The 10th JFPS International Symposium on Fluid Power FUKUOKA 2017 Oct. 24-27, 2017 The Japan Fluid Power System Society

COMPARISON OF TWO TYPES OF GRAVITATIONAL POTENTIAL ENERGY REGENERATION SYSTEMS FOR EXCAVATOR

Shuce ZHANG * and Kazushi SANADA **

* Department of Mechanical Engineering, Graduate School of Mechanical Engineering,
Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa, 240-8501, Japan
(E-mail: sanada-kazushi-sn@ynu.ac.jp)
** Faculty of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa, 240-8501, Japan

Abstract. The energy regeneration system (ERS) coupled with hydraulic hybrids, can save more energy for hydraulic hybrid excavator. Bladder accumulator, as an energy regeneration component, is widely used in hydraulic excavator. However, heat loss is one of its disadvantage and the quantitatively evaluation is a well-known problem. In this study, two types of ERS assist-driving-boom cylinder by regenerating gravitational potential energy, suction-boost circuit (SBC) and variable displacement motor-assist circuit (VDMC) are compared. The influence of accumulator parameters to energy regeneration is investigated. Coupled with the main fixed pump in VDMC, a variable displacement hydraulic motor, which is driven by inconstant flow power by accumulator, is employed in the purpose to improving energy regeneration efficiency.

Keywords: Hydraulic excavator, Energy-saving, Hydraulic hybrid, Accumulator, Simulation

NOMENCLATURE

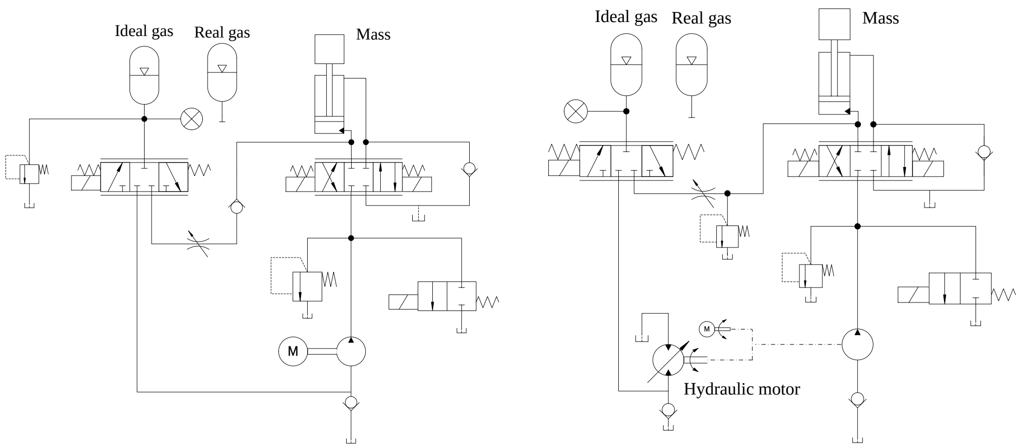
A	The wall area	[m^2]	Q	Flow rate	[m^3/s]
c_v	Constant volume specific heat	[W/(m^{2}K)]	t	Time	[s]
d	Pipe diameter	[m]	T	Gas temperature	[K]
l	Pipe length	[m]	V	Gas volume	[m^3]
m	Gas mass	[kg]	λ	Friction coefficient of pipe	-
p	Gas pressure	[Pa]	ρ	Flow density	[kg/m^3]

INTRODUCTION

Necessarily considering finite energy resources of nature and the inefficient-using of the hydraulic power, novel energy regeneration system for heavy machinery shows improvements in energy efficiency. For hydraulic hybrid excavator, a bladder accumulator can be installed to store energy in energy regeneration system (ERS) in the working line. For designs of improved architectures for energy storage, during braking of arm and swing, lowering of boom, it’s possible to capture energy and stored in accumulator. The influence of accumulator to energy regeneration should be investigated. A detailed instruction of the role of heat transfer in fluid power losses has been proposed by Elder F. T. et al [1] based on a piston accumulator applied on a sinusoidal load cycle. Various system configurations of ERS have been presented by focusing on actuators for hydraulic excavators. SHEN [2] proposed a common pressure rail hydraulic system which is composed of high-voltage line and low-voltage line and the cylinder is controlled by a new kind of hydraulic transformer. SUGIMURA [3] designed a fully hydro-mechanical valve controlled constant pressure system suits to mini-excavator. The effects of varying different parameters of accumulator to regenerate braking hydraulic energy for a vehicle are analyzed by Panchal S, et al [4].Gravitational potential energy regeneration has been discussed by researchers focusing on control strategies and parameter matching [5, 6]. In this study, based on the suction-boost circuit (SBC) proposed by XIA and YAGISAQA [7, 8], which relatively efficiently drives boom cylinder, accumulator parameters and cylinder control performance are focused for the purpose of analyzing energy efficiency. In addition, another ERS assist-driving-boom cylinder by regenerating gravitational potential energy is designed.

To keep high efficiency working, a variable displacement hydraulic motor is employed in ERS, which is named as variable displacement motor circuit (VDMC).

SYSTEM CONFIGURATION



(a) Suction-boost circuit （SBC） (b) Variable displacement motor-assist circuit （VDMC）

Fig. 1 Two types of energy regeneration system (ERS)

SBC schematic diagram is shown in Fig. 1(a). The accumulator is directly connected to the suction side of the pump. In the process of boom cylinder lifting, instead of the oil tank, the pressurized oil from accumulator flows into the pump thereby decreases the electric motor power. Another promising way by introducing a variable displacement hydraulic motor in energy regeneration circuit (VDMC) is shown in Fig. 1(b). Nitrogen is the recommended gas to be used to charge an accumulator. For the pressurized real gas in the accumulator, heat transfer will occur while ideal gas is assumed to be immune to heat loss. In the AMESim modeling evaluation, thermal time constant was used for modeling the heat exchange based on the description by Redlich-Kwong-Soave real gas law [9, 10]. The heat loss T_{loss} [K] in accumulator can be written

$$T_{loss} = \left(-\frac{T}{m \cdot c_v} \cdot \left(\frac{\partial V}{\partial T} \right)_P \cdot \frac{dp}{dt} + \Upsilon \cdot \frac{dT}{dt} \right) \cdot \tau, \tag{1}$$

where Υ is the specific heat ratio and the time constant τ is defined as follows

$$\tau = \frac{m \cdot c_v}{H \cdot A}. \tag{2}$$

where H is the overall heat transfer coefficient for the heat exchange between gas and environment. The time constant is dependent of the surface area between gas and wall. Assuming different thermal time constant values, the regenerated energy calculated is different. Previous studies [11, 12] presented an anelastic model which is able to predict the thermal losses for the ± 5 percent gas volume variation, and then presented a thermal time-constant model to evaluate the time-constant correlation in accumulator without experimental evaluation of τ .

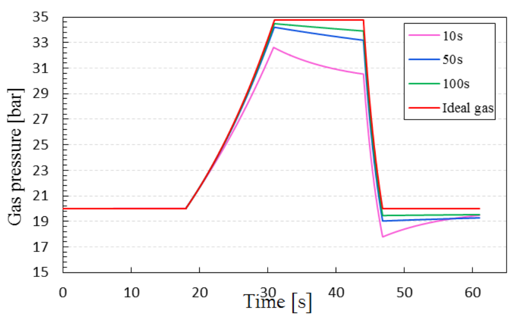


Fig. 2 Effect of gas thermal time constant

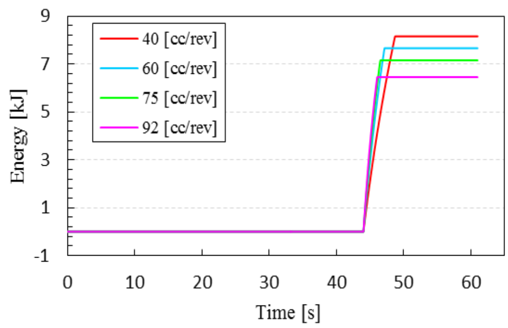


Fig. 3 Variable displacement values for VDMC

Curves of gas pressure in accumulator represented by Fig. 2 are positively related to thermal time constants in which its value of ideal gas is assumed infinite. For the ideal gas model, being compressed quickly, its pressure will be continuously stable after charging which means there is no heat loss in the accumulator. For the real gas model the gas pressure will decrease to different extent after charging because of the heat transfer. The small thermal time constant will cause more heat loss. Once use short thermal time constant case, the heat in accumulator dissipates quickly during and after charging.

From Fig. 3, In VDMC hydraulic motor models with different displacement values are compared. Larger displacement results in lower energy regeneration because of increasing pressure drop. In the hydraulic circuit driving the excavator, the fixed displacement pump is necessary to keep the actuators relatively smoothly working. The variable displacement of hydraulic motor is to match with the varying pressure from accumulator. To quantitatively understand the heat loss in the accumulator, we can calculate the energy efficiency by integrating the compression phase and by dividing it with the integral of the expansion phase as shown in equation (3).

$$\eta=\frac{E_{out}}{E_{in}}=\int_{t3}^{t4} p(t)\cdot V(t)dt \Big/ \int_{t1}^{t2} p(t)\cdot V(t)dt \ . \tag{3}$$

Table 1 Key parameters of hydraulic system of excavator

Components	Parameters	Value
Boom mechanism	Mass	2000 kg
Boom cylinder	Stroke length	1m
	Piston diameter	63mm
	Rod diameter	30 mm
Pump	Displacement	45 cc/rev
Accumulator	Precharge pressure	20 bar
	Volume	10 L

Table 2 Efficiency of the two types of ERS

ERS	Efficiency
SBC	93.5%
VDPC	97.1%

To compare these two types of ERSs, the simulation models were built and the test parameters are listed in Table 1. For SBC, the ERS is directly connected with the fixed pump. In fixed displacement pumps the amount of flow which has to be displaced by each pump shaft rotation cannot be altered. Thus, the pump's displacement is varied only by changing the speed of the pump. The ERS produces varying pressure during discharge operation, hence the main hydraulic circuit of SBC cannot operate in the high-efficiency area couples with ERS and this process converts the unwanted energy directly into heat. To improve it, an ERS with a variable displacement motor, VDMC, is employed. Comparing SBC and VDMC, as shown in Fig. 4, VDMC relatively slowly releases pressure from the accumulator and produces higher regenerated energy than SBC. The calculated energy efficiencies of SBC and VDMC are shown in Table 2. The power needed by SBC and VDMC are plotted in Fig. 5. Solid lines are engine power, and dotted lines are regenerated power by ERS. Engine power is needed while boom cylinder lifting, other periods it will be unloaded. After hydraulic power stored in accumulator, it will provide power to assist the main engine for lifting the boom cylinder.

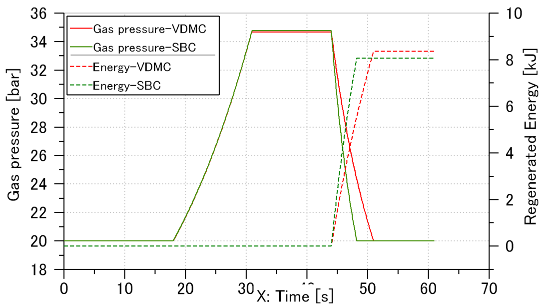


Fig. 4 Gas pressure & regenerated energy by SBC and VDMC

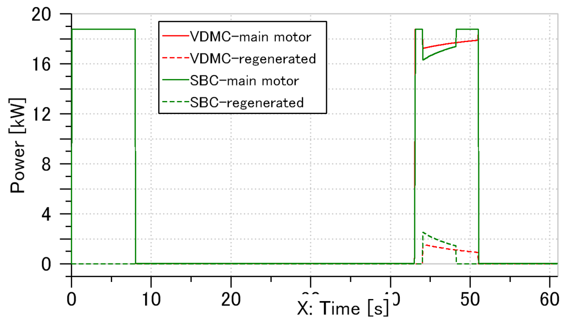


Fig. 5 Power of SBC and VDMC

RESULTS

In this paper, the performances of the accumulator and the hydraulic motor are respectively investigated and the comparison of SBC and VDMC is analyzed. Accumulator with larger thermal time constant produces less heat loss which can be regarded as isothermal process. There is no heat loss during working operation in ideal gas model while various degrees of heat loss are produced dependent of different thermal time constant in real gas model. For VDMC, according to the characteristics of the hydraulic motor, the rotational speed of the motor is inversely proportional to the displacement. The simulation result indicates that the regenerated energy increases along with the decreasing of the displacement. This result corresponds to Wei Li's research [13] and it can be ample foundation for future application in hydraulic hybrid technology. Finally, both SBC and VDMC ERSs support the working line well, and VDMC saves slightly more energy in the same conditions and accordingly decreases electric motor power while driving the pump.

REFERENCES

1. Elder, F. T., and D. R. Otis, Accumulators: The Role of Heat Transfer in Fluids Power Losses, 4th International Fluid Power Symposium, pp. 16-18, 1975.
2. SHEN W, JIANG J, SU X, et al, Energy-saving Analysis of Hydraulic Hybrid Excavator Based on Common Pressure Rail, The Scientific World Journal, ID 560694, 2013.
3. SUGIMURA K, MURRENHOFF H, Novel Hydraulic System for Mini Excavators without Electronic Controls, Symposium on Fluid Power and Motion Control, American Society of Mechanical Engineers, pp.V001T01A025-V001T01A025, 2016.
4. Panchal S, Dincer I, Agelin-Chaab M, Thermodynamic Analysis of Hydraulic Braking Energy Recovery Systems for a Vehicle, Journal of Energy Resources Technology, 138(1): 011601, 2016.
5. Lin T, Wang Q, Hu B, et al, Research on the energy regeneration systems for hybrid hydraulic excavators, Automation in Construction, 19.8: 1016-1026, 2010.
6. Kazushi SANADA, Regeneration of potential energy of load driven by oil-hydraulic cylinder, Proceedings of the 13th SICE Symposium on Industrial Application Systems (in Japanese), pp.91-95, 2012.
7. XIA L, GE L, HUANG J, et al, Potential Energy Recycling System Based on Accumulator for Hydraulic Excavator Boom, Chinese Hydraulics & Pneumatics (in Chinese), No.6, pp.52-55+62, 2015.
8. YAGISAWA, R., ITO, K., et al, Control and Energy Performance Improvement with Boosting Suction Line for Excavators, The Proceedings on Autumn Conference of Japan Fluid Power System Society 2016 (in Japanese), pp.78-80, 2016.
9. Redlich, O. and Kwong, On the Thermodynamics of Solutions: V. An Equation of State: Fugacities of Gaseous Solutions, Chem. Rev., 44, 233-244, 1949.
10. Soave, G, Equilibrium Constants from a Modified Redlich-Kwong Equation of State, Chem. Eng. Sci., 27, 1197-1203, 1972.
11. Pourmovahed A., and D. R. Otis, Effects of Thermal Damping on the Dynamic Response of a Hydraulic Motor-Accumulator System, Journal of dynamic systems, measurement, and control, 106.1:21-26, 1984.
12. Pourmovahed A., and D. R. Otis, An experimental thermal time-constant correlation for hydraulic accumulators, Journal of dynamic systems, measurement, and control, 112.1: 116-121, 1990.
13. Li W, Cao B, Zhu Z, et al., A novel energy recovery system for parallel hybrid hydraulic excavator, The Scientific World Journal, 184909, 2014.