ANALYSIS OF ENERGY CONSUMPTION BY ELECTRIC AGRICULTURAL TRACTOR MODEL UNDER OPERATING CONDITIONS

Krzysztof Plizga[*]

Faculty of Production Engineering, University of life Sciences in Lublin, Poland, e-mail: krzysztof.plizga@up.lublin.pl, ORCID 0000-0003-0977-6625

Corresponding author: e-mail: krzysztof.plizga@up.lublin.pl

ARTICLE INFO	ABSTRACT
	The aim of the paper is analysis of consumption of electric energy which is necessary to drive a farm tractor with an electric motor as a drive unit under the conditions of a drive with varied loading of the power transmission system. The object of the research was a tractor model where a combustion engine was replaced with a dc electric motor. During the tests, a decrease of voltage and current strength collected from supplying batteries as a function of tractor drive time and in relation to the mass of a tractor with a trailer, temperature of the surrounding and resistance to motion were reported, which enabled determination of the collected power and energy. For the used set of batteries, also the maximum range of the tractor drive on the paved road was determined.

Introduction

With the growing environmental pollution, it becomes necessary to protect it by means of effective management of natural resources, minimization of water consumption, natural fuels (petroleum derivatives), recycling (Andersen, 2013; Bakun, 2015; Chłopek, 2013; Engstle et al., 2012; Haidar et al., 2011; Hüpkes et al., 2011; Schneider et al., 2011). Vehicles, considered up to this day as the main road transport mean, are the biggest source of natural environmental pollution. To reduce their nuisance, more vehicles with a hybrid or electric drive are introduced to public use (Daberkow et al., 2013; Eckl et al., 2013; Marcus et al., 2009; Król and Rossa, 2017; Michałowski and Ocioszyński, 1989; Moons and De Pelsmacker, 2014).

Among many advantages of vehicles with a mixed drive (combustion and electric) or only with an electric one, it should be mentioned that energy collection in batteries, though it is time consuming and causes losses, may bring tangible benefits not only for the natural environment in the form of reduction of toxic elements of exhaust gases emission to atmosphere and also limitation of the amount of the consumed crude oil (traditional fuels produced therefrom) and substitute fuels (synthetic and biofuels). Electric cars may also improve load factors of electric grids reducing thus an average cost of electric energy production, since

charging of batteries may be carried out outside the peak hours (Eckl et al., 2013). Despite this, a small range of electric cars in comparison to cars equipped with a combustion engine is still a problem that inhibits popularization of these cars (Chłopek, 2013). To eliminate this aspect, systems which may enable conversion (recovery) of electric energy with high efficiency are constructed around the world nowadays (Schneider et al., 2011).

One of the groups of vehicles which are increasingly used are farm vehicles due to their universal character, high power, and ability to work even in difficult conditions. However, because of the increasing number of tractors and their big consumption, also these vehicles have a great participation in pollution of the natural environment. Farm tractors participate also in production of food and considerably influence its quality.

Objective

The power transmission system of a farm tractor is adjusted to develop varied drive speed necessary to perform agrotechnical treatments. Simultaneously, farm tractors move in a varied terrain very often with considerable resistance to motion.

Therefore, the objective of the paper is analysis of energy consumption through an electric model of a power transmission system of a farm tractor during performance of transport works at variable loads, resistance to motion and varied temperature of the surrounding.

Materials and Methods

A farm tractor model with a brushless electric engine type BM1424ZXF with 2.2. kW and rated voltage 60 V was used for the energy consumption test of the power transmission system. The engine was supplied from the electric batteries set with 60V (5x12V) through PWM voltage regulator. The used gel batteries V-Pro with 12 V rated voltage, 120 Ah volume made in AGM VRLA technology, that are usually used for emergency power supply of industrial automatic systems, were used in the tests. Each of the batteries was 35 kg (the total mass of the batteries set was 175 kg). The used batteries had a deep discharge option (maximum up to 50%), but due to the endurance at such a deep discharge, one measurement of the maximum distance which a tractor model may make to achieve the average voltage of 45 V of the batteries set was performed (making the voltage decrease average to 9V each) for the established conditions of research. When the set measurement length of 100 m was being made, the voltage decrease of the set was small. During the studies, a trailer where batteries were located, was mounted to the tractor.

The tractor mass without a trailer and load was 91.5 kg and the trailer mass with batteries was 225 kg. An 80-kilo weight was used as an additional load.

Consumption of energy accumulated in batteries was investigated through a measurement of the U voltage of the set and single batteries, current I collected by the engine from the supplying set, t time during operation of the tractor model at the set motion parameters and based on the obtained calculation results of power P and consumed energy E. During the studies, the vehicle was moving under the conditions of the reduced resistance (motion on dry and relatively smooth concrete) and at the increased motion resistance (on the grass) both with a trailer and batteries (the total mass of the model, trailer and set of batteries was 316.5 kg) and a trailer, batteries, and additional load (the total mass 396.5 kg).

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For measurement of electric values, a digital multimeter Voltcraft VC870 with precision of indication of 0.0001V within the range of the performed measurements and a clamp ammeter Voltcraft VC531 with precision of indications of 0.1A with a measurement function of the maximum and minimum value, were used. Time measurement was performed with a timer. Before the drive, voltage of the batteries set without the load and after driving of the set route was measured. The performed electric measurements were based on the actual values of the registered parameters.

For the tested length of 100 m, the tests were performed in ten iterations to eliminate errors of measurement for the subsequently used loads and conditions of operation. To eliminate the effect of batteries discharge on the results of particular measurements, they were charged between the subsequent tests. Whereas the tests of the maximum range of the drive on the applied set of batteries were carried out only one time for the set conditions of the tests (temperature of the surrounding and the weight of the set tractor-trailer).

The tests were performed for three selected temperatures of the surrounding: 20°C, 10°C and 0°C during the tractor drive on the length of 100 m both for the surface of a high adhesiveness factor (where the friction factor $\mu = 1$ – dry concrete) and on the grass ($\mu = 0.8$). Since the set temperatures may be achieved, the tests were performed in various seasons. The temperature of the surrounding was registered with the use of a digital thermometer before the onset of tests. The test set was stored in the temperature of the surrounding to obtain real conditions of the tractor operation.

Results and Discussion

Results of the voltage measurement of the batteries set, voltage reduction of the set after the performed tests, the current strength, driving time on the measurement length of 100 m by the model of the tractor driven with the direct current motor in relation to the temperature of the surrounding and loading during the drive on a dry and paved surface (dry concrete $\mu = 1$) and the power and energy collected from the supplying set were presented in table 1. Whereas in table 2 the measurement results of the tractor model motion parameters at the increased movement resistance were presented in table 2 (movement on the grass $\mu = 0.8$). The results were obtained after the use of popular relations and were presented with a precision to 0.01.

Table 3 presents the results of the maximum distance which may be made by a tractor model for the set loads and temperatures of the surrounding.

Based on the obtained test results presented in table 1 and 2 diagrams of relation of power and energy collected from batteries and time of drive on the measurement length of 100 m for the tests performed in 20°C, 10°C and 0°C were presented in figure 1 and 2.

Table 1.

Results of measurements of energy consumption by a tractor model during driving on dry concrete (μ = 1)

Registration of values			Average	Standard deviation
Parameter	Temperature of the surrounding (°C)	Total model mass (kg)	$\overline{X}$	σ
U_{zest} (V)			63.15	0.362859
ΔU_{zest} (V)			0.34	0.084327
I (A)	20	316.5	31.828	0.113412
t (s)			93.31	0.179196
P (W)			10.829	2.699212
E (Wh)			0.281	0.069354
U_{zest} (V)			63.47	0.048305
ΔU_{zest} (V)			0.53	0.096609
I (A)	20	396.5	35.355	0.269619
t (s)			105.61	1.288798
P (W)			18.743	1.726654
E (Wh)			0.551	0.046296
U_{zest} (V)			63.25	0.117851
ΔU_{zest} (V)			1.31	0.11005
I (A)	10	316.5	31.99	0.1076
t (s)			93.31	0.166333
P (W)			41.912	3.591533
E (Wh)			1.086	0.093357
U_{zest} (V)			63.22	0.113529
ΔU_{zest} (V)			2.46	0.107497
I (A)	10	396.5	36.075	0.218238
t (s)			109.5	0.309121
P (W)			88.757	3.984983
E (Wh)			2.701	0.119019
U_{zest} (V)			62.74	0.259058
ΔU_{zest} (V)			4.59	0.11005
I (A)	0	316.5	31.72	0.163639
t (s)			93.65	0.501664
P (W)			145.6	3.798763
E (Wh)			3.788	0.10315
U_{zest} (V)			62.59	0.128668
ΔU_{zest} (V)			5.14	0.05164
I (A)	0	396.5	36.118	0.207996
t (s)			113.3	0.678233
P (W)			185.647	2.148638
E (Wh)			5.842	0.059777

Table 2.
Results of measurement of energy consumption by a tractor model during driving at the increased movement resistance − drive on grass ($\mu = 0.8$)

Registration of values			Average	Standard deviation
Parameter	Temperature of the surrounding (°C)	Total model mass (kg)	$\overline{X}$	σ
U_{zest} (V)			63.31	0.08756
ΔU_{zest} (V)			0.74	0.069921
I (A)	20	316.5	33.494	0.343809
t (s)			93.69	0.328126
P (W)			24.782	2.30263
E (Wh)			0.646	0.058727
U_{zest} (V)			63.33	0.125167
ΔU_{zest} (V)			1.18	0.091894
I (A)	20	396.5	37.684	0.421089
t (s)			105.09	1.327864
P (W)			44.483	3.397143
E (Wh)			1.297	0.093814
U_{zest} (V)			63.26	0.069921
ΔU_{zest} (V)			1.67	0.11595
I (A)	10	316.5	34.694	0.29774
t (s)			95.63	1.048862
P (W)			57.956	4.299618
E (Wh)			1.539	0.100493
U_{zest} (V)			63.29	0.073786
ΔU_{zest} (V)			3.3	0.094281
I (A)	10	396.5	37.943	0.298293
t (s)			115.09	0.502107
P (W)			125.235	4.490769
E (Wh)			4.002	0.12891
U_{zest} (V)			62.73	0.211082
ΔU_{zest} (V)			4.57	0.125167
I (A)	0	316.5	33.751	0.492374
t (s)			100.08	0.798332
P (W)			154.294	6.328885
E (Wh)			4.287	0.143531
U_{zest} (V)			62.48	0.229976
ΔU_{zest} (V)			6.13	0.356059
I (A)	0	396.5	38.674	0.474955
t (s)			116.9	1.345775
P (W)			237.11	16.68725
E (Wh)			7.695	0.443703

Table 3.
Measurement results of the maximum distance

Parameter	Value	Temperature of surrounding (°C)	Total model mass (kg)	Distance (m)
U_{zest} (V)	63.5			
ΔU_{zest} (V)	18.5			
I (A)	32	20	316.5	2530
t (s)	2363			
P (W)	592			
E (Wh)	388.58			
U_{zest} (V)	63.5			
ΔU_{zest} (V)	18.5			
I (A)	34	20	396.5	2172
t (s)	2412			
P (W)	629			
E (Wh)	421.43			
U_{zest} (V)	63.4			
ΔU_{zest} (V)	18.4			
I (A)	32	10	316.5	2181
t (s)	2378			
P (W)	588.8			
E (Wh)	388.93			
U_{zest} (V)	63.5			
ΔU_{zest} (V)	18.5			
I (A)	35	10	396.5	1692
t (s)	2467			
P (W)	647.5			
E (Wh)	443.72			
U_{zest} (V)	62.8			
ΔU_{zest} (V)	17.8			
I (A)	33	0	316.5	1822
t (s)	2406			
P (W)	587.4			
E (Wh)	392.58			
U_{zest} (V)	62.8			
ΔU_{zest} (V)	17.8			
I (A)	36	0	396.5	1178
t (s)	2532			
P (W)	640.8			
E (Wh)	450.70			

Based on the obtained test results presented in table 3, diagrams of relation of power and energy collected from batteries, maximum distance, and drive time for tests performed in 20°C, 10°C and 0°C for the total weight of the tractor 316.5 kg and 396.5 kg which were presented in figure 3 and 4, were made.
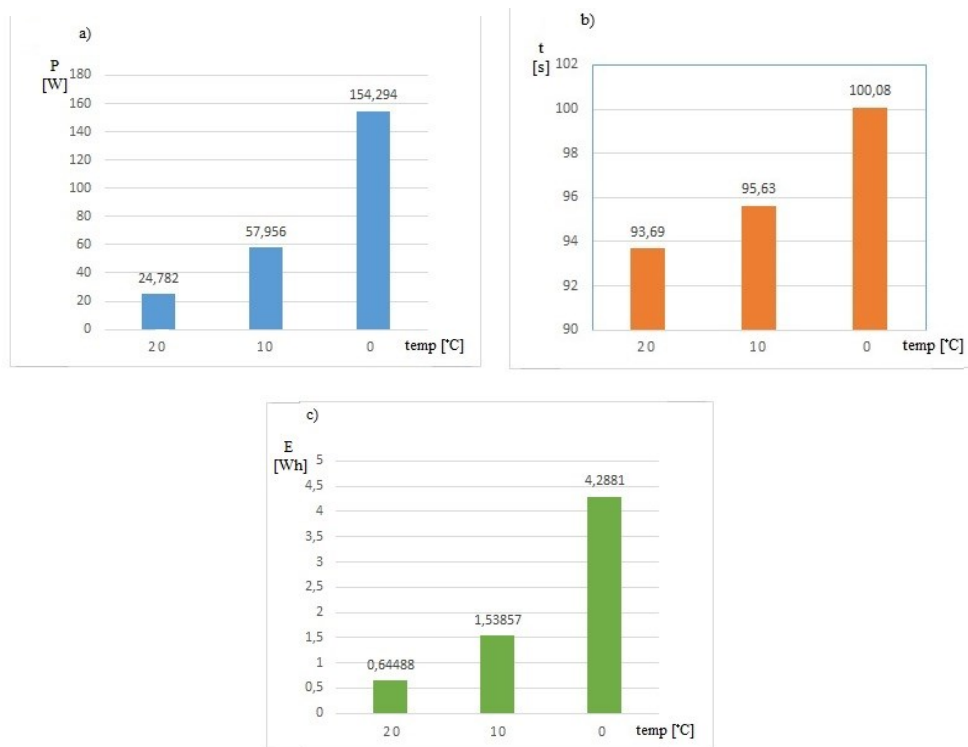
Figure 1. Relations of power and energy collected from the set of batteries, and time of drive in relation to the temperature of the surrounding for the tractor model mass 316.5 kg, a) power P (W), b) drive time t (s), c) energy E (Wh)
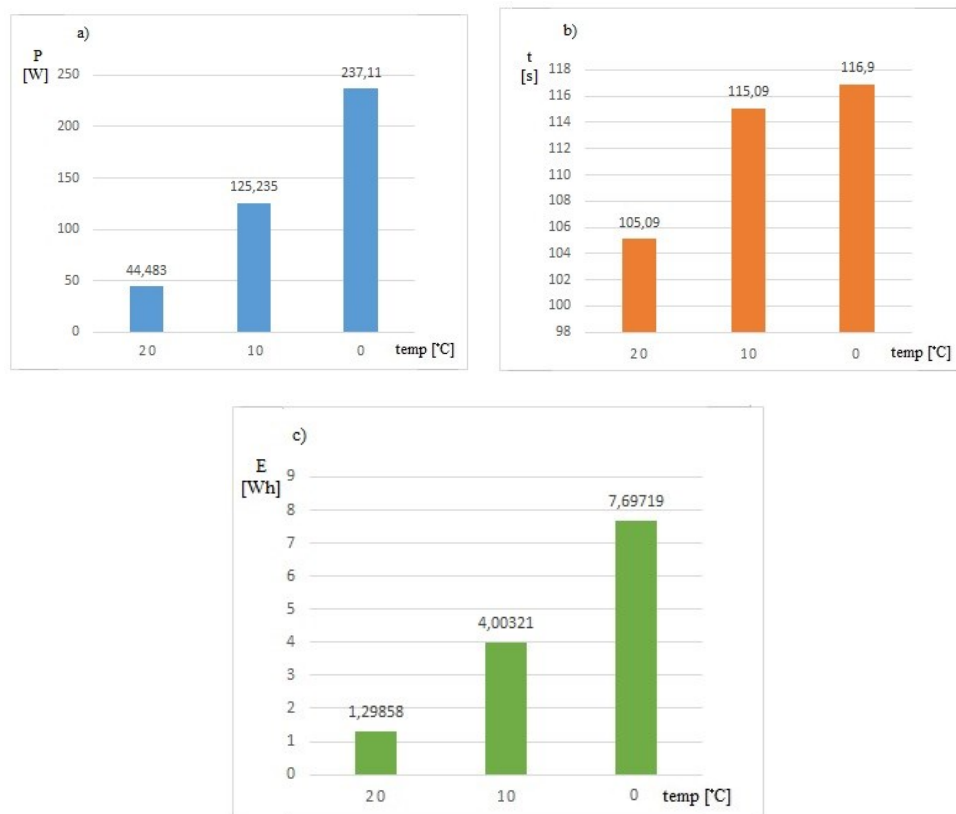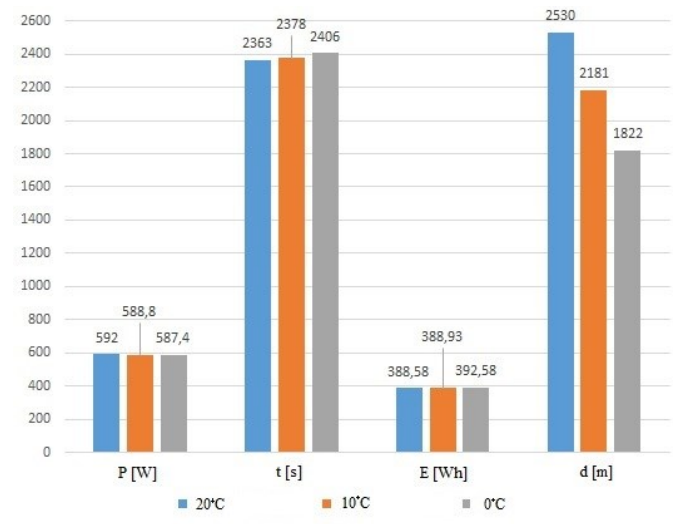
Figure 2. Relations of power and energy collected from the set of batteries and time of drive in relation to the temperature of the surrounding for the tractor model mass 396.5 kg, a) power P (W), b) drive time t (s), c) energy E (Wh)

Figure 3. Relations of power and energy collected from the set of batteries, drive time and distance in relation to the temperature of the surrounding for the tractor model mass of 316.5 kg
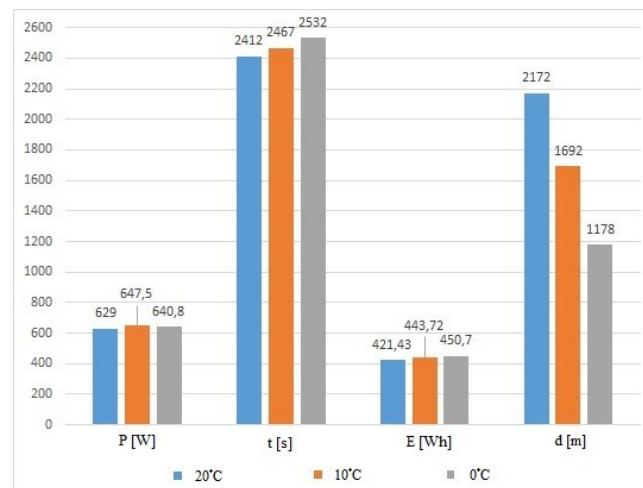

Figure 4. Relations of power and energy collected from the set of batteries, drive time and distance in relation to the temperature of the surrounding for the tractor model mass of 396.5kg

During the drive of the measured distance of 100 m with a small increase of the drive time and along with the temperature reduction, the amount of the collected power P and energy E raises for both used total masses of the tractor with the power transmission system. It is particularly visible for the relation of the collected power for both loads of the power transmission system within the range of temperature 0°C. The increase of the power value collected from the set of batteries was respectively 133% for 10% in comparison to the value of power collected at 20°C and the following 166% for the temperature of 0°C for the total mass of the tractor set of 316.5 kg and 181.5% and 89.3% for the mass of the set of 396.5 kg (fig. 2a). The reported increase of the consumed energy was respectively 138.5% for 10°C in comparison to the energy collected at 20°C and 178.7% for 0°C in comparison to the energy collected at 10°C for the total mass of the set of 316.5 kg and for 396.5 kg of the mass the increase of the value of the collected energy was respectively 208% for 10°C and another 92% for 0°C.

The diagrams of power consumption P and energy E for the applied masses of a tractor in relation to the temperature of the surrounding presented in figure 3 and 4 show that similar values were obtained regardless the external conditions. However, in this case, the drive time slightly increased at a simultaneous reduction of the maximum range of drive. During the studies, values of the driven distance of 2530 m at 20°C which was reduced to 1822 m at 0°C for the tractor set mass of 316.5 kg were obtained, whereas for the mass of the set of 396.6 kg it was respectively 3172 m at 20°C and 1178 m at 0°C. Reasons for this state of affairs should be searched for in the condition of the batteries used for studies (used).

In the available literature (Chłopek, 2013; Torbus et al., 2017) the tests on the electric energy consumption during the road tests for an electric passenger car may be found. In the paper (Torbus et al., 2017) tests on the impact of temperature on the parameters of operation of the electric traction engine supplied from Li-Ion batteries, were performed. However, the available references do not contain operation tests of an electric power transmission system of a farm tractor.

Conclusion

Due to the increasing number of vehicles and constant development of transport and thereby a constantly increasing pollution of the natural environment with exhaust gases possibilities of replacing combustion drive vehicles with another type of a drive e.g., an electric one, are searched for.

An electric drive used in the tractor model enabled performance of a basic analysis of energy consumption during the drive on the hardened surface and on the non-hardened area. The presented research results of show considerable differences in energy consumption, time of tractor operation (a drive range) in relation to the temperature of the surrounding and load of the power transmission system. Quite puzzling is the obtained growth of consumption of the collected power P and energy E from the supplying set for the temperatures of the surrounding of 10°C and 0°C in comparison to these values obtained at the temperature of 20°C. For the set measurement length of 100 m the obtained results of research show the increase of energy consumption even by 181% of the collected active power from the set of batteries and the drive time for both used total masses of the tractor model and the selected temperature of the surrounding. However, remarkably high differences of the maximum range of drive

for the applied loads in relation to the temperature of the surrounding at quite slight changes of the remaining parameters are interesting.

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ANALIZA ZUŻYCIA ENERGII
PRZEZ MODEL ELEKTRYCZNEGO CIĄGNIKA ROLNICZEGO
W WARUNKACH EKSPLOATACYJNYCH

Streszczenie. Celem pracy jest analiza zużycia energii elektrycznej niezbędnej do napędu ciągnika rolniczego z silnikiem elektrycznym jako jednostką napędową, w warunkach jazdy z różnym obciążeniem układu napędowego. Obiektem badań był model ciągnika, w którym silnik spalinowy został zastąpiony silnikiem elektrycznym prądu stałego. W trakcie prób rejestrowano spadek napięcia oraz natężenie prądu pobieranego z baterii akumulatorów zasilających w funkcji czasu jazdy ciągnika, a także w zależności od masy ciągnika z przyczepą, temperatury otoczenia oraz oporów ruchu, co pozwoliło na określenie pobranej mocy i energii. Dla zastosowanego zestawu akumulatorów określono również maksymalny zasięg jazdy ciągnika po drodze utwardzonej.

Słowa kluczowe: ciągnik rolniczy, silnik elektryczny, układ napędowy, zużycie energii