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Model for building traction information of suburban rolling stock on hydrogen fuel

Anatoly Falendysh[1*], *Volodymyr* Dzhus[2], *Olha* Kletska[1], *Oleg* Kosariev[1], and *Jan* Dizo[3]

[1] Ukrainian state university of railway transport, Heat Engineering and Heat Engines, Kharkov, Ukraine
[2] DNURT, Department Chair of rolling stock and railway, 79052 Lviv, I.Blazhkevych Str., 12-a, Ukraine
[3] University of Zilina, Department of Transport and Handling Machines, Zilina, Slovakia

Abstract. The materials consider the possibility of using hydrogen as a fuel for suburban rolling stock in Ukraine. The analysis of the use of hydrogen fuel in transport in various countries of the world is carried out. One of the main stages of calculating the rolling stock is the construction of its traction characteristic, which largely depends on the type of power plant. Therefore, a model has been developed for constructing traction characteristics of a suburban rolling stock when it is converted to hydrogen fuel. For this purpose, an analysis of power equipment with an energy source from a polymer of an exchange membrane fuel cell and methods of connecting their batteries to blocks is done. The scheme of power transmission for the rolling stock is proposed and its efficiency coefficient is preliminarily calculated. The main technical indicators of suburban rolling stock in Ukraine at the moment and using proton-exchange membrane fuel cells on it are considered. Preliminary consideration is given to the operation parameters of the electric circuit of the rolling stock under various modes of its motion. The traction characteristic of a suburban mobile suction on hydrogen fuel is constructed. The proposed model is implemented in the software product MathLab.

1. Introduction

The greater part of all transportations in Ukraine is provided by railway transport [1]. But at the same time, more than 90% of it is currently behind the world technical progress. In Ukraine, scientific works and practical research are mainly aimed at developing activities related to the extension of the life of the already existing rolling stock. At the moment, the new rolling stock in the country is being produced by Kryukovsky Carriage Works. He developed and produced an electric train ECP1 (Tarpan) and a diesel train DPKr-1 [2].

In the world there is a tendency to increase the speed of rolling stock movement and use of different types of thrust without harmful emissions into the environment. Therefore, the issue of developing our own high-speed and environmentally friendly rolling stock for Ukraine is topical. This is confirmed by the strategy for the development of "Ukrzaliznytsya" PAT until 2021, dated 12.09.2017 [3].

2. Research and discussion of the oresults

The use of hydrogen as a fuel in transport power plants is possible in two ways:

- as a fuel for internal combustion engines [4, 9];
- as a fuel cell, the principle of operation of which is based on electrolysis [5, 6, 9].

Work on the use of hydrogen fuel in transport along both tracks has been carried out in many countries around the world since the nineteenth century [4-10]. The use of hydrogen in railway transport has begun to receive attention only in the last 20 years. Therefore, further studies are continued for the use of hydrogen in power railroad transport usa- novs.

Scientists from the Tokyo Railway Research Institute (Japan) and the French company Alstom went on the second route of using hydrogen as an energy plant. For example, Alstom presented a prototype of the Coradia iLint rail car designed and built on the basis of the Lint 54 at the World Rail Transport Exhibition [10-13].

Also, the issues of the use of hydrogen in rail transport are given great attention in the United States, Britain and China. VNIIZhT scientists propose the use of hydrogen on the rolling stock of Russian railways [14]. Variants of the use of hybrid power plants on the modernized rolling stock in Ukraine are considered in [15-19].

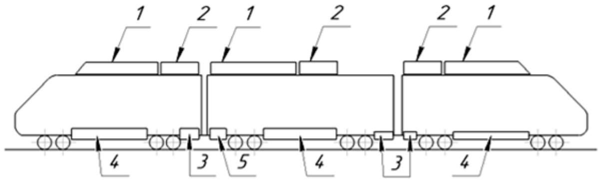
Thus, the second version of the use of hydrogen as a fuel (the use of proton-exchange membrane fuel cells in hybrid power transmission) for a motor-car rolling stock was considered in [20]. A model for the technical and economic evaluation of the rolling stock on hydrogen fuel is proposed, the necessary equipment and its location for the modernization of the diesel train are

* Corresponding author: fap_hiit@ukr.net

preliminarily determined. But the issues of traction calculations for rolling stock on hydrogen fuel are not considered.

Therefore, consideration of carrying out traction calculations for rolling stock using hydrogen fuel is currently an urgent and timely task.

Based on preliminary calculations [20], for further work on the modernization of the rolling stock by power plants using hydrogen fuel, the diesel train DPKr2 (Fig.1).



1 – Fuel tank, 2 – PEMFC, 3 – Invertor for traction motors, 4 – Li-Ion batteries, 5 – Invertor for indoor needs.

Fig.1. Location equipment on a multiple units rolling stock rolling stock with hydrogen fuel.

It is supposed to use the following equipment in advance: proton-exchange membrane fuel cells (PEMFC), fuel tanks, cryogenic for storage of hydrogen, storage batteries, drive trucks with traction electric motors.

For further calculations, the parameters of the main equipment operation and their technical characteristics were determined. The equipment was selected in the following order. First, the characteristics of traction electric motors were selected to provide the necessary tractive force. Then, taking into account the conversion of the electrical current in the inverter, the necessary voltage and current at the output of the battery pack was determined, the battery pack was formed and calculated, and the required PEMFC was subsequently determined which would provide the fastest and most economical charging of the battery pack. The main technical parameters for this equipment are presented in Table 1.

Table 1. The main technical characteristics of equipment for upgrading a suburban train.

Name	value
Traction asynchronous electric motor	
power, [kWt]	400
Maximum rotation frequency, [min^{-1}]	4126
Starting torque, [Nm]	3607
Accumulator batteries of the company “Panasonic” NCR18650PF	
Nominal capacity, [mAh]	2700
Rated voltage, [W]	3,7
Maximum discharge current, [A]	10
Maximum charging current, [A]	5,4
Weight, [kg]	0,047
amount NCR18650PF, [pieces].	12096
Cost, [USD]	$36288
Weight (without case), [kg]	568512
PEMFC	
Power rating, [kW]	240
Amperage, [A_{dc}]	0 – 1000
Voltage, [W_{dc}]	240–480
Maximum efficiency, [%]	60

The battery pack consists of “Panasonic” NCR18650PF batteries.

The connection of the batteries to the units occurs in stages in the same blocks, which are then connected together. This, first, is necessary because all connected batteries and units must have the same parameters, otherwise the parameter with the smallest value will be used in the connection.

Block A consists of 3 sub-blocks connected in parallel, the subblock consists of 4 batteries connected in series.

Block B consists of 3 sub-blocks connected in parallel, the subblock consists of 4 blocks A, connected in series.

Block C consists of 5 sub-blocks connected in parallel, the subblock consists of 4 blocks B, connected in series.

Block D consists of 2 sub-blocks connected in parallel, the subblock consists of 2 blocks C, connected in series.

The energy transfer scheme for a modern commuter train is as follows: POMTE → DC / DC converter → Rechargeable battery (120 kW) → DC / AC step-up inverter → Traction electric motor → Gear drive from the traction motor to the wheel pair.

Previously, the efficiency of this transmission was determined by the formula, %,

$$\eta_{dt} = \eta_{pemfc} \cdot \eta_{kdc/dc} \cdot \eta_{bat} \cdot \eta_{inv} \cdot \eta_{mot} \cdot \eta_{tr}, \quad (1)$$

where η_{pemfc} – efficiency of PEMFC,%, in nominal mode, we accept η_{pemfc}= 60%;

$\eta_{kdc/dc}$ – KDC/DC converter efficiency, %, $\eta_{kdc/dc}$ =97.5%;

η_{bat} – battery efficiency, %, η_{bat}=98,01%;

η_{inv} – efficiency of boosting inverter, %, η_{inv}=97,5%;

η_{mot} – efficiency of traction motor, η_{mot}=95%;

η_{tr} – efficiency of gear transmission from the traction motor to the wheel pair, %,η_{tr}=97%.

As a result of calculations, the overall efficiency of the power transmission scheme for the upgraded train was obtained, which is equal to 51.51%.

The next stage of the calculations was the determination of the parameters of the operation of the individual elements of the circuit under various modes of movement of a suburban train.

For the rolling stock in question, we determine the following modes of operation:

– traction mode (PT);

– idling speed (XX);

– Regenerative braking mode (TP);

– mechanical braking mode with the use of brake pads (TK).

In the following calculations we assume:

- when driving in traction mode when charging accumulator batteries more than 20%, the electric power from the storage batteries (SB) is transferred to the boosting inverter (BI), and from it to the TEM.

- when driving in the traction mode with a SB charge equal to 20% or less, and provided that the SB charge is not enough to continue driving to the nearest stop, PEMFC is activated, which provides enough energy for the train to travel and power the auxiliary equipment.

- when driving idling, if the SB charge is less than 20% at the end of the rolling stock movement, the PEMFC turns on and continues to operate until the battery charge reaches the level at which the battery charge at the end of the train is at least 20 %. This condition may not be met only if after idle operation the regenerative braking mode is followed by further full stop, but in this case the battery charge can't be less than 5% at the end of the rolling stock in idle.

- braking mode with brake pads (BP) is intended only for complete stopping of rolling stock in 2 cases. 1 – with standard braking, the brake pads are pressed against the rim of the gearbox to stop the SS at a speed of 5 km / h; 2 – with emergency braking, brake pads are activated simultaneously with regenerative braking to ensure maximum braking force (controlled by a computer, PEMFC does not work).

- In the PT mode, the energy comes from the TEM through the inverter on the battery. PEMFC does not work.

- to increase the overall efficiency, the battery pack is fully charged from the network at the service points, before the rolling stock is sent to the flight.

When constructing the traction characteristics of a suburban train in accordance with [9-12], the following basic equations were used.

The torque on the wheel pair is determined by the formula, Nm,

$$M_k = M_{TM} \times \mu \times \eta_{gear} \quad (2)$$

where: M_{TM} – torque on the shaft of the traction motor, Nm;

μ - gear ratio;

η_{gear} - gear efficiency.

The driving force, which is accounted for by one traction motor, is determined by the formula, kN,

$$F_{kd} = \frac{2 \times M_k}{D_w} \quad (3)$$

where D_w – wheel diameter on rim (0,95м).

The tangential force of the traction of the entire rolling stock is determined by the formula, kN,

$$F_k = m \times F_{kd} \quad (4)$$

where m – number of traction electric motors in a suburban train.

The force of traction on the adhesion of wheels with rails is calculated by the formula, kN,

$$F_{сц} = \psi_к \times P_{сц} \quad (5)$$

where $P_{сц}$ - coupling weight of rolling stock, kN;

$\psi_к$ – coefficient of adhesion.

The results of calculations and construction of traction characteristics of the modernized suburban train are presented in Table 2 and in Fig. 2.

Table 2. Traction characteristics of a suburban train with an energy power plant on hydrogen fuel.

V, [km/h]	5	10	20	30	40
$F_{k.}$ [N]	82688	82688	82688	82688	82688
V, [km/h]	50	60	70	80	90
$F_{k.}$ [N]	82688	82688	75000	65000	60000
V, [km/h]	100	110	120	130	140
F_k, [N]	53000	47500	43500	40000	36500
V, [km/h]	150	160			
$F_{k.}$ [N]	35000	34500			

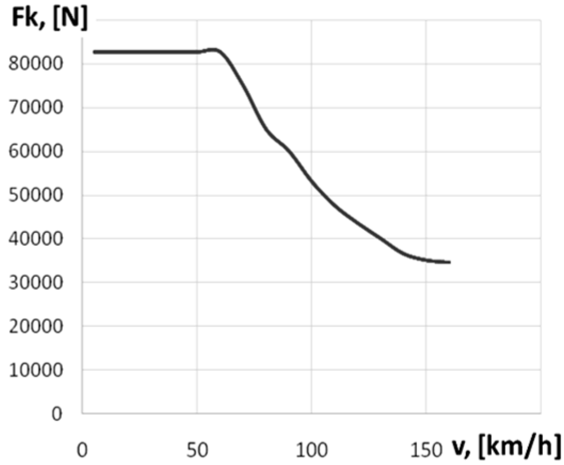


Fig. 2. Traction characteristics of a suburban train with an energy power plant on hydrogen fuel.

To verify the results obtained, traction calculations fulfilled The length of the route was chosen, the data for the site are shown in Table 3.

Table 3. Parameters of the study path.

Item number	Si, [m]	i, [°/oo]	Ri, [m]	Skri, [m]	alfa, deg	i used, [°/oo]
1	2	3	4	5	6	7
1	1400	0				0
2	1100	1,9	800	350		2,18
3	1800	2,3	900	550		2,54
4	1300	2	750	400		2,29
5	800	0	600	300		0,44
6	700	-3,1				-3,1
7	1100	-3,4				-3,4
8	700	0				0
9	1300	11				11
10	1400	5		650	20	5,38
11	1400	4,7		700	18	5.01
12	1300	1,6				1,6
13	900	3,8		700	15	4,06

Continuation of table 3.

1	2	3	4	5	6	7
14	800	2,8	900	300		3,09
15	400	3,9	800	150		4,23
16	500	0				0
17	1200	-8,1		600	25	-7,59
18	2300	-8,4		800	30	-7,94
19	2100	-8		650	24	-7,55
20	500	0				0
21	1600	-4.4	850	400		-4,19
22	1500	-4	900	500		-3,74
23	1200	-1				-1
24	1500	8		600	25	8,51
25	3300	8,5		650	22	8,91
26	1400	8,2		700	16	8,48
27	300	0				0
28	350	-3,4	800	150		-3,03
29	250	-3	900	150		-2,53
30	1900	-10,3				-10,3
31	500	0,6				0,6
32	1200	2,2				2,2
33	3500	-2,4				-2,4

The calculation of the retarding forces carried out according to known formulas [19].
The results of the calculations are presented in table 4.

Table 4. Calculation of the retarding forces acting on the train

V,[km/h]	5	10	20	30	40
F_k, [N]	82688	82688	82688	82688	82688
$w`_o$, [N/kN]	1,957	2,030	2,220	2,470	2,780
$w``_o$ [N/kN]	0,141	0,168	0,237	0,326	0,434
$W`_o$, [kN]	4087	4238	4635	5157	5804
$W``_o$, [kN]	327	390	550	756	1009
W_o, [N]	4413	4628	5185	5913	6813
F_k-W_o, [N]	78275	78060	77503	76775	75875
f_k-w_o, [N/kN]	37,49	37,39	37,12	36,77	36,34
w_x , [N/kN]	2,454	2,525	2,720	2,985	3,320
W_x, [kN]	5123	5272	5679	6232	6931
W_x+W_o, [N]	5450	5661	6229	6988	7940
w_{ox}, [N/kN]	2,297	2,338	2,456	2,623	2,837
f_i k_p, [N/kN]	0,227	0,198	0,162	0,140	0,126
B_t, [N]	112,9	98,6	80,6	69,9	62,7
b_t+w_{ox}, [N/kN]	2,351	2,385	2,494	2,656	2,867
0.5b_t+w_{ox} [N/kN]	2,299	2,340	2,457	2,624	2,838

Continuation of table 4

V, [km/h]	50	60	70	80	90	100
1	2	3	4	5	6	7
F_k, [N]	82688	82688	75000	65000	60000	53000
$w`_o$, [N/kN]	3,150	3,580	4,070	4,620	5,230	5,900
$w``_o$ [N/kN]	0,562	0,710	0,878	1,066	1,273	1,500
$W`_o$, [N]	6576	7474	8497	9645	10919	12318
$W``_o$, [N]	1307	1651	2040	2476	2957	3484
W_o, [N]	7883	9125	10537	12121	13876	15802
F_k-W_o, [N]	74805	73563	64463	52879	46124	37198
f_k-w_o [N/kN]	35,830	35,240	30,880	25,330	22,090	17,820
w_x , [N/kN]	3,725	4,200	4,745	5,360	6,045	6,800
W_x, [N]	7777	8769	9906	11190	12621	14197
W_x+W_o, [N]	9084	10419	11947	13666	15578	17681
w_{ox}, [N/kN]	3,099	3,409	3,768	4,174	4,629	5,131
f_i k_p, [N/kN]	0,116	0,108	0,102	0,097	0,093	0,090
B_t, [kN]	57,642	53,799	50,810	48,419	46,463	44,833
b_t+w_{ox}, [N/kN]	2,867	3,126	3,434	3,792	4,197	4,651
0.5b_t+w_{ox}, [N/kN]	2,838	3,100	3,410	3,769	4,175	4,630

Continuation of table 4.

V, [km/h]	110	120	130	140	150	160
F_k, [N]	47500	43500	40000	36500	35000	34500
$w`_o$, [N/kN]	6,630	7,420	8,270	9,180	10,150	11,180
$w``_o$ [N/kN]	1,747	2,013	2,299	2,605	2,931	3,276
$W`_o$, [N]	13842	15491	17266	19166	21191	23341
$W``_o$, [N]	4058	4677	5341	6052	6808	7611
W_o, [N]	17899	20168	22607	25218	27999	30952
F_k-W_o, [N]	29601	23332	17393	11282	7001	3548
f_k-w_o [N/kN]	14,180	11,180	8,330	5,400	3,350	1,700
w_x , [N/kN]	7,625	8,520	9,485	10,520	11,625	12,800
W_x, [N]	15919	17788	19802	21963	24270	26723
W_x+W_o, [N]	19977	22464	25144	28015	31079	34334
w_{ox}, [N/kN]	5,681	6,280	6,927	7,621	8,364	9,155
f_i k_p, [N/kN]	0,087	0,085	0,083	0,081	0,079	0,078
B_t, [N]	43,453	42,271	41,246	40,349	39,558	38,855
b_t+w_{ox}, [N/kN]	5,701	6,300	6,946	7,640	8,382	9,173
0.5b_t+w_{ox} [N/kN]	5,682	6,281	6,927	7,621	8,364	9,156

Calculation of the operating parameters of the equipment of the suburban train, consumption and return of energy when moving along a given section of the path are made on the basis of the parameters obtained in the graphical construction of motion curves. A fragment of the results and of the calculations presents in table 5.

Table 5. Fragment of traction calculations of a suburban train on hydrogen fuel at the site.

Item number	S	V	t	Added	Capacit
1	2	3	4	5	6
-	[m]	[km/h]	[s]	[kWt]	[%]
1-2	27	5	19,44	0,162	98,28
2-3	86	15	20,64	0,172	96,41
3-4	135	25	19,44	0,162	95,64
4-5	164	35	16,87	0,140	94,76
5-6	196	35	20,16	0,168	94,62
6-7	65	31,69	7,38	0,061	94,26
7-8	224	38,38	21,01	0,175	93,01
8-9	287	48,38	21,36	0,178	91,43
9-10	351	58,38	21,64	0,180	89,47
10-11	236	61	13,93	0,116	88,18
11-12	573	73,62	28,02	0,233	85,55
12-13	741	83,81	31,83	0,265	82,48
13-14	486	90,99	19,23	0,160	80,57
14-15	1193	98	43,82	0,365	76,13
15-16	106	103,43	3,69	0,030	75,74
16-17	800	106,03	27,16	0,226	72,85
17-18	700	108,24	23,28	0,194	72,6
18-19	1100	107.35	36,89	0,307	72,30
19-20	700	108,94	23,13	0,192	69,75
20-21	1100	111,83	35,41	0,295	65,74
21-22	1400	109,075	46,21	0,385	65,29
22-23	229	104,95	7,86	0,065	65,22
23-24	344	100,29	12,35	0,102	66,97
24-25	339	91,21	13,38	0,111	68,67
25-26	276	81,21	12,23	0,102	70,03
26-27	211	71,21	10,67	0,088	71,14
27-28	222	60,60	13,19	0,109	72,21
28-29	148	50	10,66	0,088	72,91
29-30	123	40	11,07	0,092	73,46
30-31	74	30	8,88	0,074	73,76
31-32	49	20	8,82	0,073	73,93
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75-76	300	104,49	10,34	0,086	18,78
76-77	350	103,98	12,12	0,101	18,58
77-78	250	103,64	8,68	0,072	18,45
78-79	1900	105,54	64,81	0,540	17,41
79-80	500	106,88	16,84	0,140	17,14
80-81	1200	104,45	41,36	0,344	16,47
81-82	1289	101,87	45,55	0,379	15,72
82-83	252	97,64	9,29	0,077	17,94
83-84	308	89,27	12,42	0,103	20,57
84-85	251	79,27	11,40	0,095	22,66

Continuation of table 5

1	2	3	4	5	6
85-86	94	72,13	4,69	0,039	23,46
86-87	164	65	9,08	0,075	24,79
87-88	134	55	8,77	0,073	25,83
88-89	110	45	8,80	0,073	26,63
89-90	85	35	8,74	0,072	27,24
90-91	61	25	8,78	0,073	27,62
91-92	37	15	8,88	0,074	27,81
92-93	6	7,5	2,88	0,024	27,85
93-94	9	2,5	12,96	0,108	27,66
		0	120	1	36,50

The obtained traction characteristic and verification calculations show that the power of the power plant on hydrogen fuel will be sufficient for efficient operation of the suburban train.

3. Conclusions

1. In work the international experience is considered the use of hydrogen as a fuel on rolling stock. Based on the fuel and economic indicators for a suburban train, the use of PEMFC as a power plant was chosen.
2. Technical parameters of the main equipment for a suburban train with a hydrogen fuel power plant, a scheme for energy transfer and transmission efficiency in general have been determined.
3. For the suburban rolling stock, the main modes of operation in operation have been identified and assumptions have been made in calculations taking into account the features of proton-exchange membrane fuel cells.
4. An algorithm is proposed for constructing the traction characteristics of a suburban train on hydrogen fuel and a dependence of the traction force on the speed for the modernized rolling stock is constructed.
5. In the perspective of further research, the results could be extended by emission analysis and emission reduction of toxic compounds, for example [CO2].
6. In subsequent work, it is necessary to develop systems using proton-exchange membrane fuel cells on the train DPKr2, conduct their tests and specify the payback period of the train. Particular attention should be paid to solving the issue of logistics of production and supply of hydrogen to the points of refueling in the conditions of Ukraine.

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