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OPERATIONAL REGIMES OF DE LOCOMOTIVES AND POSSIBILITIES OF FUEL SAVINGS

Abstract

The utilization of installed power of internal combustion engines (ICE) generally, and especially in shunting locomotives and locomotives for industrial transport, is very low. The mean output of ICE in the operational mode is about 10 – 20 % of its installed power. The maximum power of ICE is used only at about 1–2 % of working time. The changes of ICE output are fast and frequent as well. The result is that most of the time internal combustion engine works in regimes that are far from optimum mode and in transitional regimes. It means that specific fuel consumption and production of harmful emissions are high. Some examples of measured operational regimes of locomotives are given in the paper.

The improvement can be achieved by using of the unconventional traction drive of locomotives. One of the possible ways is using the hybrid traction drive. The hybrid drive includes the ICE and the energy storage device. In this case the installed output of ICE can be substantially lower than in the classic traction. The parameters of such traction drive must be based on analysis of real operational regimes of locomotives.

INTRODUCTION

The fuel and energy savings and air pollution in the rail transport should be solved at the present time. A significant number of diesel locomotives with various installed power and age are in operation in the industrial transport and in shunting service on railways. In the domain of main line DE locomotives the situation is similar. Some possibilities how to solve these problems, including usage of unconventional fuels, are mentioned for example in [1, 2, 3].

It is known that the use of installed power capacity of internal combustion engine (ICE) in motive power units (especially in shunting locomotives and locomotives for industrial transport) is very low. Average utilisation of engine power is usually much less than 15 % of the installed power capacity and nominal engine output is utilised 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 is far from optimum mode with high specific fuel consumption. At this type of locomotives operation, frequent and fast changes of engine regimes occur, which results in increased fuel consumption and imperfect fuel combustion with increased quantity of harmful emissions. Shunting operation cannot be operated by low powered locomotives. The maximal engine power is needed for acceleration and high load train shunting. If low powered diesel is used there is possibility to supplement the missing power of diesel by power gained from another source of energy, e.g. accumulator, which can cover the peak and short requirements of high power. This represents hybrid traction propulsion. Other possibility is using of two low powered engines instead of one high powered engine [4].

The measurements on main line locomotives showed that utilization of engine power is better, but low as well [5]. As example we can state that the main line DE locomotive class 757 with 1 550 kW engine pulling fast train has mean output of traction generator only 317 kW which represents about 20.5 % of installed output of ICE. If this locomotive was pulling the light stopping trains, the mean output of traction generator was about 170 kW (11 % of ICE output) [6].

Kinetic energy of classic DE locomotives as well as the DMUs and trains is transformed into thermal energy during braking process. Usually it is not possible to utilize this kinetic energy in a reasonable way. The kinetic energy should be transformed into a suitable form and stored for following use [3, 7]. The hybrid traction propulsion enables at least partially utilization the braking energy. The using of accumulators enables also other ways of better utilization of fuel (for example using of energy in exhaust gases).

1. OPERATIONAL REGIMES OF DIESEL LOCOMOTIVES

The knowledge of operational regimes of locomotives is very important and forms basis for searching possible solutions leading to the design of traction drive and fuel savings.

The operational regimes of shunting and industrial locomotives were published for example in [1, 3, 5, 8, 9]. 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.

Now we will deal with operational regimes of main line DE locomotive class 757.

1.1. The operational regimes of DE locomotives of fast passenger trains

The measurements were carried out at the railway line Zvolen – Banská Bystrica – Margecany. 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 14 minutes.

The mean output of the traction alternator at this case was 317 kW. The mean otput of traction alternator was about 20.5 % of installed output of ICE. At another measurement of the same locomotive pulling the fast train from Banská Bystrica to Žilina the mean output of traction alternator was 396 kW (about 25.5 % of installed output of ICE). This shows that utilization of ICE output at such operation is much better than in case of the shunting locomotives. Percentage of engine idling (approx. 38 %) at the first measurement was slightly less than in case of shunting and industrial locomotives. But at the second measurement (Banská Bystrica – Žilina) percentage of idling was significantly higher (approx. 53 %).

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

The record of the one segment of measurement is given on the Fig. 1. This segment comprises measurement from hauling of the fast train from Banská Bystrica to Margecany (about 180 km) by locomotive Class 757. In the first part (about 96 km) railway line has upward gradient and in the second part it has downward gradient. It is evident from the record of electrodynamic braking (EDB) at Fig. 1.

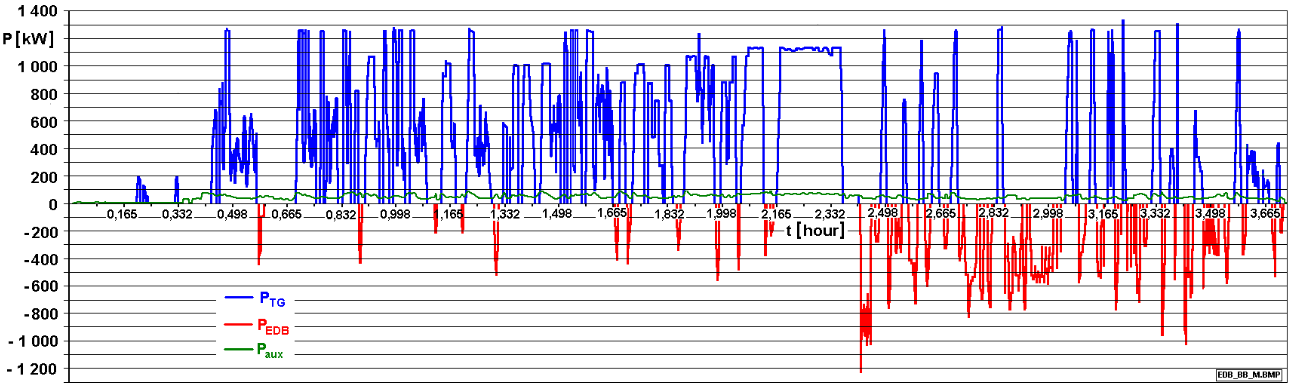

***Fig. 1.** The courses of some operational parameters (output of traction alternator, output of EDB and input of auxiliaries) of main line locomotive Class 757 at the railway line Banská Bystrica - Margecany*

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 input of all auxiliaries was 48.7 kW. The auxiliaries include fans of primary and secondary cooling circuit of engine, two fans of traction motors cooling, brake compressor and fan of traction and auxiliary generator and ventilator of EDB brake resistors. Maximal input of all auxiliaries is about 151 kW.

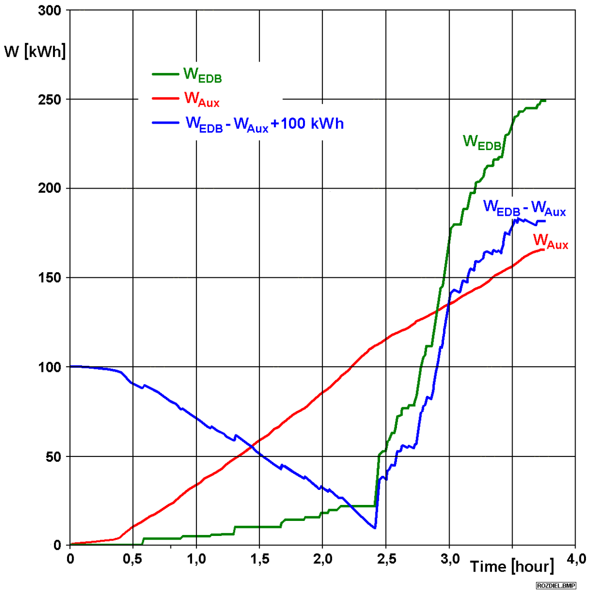

***Fig. 2.** The energy produced by EDB and consumed by auxiliaries at the railway line Banská Bystrica - Margecany*

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, so ultracapacitors must be used, 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 in Fig. 2. Fig. 1 shows that power of auxiliaries is relatively constant and power dissipated 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 equalized produced and consumed energy.

The diagram in Fig. 2 is supplemented with course of difference between energy produced by EDB and consumed by auxiliaries. This line is shifted 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. In Fig. 2 it is very clearly visible at the time of about 2.4 hour (the top of railway line altitude). If input of auxiliaries should be 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 of this processses.

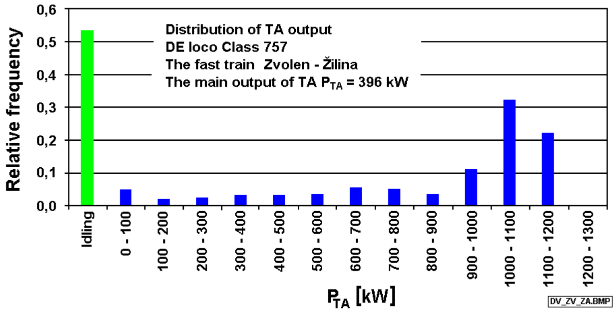

***Fig. 3.** The distribution of traction alternator output of main line locomotive Class 757 at the fast train on Zvolen - Žilina line*

The distribution of traction alternator output at the loco Class 757 pulling the fast train from Zvolen to Žilina is on the Fig. 3.

1.2. The operational regimes of DE locomotives of light stopping passenger trains

The distinct results were gained by measurements on the light stopping trains pulled by the same locomotive. As example we present the distribution of traction alternator and EDB output on light stopping train (three cars) on line Banská Bystrica - Zvolen in the Fig. 4. The mean output of traction alternator in this case was 167.3 kW (10.8 % of ICE output) [6].

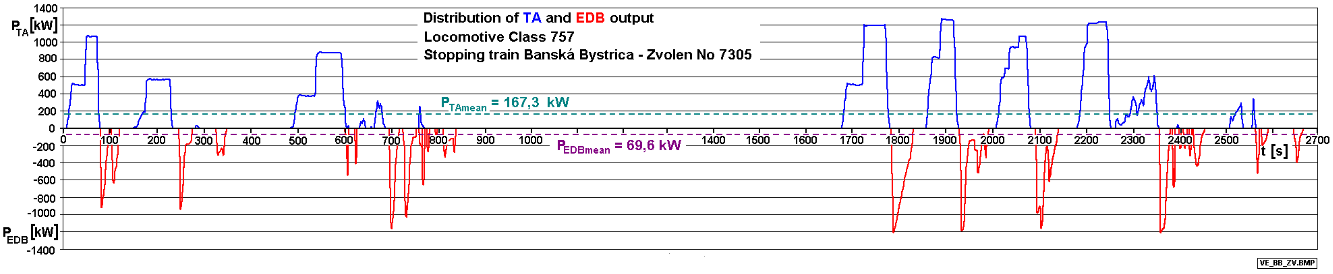

Fig. 4. The courses of output of traction alternator and output of EDB of main line locomotive Class 757 at the stopping train on the railway line Banská Bystrica - Zvolen

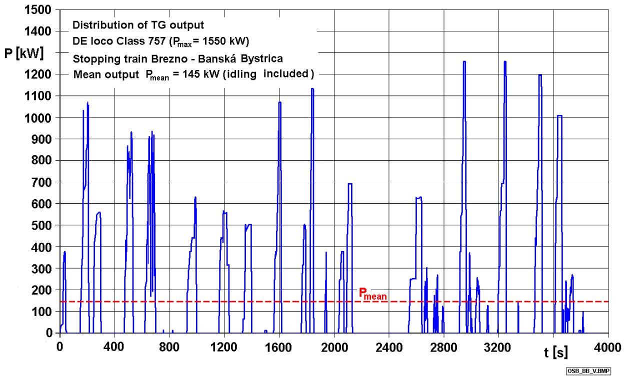

Fig. 5. The course of traction alternator output of main line locomotive Class 757 at the stopping train on the railway line Brezno - Banská Bystrica

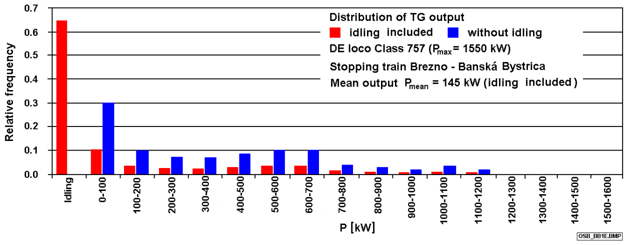

Fig. 6. The distribution of traction alternator output of main line locomotive Class 757 at the stopping train on the railway line Brezno - Banská Bystrica

For powerful main line locomotives unfavourable utilization of ICE power in such operation is typical. The consumption of power for driving of auxiliaries and feeding of pulling cars is very significant. The mean input of auxiliaries in given example was approximately 95.6 kW and mean power for car feeding was 25.7 kW. The mean power for feeding of train is very variable. We have registered the mean power for feeding cars 67.5 kW and 73.8 kW at different measurements. The measurements were carried out in autumn. The power needed for the feeding of cars heating in winter will be much higher. The mean input of traction motors was 167.3 kW and the mean output of EDB was 69.6 kW in this case.

The time behaviour of traction alternator output at another measurement at light stopping train on the line Brezno – Banská Bystrica is shown on the Fig. 5 and the distribution of traction alternator output is shown on the Fig. 6. The mean output of traction alternator in this case was only 145 kW (9.3 % of ICE output). The significant part, more than 60%, of engine work, was idling.

The mean output of EDB was 66 kW and the mean input of auxiliaries was 106 kW in this case [6].

The traction energy consumed at this 66 minutes lasting run was 151 kWh, energy consumed for drive of auxiliaries was 116 kWh and energy consumed for train feeding was 73 kWh. It is interesting that less than one half (44.4 %) of energy produced by ICE was consumed for traction drive. The share of traction energy will be even lesser in winter or in summer if passenger cars will be equipped with air-conditioning.

2. THE POSSIBLE WAYS OF FUEL SAVINGS

2.1. The hybrid traction drive

The hybrid traction drive is one important way for fuel economy for shunting and industrial locomotives. This was proved by testing of the hybrid shunting locomotive Class TA 436 (718) made in company ČKD in Prague in the year 1986 [10]. The traction parameters of TA 436 were very similar to shunting DE locomotive Class 730. The output of hybrid locomotive ICE was only 189 kW. On the locomotive Class 730 ICE has 600 kW. The results of measurements showed that hybrid locomotive is more effective in majority of shunting regimes and had fuel consumption up to 24 % lower than DE locomotive Class 730 depending on the service regime.

In the work [11] a hybrid drive for main line locomotive was proposed and simulated in MATLAB-Simuling programme. 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. 150 NiMH batteries were used (Saft Ferak type NHE 5-200) with overall 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.

During the computer simulation the diesel worked in three regimes: maximum output (970 kW), output in optimal regime with minimal fuel consumption (600 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. 7. The course of the battery pack charging and discharging was also presenting on the graph. The ride of the fast train was simulated.

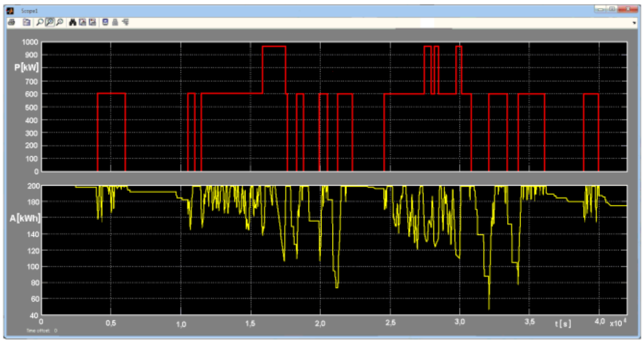

Fig. 7. The simulation of the proposed hybrid locomotive run on the railway line Zvolen – Banska Bystrica – Margecany and back

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 note that simulation proved that it is possible to gain some little fuel saving by application of the hybrid drive at operation of the main line locomotives which is not very appropriate for utilization of the hybrid drive.

The situation in the case of main line locomotives for passenger trains is different. The utilization of full hybrid traction drive is not the optimal solution here. But the using of the partial hybrid drive may be useful. The energy gained from EDB can be exploited for example for driving auxiliaries or partially for car supply. The accumulation devices needed for hybrid drive can be very useful for utilization of other sources of wasted energy, e.g. from exhaust gases.

2.2. The dual engine installation

Another possibility is usage of two ICEs on a locomotive.

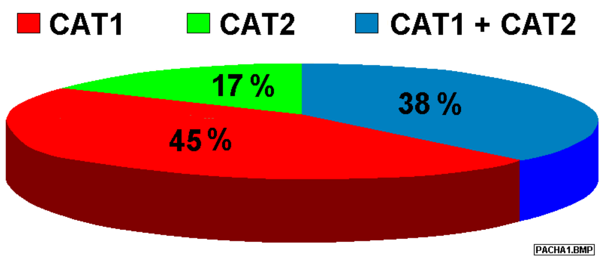

Fig. 8. The dual engines utilization

Probably the easiest option, how to favorably influence fuel consumption is the use of two engines with about half power of original engine for propulsion of shunting locomotive. As an example we mention the reconstruction of the locomotive SM42 made by CZ LOKO company for Polish customer. Two Caterpillar C15 engines with power of 2x403 kW were used instead of the original engine with an output of 588 kW, respectively Cat C27 with an output of 703 kW were used. It turns out that 62% of the total time locomotive worked with only one engine, which brings saving especially when ICE works in idling, respectively when there are lower demands on power output [4]. The utilization of particular ICEs is shown in the Fig. 8. The idling consumption of smaller ICE is lower than bigger one. Besides, the optimum regime of ICE is closer to the mean output of locomotive.

The usage of two engines should be appropriate arrangement for main line locomotives for passenger trains. The power needed for feeding of connected wagons significantly depends on design of wagons and on season of the year. One of engines should be used for train feeding.

2.3. The design and control of auxiliaries

The significant part of energy is consumed for auxiliaries drive particularly in case of locomotives pulling light stopping trains. Another way for energy savings is better design and control of auxiliaries. The mean value of traction current of traction motors of locomotive Class 757 was in the case of stopping trains only about 122 A. The constant current of used traction motor is 590 A for cooling air flow 80 m³/min. The very short peaks of current were approx. 500 A or less. The mean input of cooling fans of traction motors was about 32 kW (Fig. 9). This input envisages the biggest part of auxiliaries consumption. If reasonable control of cooling fans drive will be used, the major part of fans power consumption could be saved.

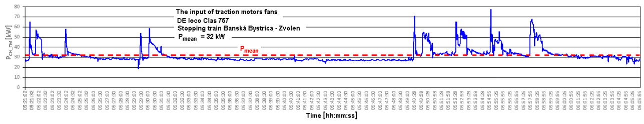

Fig. 9. The input of the traction motors fans

2.4. The 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. 10.

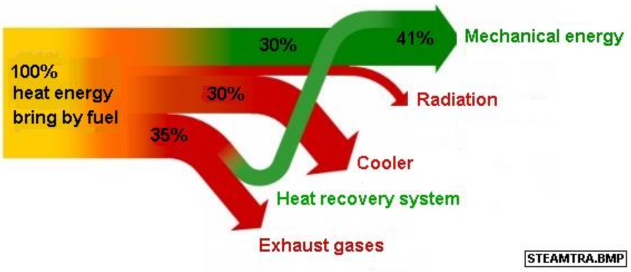

Fig. 10. The separation of energy gained from fuel in ICE

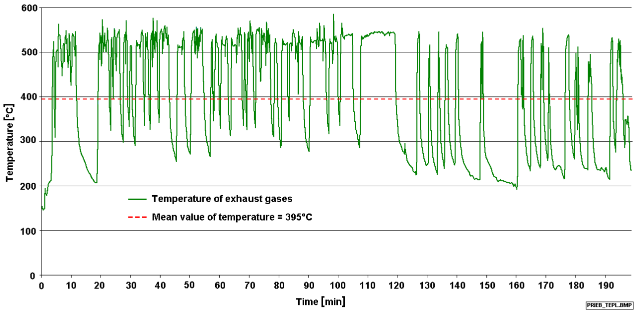

Fig. 11. The course of the temperature of exhaust gases at the locomotive Class 757 in main line operation

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. 11 [12]. Temperature of exhaust gases is high and contains lot of energy. The mean temperature of gasses was in this case 395 °C and peak temperature was approx. 550 °C. The problem of using of energy of exhaust gases lies in considerable variability of its temperature.

Voith Turbo GmbH & Co. KG offers answer to this problem by SteamTrac System – waste heat recovery system, Fig. 12 [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.

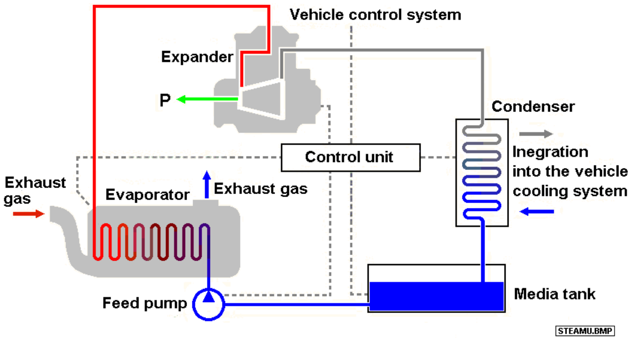

Fig. 12. *Basic block diagram of Voith´s waste heat recovery system StemTrac System*

Another way of utilization of the exhaust gases energy is a usage of the turbo generator which processes residual energy of gases – Electric Turbo Compounding technology. 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 part of the hybrid propulsion as well.

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

CONCLUSION

For 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 for 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 of the fuel consumption of shunting locomotive by introducing hybrid traction drive. In the case of main line locomotive fuel savings are significantly smaller (usually about 10 %).

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 locomotives.

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

ACKNOWLEDGEMENT

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PREVÁDZKOVÉ REŽIMY DE RUŠŇOV A MOŽNOSTI ÚSPOR PALIVA

Resumé

Využitie výkonu spaľovacieho motora na hnacích koľajových vozidlách je veľmi nízke. Priemerný výkon trakčného generátora je v prípade posunovacích rušňov okolo 10 – 20 % maximálneho výkonu spaľovacieho motora a niekedy aj výrazne menej. V prípade traťových rušňov je situácia mierne lepšia, ale aj tu priemerný výkon trakčného generátora predstavuje okolo 20 – 30 % výkonu SM v prípade rýchlikov a okolo 10 – 15 % v prípade ľahkých osobných vlakov. Najmä v prípade traťových rušňov sa značná časť energie uvoľnenej z paliva spotrebuje na pohon pomocných strojov a napájanie pripojených osobných vagónov vlaku. Z trakčnej práce sa značná časť zničí v EDB pri brzdení. Tiež značná časť uvoľnenej energie odchádza horúcimi výfukovými plynmi. Dobrá znalosť prevádzkových režimov trakčných zariadení motorových rušňov podmieňuje návrh vhodných riešení vedúcich k úsporám paliva.

Zlepšenie využitia energie uvoľnenej v SM z paliva (zníženie jeho spotreby) môže byť dosiahnuté viacerými spôsobmi. Prínosom je použitie hybridného pohonu buď úplného, alebo v niektorých prípadoch čiastočného. Základné komponenty hybridného pohonu, najmä zariadenia na akumuláciu energie, umožňujú aj využitie iných zdrojov stratenej energie, najmä energie výfukových plynov.

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