Daniel KALINČÁK, Martin MIKOLAJČÍK

OPERATIONAL REGIMES OF MOTIVE POWER UNITS AND THEIR HYBRID PROPULSION

In this paper the authors present some outcomes of research of operational regimes of rail motive power units and possibilities of hybrid drive utilization. The paper is focused on operational regimes of shunting locomotives and main line locomotives as well. The hybrid propulsion utilization is supposed mainly on shunting and industrial locomotives and diesel units for regional operation. Some results of simulation calculation of hybrid propulsion on the proposed of rebuilding main line locomotive Class 757 are shown. But there are some ways of the better using of ICE in the case of main line locomotives leading to fuel savings. There are mentioned some another methods and means contributing to better using of internal combustion engines at rail vehicles and to fuel savings and reduction of pollution emissions.

INTRODUCTION

Railways systems alway have been cosidered as competetive, sutainable and environmentally friendly modes of transport. Hybrid vehicle are seen as a solution to improving fuel economy and reducing pollution emission from vehicles, including rail vehicles. By recovering kinetic energy during braking and optimizing the engine operation toreduce fuel consumption and emission a hybrid drive can outper-form a traditional propulsion. In designing a hybrid drive, the task of finding optimal component size, particularly otuput of engine, capacity and output of accumulator of energy and appropriate control strategy is key to achieving maximum fuel economy.

A knowledge of operational regimes of motive power units is a base for right design of parameters of the hybrid dirives. The basic devices used by hybrid drive enable applications of another unconventional means for fuel savings as well.

1. ANALYSIS OF SOME OPERATIONAL PARAMETERS OF MOTIVE POWER UNITS

Analysis of operational regimes of motive power units in rail operation is essential precondition for evaluation of hybrid propulsion utilization. There are many publications to this theme, e.g. [1, 3, 4, 5, 6 etc] .

1.1. Analysis of some operational regimes of shunting locomotives

It is known that the use of installed power capacity of ICE in motive power units (especially in shunting locomotives and locomotives for industrial transport) is very low. Average utilization of engine power is usually less than 20% of the installed power capacity and nominal engine performance is utilized only during minimal period of the total time of engine operation (at the level of approx. 1%). The result of this is that most of the operational time the internal combustion engine works in regimes that are far from optimum mode. It means that specific fuel consumption is high.

At this type of locomotives operation the frequent and fast changes of engine regimes occur, which results in increased fuel consumption and imperfect fuel combustion with increased quantity of harmful emissions [3].

We can also find differences between light and heavy shunting operation which are at diagrammatic drawing (Fig. 1, [9, 10]). The first recorded power mission is a light shunting operation, where the power demand is concentrated in short periods of time. The train accelerates usually up to 15 to 20 km/h very quickly and then the throttle is set to idle. In light shunting operation the train stops more often and the trainset is braked only by the locomotive. The braking energy can be stored in some energy storage device such as accumulators or supercapacitors. Absolute value of braking energy is low due to low speeds and low train loads. Thus energy savings depend on circumstances. On the other hand, conventional accumulators are not suitable for high power charging, thus the energy savings are limited. Supercapacitor is a better solution in this kind of operation.

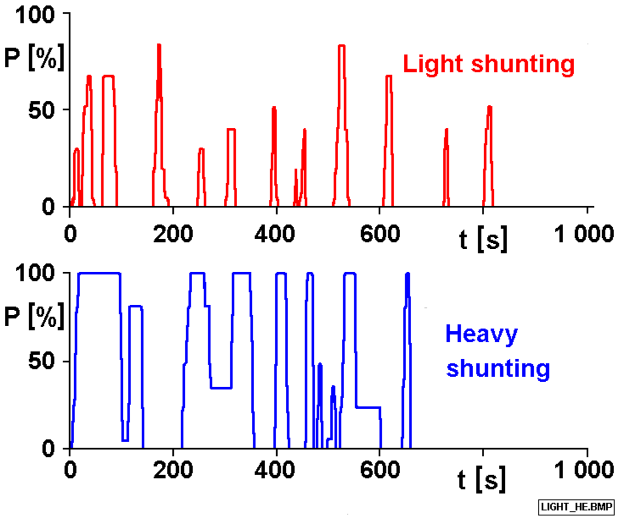

Fig. 1. *Light and heavy shunting comparison*

Heavy shunting operation is represented by the second power mission record on Fig. 1. Longer period of operation at full throttle is given by pulling heavy trains uphill over the hump-yard or moving such trains from one yard to another. Thus a high power interval is usually followed by a low power interval, when the locomotive returns back. When braking a heavy train, absolute value of braking energy is high-er and most of it can be stored in supercapacitor or similar energy storage with higher charging power capabilities.

Aside the low diesel power utilization, high rate of change of power demands causes the engine to operate mostly in transient states particularly in the case of light shunting, what causes additional fuel consumption [5, 6]. If some energy storage is presented, as an additional power source, it can be used to smooth the diesel engine operation. Such a power source can be also used to boost the loco-motive power if needed.

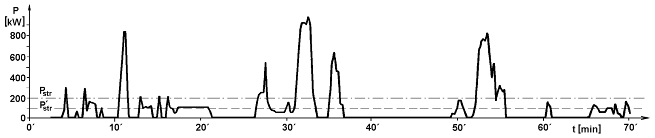

Fig. 2. *Example of power level of engine output of the 883 kW shunting diesel locomotive over time period*

Another example of distribution of diesel locomotive power with the same installed output is at the Fig. 3 [12]. The locomotive Class 742 was at shunting service in the Sugar factory at Považská Bystrica. The measurement recorded in Fig. 3 was executed during dislocating wagons (mass of wagons was about 300 t).

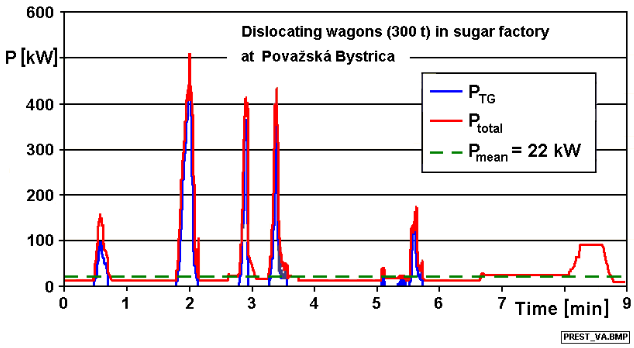

Fig. 3. *Distribution of locomotive Class 742 power at shunting service at the Sugar factory in Považská Bystrica*

The next example is from measurements at the Trenčianská Teplá railway station again on locomotive Class742. The course of power at shunting of wagons (450 t) is on the Fig. 4 [12].

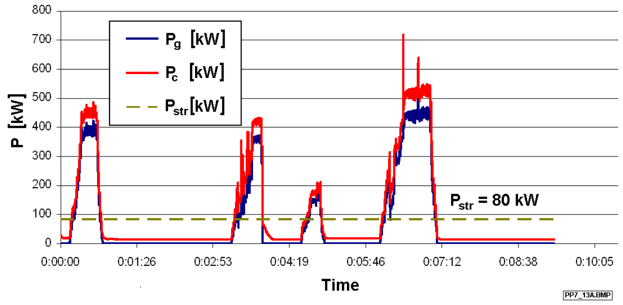

Fig. 4. *Distribution of locomotive Class 742 power at shunting service at the Trenčianska Teplá station*

The diesel-electric locomotives Class 740 and 742 (Fig. 5) are equipped with 883 kW turbocharged diesel engine ČKD K 6 S 230 DR. The maximal input of all auxiliaries (braking compressor, ventilators, charging generator, exciter etc.) is approximately 115 kW (at maximal engine speed and if all of them are active).

Fig. 5. *Shunting locomotive Class 742*

All examples show light type of shunting. In the all examples the mean output of the traction generator is very low. In the first case it is about 100 kW (about 11 % of installed output of ICE), in the second case it is only 22 kW (approximately 2,5 % of installed output of ICE) and in the third case it i s about 80 kW (approximately 9 % of installed output of ICE).

1.2. Analysis of some operational regimes of maine line locomotives

Modernized diesel-electric locomotive class 757 (Fig. 6), intended for passenger transport, is equipped with diesel engine Caterpillar 3512CHD with installed power of 1550 kW and EDB (electrodynamic brake). All auxiliaries are driven by electric motors. The maximal input of all auxiliaries (braking compressor, ventilators, charging generator, exciter etc.) is approximately 151 kW.

Fig. 6. *The main line DE locomotive Class 757*

The measurements were carried out at railway line Zvolen-Banska Bystrica – Margecany – Banska Bystrica – Zvolen. Measurements were realized from 7:40 to 20:36. During this period engine was stopped 5 times with total duration of stopped ICE for 2 hours a 14 minutes.

The courses of some operational parameters of locomotive class 757 during all work shift is shown at the Fig. 7 [4] and one part of shift is presented in more detailed form. the mean output of the traction generator was 317 kW. The mean otput of traction alternator was about 20,5 % of installed output of ICE which is much more than at shunting locomotives. Percentage of engine idling (approx. 38 %) was slightly less as in case of shunting and industrial locomotives.

In the case of main line locomotives is application of hybrid drive not appropriate in classic sense. But there are another possibilities of hybrid drive utilization.

The record of the one segment of measurement is given on the Fig. 8. This segment comprises measurement from hauling of the fast train from Banská Bystrica to Margecany (about 180 km) by locomo-tive Class 757. In the first part (about 96 km) railway line has upward gradient and in the second part has downward gradient. It is evident from record of application of electrodynamic brake (EDB) at Fig. 8.

It is apparent that EDB was used quite frequently and its mean output at this part of measuremnts was 66,4 kW which represents approximately 20,9 % of mean traction output (317 kW). The mean output of all auxiliaries was 48,7 kW. The auxiliaries include two fans of primary and secondary cooling circuit of engine, two fans of traction motors cooling, compressor of brake system and fan of traction and auxiliary generator and also ventilator of EDB brake resistors.

Theoretically it would be possible to cover the energy consumption of auxiliaries with the energy produced during electrodynamic braking, but there is a problem with the storage, because EDB produces large amounts of energy for a short period of time. Therefore, they cannot be used for energy storage batteries, because they can´t be charged with high power, which produces EDB, but must be used ultracapacitors, which are capable to accumulate large amount of energy over a relatively short period of time.

The energy produced by EDB and energy consumed by auxiliaries during the trip from Banská bystrica to Margecany is represented at Fig. 9. Fig. 8 shows that power of auxiliaries is relatively constant and power dissipate by EDB has pulse character. In order to be possible to utilize energy produced by EDB as input of auxiliaries it must be stored in accumulation device. The accumulator equalize produced and consumed energy.

The diagram is supplemented with course of difference between energy produced by EDB and consumed by auxiliaries. This line is pushed by 100 kWh upwards.

A character of the actual railway line with long upward gradient and subsequent long downward gradient implicate different character of production of energy by EDB. At Fig. 9 it is very clearly visible at the time about 2,4 hour (the top of railway line rising). If should be input of auxiliaries covered by production of energy by EDB, accumulator must have some initial energy (say mentioned 100 kWh) in this case. The energy produced by EDB exceeds energy required by auxiliaries by approximatelly 66 kWh at this case. This amount of surplus energy can cover losses conected with charging and discharging of accumulator and efficiency.

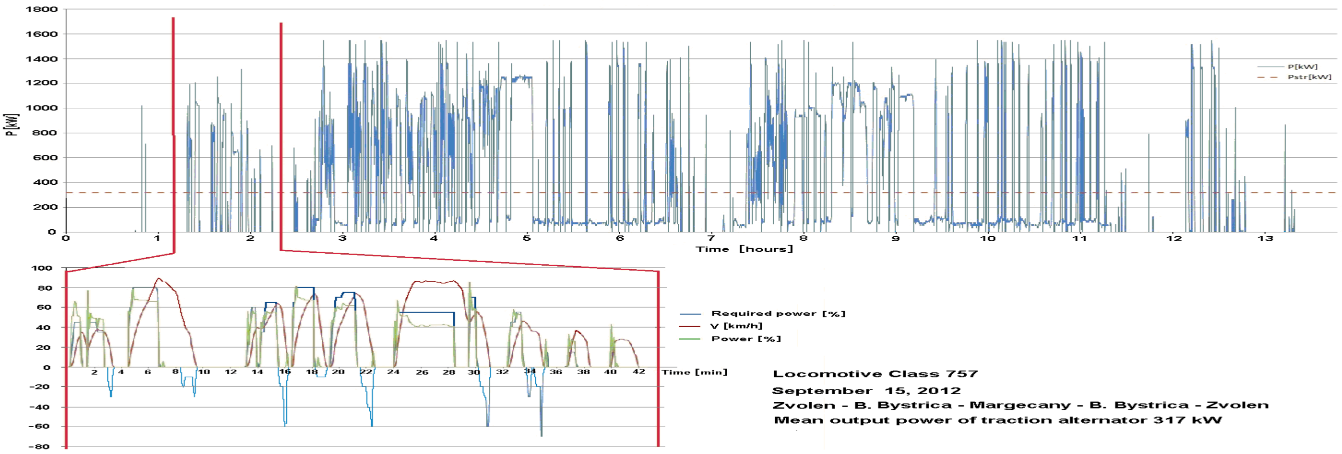

Fig. 7. *The courses of some operational parameters of main line locomotive Class 757*

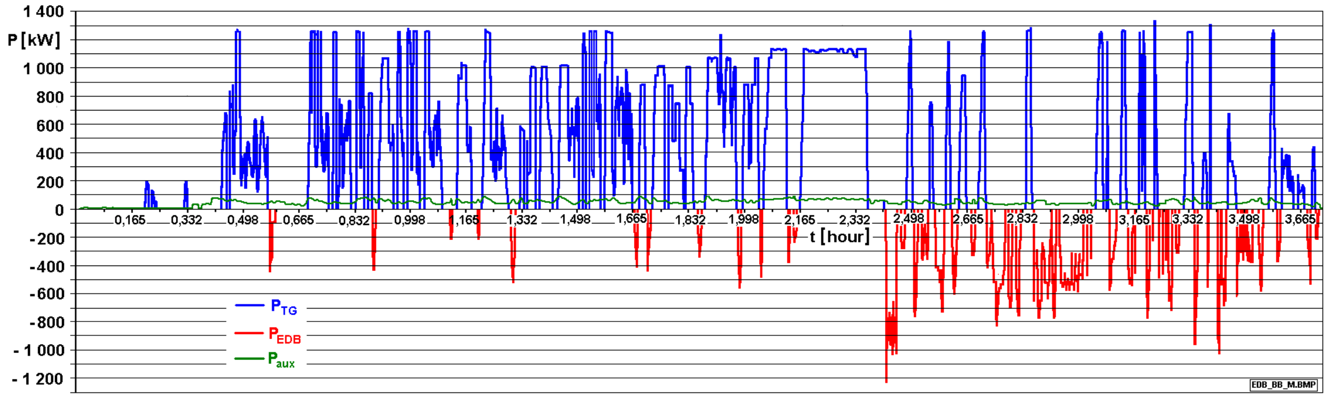

Fig. 8. *The courses of some operational parameters (output of traction alternator, output of EDB and input of auxiliaries) of main line locomotive Class 757 at the fast train on railway line Banská Bystrica – Margecany*

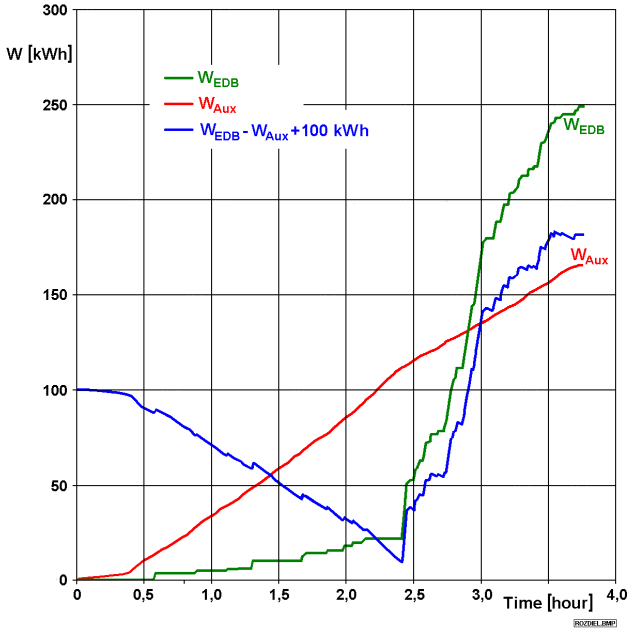

Fig. 9. *The energy produced by EDB and consumed by auxiliaries*

2. THE PROPOSAL OF MAIN LINE LOCOMOTIVE HYBRID DRIVE

In the work [2] was proposed and simulated in MATLAB-Simuling programme hybrid drive for main line locomotive. The basis for proposal was main line locomotive Class 757. The original diesel with output 1 550 kW was replaced by diesel Caterpillar 3508 B with considerably lower output 970 kW. There was used NiMH accumulators Saft Ferak type NHE 5-200. It was used 150 accumulators with total voltage 900 V, volume about 3.15 m^3 and mass about 2.8 t. The capacity of accumulators was 200 Ah, maximum output 550 kW, nominal output 270 kW and utilizable energy 144 kWh. The block diagram of proposed hybrid locomotive is represented at the Fig. 10.

During the computer simulation diesel will work in the three regimes: maximum output (970 kW), output in optimal regime with minimal fuel consumption (730 kW) and switched out. The mean output of ICE in this case was about 317 kW (20.5 % of maximal output of ICE). The results of computer simulation are in the Fig. 11. In the graph is also drawn the course of the charging and discharging of the accumulator. Simulated was ride of the fast train.

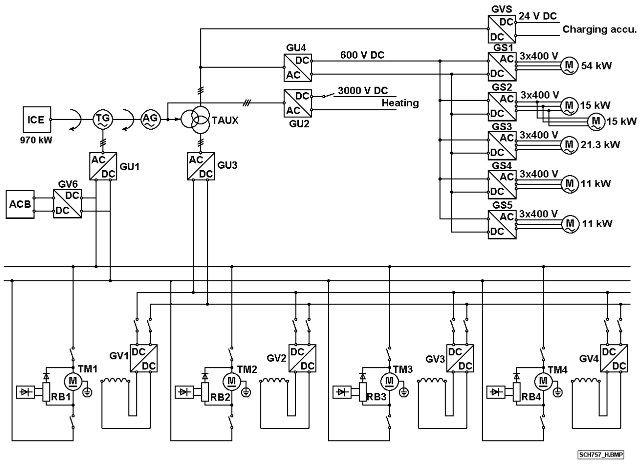

Fig. 10. *The block diagram of proposed hybrid traction drive of the proposed main line locomotive*

The fuel consumption was calculated on track sections Banská Bystrica – Červená Skala and Margecany –Červená Skala, thus on the steepest rising gradient. The fuel saving on those sections was about 3.2 % in comparison with locomotive Class 757. It is possible to suppose that on the whole track the fuel saving may be about 10 %. We remark that simulation proved that it is possible to gain some little fuel saving by application of the hybrid drive at operation of locomotives which is not very appropriate for utilization of the hybrid drive.

The new measurement shows, that locomotive Class 757 in passenger train operation (with more stops as in the case of fast

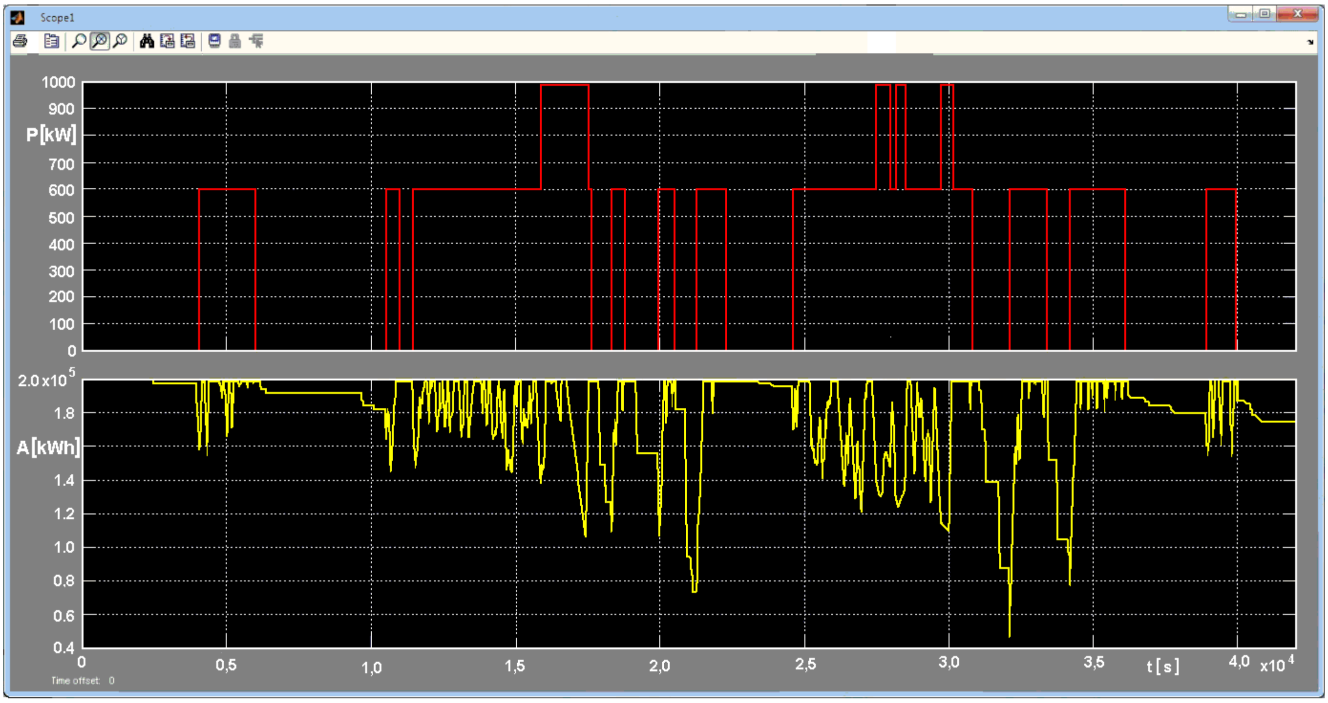

Fig. 11. *The simulation of the proposed hybrid locomotive run on the track Zvolen – Banska Bystrica – Margecany and back*

train and lower hauled mass) has much lower mean output. For example on the track section Brezno – Banská Bystrica it was only 138 kW (about 9 % from maximum output) and on the track section Banská Bystrica – Zvolen it was 187 kW (about 12 % from maximum output).

In this case we can presume more significant fuel savings as in the case which was simulated (fast train).

3. HEAT RECOVERY FROM EXHAUST GASES

During the combustion of fuel only approximately 40 % of energy released from fuel is transformed into mechanical energy. About 36 % of released energy is lost by exhaust gases, Fig. 12.

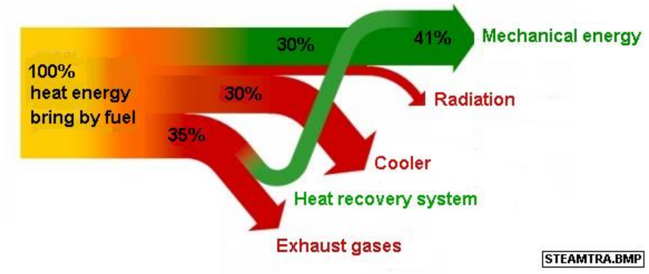

Fig. 12. *The separation of energy gained from fuel in ICE*

The course of exhaust gases temperature measured at tests of main line locomotive class 757 at railway line Banská Bystrica - Margecany is shown at the Fig. 13 [3]. Temperature of exhaust gases is high and contains lot of energy. The problem of using of energy of exhaust gases lies in considerable variability of its temperature.

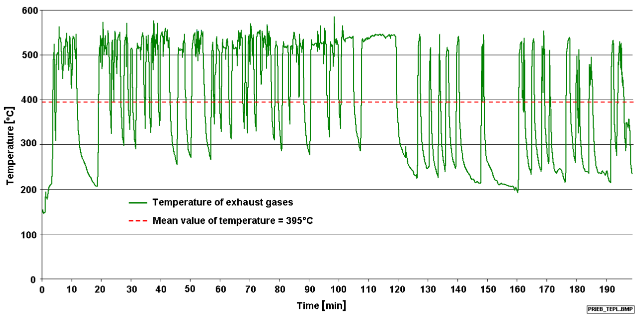

Fig. 13. *The course of the temperature of exhoust gases at the locomotive Class 757 in main line operation*

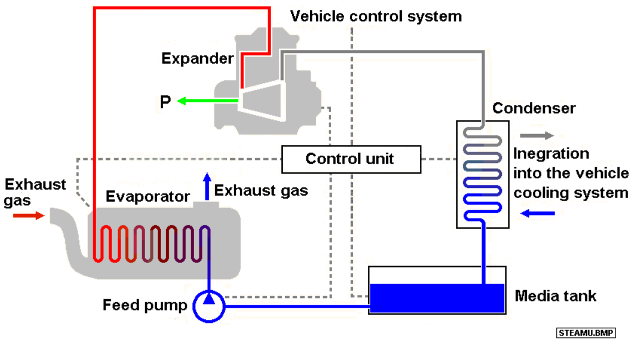

Fig. 14. *Basic block diagram of Voith´s waste heat recovery system StemTrac System*

Voith Turbo GmbH & Co. KG offers answer to this problem by SteamTrac System – waste heat recovery system, Fig. 14 [13]. The system enables about 10% fuel savings and about 12 – 15 % higher performance. Its function is based on warming and evaporating of operation medium by heat of exhaust gas. The superheated steam is expanded into piston expansion machine. The system should be used with cooperation with accumulation of retrieved energy.

Another way, how to utilize the exhaust gases energy is using of a turbo generator which processes residual energy of gases. It is possible to gain about 6 – 9 % more energy by this way [14]. The possibility of utilization of this source of energy is conditioned by some accumulation device that is the hybrid propulsion a well.

The character of output of ICE utilization in railway service, and considerable variability of its temperature and energy content connected with it do not enable direct utilization of energy gained from the exhaust gases. For its reasonable using of it is necessary to employ accumulation of energy. This means that hybrid propulsion enables utilization of exhaust gases energy as well.

CONCLUSION

At some types of motive power units the utilization of the output of internal combustion engines is very poor. As was demonstrated, the mean output in many cases is below 15 % of installed output (even at the main line locomotives). This leads to uneconomical operation. One of the possible ways how to solve the problem is using of the hybrid traction drive. Knowledge of operational regimes of locomotives is inevitable for right choice of appropriate parameters of hybrid traction drive.

It is possible to gain about 15 – 20 % savings in fuel consumption of shunting locomotive by introducing a hybrid traction drive. In the case of main line locomotive are fuel savings significantly smaller (usually smaller than 10 %) as was proved by computer simulations.

It is possible to improve fuel economy also in case of main line locomotives by utilization of energy gained from electrodynamic braking for drives of auxiliaries (so called micro hybrid). This was proved by results of measurements in the real operation of main line locomotive.

There are other possibilities of reduction of fuel consumption, for example using two smaller engines instead of one big, using recovery of exhaust gases energy or using of solar energy. The hybrid drive enable to implement mentioned possibilities of fuel economy and make easier introducing new sources energy as fuel cells or unconventional engines.

BIBLIOGRAFIA

1. Barta D., Galliková J., *Wheels vehicles – troleybuses and alternative drives (in Slovak)*, Žilinská Univerzita v Žilline v EDIS, 2013. ISBN 978-80-554-0751-7.
2. Bartík, Ľ., *Optimization of energy utilization of independent traction locomotive (in Slovak),* Thesis. University of Žilina, 2013.
3. Kalinčák D., Bartík Ľ., *The possibilities of fuel economy – The hybrid traction propulsion*, Prace Naukowe – Transport, z. 98, 2013, Oficina wydawnicza Politechniki Warszawskiej. ISSN 1230-9265. Str. 225 -235, Warszawa, 2013.
4. Kalinčák D., Bartík Ľ., Grenčík J. *Some ways of fuel consumption reduction of diesel railway vehicles*, Autobusy – Technika, Eksploatacja, Systemy Transportowe, Nr. 3/2013, Instytut Naukowo-Wydawniczy „SPATIUM" sp. z o.o., Radom, ISSN 1509-5878. pp. 1957 – 1966, Radom, 2013.
5. Kalinčák D., Mikolajčík M., Grenčík J. *The possibilities of fuel economy in railways – The hybrid traction propulsion.* Logistika Nr 4/2015, Instytut Logistyki i Maganizowania. ISSN 1231-5478. Pp. 3912 – 3921.

6. Kalinčák D., Palko P. *Operational utilization of the internal combustion engines at the motive power units and unconventional traction drives (in Slovak)*. Proc. of 4th Int. Scientific Conference "Challenges in Transport and Communication", Part III, University Pardubice 2006. ISBN 80-7194-880-2, pp. 1247 – 1252.
7. Mikolajčík M., Kalinčák D. *New trends for decreasing fuel consumption of rail vehicle of independent traction (in Slovak)*. Proc. of 22nd int. conference „Current problems in rail vehicles – PRORAIL 2015", vol. 2. VTS pri ŽU 2015. ISBN 978-80-89276-49-3. pp. 61 – 68.
8. Müller, J. Hybridní pohon a rozdělení provozních režimů posunovací lokomotivy. In: Železniční technika (13), 2/1983, pp. 55 - 56.
9. Pácha M., Štěpánek J. *Energy Savings and Performance Optimizations of Hybrid Shunting Locomotives*. Proc. of 2012 Elektro, University of Zilina, 2012. ISBN 978-1-4673-1178-6.
10. Pácha M., Štěpánek J. *Novel design of a supercapacitor driven hybrid locomotive for heavy yard switching operations.* MET´2013, XIth międzynarodowa konferencja naukowa „Nowoczesna trakcja elektryczna". Warszawa, 10 – 12 października 2013. Instytut Maszyn Elektrycznych PW, 2013. ISBN 978-83-908116-1, pp. 112 – 116.
11. Pácha M., Štěpánek J. *Performance and fuel consumption optimization of hunting hybrid locomotives*. Communication: scientific letters of the University of Žilina, vol 15, № 2A (2013). ISSN 1335-4205, pp. 107 – 112.
12. Palko, P. *Hybrid drive systems in rail vehicles (in Slovak)*. Thesis. University of Žilina, 2008.
13. http://voith.com/en/products-services/power-transmission/waste-heat-recovery-10360.html.
14. http://www.bowmanpower.com

Prevádzkové režimy hnacích vozidiel a ich hybridné pohony

Využitie inštalovaného výkonu spaľovacieho motora na hnacích koľajových vozidlách (najmä posunovacích rušňov a rušňov pre priemyslovú dopravu) je veľmi nízke. Priemerný výkon spaľovacieho motora v takýchto prevádzkových podmienkach je okolo 10 – 20 % jeho menovitého výkonu. Výsledkom je, že motor pracuje počas dlhej doby v režimoch, ktoré sú vzdialené od optimálneho režimu. To znamená, že merná spotreba je veľká. Niekoľko príkladov nameraných prevádzkových režimov rušňov v posunovacej službe a iných hnacích vozidiel sú uvedené v príspevku.

Kinetická energia klasického motorového rušňa ako aj motorovej jednotky a vlaku je transformovaná do podoby tepelnej energie v procese brzdenia. Bežne nie je možné využiť túto kinetickú energiu. Aby sa dosiahla úspora paliva, kinetická energia by mala byť transformovaná do vhodnej formy a uložená pre ďalšie využitie, na čo je možné využiť komponenty hybridného pohonu.

Zlepšenie môže byť dosiahnuté použitím nekonvenčného pohonu koľajového vozidla. Jedna z možných ciest je použitie hybridného pohonu. Hybridný pohon pozostáva zo spaľovacieho motora, generátora, trakčných motorov, zariadenia na akumuláciu energie a riadiaceho systému. V takomto prípade môže byť výkon SM podstatne menší ako pri klasickom pohone. Výber parametrov takéhoto trakčného pohonu musí byť podložený analýzou reálnych prevádzkových podmienok vozidla. Takéto parametre sú najmä: výkon SM, výkon trakčných motorov, kapacita a výkon zariadenia na akumuláciu energie (akumulátorov).

V príspevku je stručne predstavený aj návrh aplikácie hybridného pohonu na traťovom rušni radu 757 a výsledky počítačovej simulácie tohto pohonu.

Existujú aj iné spôsoby úspory paliva na koľajových vozidlách, napríklad lepším využitím tepla uvoľneného z paliva a odvádzaného napríklad výfukovými plynmi.

ACKNOWLEDGEMENT

This article was supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences in project no. VEGA 1/0927/15 "Research of the possibilities of using alternative fuels and hybrid propulsion in rail vehicles with the aim to reduce fuel consumption and production of air pollutants".

Authors:
Prof. Ing. **Daniel Kalinčák,** PhD., Department of Transport and Handling Machines, Faculty of Mechanical Engineering, Univerzity of Žilina, Univerzitná 1, SK-010 26 ŽILINA, SLOVAKIA, daniel.kalincak@fstroj.uniza.sk.
Ing. **Martin Mikolajčík**, Department of Transport and Handling Machines, Faculty of Mechanical Engineering, Univerzity of Žilina, Univerzitná 1, SK-010 26 ŽILINA, SLOVAKIA, martin.mikolajcik@fstroj.uniza.sk.