Mykhaylo ZAGIRNYAK, Volodymyr USATYUK

Kremenchuk Mykhailo Ostrohradskyi National University, Ukraine

doi:10.15199/48.2020.01.50

Electromagnetic separators: the methods for the magnetization coil design

***Abstract**. The methods for the design calculation of the magnetization coils of electromagnetic separators operating in a long-term mode, whereat the temperature at all the points of the coil takes a certain unchangeable value, are proposed. This value is maximal possible for the particular conditions of heat removal. The methods take into account the special features of the magnetization coils manufacture and allow the choice of the best variant according to the set criterion.*

***Streszczenie.** W artykule zaproponowano metody obliczania cewek magnesujących separatorów elektromagnetycznych, działających w reżimie pracy długotrwałej, w którym temperatura we wszystkich punktach cewki nie zmienia wartości. Każda wartość jest możliwie największą dla usuwania ciepła. Proponowane metody biorą pod uwagę specjalne właściwości wytwarzania cewki magnesującej i pozwalają na wybór najlepszego wariantu zgodnie z przyjętymi kryteriami. (**Separatory elektromagnetyczne: metody projektowania cewki magnesującej**).*

Keywords: electromagnetic separator, equation of thermal balance, magnetization coil design.
Słowa kluczowe: separator elektromagnetyczny, równanie równowagi cieplnej, projekt cewki magnesującej.

Introduction

The thermal processes taking place during the operation of electromagnetic separators result from the release and removal of Joule heat caused by the electric current flux in the magnetization coil. To achieve the normal operability of the electromagnetic separator it is necessary and sufficient to provide the absence of the magnetization coil overheat exceeding the temperature allowed by the insulation class and the climatic version of the separator. This condition can be assumed the initial point of this analysis.

Based on standard GOST 30577-98, requiring long-term operating mode $S1$ for electromagnetic separators, it is possible to consider all the totality of the thermal processes in electromagnetic separators in a simpler way as a certain steady thermal process, whereat the temperature at all the points takes a certain steady value, which is maximum possible for the particular conditions of heat removal. At such an approach it is sufficient to limit oneself to the determination of the average temperature (or the overheat) of the magnetization coil without solving the complex problem of the distribution of the temperature field inside it, which significantly simplifies the problem of the thermal calculation of the electromagnetic separator.

Basic propositions

Thus, as in the steady thermal mode the amount of Joule heat Q_{rel}, released in the magnetization coil under the action of electric current, is equal to the amount of heat Q_{rem}, removed from the separator due to the heat dissipation in the environment,

(1) $$Q_{rel} = Q_{rem},$$

the electromagnetic separator heat calculation in the considered case is reduced to the determination of the equality left and right parts dependence on the separator parameters. In this case, (1) represents nothing but the equation of thermal balance for the steady mode of the separator heating.

If during the determination of the left part of (1) we take into account that in the heating steady mode the amount of heat released per time unit at the electromagnetic separator heating does not change, the released thermal energy Q_{rel} will be equal to the electric power of the Joule losses:

(2) $$P_{rel} = I_{coil}^2 R_{coil},$$

where I_{coil} – direct electric current flowing in the magnetization coil; R_{coil} – resistive impedance (ohmic resistance), determined by the relation

(3) $$R_{coil} = \rho_V L_{coil} / S_{con},$$

here ρ_V – the specific electric resistance of the material of the magnetization coil wire at the heating temperature of the steady mode; L_{coil} – the length of the coil wire; S_{con} – the cross sectional area of the coil conductor equal to the cross sectional area of the wire without insulation.

Now, if we represent S_{con} and L_{coil} via the magnetization coil dimensions a_{coil} and b_{coil}, it will allow transforming (2) to a more convenient form. With this purpose in view, we introduce space factor k_{sp}, equal to the relation of the coil window area $(a_{coil} \times b_{coil})$ to the cross sectional area of the whole conductor material of the coil wS_{con} (w – the number of the coil turns) and the average length of the coil turn equal to the relation of the coil wire length L_{coil} to the number w of wire turns in it. As a result, the following equalities can be written down:

$$S_{con} = a_{coil} b_{coil} / (w k_{sp}), \qquad L_{coil} = w l_{av},$$

if we put them into (3), we obtain

$$R_{coil} = \rho_V k_{sp} w^2 l_{av} / (a_{coil} b_{coil}).$$

Thus, after the relevant transformations we have

(4) $$P_{rel} = (I_{coil} w)^2 \rho_V k_{sp} l_{av} / (a_{coil} b_{coil}),$$

where $I_{coil} w$ – the electromagnetic separator magnetization coil magnetomotive force (MMF) that determines the difference of the magnetic potentials between the poles.

At the determination of the right part of (1), i.e. the power of the heat removal, it should be mentioned that heat removal in electromagnetic separators represents a complex phenomenon of the simultaneous action of three types of heat exchange: convection, emission and heat conductivity. That is why, by analogy with the thermal calculations of other electromagnetic devices, we determined heat removal power P_{rem} for the heated electromagnetic separator without exact taking into account the contribution of each of these heat exchange types into the total thermal flow – based on the known Newton's formula:

(5) $$P_{rem} = k_{h.d} S_{cool} (\theta_{st} - \theta_{a.t}) \, ,$$

where $k_{h.d}$ – heat dissipation coefficient, *W/m²·°C;* S_{cool} – the coil surface area, *m²*; θ_{st} and $\theta_{a.t}$ – the steady temperature of the coil and the ambient temperature, *°C*.

Coefficient $k_{h.d}$ in the general case is the function of many factors and that is why it is impossible to get the analytically accurate expression for $k_{h.d}$.

A specific feature of the design of the electromagnetic separator coils consists in considerable mass-dimension parameters (external diameter – up to 513 mm, height – up to 316 mm, coil thickness – up to 95 mm) [1], which prevents the use of value $k_{h.d}$ for the calculation by formula (5). The methods and recommendations obtained and developed for the electromagnetic coils of common automation devices [2-4] cannot be used either.

The above said explains the fact that semi-empirical methods based on the generalization of the data of production piece thermal testing are used for the thermal calculations of different electromagnetic separators [5-9]. This approach completely conforms to the empiric determination of coefficient $k_{h.d}$, accepted in the world practice of electric device industry, for the particular electric device design and the certain conditions of heat dissipation in it [2]. However, during the thermal calculation of electromagnetic separators it is usual to use not the dissipation coefficient $k_{h.d}$ itself, but to introduce specific (per unit of cooling area) power of heat removal $P_{sc} = k_{h.d}(\theta_{st} - \theta_{a.t})$, which allows rewriting (5) in a simpler form

(6) $$P_{rem} = P_{sc} S_{cool} \, .$$

Hence, value P_{sc} is determined not only by the dimensions of the electromagnetic coil and the particular conditions of its cooling but also by the heating temperature. Thus, it is unreasonable to adopt some constant value for P_{sc} as [5] recommends for numerical calculation by (6) for electromagnetic separating devices.

According to the traditional engineering practice of thermal calculation of magnetization coils [2], electromagnetic separators inclusive [6-10], only one typical geometrical parameter should be considered. However, it should reflect the heat removing ability of the coil of the corresponding electromagnet rather completely. The magnetization coil cooling area S_{cool} is taken as such a parameter for electromagnetic separators:

$$S_{cool} = S_{ext} + k_{ht} S_{int} + 2 S_{sur} \, ,$$

where S_{ext}, S_{int} and S_{sur} – the areas of the external, internal and end surfaces of the coil; k_{ht} – the coefficient characterizing the relation of the heat transfer of the internal and external surfaces of the coil. In this case, according to the conventional practice [3], when S_{cool} is calculated in the case of manufacturing the coil end plates of insulation materials and the coil width less than the coil length, which is typical of the most designs of suspended separators, the heat removal through the end surfaces is neglected ($S_{sur} = 0$), and coefficient k_{ht} is assumed equal to 1.

The appropriate formulae for the calculation of values S_{cool} of the separator coils produced in series can be easily obtained from obvious geometric relations for the mentioned heat removal surfaces and, having values $P_{sc} = f(S_{cool})$ [9], it is easy to find heat power P_{rem} from relation (6), which is included into the right part of the heat balance equation. In this case, it can be given a more convenient form, suitable for practical use, by substitution of corresponding expressions for P_{rel} (4) and P_{rem} (6) in this equation, which gives:

$$\left(I_{coil} w\right)^2 = P_{sc} S_{coil} a_{coil} b_{coil} \, / \, (\rho_v k_{sp} l_{av}) \, .$$

The proposed approach makes it possible to perform design calculation of the solid magnetization coil of any type separator and for most design methods is the basic one. However, there are some drawbacks of this approach. They prevent the creation of a more flexible method enabling making the design calculation of the magnetization coils at their vertical and horizontal sectioning (a highly efficient and widely used [10, 11] method of cooling intensification). An improved method cannot be used either when the magnetization coils are made in the form of several parallel branches (which is caused by practical difficulties occurring at the manufacture of separators due to the small assortment of conducting coil material available for a particular manufacturer). Such a method should also allow taking into account the particular level of the technology applied at the manufacture of massive magnetization coils by the introduction of the coefficients of laying the wire in the layer and laying the layers. These coefficients are to vary depending on the type of the wire insulation, the type of the wire coil (flatwise or edgewise), as well as the relation of the sides $a_{con} \times b_{con}$ of the wire and its cross section S_{con} .

Thus, the flexibility and, consequently, the efficiency of such a method consists in the detailed taking into account a big number of parameters most of which are constants and represent a large information base built over the data of the conducting material assortment. The authors have created such a base for the whole dimension series of rectangular cross-section coil wires according to STP-15-28-34-83 of Lugansk Engineering Plant.

The initial data and relations being the base for the proposed design method

The initial parameters for such a calculation include: bare wire dimensions $a_{con} \times b_{con}$, insulated wire dimensions $a'_{con} \times b'_{con}$, the number of turns in the coil layer n , the number of the coil layers m , the number of parallel branches a' , the way of the wire coil (flatwise/edgewise), the coefficient $k_{w.l}$ of the wire laying in the layer, the coefficient $k_{l.l}$ of layer laying, the form of coil sectioning (horizontal/vertical), the number of magnetization coil sections (the number of coils accordantly connected in series) n_{sec} , the total width of the insulation (spacer, flange, etc.) in the vertical direction (along the dimension of the coil window B) $\delta_{ins.v}$, the total width of the insulation (collar, quartz-filling mass, casing, etc.) in the horizontal direction (along the direction of the coil window A) $\delta_{ins.h}$, the width of the air channel between the coil sections δ_{ch} , diameter d_c of the core of the pole whereat the coil is located.

If there are n_{sec} sections of magnetization coil, the number of air channels between the sections is determined as $(n_{sec} - 1)$. By way of example, Fig. 1, a shows the cross section of a coil with horizontal sectioning, included into a coil widow of the dimensions $A \times B$. A coil with vertical sectioning will look analogously.

Then the dimensions of the coil window (in the "gap" of the magnetic system), depending on the way of wire coil and on the form of the coil sectioning, can be presented as four groups:

1) horizontal sectioning, edgewise wire coil

(7, a) $A = k_{l.l} m a'_{con} + \delta_{ins.h}$;

(7, b) $B = n_{sec}(k_{w.l} a' n b'_{con} + \delta_{ins.v}) + (n_{sec} - 1)\delta_{ch}$;

2) horizontal sectioning, flatwise wire coil

(8, a) $A = k_{l.l} a' m a'_{con} + \delta_{ins.h}$;

(8, b) $B = n_{sec}(k_{w.l} n b'_{con} + \delta_{ins.v}) + (n_{sec} - 1)\delta_{ch}$;

3) vertical sectioning, edgewise wire coil

(9, a) $A = n_{sec}(k_{l.l} m a'_{con} + \delta_{ins.h}) + (n_{sec} - 1)\delta_{ch}$;

(9, b) $B = k_{w.l} a' n b'_{con} + \delta_{ins.v}$;

4) vertical sectioning, flatwise wire coil

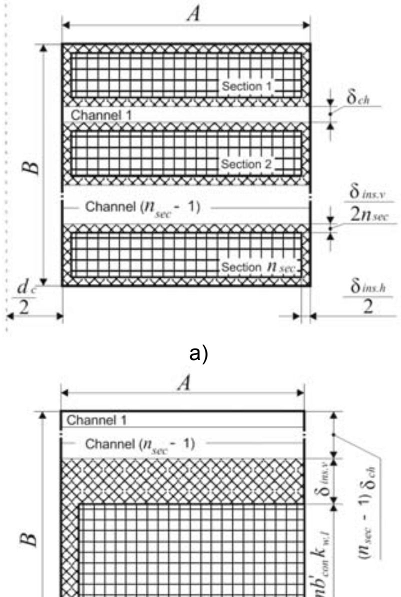
(10, a) $A = n_{sec}(k_{l.l} a' m a'_{con} + \delta_{ins.h}) + (n_{sec} - 1)\delta_{ch}$;

(10, b) $B = k_{w.l} n b'_{con} + \delta_{ins.v}$.

This method considers the number of turns w not per a coil but per the whole coil (Fig. 1, b), which is possible due to the accordant connection of coils in series and allows considerable simplification of the calculation. However, in this case it is necessary that at the horizontal sectioning the number of turns in the layer n be multiple of the number of the coil sections n_{coil}, and at the vertical sectioning the number of layers m should meet this condition.

The magnetization coil resistive impedance at the heating temperature of the steady thermal mode is determined according to (3), in which the coil wire length L_{coil} and the coil wire cross section area S_{con}, can be found as $S_{con} = a' a_{con} b_{con}$; $L_{coil} = w l_{av} = m n l_{av} = m n \pi (d_c + A)$.

It should be mentioned that the above proposed expressions for the dimension of the coil window A (9, a; 10, a) take into account the coil vertical sectioning influence on the diameter of the average turn. Then, using the value of the coil resistance in the steady thermal mode, it is possible to find the power consumed by the separator coil P_{rel}.



a)

b)

Fig. 1. The cross section of the coil with horizontal sectioning (a) and its calculation model (b)

Depending on the type of the coil sectioning, the cooling surface area S_{cool}, required for the determination of the removed power P_{rem}, can be determined as:

horizontal sectioning

$$S_{cool} = n_{sec} S_{cool(sec)} = = n_{sec}\left(\frac{\pi(D_{ext}^2 - d_{int}^2)}{4} + (1 + k_{ht})\pi(D_{ext} - d_{int})h_{sec}\right),$$

where $h_{sec} = (B - (n_{sec} - 1)\delta_{ch}) / n_{sec}$ – the height of the coil section;

vertical sectioning

$$S_{cool} = \sum_{i=1}^{n_{sec}}\left(\frac{\pi(D_{ext_i}^2 - d_{int_i}^2)}{4} + (1 + k_{ht})\pi(D_{ext_i} - d_{int_i})B\right),$$

where D_{ext} and d_{int} – respectively the external and internal diameters of the coil; i – the number of the coil section.

In other respects, the calculation relations are analogous to the relations describing the thermal processes taking place in the steady thermal mode in a solid non-sectional coil.

The proposed method for the design calculation of the magnetization coil

Let us consider in succession the application of the method in the case of a suspended separator. We set the type and dimensions of the wire from the available assortment (or according to the standardized series) and use the attendant constants from the information base (the coefficients of the wire laying in the layer $k_{.w.l}$, and the layers laying $k_{l.l}$), characterizing the level of the technology of coil manufacture during the use of exactly this wire at the chosen way of coil (flatwise/edgewise).

In this case it is necessary to remember, that for some dimension types of wires it is possible to meet the initial restrictions at several different combinations of the number of layers m and the number of turns in the layer n, for others there is only one combination. There can be a situation, whereat it is impossible to use such a coil wire within the framework of the restrictions of the adopted design and technology of coil production.

Having set the concrete values of the insulation width at the coil height $\delta_{ins.v}$ (spacer, flange, etc.) and the height of the air inter-section channels δ_{ch}, being constants at the search for the optimum, and, using the value of the core height as the height B of the coil window, we determine the number of turns in the layer n by the corresponding formula (one of the following: 7, b; 8, b; 9, b; 10, b). We round this value off to the nearest integer number meeting the condition of the multiplicity of the number n of turns in layer of the number n_{sec} of the horizontal sections of coil.

Having set the value of the admissible current density J_{adm}, we determine the preliminary value of the number of the coil turns w (without division into sections)

$$w = \frac{F_{con}}{I} = \frac{F_{con}}{J_{adm} S_{con} a'},$$

where S_{con} – the cross section area of the coil conductor. At the known value of the number w of the coil turns we determine the number m of layers in it and round this value off to the nearest integer number provided the number m is multiple of number n_{sec} of the vertical sections of the coil.

Now we determine the horizontal dimension of window A by an appropriate formula (one of the following: 7, a; 8, a; 9, a;

10, a) at the concrete values of the width of insulation in the coil width $\delta_{ins.h}$ (collar, quartz-filling mass, casing, etc.) and the width of the air inter-section channels δ_{ch}. We verify the obtained value by the condition

$$D_{ext\max} \le d_c + 2A\,. \tag{11}$$

The discrepancy of the obtained value A and condition (11) means that at the adopted admissible current density J_{adm} in the set cross section of the coil window $A \times B$ it is impossible to obtain the required magnetizing force F_{con}. If the condition is met, then, according to the conventional method used in electric devices industry (for the steady mode of coil heating) we determine in succession:

the average diameter of the coil $d_{av} = d_c + A$;

the average length of one turn $l_{av} = \pi d_{av}$;

the total length of the coil wire $L_{coil} = wa'l_{av}$;

the coil wire mass that can be one of the components of the optimization criterion $M_{con} = \gamma_{con} L_{con} / 1000$, where γ_{con} – the specific weight of the wire kg/km, the resistive impedance of the coil in the steady thermal mode characterized by the value of the steady temperature $t_{st} = \theta + t_{a.t}$, where $t_{a.t}$ and θ the standardized values of the ambient temperature and the steady excess of temperature corresponding to the separator version

$$R_{st} = \rho_{st} \frac{wl_{av}}{S_{av}a'} \tag{12}$$

,in (12) ρ_{st} – the specific resistance of copper at temperature t_{st}, determined as $\rho_{st} = \rho_x (1 + \alpha_{Cu} t_{st})$, where ρ_x – the specific resistance of copper at 0 °C, α_{Cu} – the thermal coefficient of copper resistance;

the magnetization current in the steady mode $I_{st} = U / R_{st}$;

the calculation value of the current density $J_{cal} = I_{st} / S_{con}a'$;

the calculation value of MMF $F_{cal} = I_{st} w$;

the calculation value of the released power $P_{rel} = I_{st}^2 R_{st}$;

the area of the coil cooled surface S_{cool} [9];

the calculation value of the removed power $P_{rem} = P_{sc} S_{cool}$.

Then we verify the correspondence of the obtained values: the current density $J_{cal} \le J_{adm}$; MMF $F_{cal} \approx F_{con}$ and meeting the equation of the thermal balance $P_{rel} \le P_{rem}$.

If any of the conditions is not met, we should set a new combination $(m \times n)$ or another wire dimension, the way of its coil, etc. and repeat the whole calculation.

Conclusion

Due to the use of the proposed approach, at the stage of the design, the designer can find several variants (see examples in the Table) of the magnetization coil, meeting the requirements of the necessary MMF, the admissible current density and having appropriate heat dissipation. It enables the designer to choose one of the variants based on the additional requirements. It should also be mentioned that, due to the use of the sufficient number of coefficients describing the parameters of the concrete technology in the calculation, during the manufacture it is possible to obtain the magnetization coil parameters closely approaching the calculated ones.

Table. The results of the calculation of the magnetization coils of separator Sh400 (two horizontal sections, one parallel branch)

Variant	1	2	3	4	5	6	7	8	9
Wire type	PSDT-L 2.24x6.3	PSDT-L 2.8x5.6	PSDT-L 2.8x5.6	PSD-L 2.8x5.6	PSD-L 2.8x5.6	PSDKT-L 2.24x6.3	PSDKT-L 2.8x5.6	PSDKT-L 2.8x5.6	PSDKT-L 2.8x5.6
Number of turns in section layer	24	34	22	22	34	24	22	33	34
Number of layers	79	62	81	81	62	78	81	61	63
Section dimension, mm	219.8x164.4	206.4x208.4	269.6x134.8	271.3x135.9	207.7x210.1	210.5x162.9	264.5x133.4	199.2x200.2	205.7x206.3
d_{av}, mm	681.8	668.4	731.6	733.3	669.7	672.5	726.5	661.2	667.7
l_{av}, m	2.14	2.10	2.30	2.31	2.10	2.11	2.28	2.08	2.10
M_{con}, kg	1022	1221	1130	1140	1232	996	1122	1153	1239
R_{st}, Ohm	16.8	16.64	15.4	15.4	16.67	17.22	16.09	16.54	17.78
I_{st}, A	13.09	13.22	14.29	14.25	13.19	12.77	13.67	13.3	12.37
J_{st}, A/mm^2	0.95	0.87	0.94	0.94	0.87	0.93	0.90	0.88	0.82
F (MMF), A	49649	55732	50914	50796	55623	47837	48724	53537	53014

***Authors**: Rector of Kremenchuk Mykhailo Ostrohradskyi National University Mykhaylo Zagirnyak, Pershotravneva str. 20, Kremenchuk, Ukraine, 39600, E-mail: mzagirn@gmail.com; Associate Professor of Electric Machines Department of Kremenchuk Mykhailo Ostrohradskyi National University Volodymyr Usatyuk, Pershotravneva str. 20, Kremenchuk, Ukraine, 39600, E-mail: vladimir.usatyuk@gmail.com.*

REFERENCES

[1] Mineral processing equipment: Catalog, *Inst. Gipromashugle-processing, Oblpoligraphizdat*, 2001. (Rus)
[2] Vitenberg M.I. The calculation of electromagnetic relay, *Energiia,* 1975. (Rus)
[3] Sakharov P.V. Electric device design (general problems of design), *Energiia*, 1971. (Rus)
[4] Kurbatov P.A. Fundamentals of the theory of electrical apparatus, *Vyssh. shk.*, 2015. (Rus)
[5] Sumtsov V.F. Electromagnetic iron separators, *Mashinostroieniie,* 1978. (Rus)
[6] Bul B.K., Kartashian V.O., Nesterenko A.P. The design of the optimal electromagnetic systems of suspended iron separators, *Elektrotekhnika*, 1981, nr 4, 54-57.
[7] Zagirnyak M.V. The research, calculation and improvement of pulley magnetic separators, *Inst. of system research in education*, 1996. (Rus)
[8] Zagirnyak M., Braspiz Yu. Pulley magnetic separators, *Teknica,* 2000. (Rus)
[9] Zagirnyak M.V., Usatiuk V.M. Thermal testing data analysis and design of magnetizing coils for electromagnetic, *Elektrotekhnika*, 1994, (1), 54-58.
[10] A.c. 1651968 USSR, B 03 C 1/16. Suspended electromagnetic iron separator / M.V. Zagirnyak, V.M. Usatiuk et al. (Rus).
[11] SE-7000 series Suspended electromagnets: Bulletins SB-323T AU / Eriez Magnetics. Erie, PA: Erie Manufacturing Co., 2018.