Energy usage in mast system of electrohydraulic forklift

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Abstract: In this study the energy usage of the driveline of an electrohydraulic reach truck is analyzed. The focus of the study is on the lift/lower function of the truck and the aim is to produce detailed knowledge on the energy usage of this function and to evaluate driveline's potentiality for recovering energy. The analyzed driveline consists of lead-acid battery, drive to control motor, AC induction motor coupled with hydraulic pump, control valve package and hydraulic cylinders. Analyses include results from measurements conducted utilizing diverse operational parameter values in loads, velocities and shift ranges. The results manifest that the overall system efficiency ranges from 0.26 to 0.58, depending on operational parameter values. Subsystem wise the results indicated that the efficiency factor of the electric subsystem was at lowest while using low velocities and the hydraulic subsystem's efficiency was found to be lowest with high velocities combined with small load. Based on these observations it is suggested that for reducing energy usage the most beneficial focus areas would be improving efficiency of AC-motor and limiting the losses in valve package.

The obtained results of energy usage and efficiencies of the studied energy converting components will serve as baseline against modified systems equipped with different energy recovery implementations.

Keywords: Reach truck, electrohydraulic driveline, energy usage, energy recovery

1 Introduction

Supply chain from producers to consumers usually includes several intermediate storing phases. In these the goods are typically stored in high-rise indoor storehouses where handling of goods is realized with forklifts or reach trucks, which almost without exception are electrically operated and make use of hydraulics for controlling lifting function. The actual control of lifting speed and height can be realized by controlling the volume flow to lift cylinders with valves or pump or with a combination of the previous the target being to fulfil the function with minimum losses. The control of lowering function is in turn typically realized by restricting the volume flow from lifting cylinders to reservoir with throttle valves which inevitably leads to transforming the potential energy of the goods into heat that is conducted to the surroundings and is thus wasted.

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Although the weights of the lifted and lowered goods very likely differ at each single lift-lower event, the lifting and lowering sequence of a forklift can with reasonable accuracy be assumed to be zero energy process when longer time periods are considered, at least in theory. So the recovering of the potential energy of the goods at lowering phases should give a possibility to enhance the energy balance of the forklift significantly.

In order to determine the true potential for energy recovery in a forklift the amount of theoretically recoverable potential energy in different load and operating situations must be established as well all the losses (mechanical and flow frictions) that affect on the actual recoverable potential energy. On the other hand, also the possible deficiencies of the lifting phase must also be established so that these can be eliminated and the recovered energy can be used in an effective way to enhance the total energy balance of the forklift.

Most of the studies found on the subject are focused in energy recovery. For example Nyman et al. studied the usage of "counter-balance

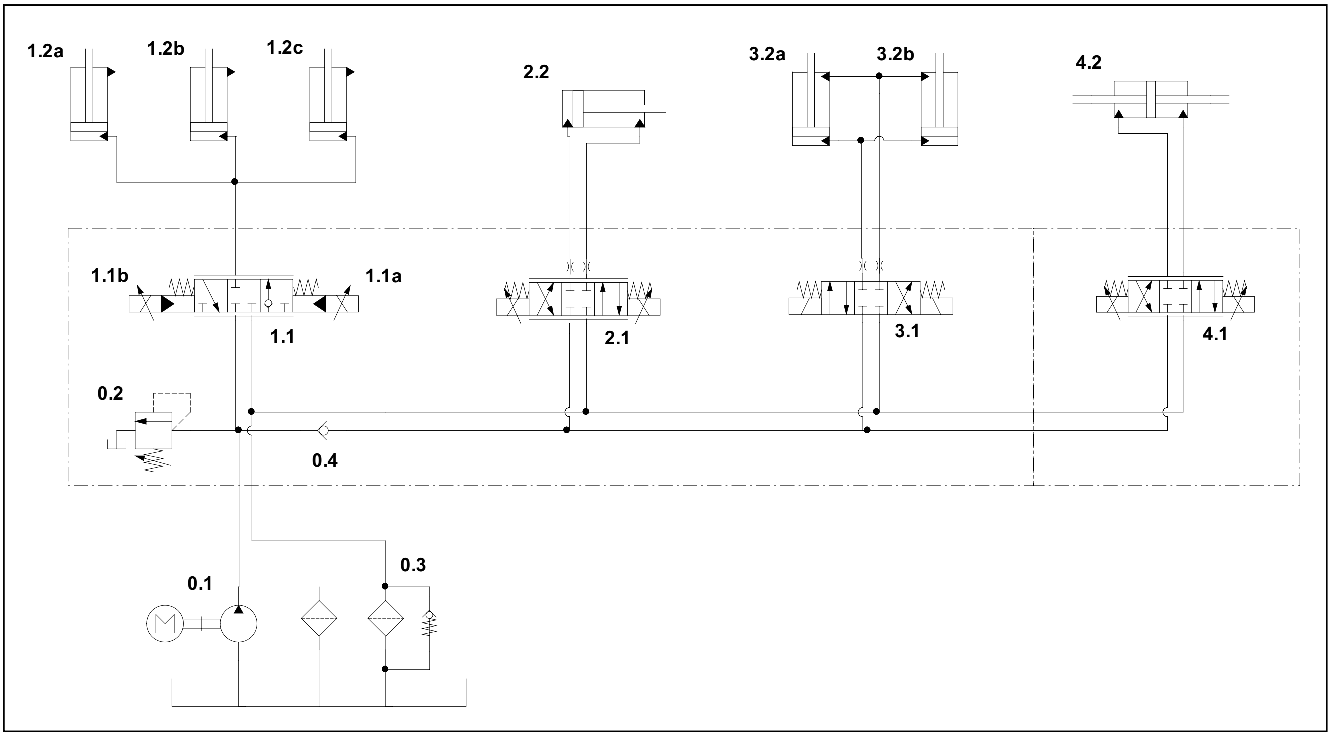

Figure 1. *Simplified hydraulic circuit diagram of reach truck mast*

accumulator” on a hydraulic lifting system [2]. However, studies with detailed component wise measurements of this truck type were not found.

In this study a forklifts or reach trucks mast functions are instrumented and measured. From these measurements an analysis of energy usage in lifting and lowering is drawn and proposals for improving energy efficiency will be given.

2 Methods

This chapter describes the studied hydraulic driveline of the reach truck, its instrumentation, the measurement program and the mathematical methods used for defining efficiencies and energy balance.

2.1. Reach truck test rig and instrumentation

The simplified circuit diagram of the hydraulically driven mast of the studied reach truck is presented in Figure 1. The mast includes following functions: extracting and retracting of the mast assembly (cylinder 2.2), lifting and lowering of fork assembly (cylinders 1.2x), tilting of the fork assembly (cylinders 3.2x) and sideshift of the fork (cylinder 4.2). The cylinders are controlled with slide valves assembled into a single package which also includes relief valve for restricting the maximum system pressure. Valves controlling lift/lower and reach functions include throttling function.

System pump (0.1) is of gear type and it is driven by a speed controlled AC induction motor. This in turn is fed with a 48 volt lead-acid battery pack with nominal energy content of 620 ampere hours. The electric driveline between battery and motor consists of a drive that converts DC to AC.

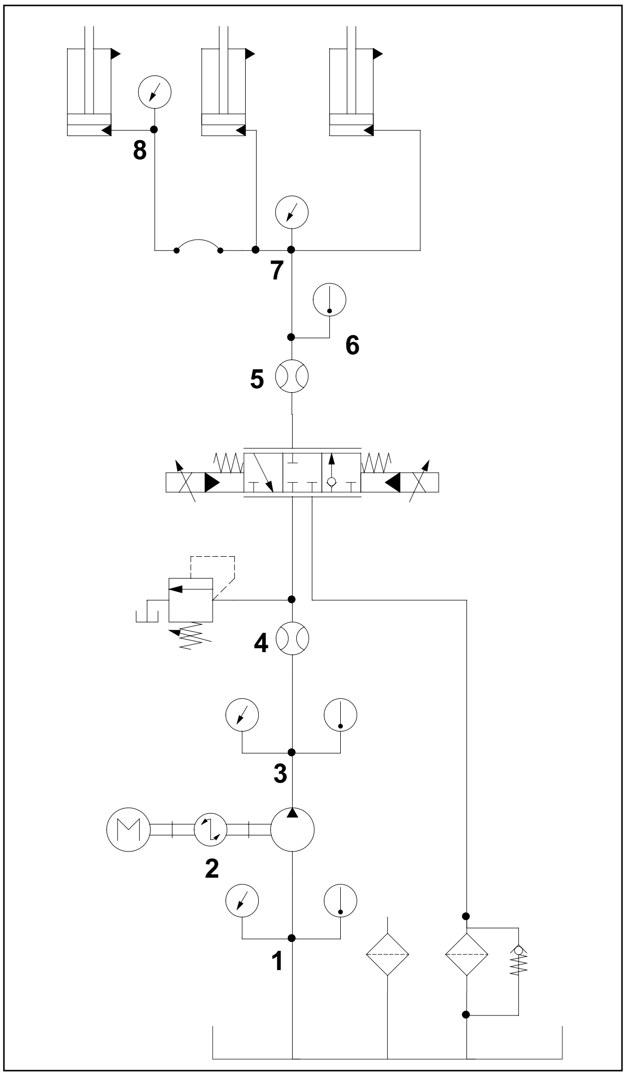

Figure 2. *Instrumentation of measured hydraulic system*

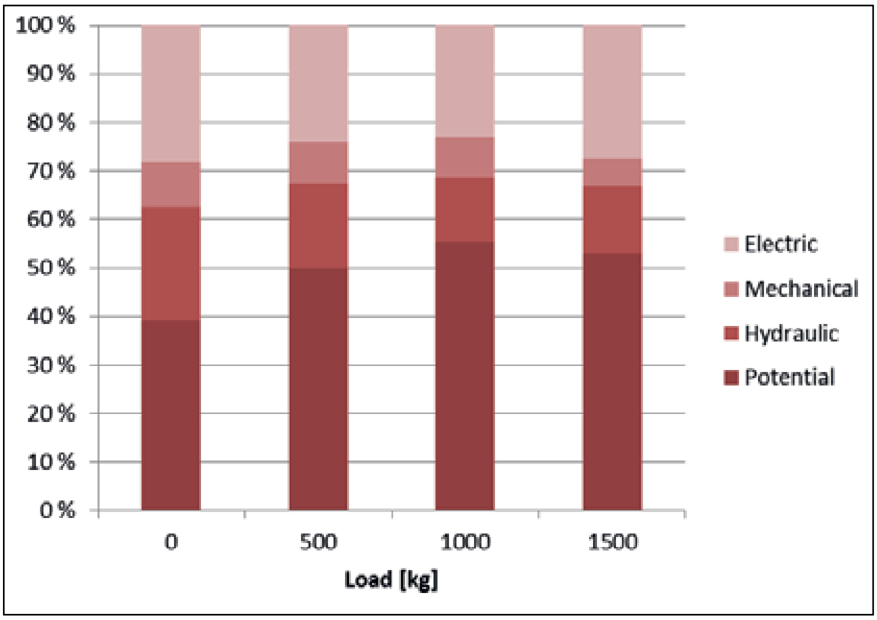

Figure 3. *Relative energy consumption in lift phase with different loads, velocity 0.4 m/*

Table 1. *Ranges for measurement parameters*

Load [kg]	**Velocity** [m/s]	**Height** [m]
0	0.1	0.5–2.5
500	0.3	3.0–5.0
1000	0.4	0.5–5.0
1500		

Use of reach truck in a storehouse includes all of the above mentioned operations; lifting and lowering of fork assembly, extracting and retracting of the mast assembly, tilting of the fork assembly and sideshift of the fork, but only the lifting and lowering operation is committed with significant amount of energy and thus constitutes basis for economically justifiable energy recovery. Therefore this operation was selected to be the target of energy balance evaluation.

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 plunger piston cylinders connected in parallel. The combined effective piston areas of latter are slightly smaller compared with the former which confirms that the stages move in correct order and in sequence. Both stages are equipped with overdrive chain gears which enables that the actual movement of the fork assembly is greater than the movement of cylinder piston. In the studied reach truck the free lift zone is realized in one entity while the upper lift zone is realized with two-stage telescopic structure. When the lifting phase is commenced the fork assembly rises first to the top of free lift zone section and after that the telescopic mast structure opens and raises the free lift section upwards. Due to this structure the hydraulic hose lengths become considerable, and are 6 meters in the studied case.

During lifting phase the valve (1.1) controlling mast upwards/downwards movement is opened completely and the speed of the movement is controlled with the rotational speed of the pump. During the lowering phase, the speed of the movement is in turn controlled by throttling the flow from cylinders to tank with valve (1.1). Pump is kept at standstill.

Instrumentation of the system covers pressures (pump inlet and outlet, cylinders), flows (pump outlet and cylinders), temperatures (pump and cylinders), rotational speed (pump), torque (pump), load force (free lift zone and upper lift zone alike) and position (load) and voltage and output current of the battery, Figure 2.

Measurements were carried out using National Instruments PCI-6031E data acquisition card and LabVIEW software. Besides data acquisition the application included possibility to control the lifting/lowering movement manually or automatically in which case the location and speed commands were read from a

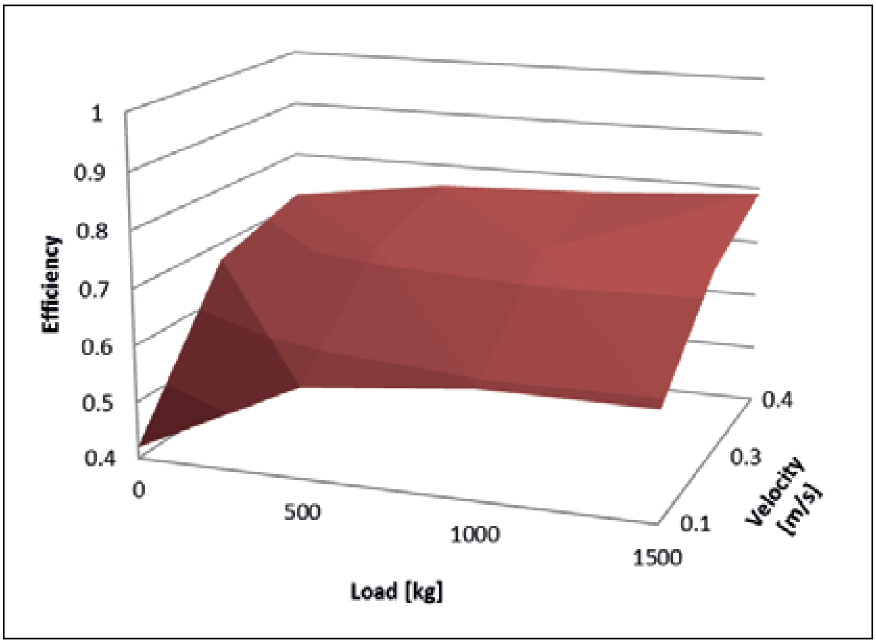

Figure 4. *Combined efficiency of electric motor and motor controller in free lift zone lifting*

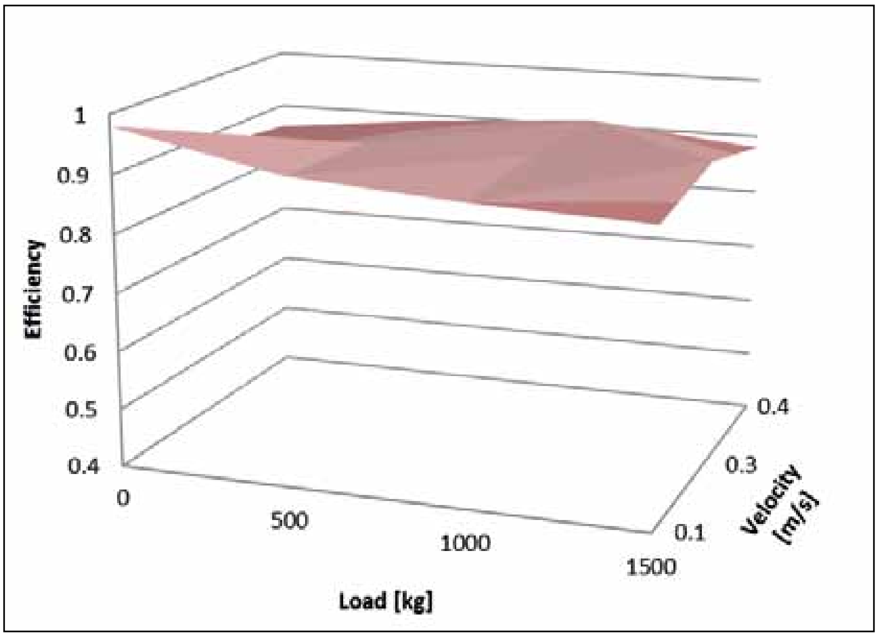

Figure 5. *Efficiency of hydraulic pump in free lift zone lifting*

command file. The application also included certain safety functions to secure the control of the movements. Data from transducers was sampled at 100 Hz and stored as raw data. All calculation of the efficiencies and energy consumptions were conducted afterwards.

2.2. Measurement program

Measurements were focused on the lift/lower functions of the reach truck. These functions were measured varying key parameters, which were mass of load, velocity of fork motion and lift height. The values of these are presented in table 1.

2.3. Mathematical methods

In this chapter formulas for calculating energy usage of components and subsystems are presented.
Electric energy taken from the battery, Δt being sample time

$$\Delta E_{\mathrm{batt}} = \sum P_{\mathrm{el}} \cdot \Delta t = \sum U \cdot I \cdot \Delta t \quad [1]$$

Mechanical work done by the electric motor

$$W_{\mathrm{mech}} = \sum P_{\mathrm{mech}} \cdot \Delta t = \sum 2 \cdot \pi \cdot n \cdot T \cdot \Delta t \quad [2]$$

Hydraulic energy from pump

$$E_{\mathrm{hyd}} = \sum P_{\mathrm{hyd}} \cdot \Delta t = \sum q_{\mathrm{V1}} \cdot (p_2 - p_1) \cdot \Delta t \quad [3]$$

Difference in potential energy, m_{tot} being combined mass of load and moving mast components

$$\Delta E_{\mathrm{pot}} = m_{\mathrm{tot}} \cdot g \cdot \Delta h \quad [4]$$

Total efficiency for lifting function is calculated from electric energy taken from battery and change in potential energy of total lifted mass.

$$\eta_{\mathrm{tot}} = \frac{\Delta E_{\mathrm{pot}}}{E_{\mathrm{batt}}} \quad [5]$$

For the instantaneous value of combined efficiency of electric motor and driver, input and output power is used in calculation

$$\eta_{\mathrm{el}} = \frac{P_{\mathrm{mech}}}{P_{\mathrm{batt}}} \quad [6]$$

Total efficiency of pump is calculated using input and output power

$$\eta_{\mathrm{pump}} = \frac{P_{\mathrm{hyd}}}{P_{\mathrm{mech}}} \quad [7]$$

Flow transducers influence is corrected when calculating relative hydraulic power loss in directional valve

$$P_{\mathrm{rel.loss,\,valve}} = 1 - \frac{P_{\mathrm{hyd}} - P_{\mathrm{loss,V1}}}{P_{\mathrm{hyd,mast}} - P_{\mathrm{loss,V2}}} \quad [8]$$

Efficiency of the mast assembly is calculated depending of the direction, in lift

$$\eta_{\mathrm{mast,up}} = \frac{E_{\mathrm{pot}}}{E_{\mathrm{hyd,mast}}} \quad [9]$$

where

$$E_{\mathrm{hyd,mast}} = \sum q_{\mathrm{V2}} \cdot p_3 \cdot \Delta t \quad [10]$$

and respectively in lowering

$$\eta_{\mathrm{mast,down}} = \frac{E_{\mathrm{hyd,mast}}}{E_{\mathrm{pot}}} \quad [11]$$

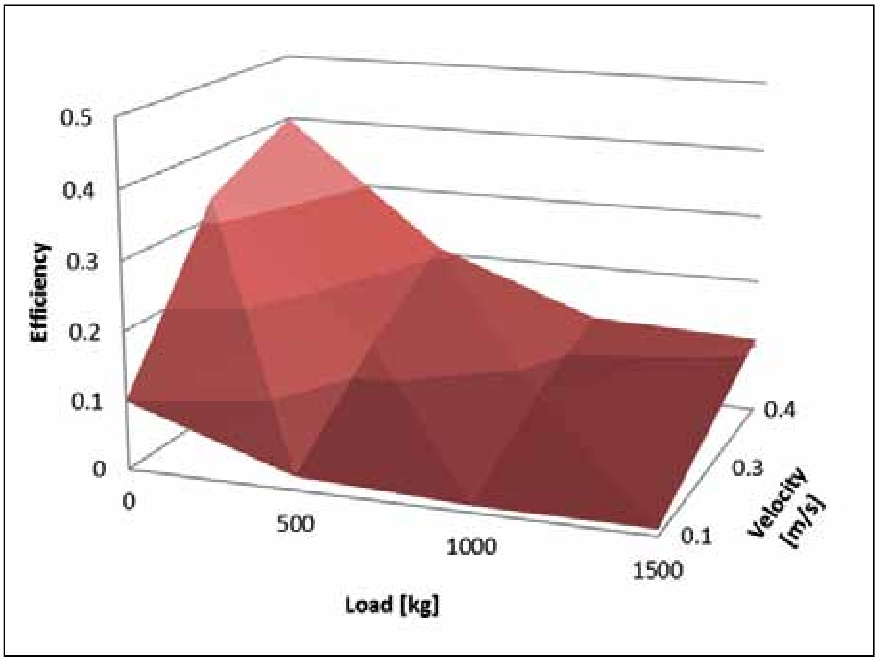

Figure 6. *Influence of velocity and load to relative power loss in valve in free lift zone lifting*

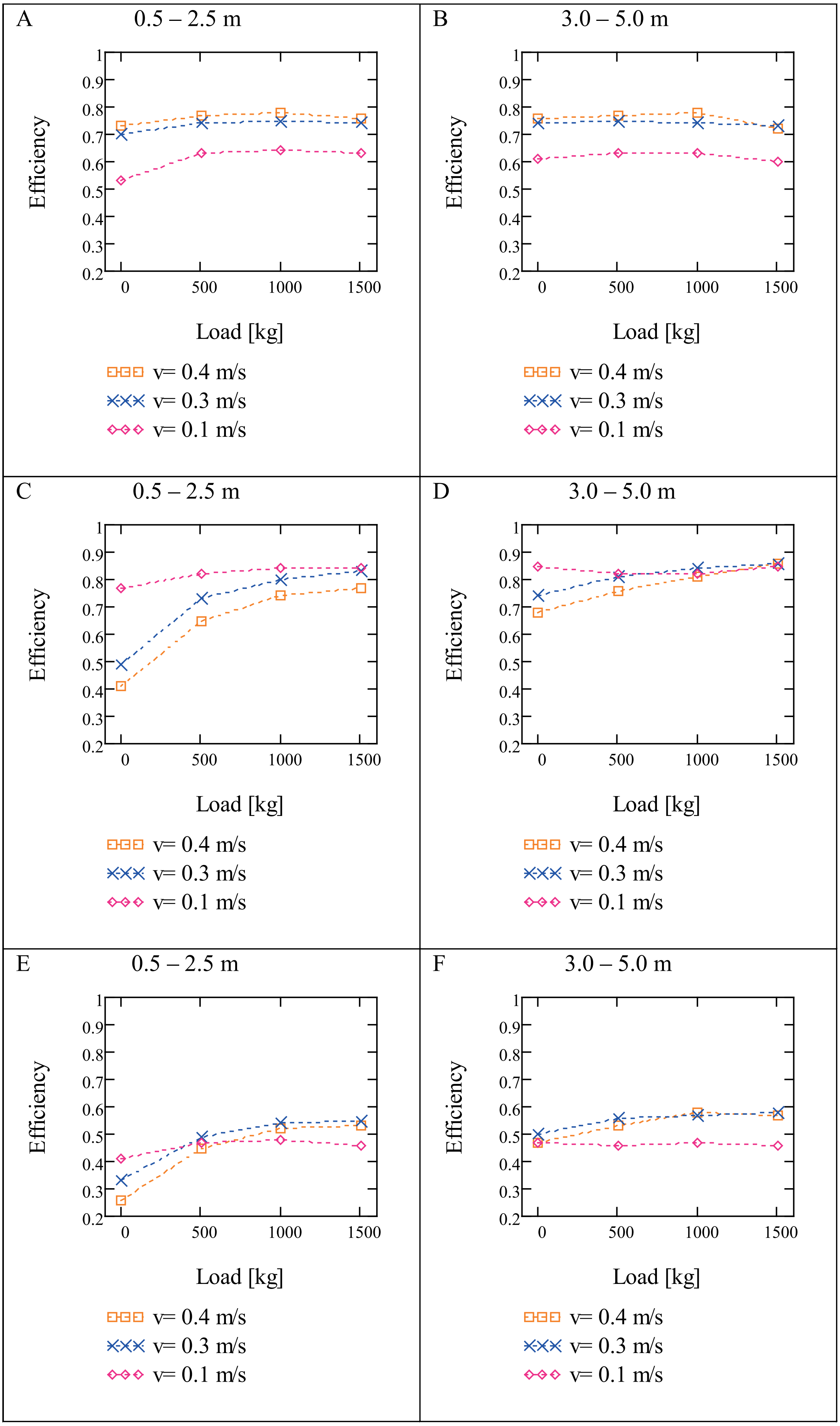

Figure 7. *Efficiencies at different loads and lifting speeds. Electric subsystem is depicted in A and B, hydraulic subsystem in C and D, total efficiency of the system in E and F.*

3 Results

Energy taken by each part of the powertrain in relation to total energy used with different loads is presented in Figure 3, where the three upmost portions of bars depict the energy losses electric, mechanical and hydraulic subsystems and below them is the actual work done in form of potential energy change of lifted load including mast structures.

Electric motor and motor controller were instrumented as a system, i.e., it was considered a single component in the calculations. The efficiency calculations for former and for hydraulic pump were conducted using input and output power. Transients were left out of focus and efficiencies were calculated as average efficiency at constant velocity. Figures 4 and 5 show efficiency factors for free lift zone.

In case of valve where energy does not change its form, relative hydraulic power loss (equation 8) is calculated instead of efficiency. The relative hydraulic losses within valve block and piping during lifting is presented in Figure

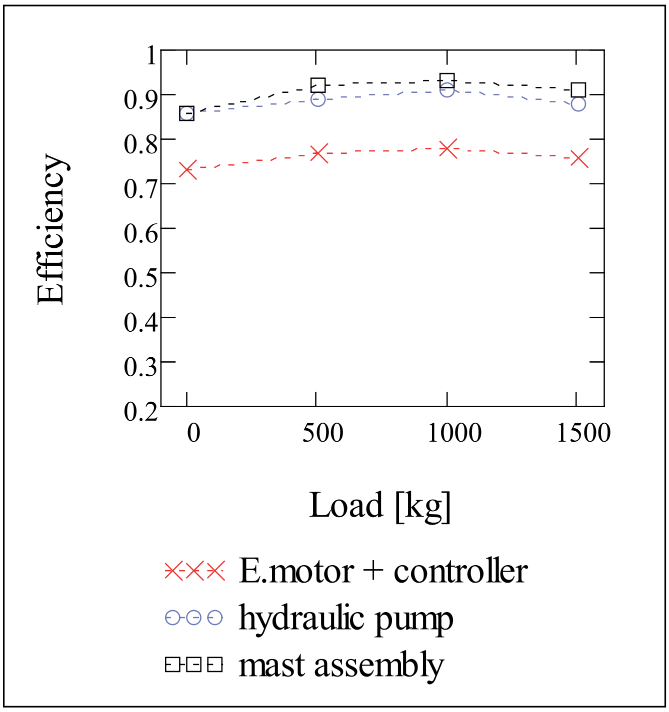

Figure 8. *Efficiencies in free lift zone lifting with velocity of 0.4 m/s*

6 as function of lifting velocity and load.

In Figure 7 are gathered the efficiencies of subsystems in both free lift zone (diagrams on the left side) and upper lift zone (on the right side). Efficiencies of electric subsystem consisting of electric motor, its controller and auxiliary electronic devises is shown in A and B. In C and D are presented the efficiencies for hydraulic subsystem consisting of pump, valve and connecting pipelines. The total system efficiencies are illustrated in E and F.

Without load the pressure level of the system is low, and therefore at lifting speed of 0.4 m/s the flow related pressure losses play more significant role decreasing the efficiency of pump and valve (C in Fig. 7) and also the total efficiency (E) of the system.

Figure 8 presents the efficiencies during lifting as a function of load for electric subsystem, hydraulic pump and mast assembly, the latter consisting of masts mechanical structure and hydraulic cylinders.

Table 2 presents efficiencies of mast assembly when transforming potential energy back to hydraulic energy in free lift zone. Measurements were made with those velocities achieved with all loads.
In upper lift zone corresponding efficiencies were consistently better than 0.98.

4 Discussion

Total energy consumption of test truck was observed to range from 60 kJ, with no load to 185 kJ with load of 1500 kg when operating with velocity of 0.4 m/s and with full lift height (0.5 to 5.0 meters).

When concerning the efficiency factors, the total system efficiency was found to range from 0.26 to 0.55 when operating in free lift zone (lift heights below 2.8 meters). In the upper lift zone they ranged from 0.48 to 0.58. The low efficiencies in free lift zone are due to the low system pressure compared to the pressure loss in valve block, especially with high flow rates. This behaviour is illustrated in Fig. 7; E.

The efficiency of electric subsystem (including control electronics, motor controller and motor) was found to be relatively consistent when lift speeds were sufficiently high. With velocities 0.4 m/s and 0.3 m/s efficiencies were between 0.7 and 0.8. However, using velocity of 0.1 m/s resulted on efficiencies between 0.52 and 0.63. Realized instrumentation did not allow the evaluation of individual efficiencies of the drive and the induction motor.

Hydraulic circuit was found to be most efficient when using low velocities and high loads, and progressively deteriorating with smaller loads. This is due to the fact that increasing velocity and decreasing load increases relative loss. However at operational points with small load the absolute energy consumption is low and therefore the increase in relative loss does not significantly worsen the overall energy balance. The efficiency factors were found to be between 0.42 and 0.85.

In transforming potential energy back to hydraulic energy, mast assembles efficiency on upper lift zone was 0.98. In free lift zone efficiency was good if load was present, ranging between 0.92 and 0.95 but with out load efficiency decreases down to 0.74 at 0.3 m/s.

When attempting to reduce the overall energy consumption, there were found to be numerous issues to address. Electric part of the power train has margin for improvement. One step to attain this could be replacing AC induction motor with permanent magnet AC motor [3]. When concerning the hydraulic part of the power train, the flow related losses in valve block were found to be the largest contributor to diminishing of efficiency.

Table 2. *Efficiency of mast assembly in free lift zone lowering*

Velocity [m/s]	**Load** [kg]			
	0	500	1000	1500
0.3	0.74	0.92	0.95	0.95
0.1	0.80	0.94	0.95	0.97

References

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[2] J. Nyman & J. Bärnström & K-E. Rydberg 2003. Use of Accumulators to Reduce The Need of Electric Power in Hydraulic Lifting Systems. The Eighth Scandinavian International Conference on Fluid Power, May 7–9, Tampere, Finland, pp. 311–326.

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Nomenclature

E	energy	P	power
g	specific gravity	q_{V1}	pump outlet flow
h	lift height	q_{V2}	flow to lift cylinders
m	mass of load	t	time
n	rotational speed	T	torque need of pump
p_1	pressure at pump inlet	W	work
p_2	pressure at pump outlet		
p_3	pressure at lift cylinder	η	efficiency factor

Poraba energije v dvižnem sistemu elektrohidravličnega viličarja

Razširjeni povzetek

Prispevek obravnava analizo porabe in porazdelitve energije pri viličarju na elektrohidravlični pogon. V prispevku analizirani pogon viličarja je sestavljen iz 48-voltnih svinčevih električnih akumulatorjev, pogonsko-krmilnega AC-elektromotorja z možnostjo spreminjanja vrtljajev pogonske gredi, zobniške hidravlične črpalke, sklopa krmilnih ventilov in hidravličnih valjev. Viličar vsebuje sedem hidravličnih valjev, ki so namenjeni za dviganje/spuščanje bremena (trije hidravlični valji), raztegovanje in krčenje stebra teleskopa, nagib teleskopa vilic (dva hidravlična valja) in za nastavitev širine dvižnih vilic. Poleg omenjenega ima viličar v hidravličnem krmilju tri proporcionalne potne ventile in enega konvencionalnega. V hidravličnem sistemu se večina energije porabi za dviganje/spuščanje bremena, zato se nadaljnja energijska analiza delovanja hidravličnega sistema nanaša samo na ti dve funkciji.

Analiza vključuje rezultate meritev pri različnih delovnih parametrih. Rezultati meritev kažejo na slab skupni izkoristek viličarja, ki je med 26 in 58 %, odvisno od delovnih parametrov. Rezultati kažejo, da je izkoristek električnega dela pogona najnižji v primeru nizkih delovnih hitrosti. Hidravlični del viličarja pa ima najnižje izkoristke v primeru največjih hitrosti v kombinaciji z majhnimi obremenitvami. Na osnovi ugotovitev je z vidika zmanjšanja porabe energije priporočeno izboljšati izkoristek AC-elektromotorja in omejiti izgube v hidravličnem ventilskem sklopu viličarja.

Ključne besede: viličar, elektrohidravlični pogon, poraba energije, vračanje energije

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