Temperature calculation for linear induction motor in transport application with multiphysics approach

To cite this article: F N Sarapulov *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **966** 012105

View the article online for updates and enhancements.

Temperature calculation for linear induction motor in transport application with multiphysics approach

F N Sarapulov[1, 3], V Goman[2] and G E Trekin[2]

[1] Ural Federal University named after the First President of Russia B N Yeltsin, 19, Mira str., Yekaterinburg, 620000, Russia
[2] Ural Federal University named after the First President of Russia B N Yeltsin, Nizhniy Tagil Technological Institute, 59, Krasnogvardeyskaya str., Nizhniy Tagil, 622000, Russia

E-mail: [3] sarapulovfn@yandex.ru

Abstract. The article describes the implementation of the mathematical model of the interrelated electromechanical and thermal processes in a linear induction motor using simulation software MATLAB-Simulink. The developed model consists of electromechanical model, thermal model and cooling system (hydraulic) model which all affect each other. Temperature calculations of the traction single-sided linear induction motor for urban transportation system are performed for different regimes. The calculation results using the developed thermal model based on the thermal detailed equivalent circuit demonstrate a close concurrence with the finite element model, temperature values differ less than in 3.8-4.8%. Safe operation range for a traction linear induction motor was determined taking into account the uneven longitudinal heating using different variants of cooling systems and coolant flow values. Recommendations on their selection were formulated. Based on the calculations and following experimental testing it was determined that operation with the maximum load with current of 270 A and load force of 8,000 N is possible with the cooling air flow rate of at least 2.2 m³/s.

1. Introduction

Linear induction motors (LIM) are a high potential type of the electric drive motor for the vehicular application, particularly for the high-speed passenger transport. This type of transport is highly relevant to the modern metropolitan cities. Many articles, such as [1-5] are dedicated to the development and optimization of LIM design for that specific use.

Investigations of the LIM are complicated by the fact that they noticeably differ from the rotary electric motors by the course of the electromagnetic processes, due to the longitudinal and transverse edge effects. These effects and peculiarities of LIM are well-studied and described in [6-10].

LIM also have significant differences in principles of thermal processes caused by construction features, as well as electromagnetic asymmetry lengthwise due to the longitudinal edge effect [11]. Many results obtained in a course of analysis of the thermal exchange in rotary motors are applicable to linear motors, for instance [12-16]. A series of publications are devoted to investigation of the thermal processes either in tubular linear motors [17, 18], or in linear synchronous motors which differ from the induction motors in their principle of operation [17-19]. In certain cases, LIMs are similar to induction heating units by principle of their operation, and specific approaches from this area can also be applied [20]. Therefore, an investigation of the electric drive operation modes based on LIM is relevant from the

perspective of thermal condition, taking into account a cooling method, in relation to the electromechanical processes. The necessity of such analysis may occur in a process of linear motor design. As a rule, objectives of a design process are optimization of the energy characteristics, reduction of losses, lowering the LIM components heating to the permissible level in operational modes.

2. Methods

In a designed model of interrelated electromechanical and thermal processes, the temperature effects of the LIM parts on the electromechanical characteristics and on the loss values are taken into account [11, 21]. The calculations of the LIM traction force, the losses in the primary and secondary based on detailed LIM electric and magnetic equivalent circuits were carried out according to the methodology [22, 23].

The model implemented in Simulink consists of 5 major elements (figure 1): 'Signal Builder' which sets the speed setpoint 'Velocity SP' and load force 'FL'; drive model 'Drive', which has such output parameters as velocity of a secondary, traction force 'Ft', electric current density 'J', loss vectors in the primary 'Pp' and secondary 'Ps', including the losses in electric winding (or conductive plate) and magnetic core (or back iron) according to the established detailing of the model in longitudinal coordinate; subsystem of the coolant velocity calculation in the channels ('Hyd. Model' in figure 1). Subsystem input parameter is a coolant flow velocity at the cooling system input. In figure 1, an example of a self-ventilation, when the air flow velocity is equal to the velocity of LIM moving part is shown. Output parameters of the subsystem are velocities of the coolant in cooling system channels 'Vi'; 'Thermal Model' subsystem with such input parameters as the temperature vectors of primary 'Tp' and secondary 'Ts', composed of the electric winding zones temperatures (conductive plate for the secondary) and magnetic core (back iron for the secondary) according to the established detailing of the model in longitudinal coordinate; given parameters are brought to 'Scope' - virtual oscilloscope using links. Similarly, the LIM temperature effects on the electromechanical processes are taken into account using links inside the 'Drive' unit (figure 2) and are not shown in figure 1. A subsystem's input parameters are the loss vectors in primary 'Pp' and secondary 'Ps' and coolant velocity in cooling system channels 'Vi'; a subsystem COMSOL Multiphysics aimed at the carrying out the thermal model verification in some operation modes by means of finite element method (FEM).
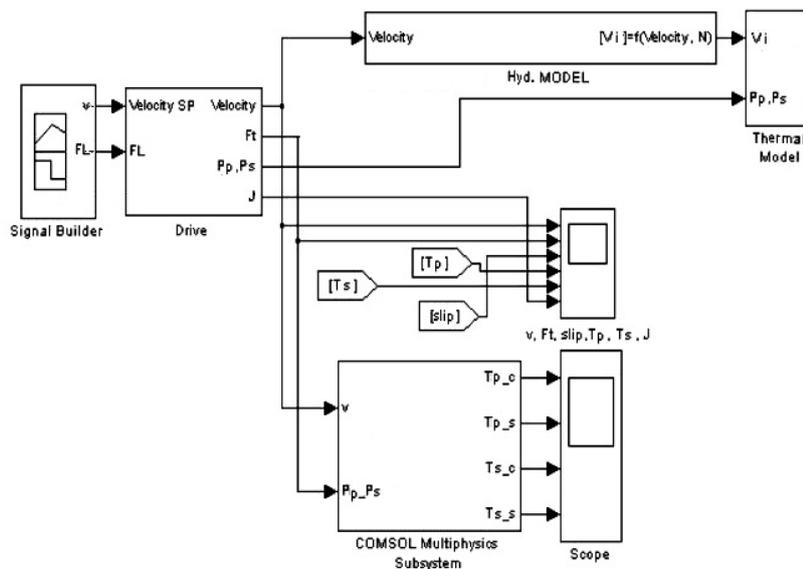

Figure 1. Model of LIM interrelated processes built in Simulink.
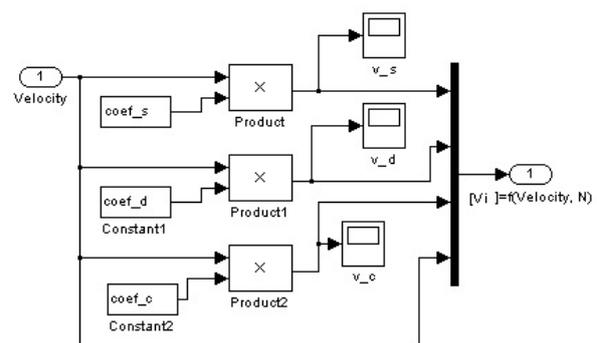
Drive subsystem includes the model of a scalar control system (*U/f* = const), LIM electromechanical model, the model of the loss calculations in the primary and secondary in the form of numeric multidimensional arrays. Electromechanical model of a LIM built in Simulink based on the four-dimensional array is shown in figure 2. Given approach, which is described in detail in the [21], allows

to avoid direct solving of different submodels, characterizing different-scale time-dependent processes: thermal, mechanical and electromagnetic. For the investigated LIM, the arrays of traction forces and losses at different power supply frequencies, slips (which is the function of the load) and temperatures of the primary winding and secondary conductive plate are preliminarily filled in. This allows for approximately tenfold reduction of thermal transient process calculation since interpolation and value selection from the multidimensional array proceed much faster than direct calculation based on the electromechanical model for the current combination of frequency, slip and temperatures of LIM parts.

Similar approach is applied to the hydraulic model of a cooling system as well. The initial data for the calculation is the cooling system configuration, the quantity of the channels and their parameters, such as length, cross sections and roughness of inner surface, presence of local elements such as curves, constrictions, broadenings, etc. A system of equations using the electrohydraulic analogy, i.e. Kirchhoff's laws, was compiled for the cooling system [24]. The solution of a system of equations required 5-7 iterations, because some of hydraulic resistance values depend on the coolant flow rate which was taken into account using recommendation of [25]. Therefore, in a general model of interrelated processes the results of such calculation for the required set of coolant velocities in cooling system input were presented in the form of simplified analytical expressions obtained in [21, 24] and sets of coefficients for the coolant velocities in slotted channels 'coef_s', distributive branch 'coef_d', collecting branch 'coef_c', as it is shown in figure 3. This approach made it possible to sufficiently reduce time for calculations of LIM thermal transient processes which have complicated multichannel cooling systems.
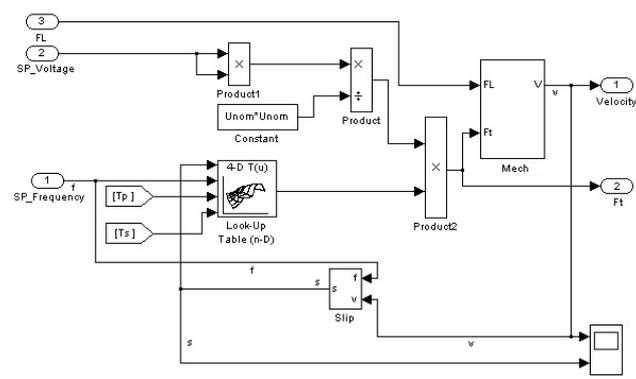
| **Figure 2.** Electromechanical model of a LIM in Simulink based on the four-dimensional array. | **Figure 3.** Simple hydraulic model of a cooling system in Simulink. |

The structure of a thermal model is shown in figure 4. The model combines the following types of subsystems: zones of the 'Central block' primary active zone comprising the primary and secondary, 'Left Block Inductor' and 'Right Block Inductor' characterized in that the additional heat exchange due to convection and by radiation from the primary external surfaces is additionally considered therein; zones of secondary before entering the active zone '(Left End Zone') and after leaving it ('Right End Zone'); first or second kind boundary conditions simulation block.

Thermal circuit is built on the basis of thermal detailed equivalent circuit of a LIM presented in [11]. The following peculiarities are taken into consideration: heat removal from the active zone during the motion of a moving part; uneven longitudinal distribution of losses due to the longitudinal edge effect and different heating levels of the construction elements; losses in secondary outside the active zone; steel losses in magnetic cores; LIM elements temperature effects on the electromechanical characteristics and losses; thermal conductivity between the construction elements; heat exchange with the environment by means of radiation, between the primary and secondary; heat transfer from the construction external surfaces with regard to the conditions of natural or forced convection; equivalent thermal conductivity of slot and frontal parts of windings in different directions with regard to the insulation thermal conductivity; dependence of the thermal conductivity coefficient on temperature.

3. Result and discussions

The calculation of the traction single-sided LIM for the transportation system was made using the described model. Empty train weight − 14-58 tons (if the number of carriages varies from 2 to 10); the maximum carriage capacity − 34 passengers.
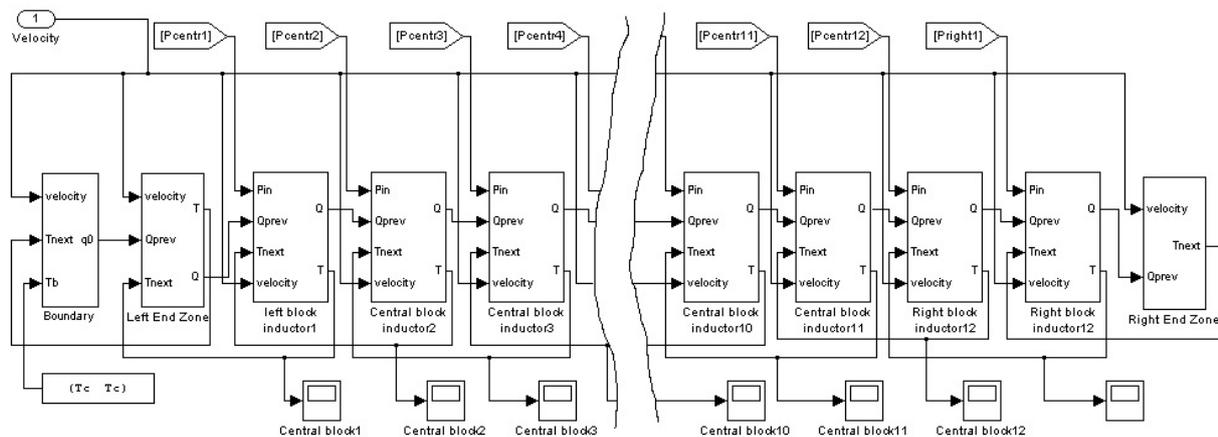

Figure 4. Thermal model of a LIM in Simulink.

While designing traction LIM the restrictions on the width have been imposed. Consequently, the winding scheme as in figure 5 has been accepted, as it provides the minimum length of the frontal parts. However, in this case almost all slots turned out to be half-filled. Restrictions on the dimensions have led to the excessive heating, since winding temperatures would not exceed the permissible ones only in case the train had a small number of passengers on board. To solve this problem a decision on cooling system development is made. The housings have been installed around the frontal parts, forming the channels which are ensuring the circulation of a cooling air through the frontal parts and half-filled slots. The calculation results of the cooling system were described in detail for the first time in the study [24]. In the [24], the charts of velocities distribution, coolant flow and pressure by primary's zones were obtained for the following cases: natural cooling: velocity of cooling air in inlet of cooling system is equal to the train velocity; forced cooling, for the air flow rate of 0.11-2.2 m³/s.

Table 1. Traction LIM parameters of the urban transportation system.

| Parameters	Value	Parameters	Value
Frequency supply	5-40 Hz	Height of the primary core	110 mm
Phase voltage RMS	40-240 V	Length of the primary core	1,740 mm
Phase current	70-270 A	Slot pitch	35 mm
Number of phases	3	Number of slots	50
Maximum traction force	8,000 N	Width of the secondary conductive plate	400 mm
Synchronous speed (at 23.2 Hz)	10 m/s	Thickness of secondary conductive plate	6 mm
Number of poles	8	Width of secondary solid back iron	400 mm
Number of turns in a slot	14	Thickness of secondary solid back iron	20.7 mm
Width of the primary core	240 mm	Air gap	10

The calculation results of the thermal model based on the thermal detailed equivalent circuit for the same cases and modes are shown in figure 6 and are demonstrating a close concurrence within 3.8-4.8%. Verification of the designed model of thermal processes is performed with the help of the model based on the FEM. Figure 7 shows FEM mesh and results of temperature calculation at phase current of 135 A in a full-filled slot no. 2 which has the worst cooling conditions and the highest thermal generation. In case of natural convection (figure 7, b) the temperature of the winding constitutes 186 °C, which corresponds to the limitation of the start-up force of 1,850 N typical for the empty train. In case of air flow velocity in the gap is 0.1 m/s (figure 7, c), the temperature of a winding decreases to 157 °C.
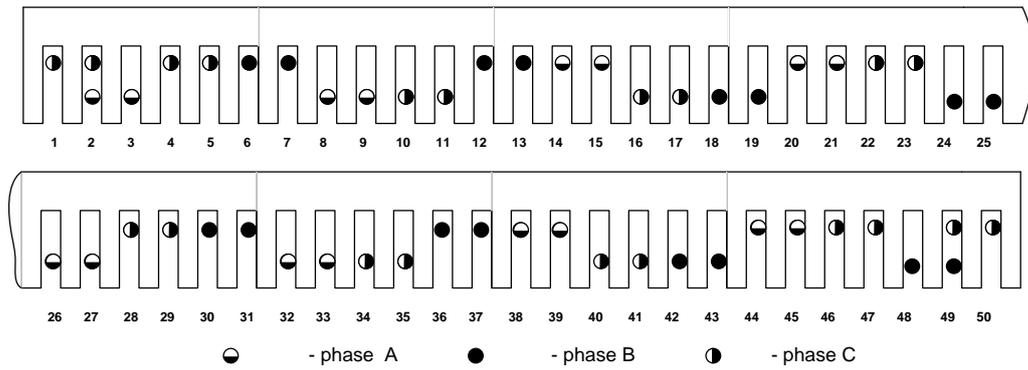
Figure 5. Scheme of the primary winding.

(a)　　　　　　　　　　　　　　　　　(b)
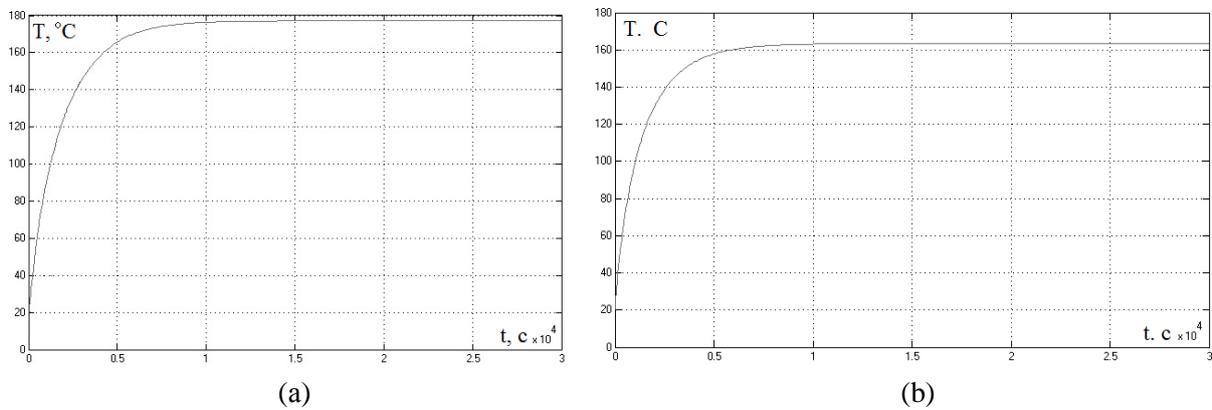
Figure 6. Primary winding temperature in slot no. 2 of a traction LIM (equivalent thermal circuit model). (a) natural convection; (b) forced convection in the air slot at the velocity of 0.1 m/s

(a)　　　　　　　　　　(b)　　　　　　　　　　(c)
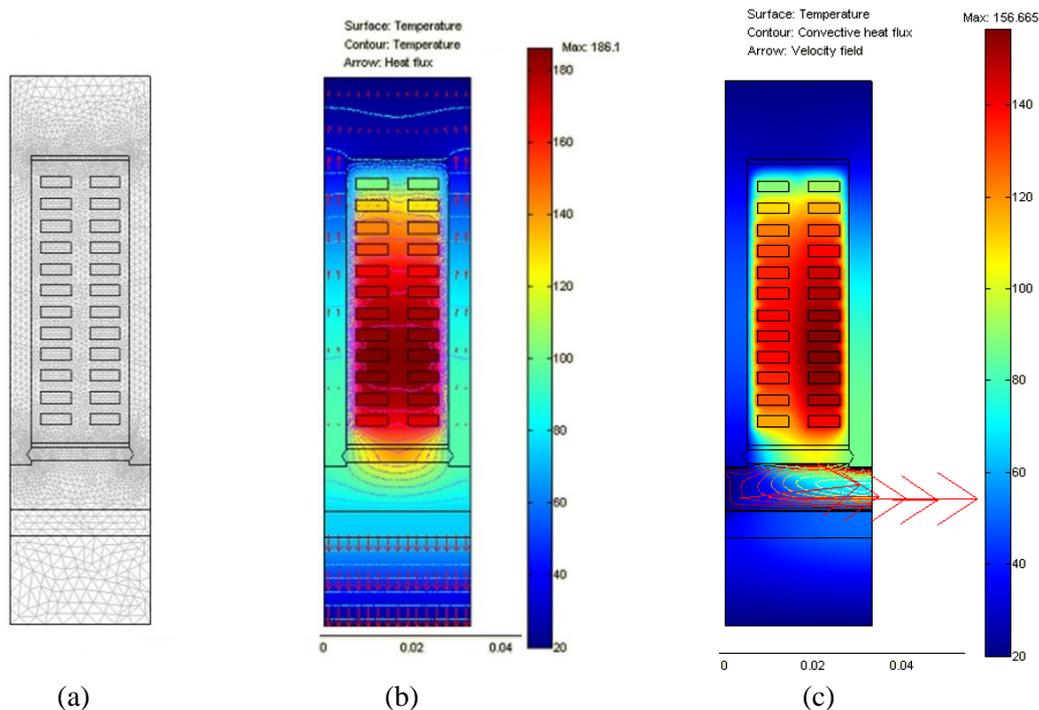
Figure 7. Temperature distribution in slot no. 2 of a traction LIM (FEM-model). (a) slot area and finite element mesh; (b) natural convection; (c) forced convection in the air gap at the velocity of 0.1 m/s.

4. Conclusion

As a result of performed research a mathematical model for the LIM thermal processes was built, with the help of which the analysis of interrelated thermal and electromechanical processes of an urban transportation system traction LIM was carried out. Verification of the model by finite elements method is performed for the number of modes. Safe operation range for a traction LIM (primary winding phase current values) was determined taking into account the uneven longitudinal heating using different variants of cooling systems and air flow values, and recommendations on their selection were formulated [11, 21]. Based on the calculations and following experimental testing it was determined that LIM operation with the maximum load (current of 270 A, load force of 8,000 N) is possible with the cooling air flow rate of at least 2.2 m³/s.

References

[1]   Huang S, Ching T W, Li W and Deng B 2018 *IEEE 27th Int. Symp. on Ind. Electron. (ISIE)* (Cairns, QLD) pp 150-4
[2]   Abdollahi S E, Mirzayee M and Mirsalim M 2015 *IEEE Trans. Magnetics* **5 7** pp 1-7
[3]   Lu Q, Li Y, Ye Y and Zhu Z 2013 *IEEE Trans. Energy Conversion* **28** pp 145-153
[4]   Lu J and Ma W Jan. 2011 *IEEE Trans. Plasma Sci.* **39 1** pp 116–120
[5]   Lv G, Zeng D, Zhou T, and Liu Z Jun. 2017 *IEEE Trans. Ind. Electron.* **64 6** pp 4382-90
[6]   Boldea I 2013 Linear Electric Machines, Drives, and MAGLEVs Handbook (CRC Press)
[7]   Yamamura S 1979 Theory of Linear Induction Motors (New York, NY, USA: Halsted)
[8]   Gieras J F 1994 Linear Induction Drives (London, U.K.: Oxford Univ. Press)
[9]   Laithwaite E and Barwell F 1969 *Proc. IEE* **116 5** pp 713-24
[10] Bolton H 1969 *Proc. IEE* **116 5** pp 725-31
[11] Sarapulov F N and Goman V V 2009 *Russ. Electr. Engng.* **80** pp 431-35
[12] Boglietti A et al. Mar. 2009 *IEEE Trans. Ind. Electron.* **56 3** pp 871–82
[13] Staton D A and Cavagnino A 2008 *IEEE Trans. Ind. Electron.* **55 10** pp 3509–16
[14] Madonna V, Walker A, Giangrande P, Serra G, Gerada C and Galea M 2019 *IEEE Trans. Ind. Electron.* **66 7** pp 5057-69
[15] Boglietti A, Carpaneto E, Cossale M, Vaschetto S, Popescu M and Staton D 2015 *IEEE Energy Conversion Congress and Exposition (ECCE)* (Montreal, QC) pp 4865-71
[16] Boglietti A, Cavagnino A and Staton D 2008 *IEEE Trans. Ind. Appl.* **44 4** pp 1150-59
[17] Huang X, Li L, Zhou B, Zhang C and Zhang Z 2014 *IEEE Trans. Ind. Electron.* **61 8** pp 3923–31
[18] Vese I, Marignetti F and Radulescu M M 2010 *IEEE Trans. Ind. Electron.* **57 1** pp 320-26
[19] Tessarolo A and Bruzzese C 2015 *IEEE Trans. Ind. Electron.* **62 3** pp 1410-20
[20] Prakht V A, Dmitrievskii V A, Sarapulov F N, Dmitrievskii A A and Safin N A 2014 *COMPEL* **33 1/2** pp 273-85
[21] Goman V V 2006 Thermal processes in linear induction motors and their mathematical modelling (Teplovie processi v lineynih asinhronnih dvigatelyah i ih matematicheskoe modelirovanie) [in Russian] PhD Thesis, Russia, Yekaterinburg, Ural State Technical University
[22] Dmitrievskii V, Goman V, Sarapulov F, Prakht V and Sarapulov S 2016 *Int. Symp. on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)* (Capri, Italy) pp 458–63
[23] Sarapulov F N, Frizen V E, Shvydkiy E L and Smol`yanov I A 2018 *Russ. Electr. Engng.* **89** pp 270–74
[24] Sarapulov F N and Goman V V 2010 *Transport Electronics and Electrical Equipment (Electronica i electrooborudovanie transporta)* [In Russian] **4** pp 29-32
[25] Idelchik I E 1994 *Handbook of Hydraulic Resistance - Coefficients of Local Resistance and of Friction* 3rd ed (CRC Begell House)