THE GUIDELINES FOR DESIGN OF THERMOELECTRIC REFRIGERATORS TO STORAGE OF FOOD

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Abstract

This paper deals with some aspects of the application of thermoelectricity in stationary refrigerators used in transport, hotel industry and households for fresh food storage. It presents changes in thermoelectric aggregates design approach, changes being a consequence of development in thermoelectric modules technology production, as well as their rapid price reduction, observed during last years. This paper presents also a proposal of use of so-called current of a pause [1] in thermoelectric refrigerators working in the mode of double-throw attemperation (two-positional temperature control) with regard to the criterion of electric energy consumption decrease. It also includes the algorithm of aggregate design for the proposed solution.

1. Introduction

Thermoelectric refrigerators designed for fresh food storage may successfully rival their compressor equivalents in these fields of market, which show their advantages like:

- small mass and dimensions,
- undisturbed work of the set, independent of the 3D-space positioning,
- high reliability (no moving parts except the fan),
- quiet work.

The main limitation in expanding field of application is low energy efficiency of thermoelectric elements. However, in recent years a rising number of manufacturers offering thermoelectric refrigerators with useful capacity of tens of litres, intended for transport, office and hotel use is observed.

2. Some guiding principles for design of thermoelectric refrigerators

During the design process of a refrigerator intended for fresh food storage, following factors should be taken into consideration:

- object's assignment,
- utilization capacity ,
- storage temperature (scope of variability)
- acceptable price of the device,
- exploitation costs,
- other exploitation features important from client's point of view.

Thermoelectric refrigerators are employed mainly where their utility properties match design criteria. Because of high electrical energy consumption, they cannot be too large (about tens of liters). However, the small dimensions of refrigerators may be required (e.g., ships, vehicles, where spaces are limited).

Store temperature is inseparably connected with requirements of food storage technology. Table 1 presents scopes of temperature conditioning the existence of micro-organisms. The remark is, that the temperature around 5 °C should be sufficient to stop life functions of two groups of micro-organisms.

Table.1 Scopes of temperature conditioning the existence of certain groups of micro-organisms [2].

Group	Temperatures [°C]		
	minimal	optimal	maximal
psychrophiles	0	15 ÷20	30
mesophiles	5 ÷25	20-40	50
thermophiles	30-40	50 ÷ 60	72

Storage temperature in thermoelectric refrigerators should be held between 2 ÷ 6 °C [1]. It should be taken into consideration, that in the paper [4] most of examined household refrigerators had the temperature higher than accepted (equal to 5 °C for refrigerators of this class), on the side-note. It could prove, that manufacturers consciously reduce electrical energy consumption of a device, deciding for higher storage temperature!

There is a close relation between price of the device and exploitation costs. Usually a lower price determines higher exploitation costs.

Sometimes, during design process of a device, other exploitation features, important from consumer's point of view, should noticed. For example, in the design of a refrigerator for hotel rooms, noise reduction is a fundamental principle.

In a refrigerator, three component blocks can be specified: case, cooling set and power source with temperature regulation system, each one correlated with the other during design process. Their interrelation, as well as general principles and solutions, are presented in paper [3]. Following design considerations are limited to thermoelectric set working in two-positional temperature regulation mode.

Few years ago, during design process of thermoelectric set, optimal leg dimensions l/A were determined (relation of length to cross-section of a leg), as well as the number of thermoelectric elements essential for required cooling capacity $\dot{Q}_o$. At present, the market offers wide assortment of serially produced modules, what allows their direct application in a set, without necessity of use of a specialistic, what means more expensive modules. Unfortunately, such design approach still can be met [5], while it is reasonable only in rare occasions.

In paper [3], the design of the thermoelectric set with application of serial modules was investigated. Having known the assignment of a refrigerator, the designer can specify a maximal ambient temperature and the highest storage temperature accepted. Required cooling capacity is derived from thermal balance of an object. In order to state design joints temperatures of a module, the author of [3] proposes to calculate differences of surface temperatures of heat exchangers in relation to surrounding mediums, from their thermal balances. Other way of solving this problem, could be assuming recommended values of temperature differences and then verifying them by calculating the heat exchange area. Next, for recommended value of a work current I_r ($I_r = 0,6 \div 0,8 I_{max}$) of a given module type, it's cooling capacity is calculated, as well as a number of modules needed. Such design algorithm is used mostly in refrigerators with two-positional temperature regulation. It's criterion is minimization of investment costs of a set, in compliance with requirements of food storage technology.

In situation, when the main design criterion is minimization exploitation costs of a set, it can be obtained in a way of:

- application module with great value of energy efficiency factor Z,
- application heat exchangers with small thermal resistance R_t,
- supplying the set with such a current intensity, that a higher cooling efficiency factor COP is acquired.

New materials, characterizing themselves by high Z-factor are still searched and also production technologies of modules are being improved. But as far as this is concerned, the designer has his search area limited.

It is well known, that work of a module is more economical with smaller difference of temperatures generated by the module, which can be presented as following:

$$\Delta T_m = \Delta T_g + \Delta T_{ch} + \Delta T_z \tag{1}$$

where:

ΔT_g – difference of temperatures between hot joint of a module and an ambience;

ΔT_{ch} – difference of temperatures between an ambience and air in a cooling chamber;

ΔT_z – difference of temperatures between air in a cooling chamber and cold joint of a module.

While we cannot practically affect ΔT_{ch}, we can minimize remaining components from equation (1) by picking heat exchangers with a small thermal resistance. Interesting from this point of view is paper [6], where one of the key parameters during design of the thermoelectric cooler is thermal resistance. In general, on hot side of a set, an intensification of heat exchange by forced convection should be used (eventually, in reasonable cases- fluid cooling). Inside the refrigerator, both, a natural or forced convection can be applied. It depends on a constructional variant of a set – with large area of heat exchange and the same- small value of ΔT_z, a natural convection can be used. In case of forced convection, it should be remembered that reducing the velocity of air flow is needed because of the food drying phenomenon.

Few years ago supplying the set with such a current intensity, that a higher COP is acquired, was limited by high module price. Because the current intensity can be minimized to a value close to I_{COPmax} by increasing the number of thermoelectric elements while retaining a required cooling capacity. Consequences of the Montreal Protocol resulted in increase of interest in thermoelectric devices, what increased the number of manufacturers of thermoelectric modules. Stronger competition resulted in a gradual drop of prices of thermoelectric modules from the beginning of the 90's of the last century. Present-day level of prices of chosen manufacturers for modules of comparable parameters is shown in table 2.

Table 2. Confrontation of prices of thermoelectric modules of comparable parameters.

Producer	Type	$t_g = 25$ °C				Dimensions a*b*h	Price
		I_{max}	U_{max}	Q_{max}	ΔT_{max}		
		[A]	[V]	[W]	[K]	[mm]	[$]
Thermonamic Electronics Co.,Ltd (China)	TEC1-12706	6.0	15.0	51.4	68	40*40*4.0	**12.10, 8.50^3**
Modul (Ukraine)	MT2 – 1.6-127	6.0	15.4	53.0	69	40*40*3.9	**6.47, 3.00^6**
Kryotherm (Russia)	TB-127-1,4-1,5	6,1	15,9	60,0	70^2	40*40*3.9	**16.80**
Tellurex (USA)	CZ-1.4-127-1.65	5.6^1	16.1^1	56.0^1	79^1	40*40*3.8	**29.00** **24.50^5**
Melcor (USA)	CP 1.4-127-06L	6.0	15.4	51.4	67	40*40*3.8	**21.70, 16.6^4**
	PT 6-12-40	6.0	15.4	52.0	65	40*40*3.8	**17.80, 14.85^4**

1 - values measured for hot joint temperature t_g =50 °C,
2 - values measured for hot joint temperature t_g =27 °C,
3 - obligatory price in purchasing of 50 – 100 pcs (above 100 pcs – price negotiable),
4 - obligatory price in purchasing no less than 25 pcs,
5 - obligatory price in purchasing no less than 250 pcs,
6 - obligatory price in purchasing no less than 50000 pcs.

Analyzing table 2, a wide range of prices can be observed. Much lower prices are in China and Ukraine, compared to American manufacturers. It can be partially explained by natural resources presence in Asia, from which thermoelectric elements are produced, as well as lower working costs than in USA. Guaranteed quality of produced module also has it's impact on a price.

Recent level of prices enables a change in a design approach – the designer can, by increasing the number of thermoelectric elements, tend to decrease electrical energy consumption by a refrigerator, while retaining acceptable production costs of a set. Thus, increasing the economical efficiency of a refrigerator will be the object function. Mathematical aspect of annual working costs of a device could have a following formula:

$$K_c = \left[\frac{p \cdot (1+p)^n}{(1+p)^n - 1} \cdot n + \frac{w}{100} \right] \cdot K_{urz} \cdot \mu + E_{el} \cdot k_j \cdot \tau_e \quad [\$/\text{rok}] \qquad (2)$$

where:
p - credit rate,
n - credit amortization period in years,
μ - amortization rate,
E_{el} – twenty-four hours electrical energy consumption [kWh/24ha],
k_j - unit costs of electrical energy consumption [$/ kWh],
τ_e - device's working time [days/year],
K_{urz} - capital investment [$/year],
w- proportional share of fixed costs in capital costs [%],

Whereas, capital costs of a device can be represented as sum of three components:

$$K_{urz} = K_{ag} + K_{iz} + K_z \qquad (3)$$

where:
K_{ag} – cost of purchase of a set,
K_{iz} – cost of purchase of refrigerator's case,
K_z – cost of purchase of power source/regulation system.

By utilizing dependences (2) and (3), the designer is able to analyze different solutions of a thermoelectric set, focusing on reduction of electrical energy consumption by increasing investment costs which are connected with purchase of thermoelectric modules and heat exchangers. Usually, the greater number of thermoelectric elements present, the more expensive the module is (now, although, the Modul company offers modules MT2 - 1.6-127 at lower price than MT2-1.6-71). Higher purchase costs of heat exchangers may be a result of larger heat exchange surface needed, what is connected with a number of modules or their dimensions.

It is necessary to pay attention to use a greater number of thermoelectric elements results, at one hand, in decrease of power, consumed by set, while, at the other hand, in increase of a heat flow, transferred to cooling chamber. Thermoelectric elements act as perfect thermal bridge contacts during stoppage of a set. Therefore, in case of using two-positional regulation, it is advised to supply the set with the so-called "current of thermal lock", which blocks the heat flow through modules.

Such approach was implemented in experimental research of refrigerator CHTK-60, with utilize capacity of 55l, where two-positional, indirect regulation by manometric temperature regulator was used. The set was supplied with current I_r (equal to $0{,}7I_{max}$) and during stoppage- with a current of smaller value. On the cold side of the set, the natural convection was used, while on the hot side- forced one, with the fan electrically connected with modules. Detailed discussion about research is presented in papers [7,8]. Whereas on figure 1, the relative decrease of twenty-four hours consumption of electrical energy in relation to base variant is shown.

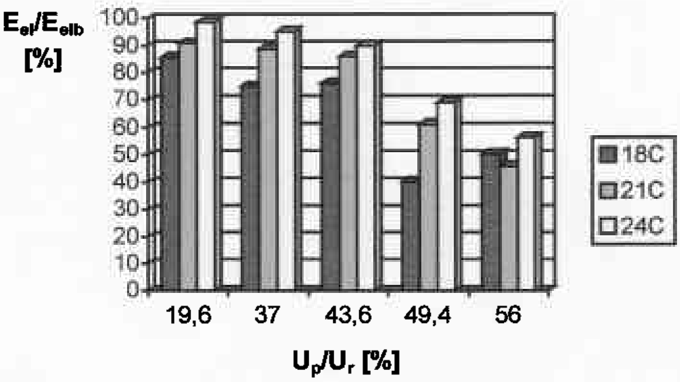

Fig. 1. Relative 24 hours consumption of electrical energy of the CHTK-60 refrigerator in relation to base variant, for three ambient temperatures: 18 °C, 21°C, 24 °C.

3. Suggestion of utilizing the so-called „current of a pause" in thermoelectric refrigerators

As a result of research analysis, an idea of supplying a set with so-called current of a pause I_p appeared, considering the criterion of decrease of electrical energy consumption in thermoelectric refrigerators working in two-positional regulation mode. The minimization of investment costs of a device was also an aim, so the set should work using inexpensive manometric temperature regulators. The system of indirect temperature regulation was implemented – sensor of a regulator remained in heat contact with a cold side heat exchanger. The statement: „current of a pause" should be understood as such value of a current of supply that would grant a steady exchange of heat between a refrigerator and an ambient, for stated design ambient temperature. Then, the mean air temperature in chamber shouldn't exceed the allowed temperature value.

In case of appearance of thermal disturbance, like opening the door and putting new food products inside, or a rise of ambient temperature, a switch of a set into work current I_r should occur. Then, under transient heat exchange conditions, a set would work in periodic mode.

In paper [1] the simplified computational model of the thermoelectric cabin refrigerator CHTK-60 is presented. It enables the calculation of I_p , as well as estimation of electrical energy consumption while working in varying heat exchange conditions.

On figure 2, the design algorithm of thermoelectric set for proposed solution is shown. After assuming the mean ambient temperature T_{ots}, maximal ambient temperature T_{otmax} and permitted storage temperature T_{kdop} , the mean and maximal value of cooling capacity of a set - $\dot{Q}_o, \dot{Q}_{o\,\max}$ is calculated from thermal balance. Next, the designer makes statement on a type of heat exchange on a cold side exchanger (natural or forced convection). For acceptable thermal resistance of a heat exchanger on a cold side of a set R_{tza} (regarding the heat conductivity of a material, along with a way of absorbing heat), temperatures on a cold side of a module - T_{z1}, T_{z2} are calculated. Now, relying on initial technical analysis of an object, the class of possible number of modules is assigned. It is well known, that in case of natural convection, a greater number of modules is preferred due to the necessity of decreasing the heat flux density.

Further design step is connected with means the designer has. In situation, when he has exact values of physical parameters of a module at his disposal (from manufacturer or better, from his own research), he can calculate I_p, basing on acceptable (in technical and economical meaning) thermal resistance of a heat exchanger on a hot side - R_{tga}. As shown in paper [7] it is best to know the dependence describing the cooling capacity of a module $\dot{Q}_{om} = \dot{Q}_{om}(I, T_z, T_g)$. The temperature T_{g1} can be described as function $T_{g1} = T_{g1}(I, T_{z1}, \dot{Q}_{os})$, using dependencies:

$$\dot{Q}_{g1} = \frac{T_{g1} - T_{ots}}{R_{tga}} \tag{4}$$

$$\dot{Q}_{g1} = \dot{Q}_{os} + P(I, T_{z1}, T_{g1}) \tag{5}$$

where: $P(I,T_{z1},T_{g1})$ – function of power supplied to modules

From a formula presented in algorithm, I_p is calculated and it's value should be close but no less than optimal value of I_{COPmax}. Although, if derived values (from class) differ much from I_{COP}max then a need to change a type of module appear.

Alternative possibility of calculating I_p, in agreement with suggested by module manufacturers approach, is that the temperature of a hot side of a module T_{g1} (or ΔT_{g1}) is assumed and producer's characteristics are used next. Initially, the value of ΔT_{g1} can be calculated from following formula:

$$\Delta T_{g1} = \dot{Q}_{os} \cdot R_{tga} \cdot \left(1 + \frac{1}{COP_s}\right) \tag{6}$$

where: COP_s – mean value of coefficient of performance attained for expected scope of temperatures

After having calculated I_p, it is necessary to check the thermal resistance R_{tg}, because of a necessity of verifying ΔT_{g1} may appear.

Next, the value of work current I_r is calculated. In order to do this, it is imperative to derive T_{g2}, relying on dependencies (4) and (5), inserting T_{otmax} and $\dot{Q}_{o\max}$ respectively.

There are two conditions to check too. If any of this conditions wasn't fulfilled, a verification of given values would be necessary. In case of condition 2, a technical safety device could be implemented, that would cut off the power from a set.

Having designed the set, proper settings of temperature regulator should be chosen and economical efficiency analysis of such initially designed refrigerator should be executed – the dependence (2) could be used for this. If investment costs were too high, changes in the project would be essential. Final verification is made during thermal research of a refrigerator, when settings of a thermoregulator are being corrected, as well as a source voltage of a set.

While designing a set for cabin thermoelectric refrigerators, it can be assigned t_{ots} = 22 °C and t_{otmax} = 27 °C, because refrigerators on board of a ship are found in air-conditioned spaces. It is assumed, that air conditioning system for most inconvenient outer conditions is able to uphold following temperatures inside a room:

- t_{ot} =22 °C in winter season,
- t_{ot} = 27 °C in summer season.

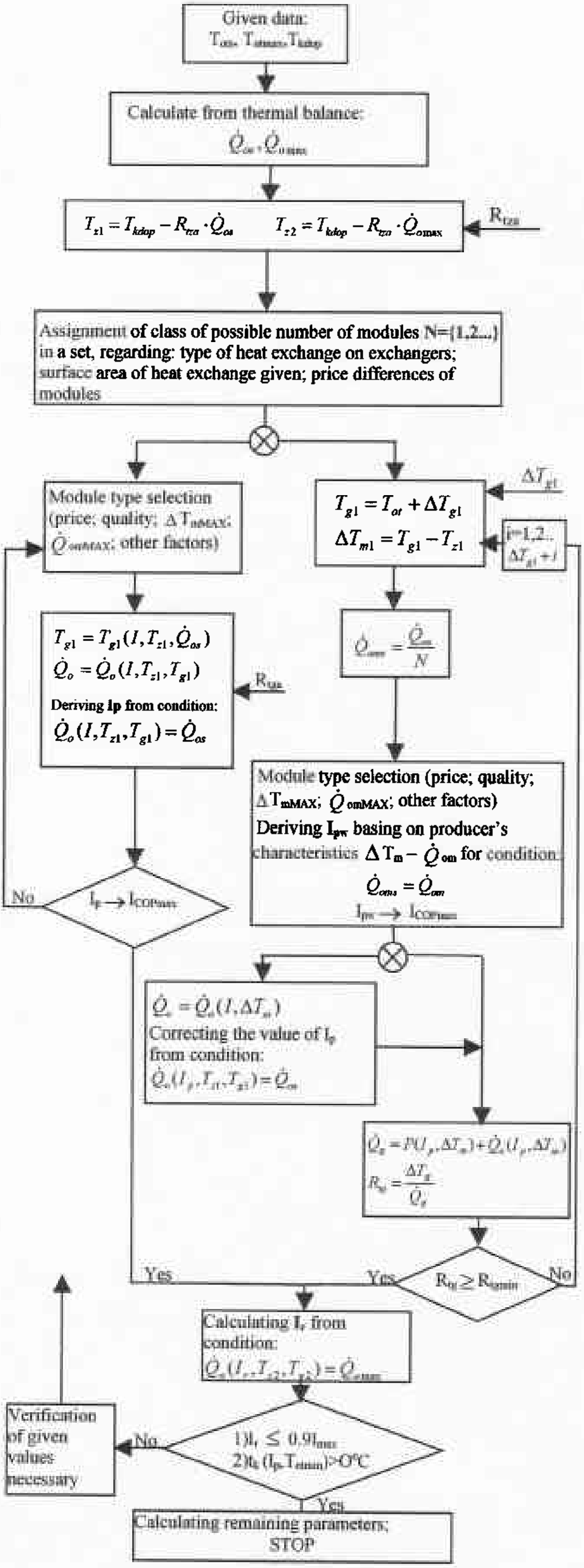

Fig. 2. An algorithm of design process of a thermoelectric set, supplied with I_r and I_p

4. Conclusion

In this paper, some guiding principles were introduced. In author's opinion, they should be taken into consideration during designing fresh- food storage thermoelectric refrigerators. Systematical decrease in prices of modules was pointed out. It enabled a design of a set, with the minimization of working costs.

Using two-positional regulation in refrigerators, the inconvenient phenomenon of conductivity of the heat flux through thermoelectric elements can be negated by the application of supplying the set with the barrier current.

Presented suggestion of implementation of the current of a pause I_p, apart from energetic aspect, characterizes also the decrease in rushes of current and their frequency, regarding the usual two-positional regulation, what results in increase of work reliability of a set.

From the design algorithm of a set powered by I_r or I_p presented, the need for easier access to physical parameters of modules by designers occurs, as well as the necessity of verifying the precision of measurements made by manufacturers too.

There is a great need for creating universal module characteristics for initial selection of a module. Characteristics of this kind are offered by Marlow company for their modules.

Another conclusion is, that with more and more dynamic progress of small thermoelectric refrigerators, the need of creation of corresponding law standards regarding the research of work characteristics for devices of this type appears.

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