ISSN: 1231-4005
e-ISSN: 2354-0133
DOI: 10.2478/kones-2019-0094

ENERGY BALANCE OF A VEHICLE EQUIPPED WITH HYBRID PROPULSION SYSTEM FUELLED WITH ALTERNATIVE FUELS

Mirosław Karczewski, Leszek Szczęch, Filip Polak

Military University of Technology
Faculty of Mechanical Engineering, Institute of Motor Vehicles and Transportation
Gen. Sylwestra Kaliskiego Street 2, 00-908 Warsaw, Poland
e-mail: miroslaw.karczewski@wat.edu.pl, leszek.szczech@wat.edu.pl, filip.polak@wat.edu.pl

Abstract

Article presents the energetic balance of small-unmanned vehicle hybrid power transmission. The vehicle equipped with serial hybrid transmission consisted of electric engines connected to the battery pack and small Diesel power generator. In mentioned construction, battery is used as energy buffer and combustion engine is used more as emergency power supply, and is turned on when battery is depleted. In other condition, power generator can be turned off, without reducing power of transmission parameters, except its range. Vehicles with hybrid drive are very common chosen vehicles by users. More and more often, we also talk about searching for replacement fuels for internal combustion engines, so also for those with hybrid drive. The research was carried out on an unmanned land platform equipped with a hybrid propulsion system supplied as standard with Diesel oil. The article presents the problems of comparing the efficiency of a hybrid vehicle fuelled with Diesel oil, but also with alternative fuels based on kerosene and other components. For test, three types of fuels were used, standard Diesel oil, F-34 and with experimental mixture of Jet A-1 fuel with 10% of 2-ethylhexanol. Energy used for charging of the battery, from tank-to-wheel, was calculated. This also enables to calculate total efficiency of such hybrid power transmission, powered with different fuels.

Keywords: *energy balance, unmanned vehicle, hybrid transmission, test stand*

1. Introduction

Unmanned vehicles can patrol area, measure contamination level of the environment, deliver supplies, operate as a movable fire stand, or help to evacuate wounded soldiers [3]. Military or civil use of those vehicles is more often introduced [1, 2]. Especially, their use in military conflict region can have impact on safety of soldiers attending in this conflict. To comply its tasks, it is necessary to ensure quiet relocation and long range or long operating time in conflict area without support. Those requirements can be met by vehicles equipped with series hybrid drive, power transmission system with electric engines enable to quiet operate in endangered area [4, 5]. High efficiency of those engines cause slight thermal trace, improve undetectability by enemy forces. Equipped with power generator, enable to load battery and increase range and operation time without need of fast come back to the base [6]. Because fuel deliveries can be interrupted (fit. in warfare conditions), or others aspects (fit. economical, ecological) will be important, besides Diesel, vehicles could use other fuels such as F-34 which is introduced as a unified battlefield fuel [8] or different mixtures of fuels that will work with CI engines [9, 10]. Because mentioned fuels have different parameters, they will impact to the engine parameters.

It is necessary to take under consideration a tank-to-wheel energy balance in efficiency point of view.

2. Laboratory testing of a hybrid power transmission

The main goal of laboratory tests of hybrid power transmission system of unmanned ground vehicle was to determine energy balance of this system after integration and install on a vehicle

hull. Test was held on stands belonging to combustion engines laboratory of Military University of Technology. Range of the tests included:
- measurements of lithium $LiFePO_4$ battery charged from on-board power generator,
- measurements of electric engines efficiency of vehicle,
- measurements of power transmission efficiency.

Based on efficiency of particular elements of power transmission system and calorific value, fuel consumption, energetic balance of unmanned vehicle was calculated and determined.

2.1. Test stands

During tests, four stands were used. First, one was designed for measuring charging of $LiFePO_4$ battery. Second one was prepared for discharging process measurements, widely presented in [7] and third one for measuring efficiency of electric engines, also presented in [7]. On the last test stand, efficiency of the power transmission of unmanned vehicle was measured.

2.2. Battery charging test stand

A stand for measuring charging characteristics of battery by power generator, powered by compressed ignition engine, enables to determine efficiency of designed assembly. This stand consists of five main elements:
1) power generator with Diesel engine,
2) current-voltage parameters acquisition system,
3) constant current power station,
4) battery,
5) fuel consumption measurement device.

Except fuel consumption measurement device, which was mounted at the wall of the laboratory, all stand elements are shown in Fig. 1.

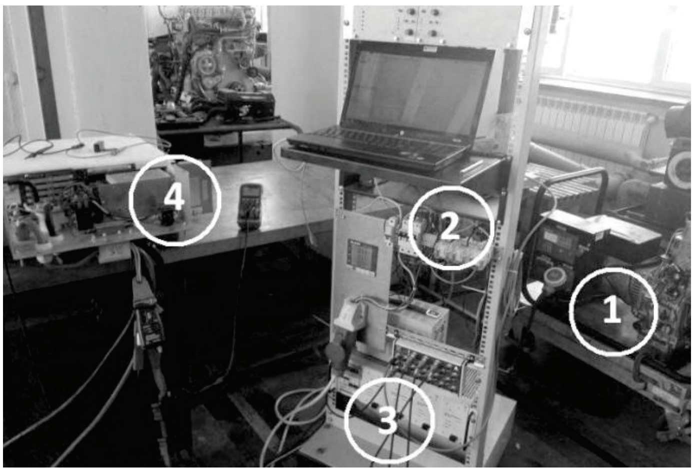


Fig. 1. Charging test stand: 1 – power generator, 2 – current-voltage parameters acquisition system 3 – constant-current power station, 4 – battery

A charging system works on two modes, at the beginning, charging process is realized by constant current (CC mode), further charging is realized by constant voltage mode (CV mode) (Fig. 3a). After activation of power station a charging process of the battery was started. 50 A of current was set at the beginning of charging process when battery voltage was in range about 40.5 V (fully depleted), up to 49.5 V (nominal voltage) This part was called CC mode. Generated power from power generator was about 2500 W at the beginning, up to 2700 W at the end of this mode, in time of ca. 50 min. Power increase was caused by holding constant current and voltage increasing (from 40.5 to 49.5). When constant current mode was over, battery voltage reach 49.5 V, CV mode was started and current started decreasing together with power from power generator, up to zero. Difference between power of power generator and power of charging process come from power station efficiency, which is equal to 92%. When charging process was finished, power of charging station reach zero amperes of charging current and standby mode was activated.

For tests, three different fuels were used:

– Diesel fuel;
– F-34 fuel;
– Jet A-1 with 10% of 2-ethylheksanol.

Jet A-1 with 10% of 2-ethylheksanol is an experimental mixture created in Air Force Institute of Technology. 2-ethylheksanol is mass-produced as a solvent or for production of different plasticizers; and it was used as a component of this fuel. Each fuel comes from one batch; and was validated as a normative. Parameters of used fuels are featured in Tab. 1.

Tab. 1. Selected parameters of used fuels

No.	Parameter	Diesel	F-34	Jet A-1 +10% 2-EH
1.	Density in 15ºC [kg/m^3]	831	804	796
2.	Calorific value [MJ/kg]	43	42.35	42.28
3.	Flash point [ºC]	66	57	–
4.	Viscosity in –20ºC [mm^2/s]	2.210	3.102	3.815
5.	Cetane number	50	45	–

Diesel fuel consumption at the beginning of experiment reached of 0.51 kg/h at idle speed. When charging process started, fuel consumption was increased and reached 0.91 kg/h (CC mode) under load (Fig. 2) and hold this consumption level to the end of CC mode. When CV mode was started, fuel consumption was decreasing. On the end phase of CV mode, fuel consumption reached 0.51 kg/h, the level from the beginning of charging process. Total amount of used fuel needed for one full loading of battery cycle was 1150 g. Charging process was finished after 93 minutes of work.

F-34 powered generator started at similar level of Diesel fuel but CC mode last longer, up to 72 minutes. After that CV mode was started and last up to 114 minutes. For Jet A-1 charging process last similar time period but CC mode last about 6 minutes longer.

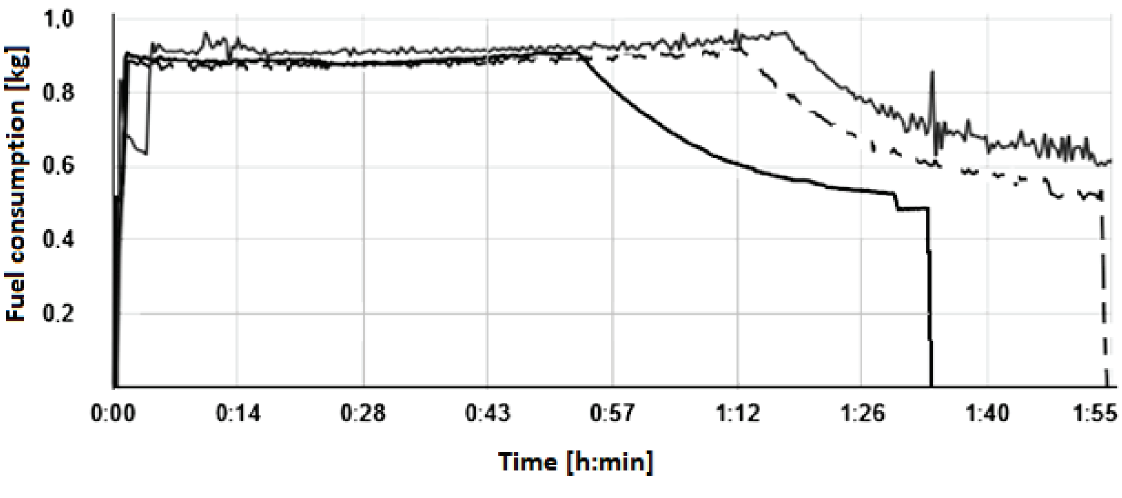
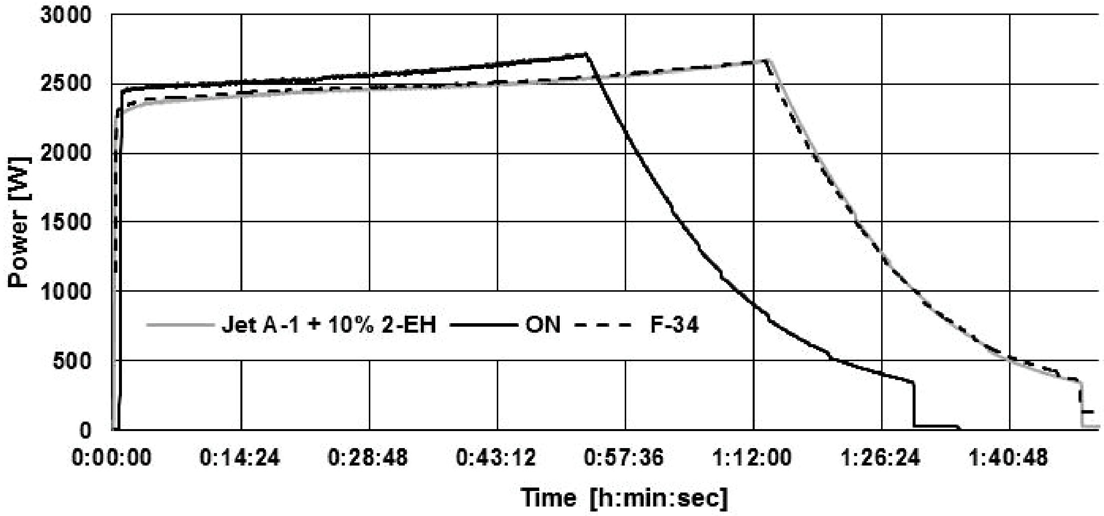


Fig. 2. Power generator momentary fuel consumption (kg/h) for three different fuels: Diesel (black) F-34 (black dashed) and Jet A-1 (grey)

Figure 3 shows power generated by three different fuels. Active power presented on a Fig. 3a is a part of a power retrieved from the source (fuel) and transformed to work or different power. Differences in fuels parameters, such as calorific value, caused differences in rotational speed of the generator. Nominally, generator is prepared to run on Diesel fuel with calorific value ca. 43 MJ/kg. Because F-34 and Jet A-1 had lower calorific value and engine regulator was not able to keep fixed speed. This slight change of speed had influence on a generated power. Used type of alternator was designed to work at fixed speed 3000 RPM. Change of speed caused change of frequency; and it had impact on alternator desynchronization and on produce more reactive power (Fig. 3b).

a)



b)

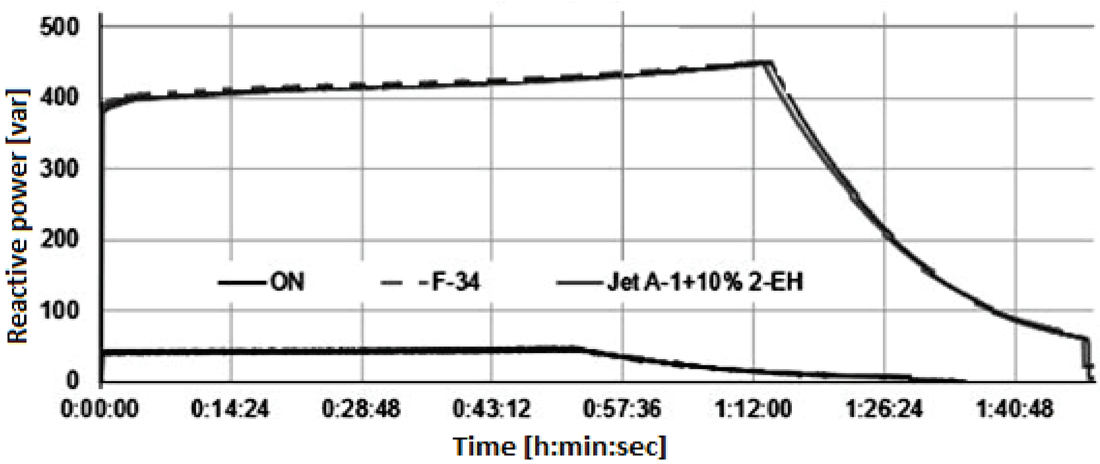


Fig. 3. Battery charging process: a) active power of generator powered with Diesel (black line) F-34 (black dashed) and Jet A-1 (grey); b) reactive power of generator powered with Diesel (black line), F-34 (black dashed) and Jet A-1 (grey)

3. Energetic balance of the hybrid power transmission with alternative fuels

Based on results of charging and discharging of the hybrid power transmission battery, measurements of internal resistances, energetic parameters of the power transmission and energetic balance were determined. Based on that calculation, it was possible to determine range of the vehicle. During calculations, internal resistances were took into account. Result was presented in Tab. 2.

To determine energetic balance, calorific value of the diesel oil was determined as 43, F-34 as 42.35 and Jet A-1 mixture as a 42.28 MJ/kg. Total energy of a single charging process of the battery was equal to 50.282 MJ, and came from Diesel fuel of 1.15 kg. Energy from fuel, powered generator and charged battery with power 10.555 MJ, after sweep to electric energy, this mean the efficiency is equal to 21%, what is satisfied value in Diesel engines. During battery charging process with F-34 fuel, a 1.51 kg of fuel was used for single charging process. That's amount is equal to 63.95 MJ and also enable single charging process, which cause decreasing of efficiency to 16.5%. During operating on a Jet A-1 mixture, engine consumes 1.65 kg of fuel, which means 69.76 MJ of energy. Efficiency of this process is equal 15.1%.

Charging the battery need 9.65 MJ of energy. During discharging process, the energy level reaches 9.0 MJ of energy. Such amount of energy should be enough to travel at distance of 16 km with speed of 5 km/h. Fuel tank capacity enable to charge the battery about 3-4 times to its full capacity, depend of fuel used. This enable to travel distance about 65 km on a flat surface with Diesel fuel, but for F-34 and Jet A-1 mixture, distance drops up to maximum 48 km.

Efficiency of driving modules reaches 75%. Theoretical efficiency of such module (from engine to wheel) should reach 80-90%; and is depending from module load. Because of precision of elements production and assembly, efficiency was lower (15-20%).

Total efficiency of hybrid power transmission, when combustion engine was turned on, reaches 13.6% (from tank to the wheel) for Diesel fuel, 10.7% for F-34 and 9.8 for Jet A-1 mixture.

Tab. 2. Efficiency of subassemblies of hybrid power transmission

Component	Energy used or produced	Average efficiency
Diesel Fuel	50.282 MJ	–
F-34 Fuel	63.949 MJ	–
Jet A-1 with 10% of 2-EH	69.762 MJ	–
Power generator – Diesel powered	10.555 MJ	21%
Power generator – F-34 powered	10.556 MJ	16.5%
Power generator – Jet A-1 with 10% 2-EH powered	10.554 MJ	15.1%
Power station	9.65 MJ	92%
Battery	9.0 MJ	94%
Average efficiency (inverter – wheels)		75%
Average efficiency of transmission elements (battery – wheels)		70%
Total efficiency – Diesel powered		13.6%
Total efficiency – F-34 powered		10.7%
Total efficiency – Jet A-1 with 10% of 2-EH powered		9.8%

Efficiency of energy conversion from chemical energy of fuel to the energy converted for wheels powering is quite small. It is caused mostly by low efficiency of combustion engine that power the generator. It is small, naturally aspirated one cylinder compressed ignition engine. His internal resistance is big if compare of power produced. Efficiency of power transmission powered from battery is bigger and reach 70%.

Knowing power consumed in different road conditions (speed, quality and type of the surface), and parameters of the power transmission, it was possible to determine range of the vehicle and its speed.

Vehicle powered only from the power generator, enable to charge the battery in about 93 minutes. During driving this time is elongated, because some part of the energy is consumed by the wheels of the moving vehicle. This time can be elongated or, if road resistance will be higher than power generated, battery will never be fully charged. In case of totally discharged or damaged battery, maximum vehicle speed is about 20 km/h, when moving on a concrete or asphalt, without charging. This speed is due to the power generated temporarily.

4. Conclusions

1) Compared fuels enable to shift them without any construction changes of the engine. Differences between heating value and viscosity caused slight rotation speed decreasing (approx. 5%), because of used injection system and type of speed regulator, which was not design for use different types of fuels.
2) Energetic parameters were set of the hybrid power transmission. Efficiency of the energy consumption was 70% when vehicle used only battery; and from 9.8 (for Jet A-1 mixture) to 13.6% for Diesel when power generator was turned on.
3) Generator charged battery in 93 minutes for Diesel and about 114 minutes for F-34 and Jet A-1. Differences in fuel parameters, caused speed and active power decreasing and in result higher generation of reactive power which in fact lengthen the charging time.

References

[1] Lopez, R., *DARPA Develops Tactical Robots for Dirty and Dangerous Missions. Unmanned Systems*, pp. 12-13, January/February 2001.
[2] Hollingum, J., *Robots for the dangerous tasks. Industrial Robo*t, An International Journal, Vol. 26 Iss. 3, 1999.
[3] Rybak, P., Wysocki, J., Hryciów, Z., Michałowski, B., Wiśniewski, A., *Experimental research on identifying data for modelling special purpose vehicles*, Journal of KONES Powertrain and Transport, Vol. 24, No. 3, 2017.
[4] Polak, F., Walentynowicz, J., *Problemy doboru zespołów układu napędowego do małego taktycznego pojazdu bezzałogowego*, Journal of KONES Powertrain and Transport, Vol. 14, No. 4. pp. 343-350, Warsaw 2007.
[5] Polak, F., Szczęch, L., *Driving module of the unmanned vehicle*, Journal of KONES Powertrain and Transport, Vol. 18, No. 1, Warsaw 2011.
[6] Redelbach, M., Özdemir, E. D., *Optimizing battery sizes of plug-in hybrid and extended range electric vehicles for different user types*, Energy Policy, Vol. 73, pp. 158-168, October 2014.
[7] Karczewski, M., Szczęch, L., Polak, F., *Energetic balance of unmanned ground vehicle hybrid power transmission*, Journal of KONES Powertrain and Transport, Vol. 25, No. 2, Warsaw 2018.
[8] Karczewski, M, Szczęch, L., *Influence of the F-34 unified battlefield fuel with bio components on usable parameters of the IC engine*, Eksploatacja i Niezawodnosc – Maintenance and reliability, Vol. 18 (3), pp. 358-366, 2016.
[9] Rimkus, A., Matijošius, J., Bogdevičius, M., Bereczky, Á., Török, Á., *An investigation of the efficiency of using O_2 and H_2 (hydrooxile gas -HHO) gas additives in a CI engine operating on Diesel fuel and biodiesel*, Energy, Vol. 152, pp. 640-651, 2018.
[10] Szabados, G., Bereczky, Á., *Use of biofuels in a compression-ignition engine – comprehensive technical and economical analysis*, Journal of KONES Powertrain and Transport, Vol. 25, No. 1, pp. 385-394, Warsaw 2018.

Manuscript received 19 August 2019; approved for printing 05 December 2019