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EXPERIMENTAL INVESTIGATIONS OF TWO-LEVEL TEMPERATURE CONTROLLERS FOR TRANSPORT THERMOELECTRIC REFRIGERATORS

This paper presents the problems of energy saving in transport thermoelectric refrigerators equipped with temperature controller, and describes the results of testing the selected object, namely embedded into furniture section thermoelectric refrigerator with compartment volume 27.7 dm^3 with different supply circuits from on-board mains, allowing practical implementation of the idea of two-level temperature control. The possibility and expedience of using this type of control with indication of concrete most efficient technical solutions is proved experimentally. The specific power consumption of tested refrigerator as compared to ON-OFF control has been reduced, on the average, by a factor of 3.

Key words: thermoelectric refrigerator, temperature control, electrical power, energy saving.

Introduction

In our everyday life we use increasingly often the concept of "energy security" integrating technical, organizational and political problems. The former can be solved on different levels and in different aspects, starting from replacement of incandescent lamps in apartments and offices by energy-saving lamps and ending in diversification of energy supply in certain country or region. Cooling equipment and air conditioners used in industry, transport and everyday life account for 20 to 80 % in the structure of nationwide energy consumption [1-6].

As had been shown in the previous works of the members of Air Conditioning and Refrigerated Transport Department of West Pomeranian University of Technology in Szczecin [7, 8], the use of two-level temperature control in compartments of various-purpose thermoelectric refrigerators (hereinafter TER) is the most efficient and at the same time accessible method for reduction of their energy consumption. For the first time this method whereby thermostat switches power of thermoelectric refrigerator cooling unit from a higher to lower voltage level was used in the design of TER-40 "Chaika" of the volume of 40 dm^3 [9]. However, the above refrigerator was not designed for continuous operation in energy saving working mode referred to by the authors as "pause current" mode. Moreover, prior art solution, as well as its later modifications, prevented from implementing the idea of two-level control when powering the refrigerator from on-board vehicle mains with a nominal voltage 12 or 24 V DC.

The object, purpose and results of preliminary test stage

As the object of test, a thermoelectric cooler with compartment volume 27.7 dm^3 embedded into furniture section was taken. This refrigerator type is used in ship and yacht cabins, trailers, auto shops, railway carriages, planes and other transport means. The internal dimensions of thermoelectric refrigerator compartment: width – 440 mm, depth – 240 mm, height – 262 mm. The compartment is made of lumber- core board 18 mm thick and heat insulation layer of polystyrene foam plate 30 mm thick. The refrigerator cooling unit comprises two thermoelectric modules of the type T-2-1.6-127 ([10], appendix 1), two heat sinks of the same type made of aluminum shapes (one on the cold and one on the hot side of the unit) and two axial fans[1] of the type VD 9225 HS, installed on each heat sink and powered by nominal voltage 12 V DC.

The refrigerator also comprises a manometric thermostat of the type Danfoss 077B7008 and electromagnetic relay of the type R8 powered by nominal voltage 12 V DC. The thermostat sensor is in a direct contact with the cold heat sink surface.

The test bench comprises several supply sources (hereinafter SS), i.e. alternating to direct current converters with output voltage and/or current stabilization. Some of their characteristics are represented in Table 1. In the test, the source PowerLab RXN3010D was predominantly used.

<u>*Table 1*</u>

Main specifications of supply sources (SS)

SS type	Control range	Resolution	Voltage/current stabilization
BP-20 (custom-made)	12…22 V up to 5 A	0.01 V* 0.01 A*	–/–
M10-DP two-channel	2 × 0…30 V 2 × 0…5 A	0.1 V, 0.01 V* 0.1 A, 0.01 A*	+/+
PowerLab RXN3010D	0…30 V 0…10 A	0.1 V, 0.01 V* 0.1 A, 0.01 A*	+/+

* – when using external devices of M838 type.

The measuring part of the test bench consists of 8-channel data recorder AR205 with J type thermocouples connected to its inputs. In temperature measurement mode the device resolution was 0.1 K. In the test, the following temperatures were measured: ambient air, the cold and hot heat sink surface, chamber air at three points at various heights according to appropriate standard requirements. Verification of temperature measurements was carried out using digital temperature meters: 10-channel CR7701-02 with thermocouples of *L* type and single-channel CR7702 with a thermistor of resistance 50 Ω. Both meters have class 0.05 accuracy with a resolution of 0.1 K. The general view of the test bench and refrigerator is represented in Fig. 1.

Fig. 1. Transport thermoelectric cooler (as seen from thermoelectric unit) during the test.

Daily electric energy consumption is measured using Energy Logger electron meters (models 3000 and 3500) with 1 W·h of resolution, which is extremely important for testing devices with low power consumption. In addition to high measurement

[1] It means that technical solution with forced compartment air convection typical of modern thermoelectric refrigerator models has been selected.

precision, several-fold reduction of test time is achieved. Apart from electric energy consumption, Energy Logger meters assure measurement of the following parameters: current values of AC voltage and current strength, mains current frequency, power factor (cos φ), effective and apparent current values of power consumption (see Fig. 2), and, on introduction of proper electricity tariffs, the cost of energy consumption is calculated with regard to the difference in day and night tariffs. Parameter measurement frequency is 1 second. The Energy Logger 3500 model offers the opportunity of on-line recording and transfer of data to a computer. Verification of electric energy consumption measurement was done with the aid of electromechanical energy meter of the type SO-I446. Time was registered by a timer with 1 second of resolution.

Fig. 2. Work moment of electric parameter recording.

Selected were 5 variants of electrical supply circuit of thermoelectric refrigerator cooling unit which are represented in Table 2 and in Fig. 3. All variants provide for power switching for a group of two thermoelectric modules when passing from a parallel to series connection, whereby each module voltage is reduced from 12 V to 6 V DC. The variants differ from each other in the way of connection and switching of fans M1 and M2. In variant I (circuit *a*) the voltage of fans in both operating modes is not varied and makes 12 V. In variant II (circuit *b*) only the internal fan M2 is switched over to lower voltage. In variant III (circuit *c*) both fans are switched over to voltage 6 V. In variant IV (circuit *d*) the fans are constantly powered by voltage 6 V. In variant V (circuit *e*) in working mode fan M1 is powered by voltage 12 V, and fan M2 is idle, while in “pause current” mode both fans are powered by voltage 6 V.

Table 2

Plan of experiment with a change in supply circuits of thermoelectric refrigerator

Unit working mode	Connection			
	Modules	external fan M1	internal fan M2	Variant number /circuits
“operation”	Parallel (12)	12	12	I, II, III (Fig. 3 *a*)
		6	6	IV (Fig. 3 *d*)
		12	0	V (Fig. 3 *e*)
“pause”	Series (6)	12	12	I (Fig. 3 *a*)
		12	6	II (Fig. 3 *b*) V (Fig. 3 *e*)
		6	6	III (Fig. 3 *c*) IV (Fig. 3 *d*)

*0, 6, 12 – supply voltage of this element

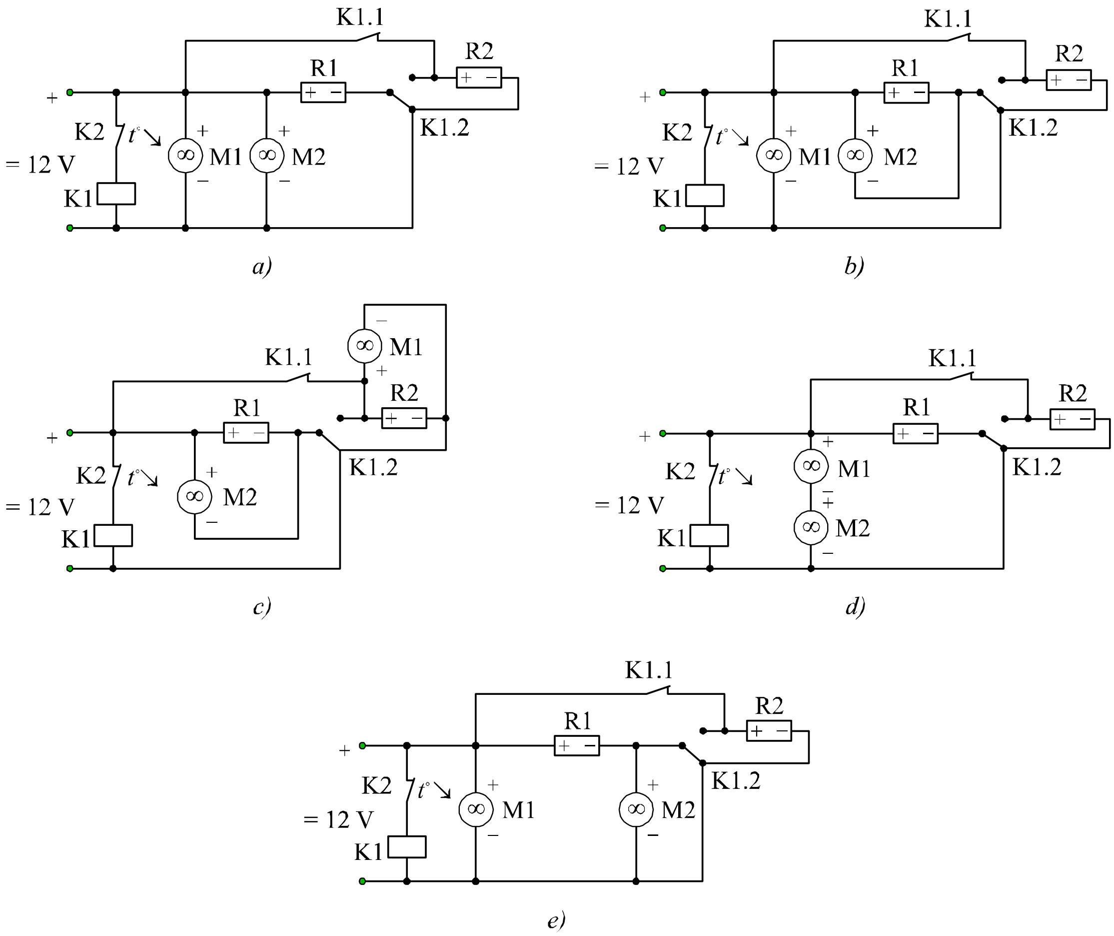

Fig. 3. Selected variants of electrical supply circuits of cooling unit of refrigerator under test.

Operating mode without temperature control at constant voltage 12 V and operating mode ON-OFF type control were assumed as a basis for comparison. Study of these two modes was the essence of preliminary test stage, and its objective was:

- experimental validation of the functionality of chosen supply circuits with a two-level temperature control in thermoelectric refrigerator compartment;
- revealing the influence of selected parameters on electric energy consumption of object under study, i.e. transport thermoelectric refrigerator (during this stage we decided to restrict ourselves to a change in supply voltage in the range from 6 to 14 V with a step 0.5 V and a change in thermostat setting);
- comparative analysis of thermoelectric refrigerator's electric energy consumption with different methods of temperature control.

Preliminary tests were performed at the same constant ambient temperature 22 °C, at different thermostat settings, with an empty compartment and in the absence of its lighting. The temperature in test room was maintained at the constant level to an accuracy of $\pm$ 0.3 K by means of air-conditioner Sanyo, model SAP KR(CR)127EHAX. The main measured parameter was thermoelectric refrigerator's daily electric energy consumption. Additionally measured and calculated were: time from the moment of start to the moment of reaching the lowest average temperature in the compartment (at constant operation), time to first thermostat actuation, operating time, pause time, cycle time, operating time factor (with a cyclic operation). Electric energy consumption was measured from the moment of thermoelectric refrigerator start, but for comparative analysis we took into account the consumption in the period of steady-state operation of refrigerator, the onset of which is determined in conformity with the concepts described in [7]. Other important peculiarities of test procedure are represented below when discussing particular results.

Preliminary test results are represented in Tables 3 and 4. In continuous working mode the average air temperature in refrigerator compartment has reduced to 4.3 °C. The registered temperature difference between the compartment air and the cold heat sink made 2.2 °C, which should be considered a very good result as compared to prior art constructions of thermoelectric refrigerators with a fan in the compartment described in [7], [8], [10].

Table 3

Results of refrigerator test in basic working modes

Measured and calculated characteristics	Working modes		
	Continuous operation	ON-OFF	ON-OFF
Thermostat setting	7 (min)	1 (max)	2
Temperature [°C]:			
Average compartment temperature in steady-state working mode and at the instants of thermostat actuation	4.3 –	9.5 7.3/11.6	7.6 5.2/10.0
Average temperature of cold heat sink or its temperatures at the instants of thermostat actuation	2.1	5.0/10.4	2.9/8.5
Average temperature of hot heat sink or its temperatures at the instants of thermostat actuation	32.0	32.6/23.2	32.0/23.0
Temporal			
Time to achieve steady-state working mode [min]	150	30[1] 108[2]	65[1] 50[2]
Time of cycle (time of “operation” mode + time of “pause” mode) [s]	–	1270 (840 + 430)	2115 (1620 + 495)
Working time factor [–]	–	0.661	0.766
Electric and energy			
Unit supply voltage [V]	12.00	12.0/0	12.0/0
Strength of unit supply current in steady-state mode or at the instants of thermostat actuation [A]	5.14	5.46/5.22/0	5.32/5.12/0
Unit power consumption in steady-state working mode or at the instants of thermostat actuation [W]	61.7	65.5/62.6/0	63.9/61.4/0
Power consumption of supply source (from AC mains) [W]	157.2	169.1/158.2/27.3	169.0/156.3/27.4
Average electric efficiency of supply source [–]	0.392	0.399[3]	0.399[3]
Daily energy consumption of supply source [kWh]	3.78	2.72	3.10
Daily energy consumption of unit [kWh]	1.48	1.01	1.15
The factor of specific power consumption P_{spec} of refrigerator [W/dm^{3}K]	0.126	0.185	0.157

[1] – time to the first actuation of thermostat; [2] – time of cycle parameters stabilization; [3] – in “working” mode.

Table 4

Supply voltage dependence of thermoelectric refrigerator and supply source parameters in continuous working mode

Supply voltage of the unit U, [V]	Current strength I, [A]	Power consumption of the unit P_u, [W]	Power consumption of supply source P_{ss}, [W]	Average electric efficiency of supply source ε_{ss}, [–]	Average compart-ment tempera-ture T_{comp} [°C]	Cold heat sink tempera-ture T_c [°C]	Hot heat sink temperature T_h [°C]
5.0	2.09	10.5	60.9	0.172	9.0	6.5	26.4
6.0	2.54	15.2	68.0	0.224	7.7	5.3	27.0
7.0	2.96	20.7	75.2	0.276	6.4	4.0	27.8
8.0	3.40	27.2	114.2*	0.238*	5.5	3.0	28.4
9.0	3.84	34.6	126.0	0.274	4.8	2.5	29.2
10.0	4.28	42.8	135.8	0.315	4.7	2.4	30.6
10.5	4.50	47.3	141.2	0.335	4.6	2.3	30.9
11.0	4.72	51.9	146.2	0.355	4.5	2.2	31.2
11.5	4.93	56.7	151.8	0.374	4.4	2.2	31.6
12.0	5.14	61.7	157.2	0.392	4.3	2.1	32.0
12.5	5.35	66.9	163.9	0.408	4.4	2.1	32.5
13.0	5.55	72.1	166.4	0.433	4.5	2.2	33.1
13.5	5.75	77.6	172.1	0.451	4.5	2.2	33.5
14.0	5.95	83.3	176.8	0.471	4.6	2.3	34.1

* – stepwise change in P_{ss} (u) and ε_{ss} (u) dependences is related to supply source construction and follows from dividing voltage control range into sub-ranges, one of the boundaries between the sub-ranges being close to voltage 7.1 V.

The values of power consumption and daily energy consumption of supply source and thermoelectric refrigerator were determined. Moreover, in order to facilitate subsequent comparative analysis, the factor of specific power consumption was determined [7] whose values are represented in Table 3.

At ambient temperature 22 °C the use of chosen thermostat type in refrigerator under test allows two-level temperature control in its compartment only in setting range from ① to ②. This restriction, no doubt, narrows down possible range of temperature setting in compartment, but does not complicate comparative analysis that can be explained as follows. On the one hand, expansion of thermostat dead band upwards, i.e. above 7.3 °C[2], does not fit in the concept of general-purpose

[2] With the adopted tuning scale it would imply its change, for instance, from ① to ⓪.

refrigerator, and, on the other hand, reduction of actuation temperature below 2.1 °C (which is identical to transition from setting ② to ③) will bring about the situation when no thermostat actuation takes place and the unit will remain in continuous working mode.

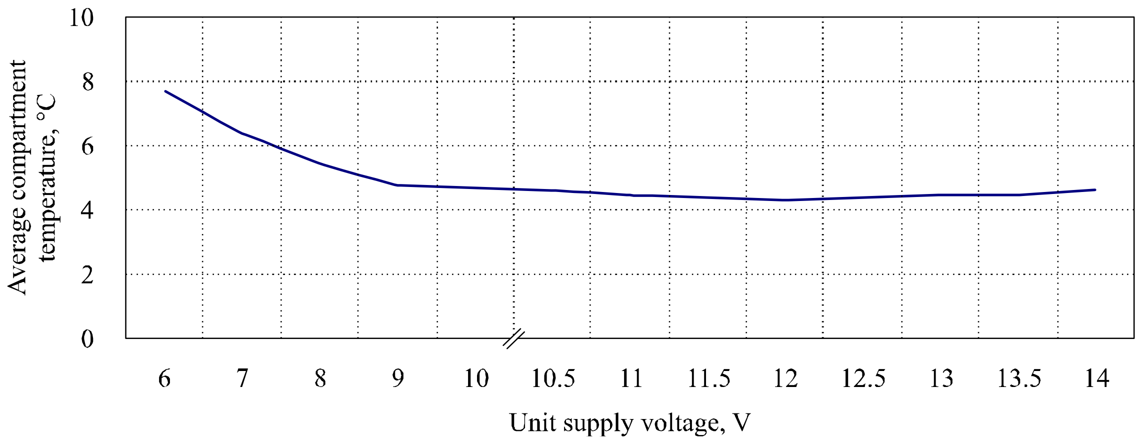

Fig. 4. Average temperature in thermoelectric refrigerator compartment versus supply voltage in continuous working mode at ambient temperature 22 °C.

Analysis of results represented in Table 4 shows that minimum average compartment temperature T_{comp} corresponds to supply voltage 12.0 V. This result testifies to correctness of underlying technical solutions for continuous working conditions. A very flat type of the dependence T_{comp} [U] in the region of voltage variation from 9 to 14 V (Fig. 4) qualitatively well coincides with the results obtained for thermoelectric refrigerators of other types [10], [11], including those without a fan in the compartment [12]. This feature of thermoelectric refrigerator should be estimated as positive, since it makes the refrigerator less sensitive to supply voltage variations and voltage changes due to switching from the battery (12 V) to the generator of on-board vehicle mains (13.5...13.8 V).

A relatively small difference in temperatures T_{comp} with different supply voltages 12 V and 6 V (4.3 °C and 7.7 °C, respectively) allows the following conclusions:

– the refrigerator remains functional in a very wide range of supply voltage variation;
– according to the results of refrigerator test in basic working modes it can be expected that, with no change in the supply circuit of the fans, switching of modules power supply from a parallel to series circuit will not raise chamber temperature so high as to cause a reverse thermostat actuation and return to working mode. That is, the unit will continue working in the energy saving mode (“pause current”), when power consumption is about 4 times less than in working mode. This implies the possibility of achieving the same effect that was obtained in thermoelectric refrigerators powered from alternating current mains with the use of supply sources specially designed for this purpose. This conclusion should be confirmed by the next test stage.

Conditions and results of principal test stage

The list of parameters measured in experiment and the measured results are presented in Table 5. Just as for the basic ON-OFF variant, all the variants were tested for two thermostat settings ① and ②. Energy consumption was measured on a permanent basis, meter readings were taken every 15 minutes, as well as at thermostat actuation moments. In determination of daily energy consumption account was taken of only the period of steady-state working conditions (at stabilized chamber temperatures) of duration at least 3 hours.

<u>*Table 5*</u>

Refrigerator test results for different variants of supply circuits

Circuit variant and thermostat setting Characteristics	I (circuit *a*)		II (circuit *b*)		III (circuit *c*)		IV (circuit *d*)		V (circuit *e*)	
	①	②	①	②	①	②	①	②	①	②
Temperature										
Average chamber temperature in steady-state working mode, [ºC]	8.0	7.7	5.3	5.6	6.3	6.2	6.8	6.3	4.2	4.6
Average ambient temperature during test, [ºC]	21.7	21.4	21.8	22.9	22.1	22.1	21.6	21.4	21.1	22.1
Temperature difference created by thermoelectric refrigerator, [K]	13.7	13.7	16.5	17.3	15.8	15.9	14.8	15.1	16.9	17.5
Cold and hot heat sink temperatures at the instant of thermostat actuation, [ºC]	4.1 33.6	2.5 33.4	4.2 32.9	2.2 32.8	4.1 34.3	2.5 32.7	4.0 38.9	2.5 39.2	0.9 32.6	–0.7 32.9
Cold and hot heat sink temperatures in steady-state mode [ºC]	6.2 26.0	6.0 25.8	2.2 26.3	3.0 28.2	3.7 27.8	3.6 27.5	4.4 27.8	3.9 27.5	1.8 25.9	2.3 25.8
Temperature nonuniformity along the compartment height (top-bottom), [ºC]	0.6	0.6	0.6	0.6	0.6	0.7	0.7	0.6	0.7	0.6
Temporal										
Time from switching to the first thermostat actuation, [min:s]	30:35	67:00	25:10	58:00	38:18	71:00	29:10	42:00	13:30	17:40
Time to stabilization of working conditions after thermostat actuation [min:s]	25:00	23:00	35:00	32:00	33:00	27:00	24:00	28:00	47:00	51:00
Energy										
Supply voltage of the unit, [V]	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Supply current of the unit (at switching /at thermostat actuation / under steady-state mode), [A]	6.3/ 5.5/ 1.7	6.3/ 5.5/ 1.7	6.3/ 5.6/ 1.5	6.3/ 5.5/ 1.5	6.3/ 5.5/ 1.3	6.3/ 5.5/ 1.3	6.3/ 5.0/ 1.3	6.3/ 5.0/ 1.3	6.4/ 5.3/ 1.5	6.3/ 5.3/ 1.5
Average power consumption of the unit, [W]	20.4	20.4	18.0	18.0	15.6	15.6	15.6	15.6	18.0	18.0
Power consumption of supply source [W] (meter reading and calculated as the difference in energy consumption	73.9 73.94	73.8 74.66	69.1 69.33	68.8 68.66	64.8 64.5	64.4 65.13	64.7 64.87	64.8 65.00	69.9 70.00	69.5 69.66
Average electric efficiency of supply source [-]	0.276	0.273	0.260	0.262	0.242	0.236	0.243	0.240	0.257	0.258
Daily energy consumption of supply source [kW·h]	1.77	1.79	1.66	1.64	1.55	1.56	1.56	1.56	1.68	1.67
Daily energy consumption of the unit [kW·h]	0.49	0.49	0.432	0.432	0.375	0.375	0.375	0.375	0.432	0.432
Specific power consumption P_{spec} of the refrigerator [W/dm^3·K]	0.0538	0.0538	0.0394	0.0376	0.0354	0.0354	0.0380	0.0373	0.0384	0.0371

Analysis of results and conclusions

All five selected supply circuits (see Fig. 3 and Table 5) assure the possibility of long refrigerator operation in the energy-saving working mode, when the temperature in the compartment does not rise to the upper boundary of the employed thermostat dead band[3]. As compared to continuous working mode at operating current, when created temperature difference is maximum: $\Delta T_{max} = 17.7$ K, the same parameter for the above circuits fits in the limits from 13.7 K (variant I) to 17.5 K (variant V), which makes from 77.4 % to 98.8 % ΔT_{max} respectively (Fig. 5). In terms of purely mathematical analysis such a result might be considered satisfactory. However, if we consider the average temperatures in the compartment, then variant I where this temperature made 7.7...8.0 °C is already of limited application bearing in mind the variety if products stored in a thermoelectric refrigerator. For instance, this temperature level according to regulatory documents is inadmissible for storage of such confectionery products as cakes and pastries[4], but is quite acceptable in the refrigerators and window displays for storage and demonstration of the majority of sorts of wines and beverages. Other variants have no such limitations, despite slight excess of the threshold 6.0 °C (variants III and IV), that can be easily avoided by minimum strengthening thermoelectric refrigerator heat insulation.

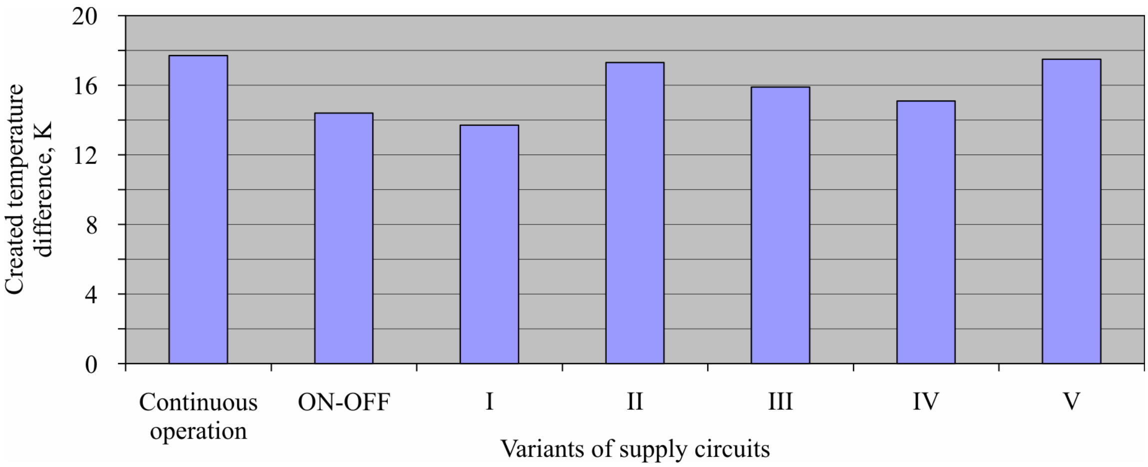

Fig. 5. Comparison of temperature differences created by the refrigerator for the investigated variants of supply circuits at thermostat setting ②.

Despite the more intensive air circulation in the compartment of variant I, the temperature in the compartment of thermoelectric refrigerator in this case is higher (see Table 5). This paradox has its own explanation. The rated capacity of a fan installed in the compartment (powered by voltage 12 V) is too high for a relatively small compartment volume. As a result, cold air "escapes" faster from the compartment through the insulation openings. Moreover, heat transfer coefficient from the internal compartment walls is rather high, leading to increase in total heat transfer coefficient K of cooling compartment and increase in heat inputs through the insulation. Hence a conclusion which agrees with the conclusions of previous research [12] that the internal fan of thermoelectric refrigerator should be powered by reduced voltage and current or a fan of at least half the power of the hot side fan should be used.

Further analysis of the refrigerator temperature characteristics shows that temperature nonuniformity along the height of its compartment does not depend on the operating mode of fan M2. Only with an idle fan, hence, the absence of forced convection in starting period for variant V the

[3] In the present thermoelectric refrigerator this temperature is 11.6 °C for setting ① and 10.0 °C for setting ②.
[4] The range of storage temperatures for confectionery products is from 0 to +6 °C. The same demands are placed on single-compartment refrigerators of general purpose.

uniformity increases to 1.0...1.3 °C[5]. With regard to the basic temperature characteristics in the energy saving operating mode of thermoelectric refrigerator, especially compartment temperature, hot heat sink temperature and created temperature difference, variant II seems to be the most balanced solution.

Measurements of temporal (dynamic) characteristics of refrigerator provide a lot of interesting information for the future more detailed analysis of refrigerator behaviour with a sudden growth of thermal load[6], leading to temporary, generally one-time transition to working mode. From the data in Fig. 6 and Table 5 it follows that advantage is offered by variant V characterized by the shortest time of operation in working mode, i.e. fast transition to energy saving mode. This results in the reduction of daily energy consumption of refrigerator. However, as follows from [8], this thesis is valid only for an empty refrigerator or in the absence of additional loading of refrigerator with warm products.

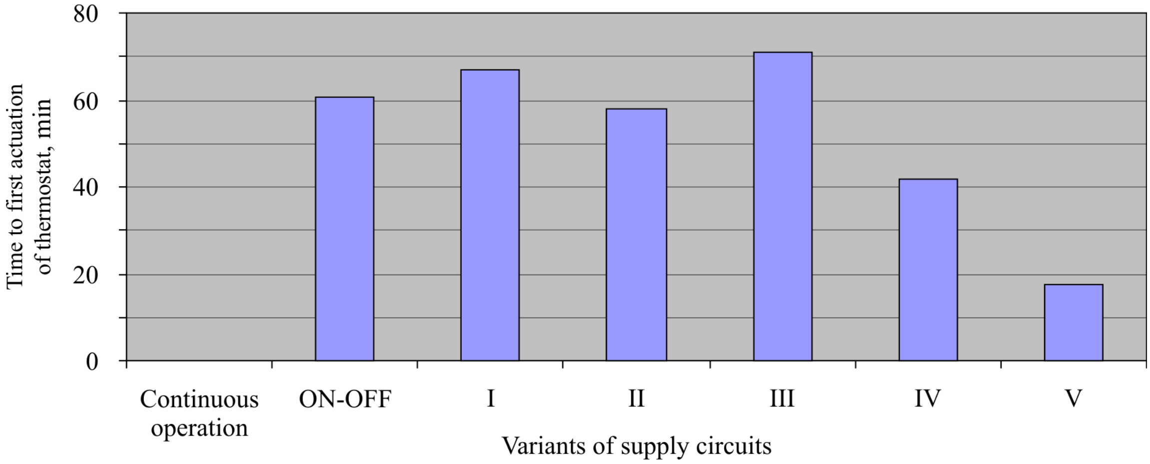

Fig. 6. Comparison of refrigerator operation time in working mode (up to the first actuation of thermostat) for the investigated variants of supply circuits at thermostat setting ②.

In general, the time to the first actuation of thermostat for setting ② varies within 1 hour, and for setting ① it is almost half as much, which depending on the manner of refrigerator employment can make from 0.5 % to 8 % of total daily time of refrigerator operation with a respective growth of its daily energy consumption. A more detailed analysis of thermoelectric refrigerator working modes with regard to thermal load variation will be the subject of further research.

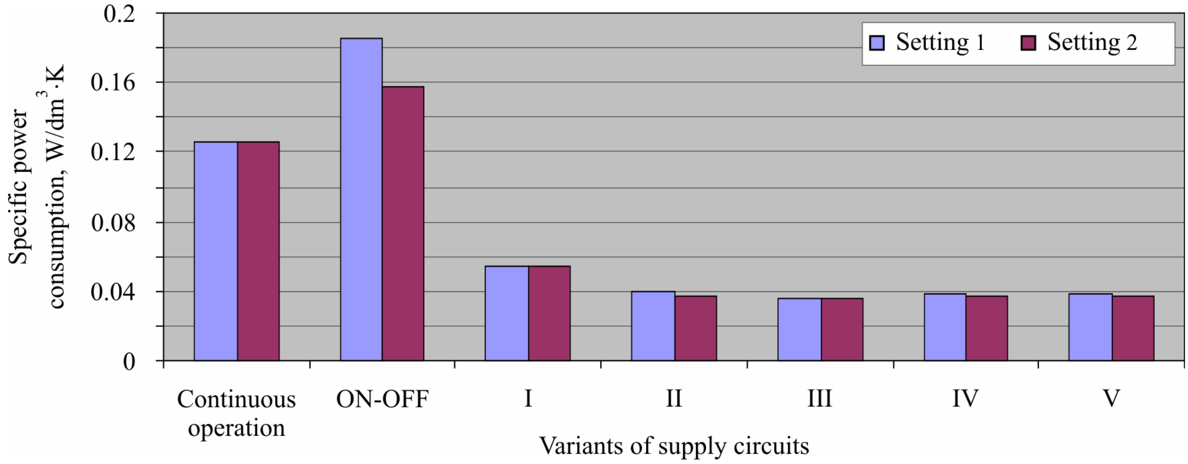

Fig. 7. Comparison of refrigerator specific power consumption for the investigated variants of supply circuits.

[5] This data is not presented in Table 5, but is available in test protocols.
[6] The most typical situation of this kind is slow opening of refrigerator door.

The most important results of the work performed are related to the energy characteristics of the investigated variants of supply circuits of thermoelectric refrigerator unit. As compared to ON-OFF working mode there is 3-4-fold reduction of power consumed from direct current mains (Table 5). This also accounts for nearly 3-fold reduction of specific power consumption (Fig. 7). From the standpoint of energy, the least-cost option is variant III (Fig. 3, circuit *c*). Its advantage over variant II can be explained by a greater share of power consumed by the fans in the total power consumption of the unit. This factor prevails over the marginal effect of reduction of temperature difference created by thermoelectric refrigerator.

The measured strength of current flowing through relay K1 was 90 mA. In terms of power consumption, the relay accounts for 1.8 % of the total unit power consumption. Taking into account that the relay consumes power only in working mode, it is of minor importance in refrigerator energy consumption, hence, the use of supply circuit with employment of electromechanical relay is reasonable.

To formulate more detailed final recommendations, one should continue research using a larger number of test objects and more precise measuring instruments, for instance, direct current energy meter. At the same time, the results obtained allow us to assert that the target goal has been achieved: the possibility and advisability of using two-level temperature control “with pause current” in transport thermoelectric refrigerators has been experimentally substantiated with indication of concrete most efficient technical solutions according to the task set (circuits *b, c* or *e*).

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