Equipping reach truck with hydraulic energy recovery system

Henri HÄNNINEN, Heikki KAURANNE, Antti SINKKONEN, Matti PIETOLA

Abstract: In this study a hydraulically operated mast system of a reach truck is implemented with energy recovery system, whose main components are pressure accumulators for storing the recovered energy and a digital valve package for controlling the volume flows of lift cylinders and accumulators. Energy is recovered during lowering phase of the load and during lifting phase the stored energy is used to assist the hydraulic pump by decreasing the pressure difference between pump outlet and inlet. This in turn decreases the torque and power need of the pump. The recovery system was designed so that it will not alter operational characteristics of the truck, and this was also achieved.

The aim of the study is to discover the magnitude of the savings in energy consumption that are achievable with this arrangement compared with a conventional truck. The comparison is based on measurements over individual lift phases and over a given multiphase work cycle. The measurement results are also used in validation of corresponding system model the author has presented earlier.

The results manifest that the measured energy consumption reductions were up to 32 per cent with individual lift phases depending on the values of operating parameters. Energy consumption over the multiphase measurement cycle was found to decrease by 10 per cent. Simulations in turn suggested a reduction of 13 per cent, which indicates some inaccuracies in simulation model or models.

Keywords: Reach truck, energy recovery, energy regeneration, hydraulic accumulator

1 Introduction

A work cycle of a reach truck working in a storehouse consists of series of sequential mast and drive operations. The former include following functions; lifting and lowering of varying sizes of loads, extracting and retracting of the mast and tilting of the fork assembly. The latter in turn includes the function of transferring the loads between loading platform and different storehouse locations. Since both of these operations are associated with large moving masses, they offer a possibility to recover significant amount of energy, albeit in mast operation the only significant function in this sense is the load lowering phase since the releasing energy connected to other mast functions is exiguous.

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Since every energy conversion from a form to another induces losses, the economically most advantageous way to recover, store and reuse energy is to keep it in its original form. With moving masses this, however, would mean using flywheels and mechanical gearing which are less suitable solutions for reach trucks with considerable lifting heights. Therefore the recovered kinetic or potential energy has to be stored either in the form of the source of energy used in the truck or into some intermediate form between this and the recovered energy.

In reach trucks operating indoors the typical source of energy is electric battery and the power transmissions used in the truck are normally hydrostatic transmission for mast functions and electrical transmission for drive function. Thus the battery could be used for storing both the released kinetic energy of the truck and the released potential energy of the load and mast. Referring to aforesaid this is reasonable regarding to the drive function but not to the mast functions, since it would

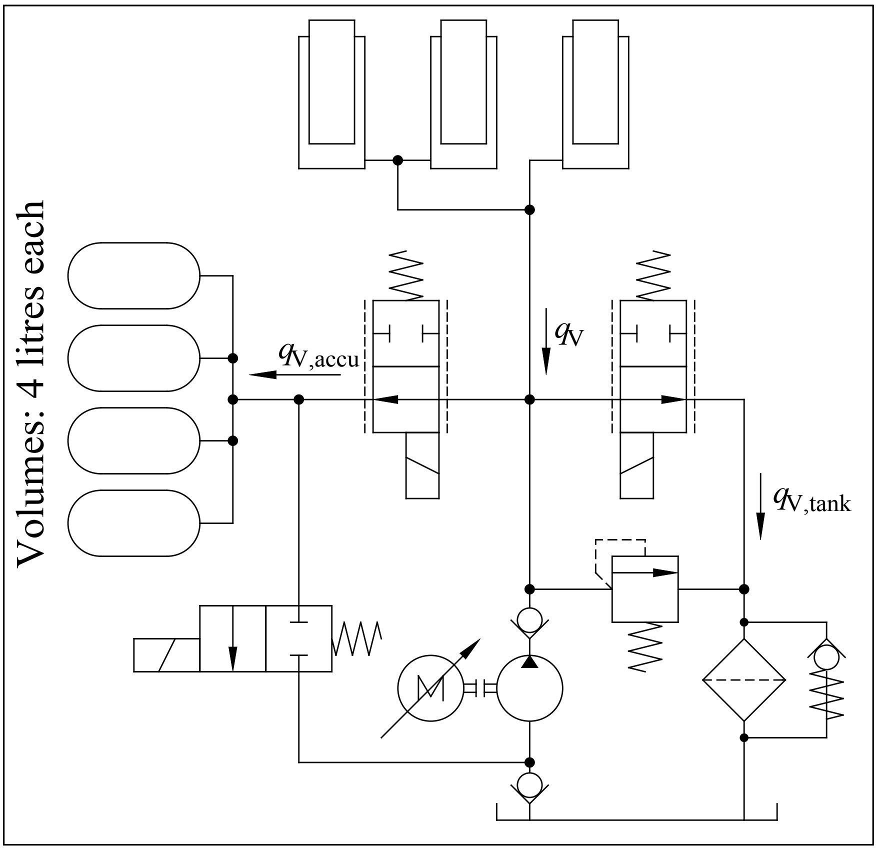

Figure 1. *Circuit diagram of test system*

require three back and forth energy conversions (potential energy ↔ hydraulic energy ↔ mechanical energy ↔ electrical energy) when the potential energy is first recovered, stored and then reused to produce potential energy again. Since pressure accumulators offer a means to store hydraulic energy, it is justifiable to use these components for storing the released potential energy resulting into only two energy conversions in total between recovering and reusing.

In this study hydraulically operated mast system of a reach truck is implemented with energy recovery and regeneration system consisting of several pressure accumulators and a digital valve package including ten poppet type valves. These valves of leak-free type replace the slide and throttle valves that are used for controlling mast's lowering speed in conventional truck. Leak-free valves are required to prevent the stored hydraulic energy being wasted in form of flow losses of energy controlling elements.

The recovered potential energy of the load and mast is used for decreasing pressure difference between the outlet and inlet of system pump during the lift phase thus decreasing the torque and power need of the pump. This study is limited to examining the energy issues of only the mast's lift- and lower functions and the aim is to discover the magnitude of the savings in energy consumption that are achievable with this arrangement compared with a conventional truck.

The study is compounded of measurements with a traditional truck mast hydraulics and with an energy recovery system enhanced mast hydraulics, and also simulations of both. The measurements of latter system are introductory, that is, some sections of the energy recovery system are not yet optimised. The models of mechanical, hydraulic and electric components of the systems are based on general catalogue data and measurements.

2 Methods

This chapter describes the energy recovering, storing and reusing test system and the corresponding simulation model. In addition the test cycle and its parameters are introduced.

2.1 Energy recovery system – test setup and operation

Since the other mast functions (extracting/retracting of the mast and tilting of the fork) are of minor importance considering energy recovery, the test system concentrates only on the lifting and lowering functions. Circuit diagram of the system is presented in *Figure 1*. The system retains the original truck system's telescopic three cylinder mast with hoses, pressure relief valve, tank with inclusive equipment and speed controlled electric motor operating the system pump. Original slide valve and throttle valve for controlling the lowering speed of the mast are replaced with two-control-edge digital valve package (Digital Flow Control Unit, DFCU) for controlling flow from lift cylinders to the energy recovering pressure accumulators and to tank. Check valve in the inlet line of the system pump enables pressurization of the inlet and the two-way poppet type valve enables connection between accumulators and inlet line. The original gear type pump was replaced with same displacement size (V_{i} =19 cm^3/r) piston type pump/motor since the former did not allow pressurization of pump inlet.

Due to practical reasons the pump/motor used in this study was of type mainly used for motor purposes. Size of this component and the additional components needed in the regenerative system together with the cramped free space in truck chassis led to use of over-length pipe/hose assemblies that in turn led to serious cavitation in the suction line of the pump especially at high rotational speeds. In order to conduct measurements also at moderate and high lift speeds the system was equipped with auxiliary feeding pump. This vane-type pump and its hydraulic system was dimensioned and designed so that it could match the flow of the main pump while giving a steady 0.5 bar to the inlet of the main pump. The error of this slight assistance of non-system component was cancelled from the result using the measured flow and the pressure in the inlet of the main pump.

Total accumulator capacity is partitioned into four 4 litre piston type units which are connected via a divider manifold. Partitioning enables easy modification of total accumulator capacity in forthcoming measurements.

Instrumentation of the system covers pressures, flows, temperatures, rotational speed, torque, load forces and load position. The instrumentation of original truck system is described in more detail in [1]. The system depicted in *Figure 1* was additionally instrumented with a flow transducer for measuring the accumulator flow, and three pressure transducers for measuring pressures at digital valve block. This instrumentation was required for controlling the flows of digital valves. In addition to this, one of the accumulators was instrumented for measuring piston position, gas chamber pressure and temperature of gas.

Measurements were carried out using Simulink xPC Target software, which included also a controller for the DFCU. The controller defines which valves of the DFCU (both control edges) are to be opened and which closed in order to fulfil simultaneously the charging of the accumulators and the demanded lowering speed. The controller calculates the flow through control edges using data from pressure transducers. These calculations are based on the orifice flow equation given with

$$q_{\mathrm{V}} = C_{\mathrm{q}} \cdot A \cdot \sqrt{\frac{2 \cdot \Delta p}{\rho}} \qquad [1]$$

where C_q is flow coefficient, A is area and Δp is the pressure difference of a given orifice. However, due to flow obstructions in the valve block and additionally in the piping, this equation does not precisely depict the real proportion between pressure difference and flow when using nominal values for parameters. In order to achieve more accurate flow estimation, the equation (1) is formulated to

$$q_{\mathrm{V}} = K \cdot \Delta p^{z} \qquad [2]$$

where the corresponding values of K and z are individually identified for each poppet valve on DFCU and adapted to the controller. The controller is introduced more thoroughly in [2].

The mast movement is hydraulically divided into two stages, a free lift zone that is realized with a single plunger piston cylinder, and a upper lift zone realized with two parallelly connected plunger pistons. The combined effective piston areas of latter are slightly lesser compared with the former in order to confirm the right movement order of the stages. Both stages are equipped with chain gears between cylinders and mast sections in order to reach larger movements.

In lifting phase the opening speed of the mast (rate of climb of the load) is controlled through the speed of the pump operating electric motor. In lowering phase the speed is controlled with DFCU which divides the flow from cylinders between accumulators and tank. As long as the pressures at accumulators are low enough to maintain required lowering speed of the load, the flow is directed to accumulators which are being charged. The combination of opened DFCU valves is selected on the grounds of required speed and the pressure difference between accumulator package and cylinders. When the accumulator pressure rises and the pressure difference over the control edges of DFCU valves decreases the combination of opened DFCU valves is changed to yield larger opening area. At some point the maximum opening area is reached and after that the required lowering speed can no longer be maintained by directing flow to accumulators. Now the valves of the other control edge of DFCU are opened and the cylinder flow is bled to tank in order to maintain the required speed. Since this flow (/pressurized volume) is wasted it is to be kept minimum, which calls for optimization of accumulator capacities and pre-charging pressures in compliance with typical loads and lifting heights.

When the next lift commences the poppet valve connecting accumulators and pump inlet is opened which leads to pressurization of pump inlet. This in turn diminishes the pressure difference over pump ports and leads to lower torque need at pump axle and therefore also lesser power requirement from the electric motor.

2.2 Simulation models

Simulation model of the conventional mast hydraulics is restricted to lift/lower function only and consists of sub-models of pump, its drive motor (electric 3 phase motor), proportional flow control valve, and mast system including three lift cylinders. The model of electric motor is simplified and uses only static efficiency factor. This is fairly accurate when the rotational speed and load are sufficient, as they are in this case. The pump is modelled with Schlösser model [3]. The mast system includes the mechanical structures and mast hydraulics inclusive piping. Flow control valve is modelled based on equation (1).

In simulation model of the energy recovering system the flow control valve is replaced with model of the DCFU, which is based on real DFCU block used in Aalto University. However, in measurements a slightly different, and not yet modelled DFCU was used, which leads to a small difference between the parameters of the simulated and measured DFCUs. The accumulators are modelled using real gas equations. Both simulation models are more thoroughly presented in [2] and [4].

2.3 Tests with individual lift phases

To achieve an understanding on

Table 1. *Test parameters. Set 1: Static parameters; v=0.4, ppre=60 bar, V=16 l. Set 2: v=0.4, M=1000, h=5500 mm. Set 3: M=1000, h=5500 mm, ppre=60 bar, V=16 l*

	Set 1	Set 2	Set 3
Test 1	M=500 kg; h=2700 mm	p_{pre}=80 bar; V=16 l	v=0.4 m/s
Test 2	M=500 kg; h=5500 mm	p_{pre}=80 bar; V=8 l	v=0.3 m/s
Test 3	M=1000 kg; h=2700 mm	p_{pre}=60 bar; V=16 l	v=0.2 m/s
Test 4	M=1000 kg; h=5500 mm	p_{pre}=60 bar; V=8 l	v=0.1 m/s
Test 5	M=1500 kg; h=2700 mm	p_{pre}=40 bar; V=16 l	
Test 6	M=1500 kg; h=5500 mm	p_{pre}=40 bar; V=8 l	

Table 2. *Work cycle parameters (m = mass of the mast, arrow indicates direction of motion)*

	Phase 1	Phase 2	Phase 3	Phase 4
Mass *M* [kg]	↑1500 + m ↓m	↑m ↓500 + m	↑m ↓1000 + m	↑1000 + m ↓m
Lift height [m]	2.4	4.0	4.8	2.4
Interval *t* [s]	30	50	60	-

the effects of the values of operational parameters on the system efficiency, a test program was devised. This program focused on individual phases (*Table 1*) consisting of lifting operation without assistance, lowering operation (energy recovering) and lifting with assistance.

The measurements in Table 1 are as follows: measurements of Set 1 were conducted with constant lift/lower speed, accumulator pre-charge pressure and volume, but with varying load masses and movement ranges. Measurements of Set 2 were in turn carried out with constant lift/lower speed, load mass and movement range, but with varying accumulator pre-charge pressure and volume, and finally measurements of Set 3 were conducted with constant load mass, movement range, accumulator pre-charge pressure and volume, but with varying lift/lower speeds.

2.4 Tests and simulations of multiphase work cycle

The work cycle was constructed to represent a typical operational situation in a storehouse. The cycle consists of four lift and lower operations, presented in *Table 2*. At the beginning of the cycle the pressure accumulators are empty, and the possible residual energy at the end of the cycle is calculated with:

$$E_{res} = pV \qquad [3]$$

where p is pressure in accumulator and V is volume of pressurized fluid in accumulator. This energy is then deducted from the measured or simulated energy consumption.

Theoretically using an ideal (lossless) system with ideal energy recovery the test cycle would yield 8 kJ of excess energy (lifts 97 kJ, retrievable energy in lowering 105 kJ).

3 Results

This chapter describes the results of measurements with individual phases and with multiphase cycle. In the latter case, also comparison with simulations is conducted.

3.1 Results of individual lift phases

Figure 2 presents typical results for both non-assisted lift (left half of diagram) and assisted lift (right half of diagram). The former refers lifts with conventional-type system, and the latter to lifts with regenerative system that uses accumulator stored energy for reducing the energy needed from the electric battery. All the measurements were conducted with system presented in Figure 1, but in case of non-assisted lifts, assistance energy was not fed to pump inlet. The characteristics of this configuration in terms of energy consumption were found to be very similar to the conventional mast hydraulics, which justified it being used to approxima-

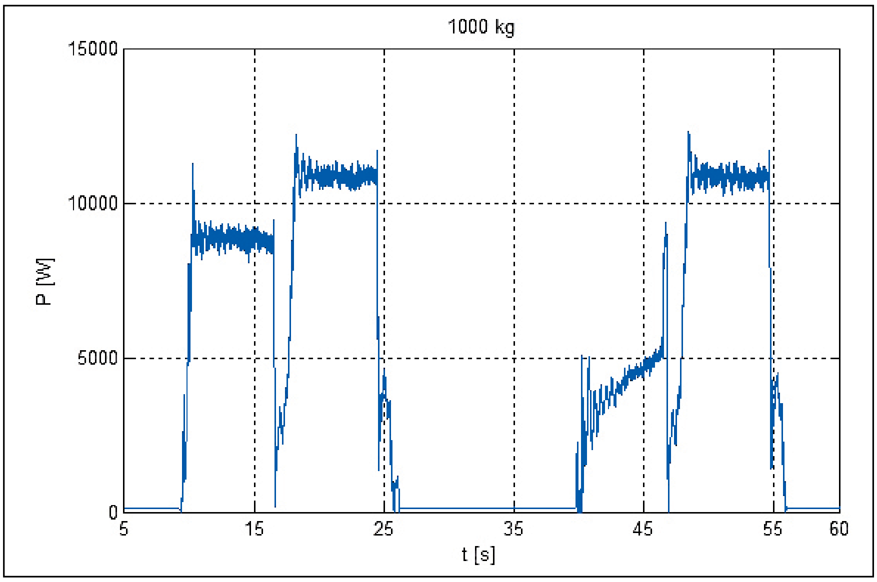

Figure 2. *Example of measured electric power drawn from battery. Set 1, Test 4 (v=0.4, p_{pre}=60 bar, V=16 l, M=1000, h=5500 mm)*

Table 3. *Energy consumption reductions in per cents in individual lift phases (non-assisted vs. assisted lift)*

	Set 1	Set 2	Set 3
Test 1	0	18	23
Test 2	13	10	24
Test 3	7	23	25
Test 4	23	16	22
Test 5	32	15	
Test 6	20	14	

te conventional system. The Figure 2 clearly depicts the different power usages in the two mast zones (different pressure levels) and the effect of assistance on power usage in latter assisted lift.

The reduction in energy consumption when transferring from non-assisted to assisted lifts is calculated from the differences of electrical energy consumptions drawn from battery within corresponding lift phases, *Table 3*.

Results manifest of existing significant link between savings and load mass/movement range -combination, and also with accumulator volume/pre-charge pressure -combination, but not with lift/lower speed.

3.2 Results with multiphase work cycle

These measurements were conducted using the four-phase work cycle presented in *Table 2*. This results into a certain saving in overall energy consumption, but significantly different and better results could be achieved if the work cycle was selected otherwise. For example lifting empty forks and lowering large masses would result into high savings, but would not represent a typical use of a reach truck contrary to the selected work cycle.

Figure 3 presents the electrical power drawn from truck battery over the measurement cycle. The power is calculated from measured values of drawn current and battery voltage. On left is the power usage of total cycle and on right is the scaled plot of fourth phase, which illustrates the effect of accumulator assistance on power requirement.

The energy consumption is calculated with discrete integration from the electric power data. The energy consumption on the test cycle for both the original system and the regenerative system are illustrated in *Figure 4*.

Neither the power requirement (Fig. 3) nor the energy consumption of regenerative system, illustrated in Figure 4, is corrected with adding the energy consumption of assisting external pump. The assisting pressure in lift was measured to be 0.8 bars in average yielding to an error of 2 kJ over the cycle. The figures given in *Table 4* are corrected with this value.

4 Discussion

When concerning the difference between measured and simulated energy consumptions in multiphase work cycle, there appears to be a relatively significant deviation. Major part of this can be explained by the idling current of truck electronics that was not implemented into the models. It was measured to be about 3 amperes which yields roughly to a total energy consumption of 29 kJ over the 200 second cycle duration. This current is caused by auxiliary devices such as fans, electronic controllers and display.

The tests indicated that the power consumption using the four-phase cycle was reduced by 10 per cent compared to the original non-modified system, while the simulations suggested a reduction of 15 per cent. However, when the energy consumptions in simulations are compensated with the 29 kJ additional consumption caused by idling current, the reduction suggested by simulations drops to 13 per cent. The main reason for the residual 3

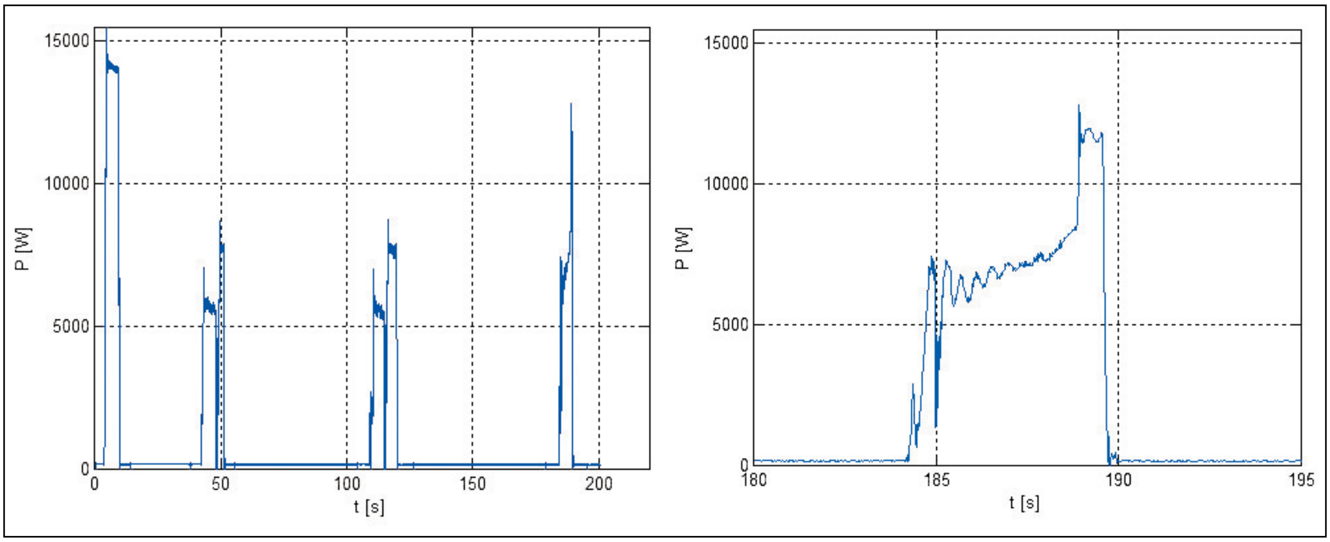

Figure 3. *Left: Electric power drawn from battery over measurement cycle. Right: Scaled power consumption of phase 4.*

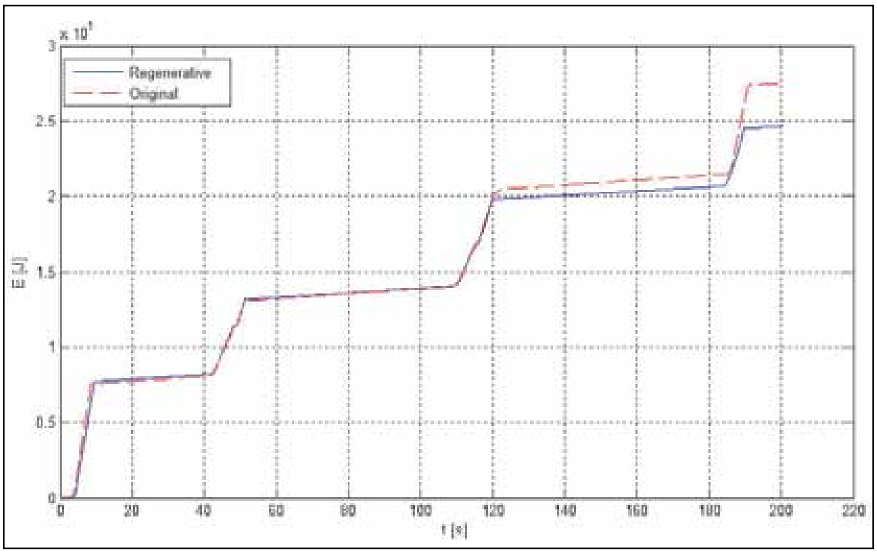

Figure 4. *Measured energy consumption over test cycle with original and modified regenerative system*

per cent point discrepancy between simulations and measurements remains to be unclear at this point, but there are many potentially furthering factors identified. One contributing factor is that the measurements for this study were carried out shortly after initial system test phase due to schedule restrictions. This limited the possibilities for testing and fine tuning the system. For example, the DCFU controller was tuned so that it achieved stable operation conditions, but there was no optimisation done for maximizing the flow to accumulators. Another possible factor is that the system was build, due to practical reasons, outside of the trucks frame resulting in long piping and hence larger pressure losses.

Tests with individual lift-lower-lift phases demonstrated energy consumption declines up to 32 %. The non-assisted and corresponding assisted lifts were conducted with same drive parameter values (see Table 1) the only difference being the exclusion or inclusion of hydraulic assistance on the system pump. In addition, one special test was also conducted where different loads were used in lift and lower movements. In this test a load of 1500 kg was lowered from height of 2.7 metres at speed of 0.4 m/s and following this, empty forks were lifted back to initial height with hydraulic assistance using same speed. This type of cycle corresponds to order picking operations in warehouse, and using this process the energy consumption was measured to reduce by 64 % compared to lifting empty forks without assistance.

Since the pump and also pump type was altered when constructing the energy recovering system it was predicted prior to testing that this would have an effect on the efficiency of the truck. Usually piston type pump, as with modified system, should have better efficiency factor than the original gear type pump. Based on the measurements the effect of pump replacement was found to be negligible, as observed from Fig. 4 with first two lift operations. The efficiency factors of both pumps will be revised (with data of T, n, p_1, p_2 and q_V) in near future.

The hydraulic power of external assistance pump was measured to be roughly 60 Watts, hence creating very minor error in power and energy graphs. From the results of multiphase cycle given in Table 4 this was cancelled out altogether. The requirement of assisting pump could be avoided simply by using a pump/motor unit with less restrictive inlet port and by designing inlet piping and check valves to be less constrictive. The latter would however require structural changes to the truck which was not considered to be justifiable at this stage.

The strongest advantages of this type of energy regeneration system are the simplicity and affordability of the required additional components. This setup also keeps the operational characteristics of the truck unaltered. For flow control in lowering phases the two control-edged DFCU was the logical choice, however, it could also be substituted with two proportional valves coupled with two poppet type on/off-valves. The most prominent negative aspect of this arrangement is the systems lack of ability to store energy efficiently in most operating situations (optimized for only one load and lift height), as the flow that cannot be fed to the accumulators will be directed to tank and therefore is unused for regeneration.

5 Conclusions

An energy recovering and regenerating test system for electrohydraulic reach truck was developed. Initial measurements indicated a 10 per cent decline in energy consumption over a given multiphase test cycle. Simulations with idling current com-

Table 4. *Total energy consumption over work cycle*

	Original, measured	Regenerative, measured	Original, simulated	Regenerative, simulated
Energy consumption [kJ]	275.2	248.8	231	197
Reduction compared to corresponding original [%]	-	10	-	15

pensation suggested a decline of 13 per cents, leaving a 3 per cent point gap between the two.
Measurements with individual phases indicated reductions up to 32 per cent when using same loads in upward and downward motions. In specialized order picking cycle the reduction was measured to be 64 per cent.

In near future the system will be implemented with a "multi preload modification". This system uses accumulators with two diverging simultaneous preload settings (one for each of the mast lift/lower zones), which will improve the system efficiency with full lift ranges. After full analysis of this system, a more effective setup will be created.

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Nomenclature

A	area of orifice
C_q	flow coefficient
E	energy
h	lifting height
M	load mass
n	speed of rotation
P	power
p_1	pressure at pump inlet
p_2	pressure at pump outlet
p_{pre}	gas preload pressure of accumulator
Δp	pressure difference
q_V	volumetric flow
t	time
T	torque need of pump
V	oil volume in accumulator
v	velocity (of forks)
V_i	displacement of pump
ρ	density of hydraulic fluid
DFCU	Digital Flow Control Unit

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Oprema viličarja s hidravličnim regenerativnim sistemom

Razširjeni povzetek

Glavni sestavni elementi v tem prispevku raziskovanega regenerativnega hidravličnega vezja dvigala so hidravlični akumulatorji (HA), uporabljeni kot shranjevalniki energije, ter digitalni (vklopno-izklopni) ventili, uporabljeni kot tokovni ventili za stopenjsko nastavitev hitrosti dviganja/spuščanja bremena. V hidravličnih akumulatorjih se energija shranjuje pri spuščanju bremena in porablja (regenerira) pri dviganju. Shranjena hidravlična energija se iz HA vrača v hidravlični sistem po sesalnem priključku črpalke (sl. 1). Z zmanjšanjem tlačne razlike med vstopnim in izstopnim priključkom črpalke je potreben manjši vrtilni navor za njen pogon. Glavni namen prispevka je ugotoviti velikost dejansko prihranjene energije hidravličnega dvigala z uporabo regenerativnega vezja za funkcijo dviganje/spuščanje v primerjavi z dvigalom podobnih delovnih karakteristik brez regenerativnega vezja.

Na dejanskem viličarju se je merilo več veličin: tlaki, pretoki, temperature, hitrosti vrtenja črpalke, navor ter velikost (sila teže) in položaj bremena. V enem izmed štirih batnih akumulatorjev sta se merila tudi položaj bata ter tlak in temperatura plina. Meritve in krmiljenje dvigala so se izvajali z uporabo programskega paketa Simulink xPC. Krmilnik je računal pretok skozi krmilne robove (en. 2) s pomočjo izmerjene razlike tlakov med eno in drugo stranjo krmilnega robu.

Hitrost dviganja je nastavljiva s kontroliranim spreminjanjem vrtljajev pogonskega elektromotorja črpalke, hitrost spuščanja bremena pa z ustrezno regulacijo digitalnih 2/2-potnih ventilov, ki usmerjajo pretok proti HA, in tistih 2/2-potnih ventilov, ki usmerjajo pretok v povratni vod proti rezervoarju.

Meritve in simulacije delovanja so bile prilagojene dejanskim razmeram delovanja dvigala v skladišču. Meritve so se izvajale pri štirih različnih režimih dviganja/spuščanja (preglednica 2).

Simulacije so bile izvedene z manjšimi, manj vplivnimi ponastavitvami. Črpalka je bila modelirana po principu Schlösserjevega modela.

Meritve so bile izvedene pri različnih parametrih: tri različne uteži, dve različni višini dviganja/spuščanja, tri različne predpolnitve HA, štiri različne hitrosti dviganja/spuščanja in dve različni velikosti HA.
Rezultati meritev prikazujejo do 32 % privarčevane energije v primeru uporabe regenerativnega hidravličnega vezja za posamezno dvižno fazo. Pri spremljanju efektivnosti vrnjene oz. privarčevane energije skozi zaporedno večfazno dviganje/spuščanje se pokaže, da je privarčevane energije le približno 10 %. Prispevek poleg izmerjenih vrednosti prikazuje tudi rezultate simulacij in jih primerja med seboj.

Ključne besede: viličar, vračanje energije, obnavljanje energije, hidravlični akumulator