11] and Liebherr [12]. In the electrical ERUS, used in Kobelco [13] and KYB [14, 15], the potential energy of boom is changed into electric energy accumulated by a battery or capacitance when the boom falls, and the accumulated electric energy is transformed into kinetic energy by the electric motor and to drive the main pump with the engine when the boom rises. Due to the oil of the none-rod cavity of boom cylinders (NRCBCs) flows back to tank, leading to flow loss when the boom of TE moves downward, the flow regeneration was proposed to lead partial oil of NRCBCs into rod cavity of boom cylinders (RCBCs) to reduce the flow loss in the literature [8]. In the balance theory ERUS, a balance cylinder is arranged parallel to the boom cylinders. When the boom moves downward, the potential energy of the boom is converted into hydraulic energy collected by a HA. According to the literature, energy

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Technical Editor: Fernando Antonio Forcellini, Dr.

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saving efficiency of the above four types of ERUS is about 10–27%, 15–25%, 33% and 20–29%, respectively.

Based on the ERUSs above, the flow regeneration ERUS has been synthesized to hydraulic and electrical ERUSs and formed hydraulic and electrical flow regeneration ERUSs [16, 17], respectively. Although these two synthesized systems can achieve the functions of the hydraulic or electrical and flow regeneration ERUSs, they need hydraulic–electric–hydraulic or hydraulic–hydraulic storage and release energy circuits, to achieve the conversion and utilization of energy. Based on the flow regeneration and balance theory, a new flow regeneration and balance theory ERUS is proposed for a 20-ton TE in this study, in which partial potential energy of excavator boom can be utilized directly, and other partial potential energy of excavator boom is accumulated and released within only one hydraulic–hydraulic circuit. The models of working device and working device with the new ERUS of the 20-ton TE are established by the AMESim software based on detail designing of the new system. Performance of the new ERUS is simulated by the models.

This paper is arranged as follows: The operation principle of new ERUS is illustrated in Sect. 2. The main parameters of the HA, balance cylinder and boom cylinders are designed in Sect. 3. The simulation models of the working device and working device with new ERUS are established by the AMESim software in Sect. 4. The performance of new ERUS is analyzed in Sect. 5. Conclusions are summarized and listed in Sect. 6.

## 2 Operation principle

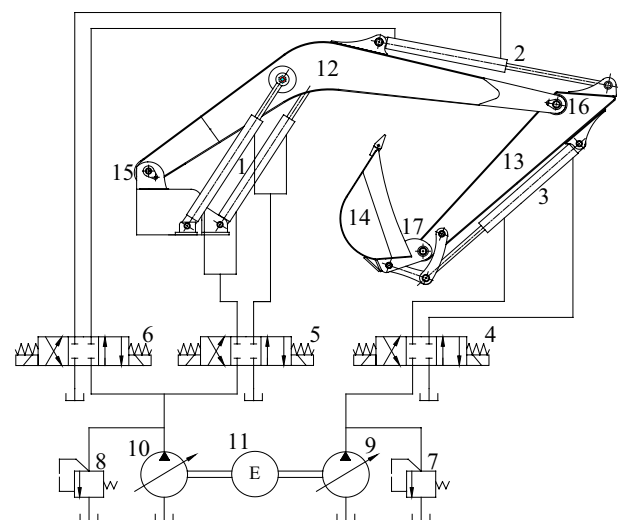
### 2.1 The working device of TE

The composition and hydraulic principle of working device of a 20-ton TE are shown in Fig. 1. And its main parameters are listed in Table 1. The boom 12, arm 13 and bucket 14, driven by cylinders 1–3 which are controlled by the reversing valves of 5, 6, 4, and supplied oil by main pumps, rotate around the hinge points of 15–17, respectively.

The circuit of excavator boom, shown in Fig. 2, is composed of boom cylinders 1–2, reversing valve 3, engine 4, main pump 5 and relief valve 6. During the process of boom falling, the potential energy of boom is transformed into heat energy when the oil is pumped into the RCBCs passing the choke of reversing valve 3. And during the process of boom rising, the oil enters the reversing valves to NRCBCs.

### 2.2 Flow regeneration

When one-way valves 7–8 and throttle valves 9–10 are added to the circuit of excavator boom, the flow regeneration circuit will be formed, as shown in Fig. 3 [8]. In the flow



1: Boom cylinder; 2: Arm cylinder; 3: Bucket cylinder; 4–6: Reversing valves; 7, 8: Relief valves; 9, 10: Main pumps; 11: Engine; 12: Boom; 13: Arm; 14: Bucket; 15–17: Hinge points.

Fig. 1 The working device of TE

regeneration circuit, the oil return pressure of the NRCBCs is increased by the one-way valve 7 and throttle valve 10; and one part oil of the NRCBCs enters into the RCBCs via the reversing valve 3 to realize the flow regeneration, and the other part returns to tank via throttle valve 10 when the boom falls.

### 2.3 Balance theory

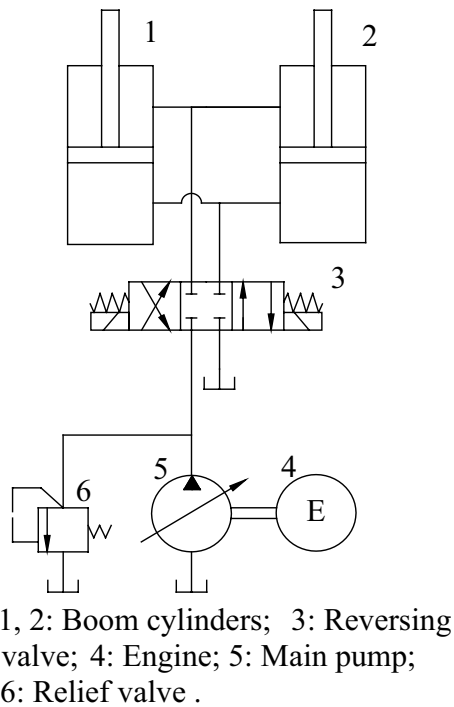
The ERUS based on balance theory, shown in Fig. 4, is formed by adding a balance unit to the circuit of excavator boom [9]. The balance unit consists of balance cylinder 7, HA 8, reversing valves 9–11 and relief valve 12 [10]. And the balance cylinder 7 is arranged parallel to the boom cylinders 1–2. When the boom falls, the oil is pumped into the RCBCs through reversing valve 3 and partial potential energy is converted into hydraulic energy by balance cylinder 7 and collected by a HA via the reversing valves 10–11. When the boom rises, the high pressure oil of HA enters into the none-rod cavity of balance cylinder via the reversing valves 10–11. The boom is driven by HA and main pump. When the boom falls to fulfill the digging action, the oil is released from HA to the rod cavity of balance cylinder via the reversing valves 11 and 9 to increase the digging force of the bucket or arm.

### 2.4 A new ERUS based on flow regeneration and balance theory

Based on the operation principle of flow regeneration and balance theory, a new ERUS is synthesized in this paper as

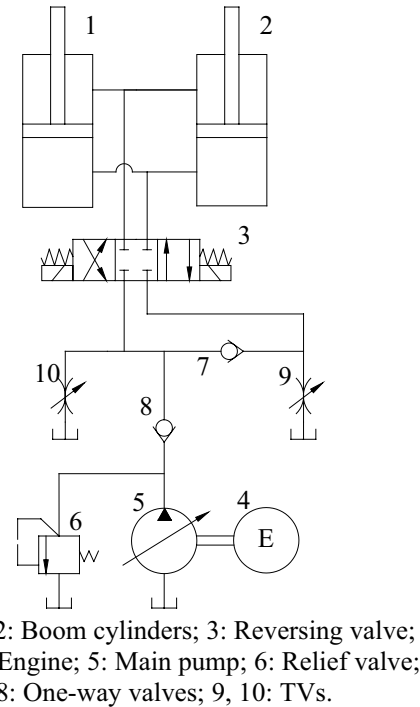
**Table 1** The main parameters of the 20-ton TE

Parameter	Value
Rated speed of engine ( $R_E$ )	2000 r min <sup>-1</sup>
Displacement of main pump ( $D_M$ )	218 ml r <sup>-1</sup>
Quantity, piston diameter, piston rod diameter and stroke of boom cylinders ( $Q_D - D_D \times d_D \times S_D$ )	2-125 × 80 × 1335 mm
Maximum pressure of NRCBC ( $p_{max}$ )	26.5 MPa
Maximum output flow of NRCBC ( $q_{max}$ )	232 L min <sup>-1</sup>
Quantity, piston diameter, piston rod diameter and stroke of bucket cylinder ( $Q_{DC} - D_{DC} \times d_{DC} \times S_{DC}$ )	1-130 × 90 × 1020 mm
Quantity, piston diameter, piston rod diameter and stroke of arm cylinder ( $Q_A - D_A \times d_A \times S_A$ )	1-140 × 100 × 1635 mm



**Fig. 2** The circuit of excavator boom

shown in Fig. 5. For this new ERUS, when the boom falls, one part oil of the NRCBCs enters into the RCBCs via the reversing valve 3, one-way valve 13 to directly realize utilization of potential energy and the other part oil of the NRCBCs returns to tank via throttle valve 16; at the same time, a part of boom potential energy is converted into hydraulic energy in the none-rod cavity of balance cylinder 7, and when the oil in the none-rod cavity of balance cylinder 7 get into the HA 8, the hydraulic energy is accumulated; when the potential energy is utilized, the operation principle of the new ERUS is similar to the ERUS based on balance theory. The energy recovery and utilization of the new ERUS is realized only in the balance unit.



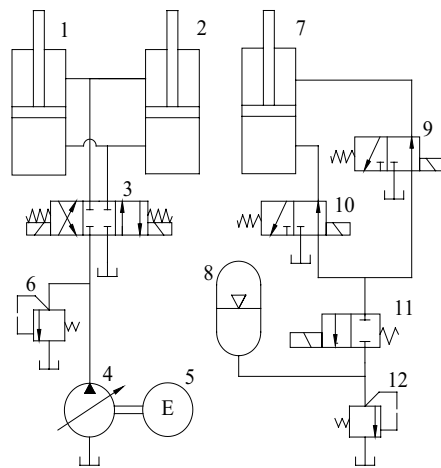
**Fig. 3** The flow regeneration circuit

### 3 Parameter matching for the new ERUS

#### 3.1 The determination of the cylinders specification

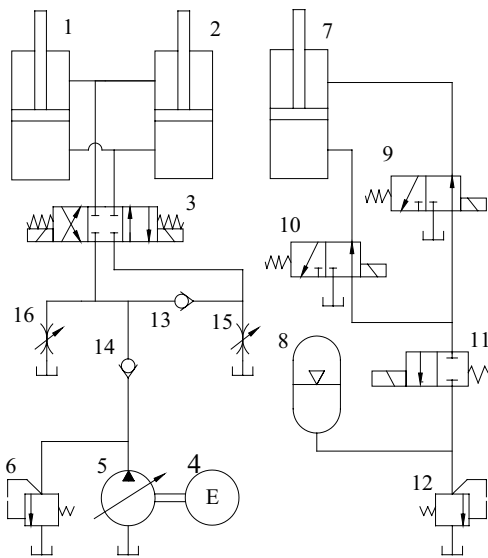
To meet the working requirements of TE, the sum of area of balance cylinder and boom cylinders in the new ERUS should be equal to the area of boom cylinders of TE. According to the requirement of component unification, the size of balance cylinder is selected equal to the boom cylinders in the new ERUS. It means:

$$\frac{3\pi}{4}D_b^2 = \frac{\pi}{2}D_D^2 \tag{1}$$



1, 2: Boom cylinders; 3, 9-11: Reversing valves; 4: Main pump; 5: Engine; 6, 12: Relief valves; 7: Balance cylinder; 8: HA.

Fig. 4 The ERUS based on balance theory



1, 2: Boom cylinders; 3, 9-11: Reversing valves; 4: Engine; 5: Main pump; 6, 12: Relief valves; 7: Balance cylinder; 8: HA; 13, 14: One-way valves 15, 16: TVs.

Fig. 5 The new ERUS based on flow regeneration and balance theory

$$\frac{3\pi}{4} (D_b^2 - d_b^2) = \frac{\pi}{2} (D_D^2 - d_D^2) \tag{2}$$

where  $D_b$ ,  $d_b$  are the piston and piston rod diameters of balance cylinder and boom cylinders of the new ERUS.  $D_D$ ,  $d_D$  are the piston and piston rod diameters of boom cylinder of TE. According to Table 1,  $D_b$  and  $d_b$  are calculated and rounded as 100 mm and 70 mm, respectively.

### 3.2 The operational principle of hydraulic HA

In this paper, the bladder HA is selected as the energy storage component in the new ERUS for its fast response and low cost. The bladder HA is mainly composed of air valve 1, bladder 2, steel shell 3 and mushroom valve 4 as shown in Fig. 6. And Fig. 6(a), (b), (c), (d) illustrates the initial, released energy, accumulated energy and arbitrary working states of HA, respectively, where the  $p_i$  and  $V_i$  ( $i=0, 1, 2$  and a) are the pressure and volume of HA corresponding to the four states.

During the process of boom falling, if  $p_a$  is lower than  $p_2$ , the oil of the none-rod cavity of balance cylinder enters into the HA, and the HA is accumulating energy; if  $p_a$  reaches  $p_2$ , the HA stops accumulating energy and keeps in its accumulated energy state. During the process of boom rising, if  $p_a$  is higher than  $p_1$ , the high pressure oil of HA enters into the none-rod cavity of balance cylinder and the HA is releasing energy; if  $p_a$  reaches  $p_1$ , the HA stops releasing energy and keeps in its released energy state. The efficiency of HA is determined by its  $p_0$ ,  $p_1$ ,  $p_2$  and  $V_0$ .

### 3.3 Determination of Working pressures of HA

According to the Boyle's law [18], the air in the HA follows the ideal air law, so

$$p_0 V_0^n = p_1 V_1^n = p_2 V_2^n = p_a V_a^n = \text{const} \tag{3}$$

where  $n$  is the air polytropic exponent and equal to 1.4 for the falling time of the boom is short.

During the process of boom falling, the oil pressure of the none-rod cavity of balance cylinder increases with the increase in  $p_a$  of the HA, which will lead to the difficulty of the boom falling and affect the work and efficiency of the new ERUS. To avoid this phenomenon,  $p_2$  of the HA should be lower than the maximum pressure of NRCBC of TE. According to Table 1,  $p_2$  should no more than 26.5 MPa. The accumulated energy  $E$  of the HA can be calculated as follows:

$$\begin{aligned} E &= - \int_{V_1}^{V_2} p_a dV_a = \frac{p_1 V_1}{1-n} \left[ 1 - \left( \frac{p_1}{p_2} \right)^{\frac{1-n}{n}} \right] \\ &= \frac{p_0 V_0}{1-n} \left[ \left( \frac{p_2}{p_0} \right)^{\frac{n-1}{n}} - \left( \frac{p_1}{p_0} \right)^{\frac{n-1}{n}} \right] \end{aligned} \tag{4}$$

Equation (4) indicates that the accumulated energy  $E$  of HA increases with the increase in  $V_0$ . If the energy density  $E_v$  of HA, which is calculated as Eq. (5), reaches its maximum, the limited installation space of HA on the excavator can achieve the maximum utilization. And the maximum energy density

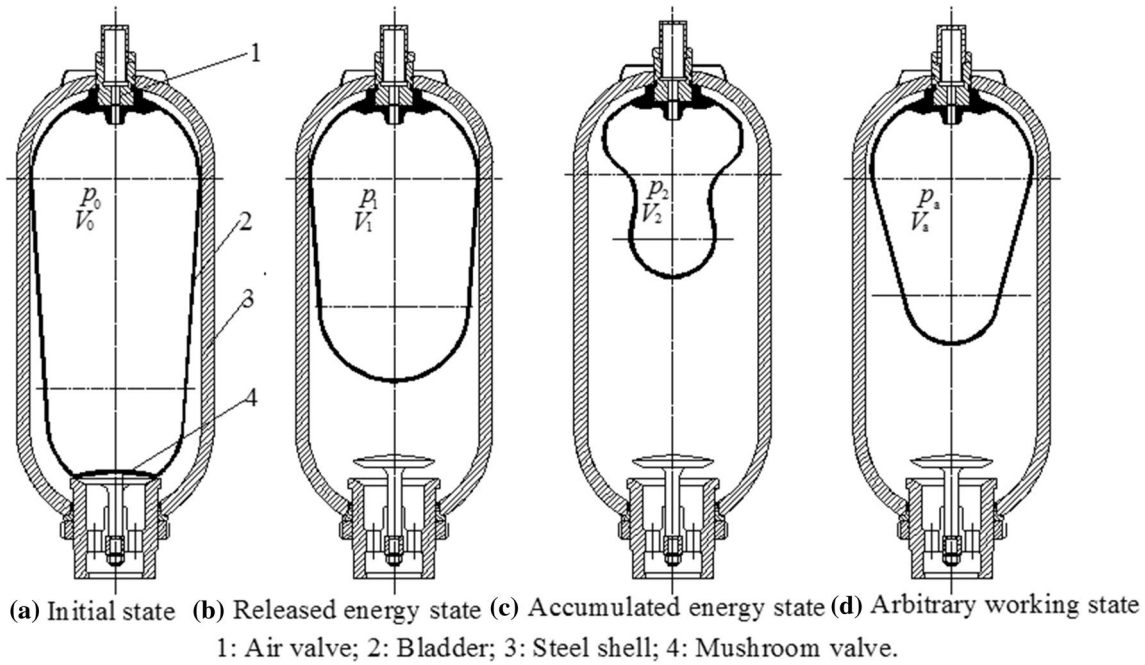


Fig. 6 The structure and working principle of HA

of HA can be calculated by derivative of  $p_1$  with respect to  $E$  as Eq. (6). Then, the relationship of  $p_1$  and  $p_2$  can be obtained as follows:  $p_1/p_2 = 0.308$ .

$$E_v = \frac{p_1}{1-n} \left[ 1 - \left( \frac{p_1}{p_2} \right)^{\frac{1-n}{n}} \right] \tag{5}$$

$$\frac{dE_v}{dp_1} = 0 \tag{6}$$

If the volume of bladder HA is often changed at oversize, it will influence its service life. To prevent the volume of bladder HA changes too large to contact the inner shell of HA,  $p_2$ ,  $p_0$  and  $p_1$  of HA should satisfy [19]:

$$0.25p_2 < p_0 < 0.9p_1 \tag{7}$$

So the working pressure of the HA is primarily selected as follows:  $p_0 = 5.5$  MPa,  $p_1 = 6.2$  MPa,  $p_2 = 20$  MPa.

### 3.4 Determination of $V_0$ of HA

From the literature [19], the  $V_0$  of HA can be calculated as follows:

$$V_0 \geq \frac{\Delta V_{\max}}{\left( \frac{p_0}{p_1} \right)^{\frac{1}{n}} - \left( \frac{p_0}{p_2} \right)^{\frac{1}{n}}} \tag{8}$$

where  $\Delta V_{\max}$  is the maximum volume change of the HA. According to the operation principle of the new ERUS,  $\Delta V_{\max}$  is equal to the maximum volume change of the non-rod cavity of balance cylinder, that is,

$$\Delta V_{\max} = \frac{\pi D_b^2}{4} S_b \tag{9}$$

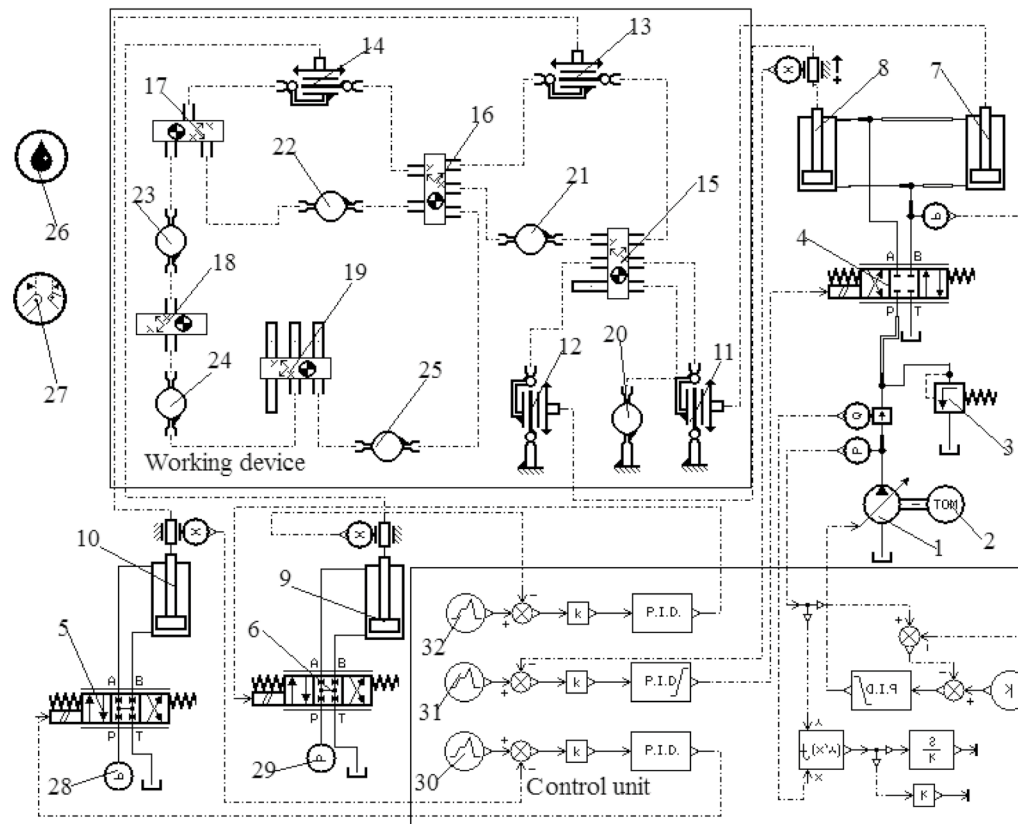
where  $S_b$  is the stroke of balance cylinder. Based on Chapter 3.1 and Table 1, the  $V_0$  is initially determined as 25 L.

## 4 Model simulation

### 4.1 Establishment of simulation model

According to Figs. 1, 5, Table 1 and the initial parameters matched for new ERUS, the models of working device and working device with the new ERUS of the 20-ton TE are established by the AMESim software, as shown in Figs. 7 and 8, respectively.

Because this paper focuses on the research of ERUS of boom potential, to simplify the modeling process, the engine is simulated by a motor and the arm, and bucket cylinders are actuated by means of a constant pressure source in the two models. And these simplifies have no impact on the ERUS of boom potential. In order to fulfill the typical working cycle of falling–digging–rising–returning action of working device [20, 21], also the control units, in which the



1: Main pump; 2: Motor; 3: Relief valve; 4-6: Reversing valves; 7-8: Boom cylinders; 9: Bucket cylinder; 10: Arm cylinder; 11-14: Mechanical units corresponding to boom, arm and bucket cylinders; 15: Boom; 16: Arm; 17: Rocker; 18: Link; 19: Bucket; 20-25: Hinge points; 26: Oil; 27: Zero port; 28-29: Constant pressure sources; 30-32: Displacement signals of arm, boom, bucket.

Fig. 7 The model of working device

PID control strategy is selected, are included besides the working device and hydraulic system in the two models.

In Fig. 7, the PID control strategy is used to control the speeds of boom, arm and bucket via adjusting reversing valves 4–6.

In Fig. 8, the PID control strategy is used to control the speeds of boom, arm and bucket and the energy accumulation and release time of HA via adjusting the reversing valves 5–10 and throttle valves 12–13.

#### 4.2 The simulation actions of boom cylinders

The actions of boom cylinders are simulated by the two models. And the piston displacement and velocity of the boom cylinders of TE and TE with the new ERUS are shown in Fig. 9(a) and (b). It can be seen that the two models of TE and TE with the new ERUS can realize the simulation of typical working cycle of TE successfully under the PID control strategy. In the typical working cycle, the actions of

boom falling, digging, rising and returning take place about in 0–3.5 s, 3.5–7.5 s, 7.5–12 s, 12–15.5 s and 15.5–20 s, respectively.

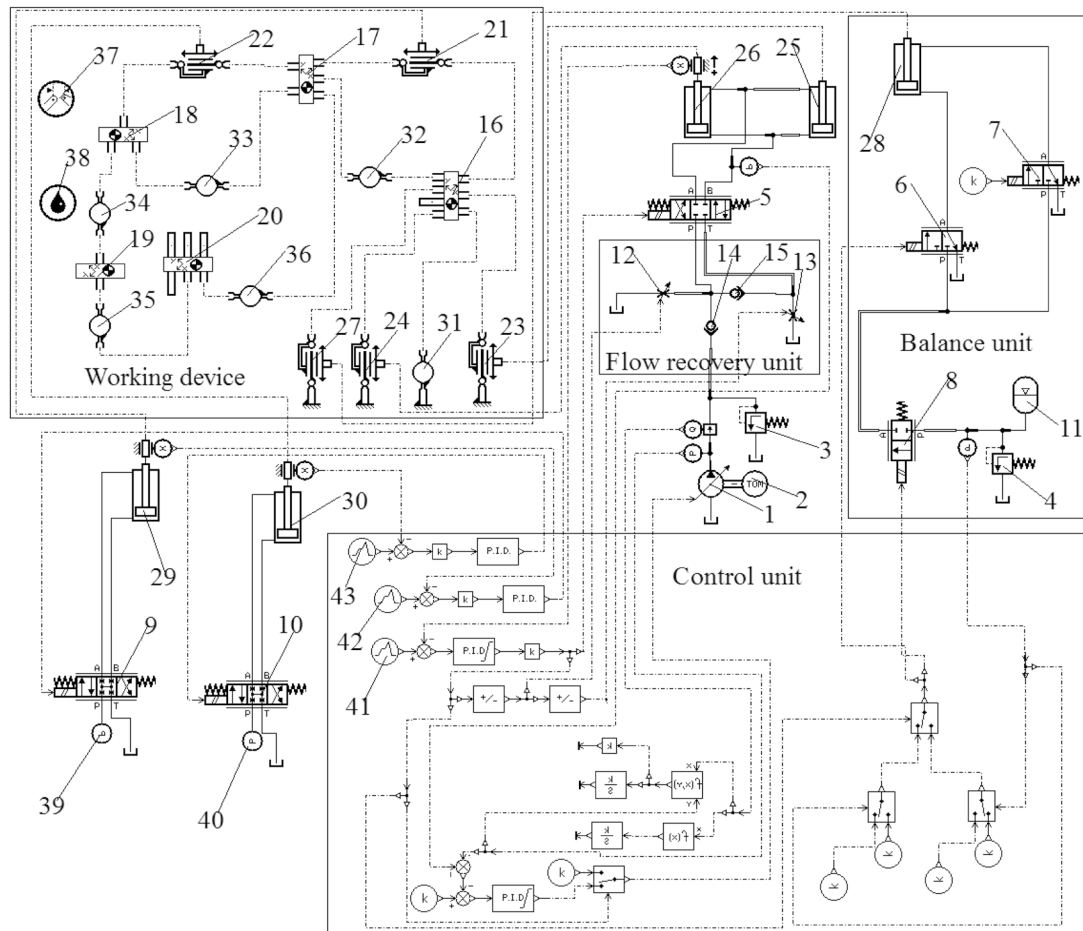
Figure 9a, b reveals that although there are some deviations between the piston displacement and velocity of boom cylinders of new ERUS with initial parameters and the ones of TE, the action process of the piston displacement and velocity of the boom cylinders of the two system basically coincide with each other. Therefore, the new ERUS can meet the working requirement.

### 5 The performance analysis of new ERUS

#### 5.1 The influences of the main parameters on the energy saving efficiency

Analyzing the operation principle of the new ERUS, the energy saving efficiency of new ERUS will be influenced





1: Main pump; 2: Motor; 3-4: Relief valves; 5-10: Reversing valves; 11: HA; 12-13: throttle valves; 14-15: Check valves; 16: Boom; 17: Arm; 18: Rocker; 19: Link; 20: Bucket; 21-24: Mechanical units corresponding to arm, bucket, boom cylinders; 25-26: Boom cylinders; 27: Mechanical unit corresponding to the balance cylinder; 28: Balance cylinder; 29: Arm cylinder; 30: Bucket cylinder; 31-36: Hinge points; 37: Zero port; 38: Oil; 39-40: Constant pressure sources; 41-43: Displacement signals of boom, arm, bucket.

**Fig. 8** The model of working device with the new ERUS

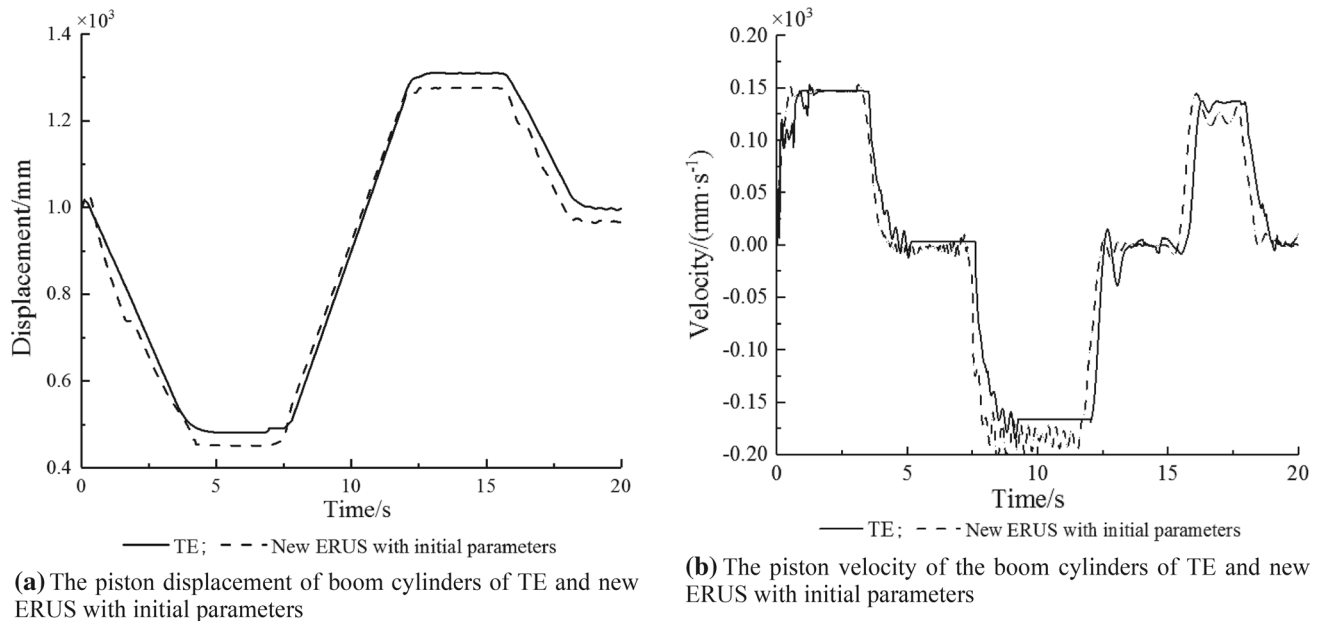
by  $p_0$  and  $V_0$  of HA and choke area of throttle valve 16 (CATV), which is set in the NRCBCs return circuit as shown in Fig. 5. The influences of  $p_0$ ,  $V_0$  and CATV on the energy saving efficiency are calculated with the model of new ERUS as shown in Fig. 10a–c, respectively.

From Fig. 10, it can be found that the influences of  $p_0$ ,  $V_0$  and CATV on the energy saving efficiency of the new ERUS are roughly similar. The energy saving efficiency increases first and then decreases with the increase in  $p_0$ ,  $V_0$  and CATV. And the energy saving efficiency achieves the maximum value when  $p_0$ ,  $V_0$  and CATV are 4.4 MPa, 25 L and 17 mm<sup>2</sup>, respectively.

## 5.2 The action of boom cylinders with the optimal parameters

The model of new ERUS with the optimal parameters is simulated, and the displacement and velocity of the boom cylinder piston, compared with the ones of TE and new ERUS with initial parameters, are shown in Fig. 11a, b.

According to Fig. 11, it can be seen that the displacement and velocity of boom cylinders of new ERUS with the optimal parameters are more consistent with the TE than those of the new ERUS with initial parameters. And



**Fig. 9** The piston displacement and velocity of the boom of TE and new ERUS with initial parameters

the new ERUS with initial parameters can better meet the working requirement.

### 5.3 The performance of new ERUS with optimal parameters

#### 5.3.1 Analysis of potential energy recovery and utilization

According to the simulation, the energy recovery and energy utilization of new ERUS with optimal and initial parameters are shown in Figs. 12 and 13.

From Fig. 12, it can be observed that 44.8 kJ and 21.9 kJ of 178.2 kJ potential energy of the boom of TE are converted into hydraulic energy in new ERUS with optimal and initial parameters, respectively, during the process of boom falling. And the recovery rates of potential energy of new ERUS with optimal and initial parameters are 25.1% and 12.3%, respectively.

According to Fig. 13, it can be seen that 35.8 kJ and 16.5 kJ of hydraulic energy, accumulated by HA, are utilized during the process of boom rising in new ERUS with optimal and initial parameters. And the energy utilization rates of the converted hydraulic energy are 79.9% and 75.3% in new ERUS with optimal and initial parameters, respectively.

Consequently, the potential energy utilization rates of boom are 20.1% and 9.3% in new ERUS with optimal and initial parameters, respectively.

#### 5.3.2 Analysis of flow regeneration

In view of the simulation, to complete the typical working cycle, when the boom falls, 24.9 L and 0 L oil are supplied by main pump in the TE and the new ERUS; when the boom rises, 43.9 L and 31 L oil are supplied by main pump in the TE and the new ERUS as shown in Table 2. It means that 24.9 L oil is regenerated and 37.8 L oil is saved in one working cycle in the new ERUS.

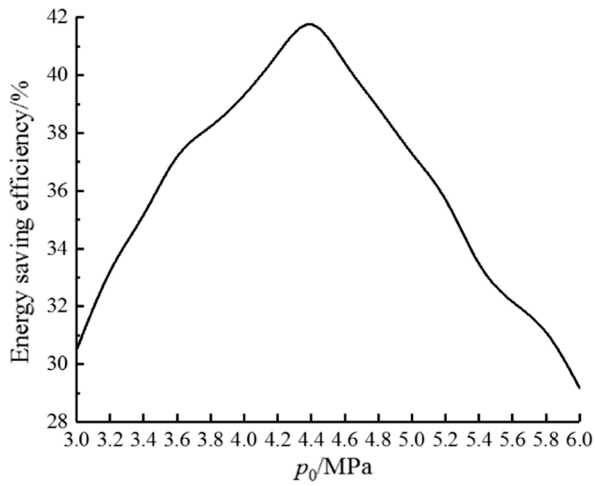
#### 5.3.3 Analysis of the energy saving

The energy supply of main pump in the TE and new ERUS with initial and optimal parameters is shown in Fig. 14. It can be seen that energy needs to be continuously supplied by main pump with a total energy requirement of 1482.8 kJ in the TE. However, for the new ERUS with optimal and initial parameters, no energy need to be supplied in 0–7.5 s and only 865.6 kJ and 999.4 kJ energy need to be supplied in 7.5–12.5 s. In other words, compared with the TE, the new ERUS with optimal parameters saves 41.6% energy.

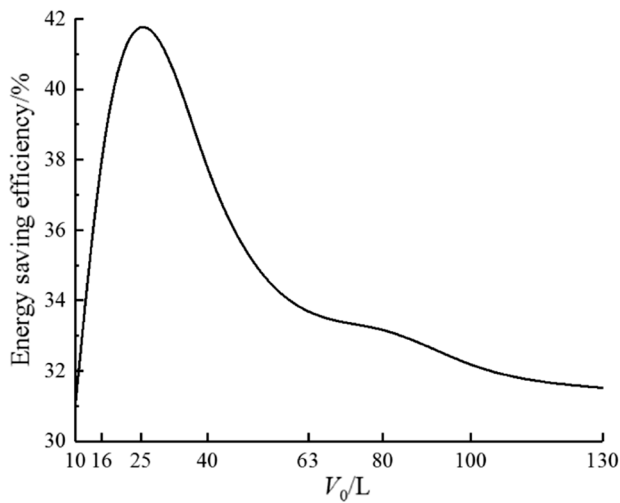
## 6 Conclusion

In order to improve the energy utilization rate of the TE, a new ERUS of excavator boom is proposed and designed for a 20-ton TE based on flow regeneration and balance theory. When the simulation models of the working device and

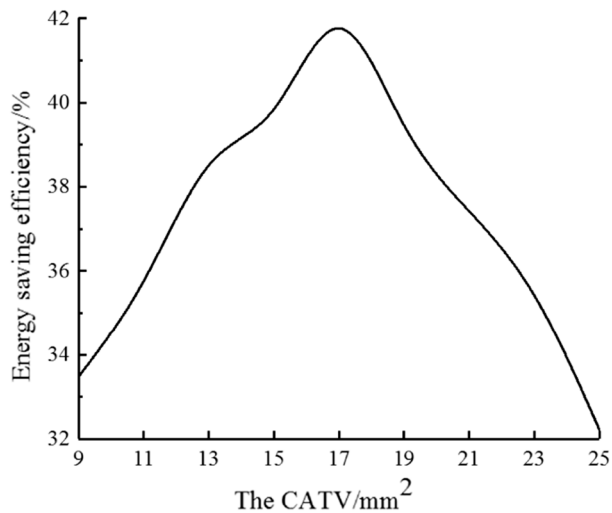




(a) The influence of  $p_0$  on energy saving efficiency

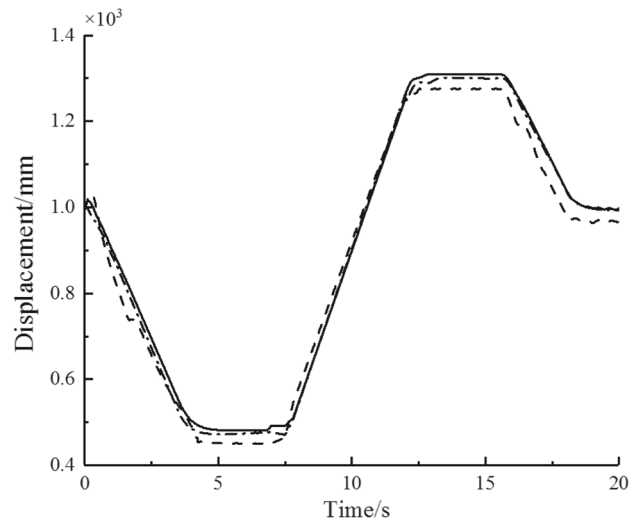


(b) The influence of  $V_0$  on energy saving efficiency



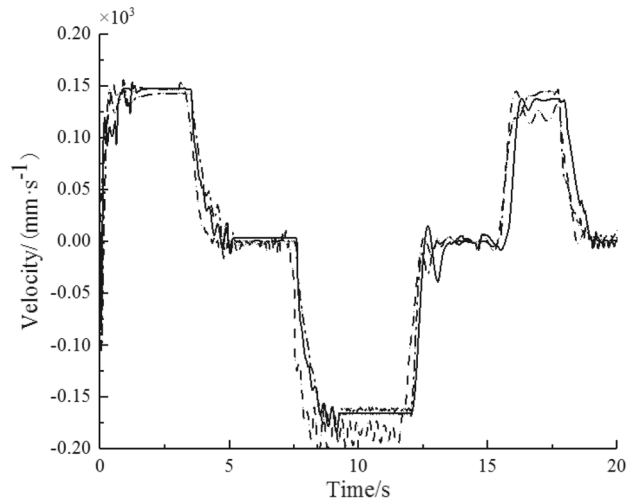
(c) The influence of CATV on energy saving efficiency

**Fig. 10** The influences of the various parameters on the energy saving efficiency



— TE; - - - New ERUS with initial parameters;  
- · - · New ERUS with optimal parameters

(a) The piston displacement of boom cylinders of TE and new ERUS with optimal and initial parameters



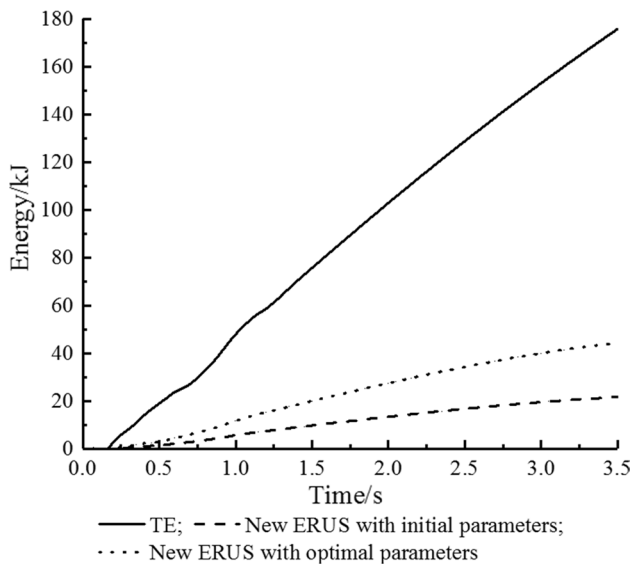
— TE; - - - New ERUS with initial parameters;  
- · - · New ERUS with optimal parameters

(b) The piston velocity of boom cylinders of TE and new ERUS with optimal and initial parameters

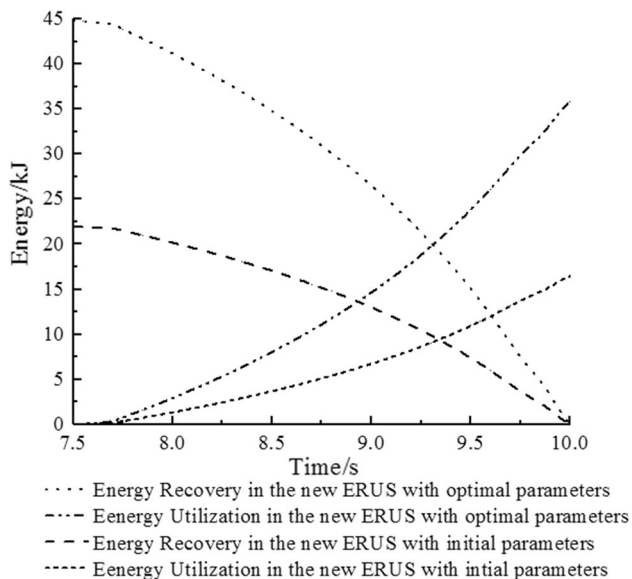
**Fig. 11** The piston displacement and velocity of boom cylinders of TE and new ERUS with optimal and initial parameters

working device with the new ERUS are built with AMESim software, the influences of main parameters are calculated and the performance of the new ERUS is analyzed. And some conclusions are as follows:

1. The optimal parameters of  $p_0$ ,  $V_0$  and CATV are obtained. Analyzing the actions of boom cylinders, it can be inferred that the actions of boom cylinders with optimal parameterized new ERUS is more consistent with that of the TE than with the initial parameterized



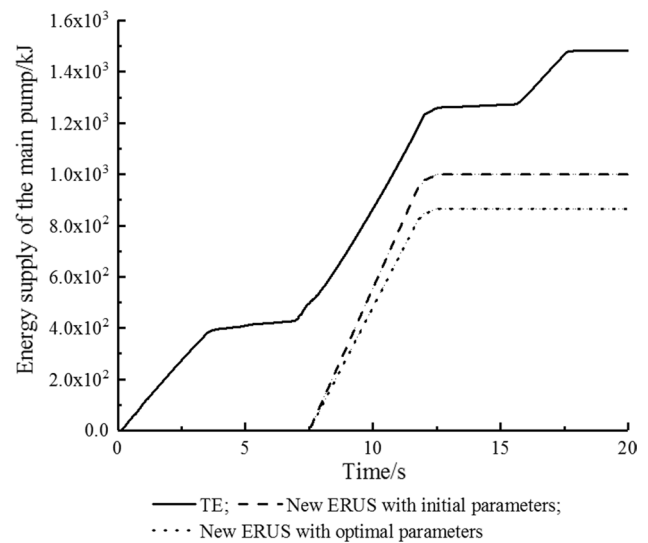
**Fig. 12** The potential energy of TE and energy recovery in new ERUS with optimal and initial parameters



**Fig. 13** The energy utilization in new ERUS with optimal and initial parameters

**Table 2** The oil supplied by main pump

	Boom falls (L)	Boom rise (L)	Total(L)
Traditional excavator	24.9	43.9	68.8
The new ERUS with optimal parameters	0 L	31	31
The new ERUS with initial parameters	0 L	31	31



**Fig. 14** The energy supply of main pump

one. And the new ERUS with optimal parameters can better meet the working requirement of TE.

2. Compared with the TE, potential energy utilization rates of boom are 20.1% and 9.3% in new ERUS with optimal and initial parameters, respectively.
3. According to the simulation of the models, 24.9 L oil is regenerated and 37.8 L oil and 41.6% energy are saved in one working cycle in the new ERUS with optimal parameters.

**Acknowledgements** This research was supported by Shandong Province Key Laboratory of Mine Mechanical Engineering (Grant No. 2019KLMM204) and NSFC-Shanxi coal-based low carbon joint fund focused on supporting project (Grant No. U1510205).

**Compliance with ethical standards**

**Conflict of interest** The authors declare that they have no conflict of interest.

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