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FEM ANALYSIS OF THE IRREGULARITY OF THE MAGNETIC FIELD DISTRIBUTION INSIDE THE STATIC MAGNETIZER COIL

Summary. The paper deals with the analysis of the magnetic field distribution irregularity inside a static magnetizer coil used for magnetization of polymeric membranes made on a basis of neodymium (Nd). The FEM calculations of the magnetic field distribution are presented.

Keywords: static magnetizer, FEM analysis, magnetic membrane gas separation

ANALIZA POLOWA NIERÓWNOMIERNOŚCI ROZKŁADU POLA MAGNETYCZNEGO WE WNĘTRZU MAGNEŚNICY STATYCZNEJ

Streszczenie. W artykule przedstawiono analizę nierównomierności rozkładu pola magnetycznego we wnętrzu magneśnicy statycznej, służącej do magnetyzowania membran polimerowych zbudowanych na bazie neodymu (Nd). Obliczenia rozkładu indukcji pola magnetycznego przeprowadzono przy użyciu metody elementów skończonych.

Słowa kluczowe: magneśnica statyczna, analiza FEM, magnetyczna membranowa separacja gazów

1. INTRODUCTION

The polymeric membranes have a wide range of applications in the modern industry [1, 2, 3]. Based on the diffusion process they are used to desalinate seawater, filter water and gas or purify liquids for industrial use.

The fabrication of polymeric membranes consists in mixing powder of magnetic material with polymeric compounds at the beginning [1]. After that by rolling, pressing or injection the shape and dimension of membrane is achieved. During drying the membrane is exposed to the static magnetic field what causes that its magnetic particles are placed in the way that guarantees the maximal homogeneity and the maximal value of magnetic flux density in the membrane.

2. THE AIM OF THE WORK

The aim of the work was to design, to build and commission the static magnetizer for generating static magnetic field with magnetic field density kept within given limits.

The main part of the magnetizer is the coil. The homogeneity of the magnetic field, generated inside the magnetizer coil was an important issue. It depends on geometry of the coil as well as on the AC component of the current flowing through the coil. Therefore the work was focused on such solution that generates required homogeneous magnetic field.

The 2D magnetic field density distribution was determined by means of the ANSYS software using the finite element method (FEM). Using ANSYS the shape of the magnetizer coil was optimized for the highest homogeneity level required.

The following assumptions were assumed when starting the construction of static magnetizer:

- the dimensions of the sample polymeric membrane: 90 mm of diameter and 0.5 mm of thickness;
- the value of generated magnetic field density: B_{AV} = 50 mT ± 2 mT (for X=0, Y=0, with zero ripple);
- the deviation of generated magnetic field density in time: $\Delta B(t)$ = 2 mT;
- the deviation of generated magnetic field density in space: $\Delta B(x,y)$ = 2 mT;
- the ambient temperature: T_{AIR}=25°C;
- the cooling: natural heat convection;
- the time of drying of the polymeric membrane: 1 hr.

3. DESCRIPTION OF STATIC MAGNETIZER

The scheme of the magnetizer is given in fig. 1. It consists of two parts - namely the coil of magnetizer, and the supplying circuit.

3.1. Coil of static magnetizer

The role of the static magnetizer coil is to generate very homogeneous static magnetic field for magnetizing the sample membrane. Because of the dimensions of the sample the minimal internal spool diameter of the coil is 100 mm. The height of the coil should be considered in two aspects: i) a coil of higher height generates more homogeneous magnetic field, ii) a coil of lower height generates higher values of the magnetic field density. After FEM analysis the height of the coil has finally been chosen as 200 mm. The coil is fed by DC current for generating the static magnetic field. The maximal current is $I_{Mm} \cong 1.9$ A (cf. the fig. 3). It results in diameter of the wire of d_M = 0.9 mm for assumed current density of J_M = 3 A/mm^2. The winding of the coil is made of the enameled cooper wire. The coil

consists of 5 000 turns, which are plated regularly in 25 layers and 200 turns in each layer. The total dc resistance of the coil winding depends on temperature and is $R_M = 65\ \Omega$ in the ambient temperature of $T_{AIR} = 25°C$. With the maximal current I_M the time necessary for stabilization of the coil temperature is 70 minutes. This time is determined for natural heat convection and with sample membrane placed inside the coil. After this time the resistance of the coil reaches its steady value of $R_M = 74\ \Omega$ with the temperature inside the coil $T = 55°C$ (for X = 0, Y = 0). The temperature of the coil winding in the thermal steady-state is $T_M = 76°C$ (the temperature probe placed between turns of winding). For the temperature measurement Thermometer C.A 864 Chauvin-Arnoux with K thermocouple was used [4]. In this state the total power losses generated in the coil winding are $\Delta P_M = 267$ W and are dissipated by the natural heat convection. The coil is placed 30 mm above the base what enables the cooling air to flow free in the coil. The static magnetizer coil is presented in fig.2.

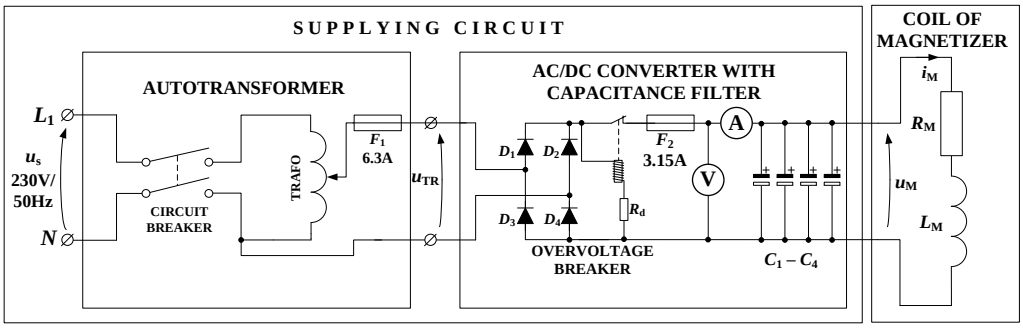


Fig. 1. Magnetizer: scheme of supplying circuit and the coil
Rys. 1. Magneśnica: schemat obwodu zasilania i cewka

3.2. The supplying circuit and measurements

The scheme of supplying circuit and the scheme of the coil of the magnetizer are presented in fig.1.

The magnetizer is supplied from the 1-phase power grid. The supplying circuit consists of two main blocks: i) the autotransformer with adjustable output voltage u_{TR} (with the fuse F_1 at the output) and ii) the AC/DC converter with capacitance filter with the over-voltage breaker and fuse F_2. The equivalent circuit of the coil of the magnetizer is represented by its inductance L_M and resistance R_M.

The main role of the autotransformer is to supply the rest part of static magnetizer with required voltage u_{TR}. The needed value of magnetic field density is set-up with the voltage u_{TR}.

The AC/DC converter with capacitance filter (C_1 - C_4) is dedicated to convertion of the alternate voltage u_{TR} to the direct voltage u_M with the lowest possible level of the voltage ripple [5]. This aspect is very important, particularly with maximal current flowing in the magnetizer coil winding, because the voltage ripple has influence on the ripple of the

generated magnetic field. The four capacitors (C_1 - C_4) of the filter (4 x 1000 μF/450 V) are connected in parallel. The capacitors together with the inductance of the coil L_M = 1.38 H smooth the coil current giving voltage ripple of ΔU_M = 2.86 % for the output voltage $U_{M(AV)}$ = 140 V and giving current ripple of ΔI_M = 0.01/1.9 ≈ 0,5% for current I_{Mm} = 1.9 A – fig. 3.

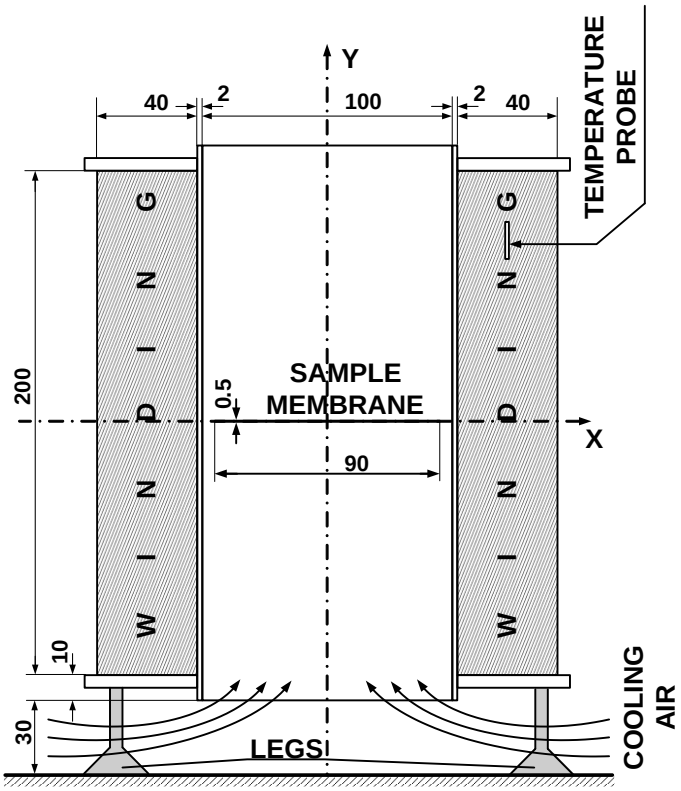


Fig. 2. Static magnetizer coil (cylinder shaped)
Rys. 2. Konstrukcja cewki magneśnicy statycznej (cylindryczna w kształcie)

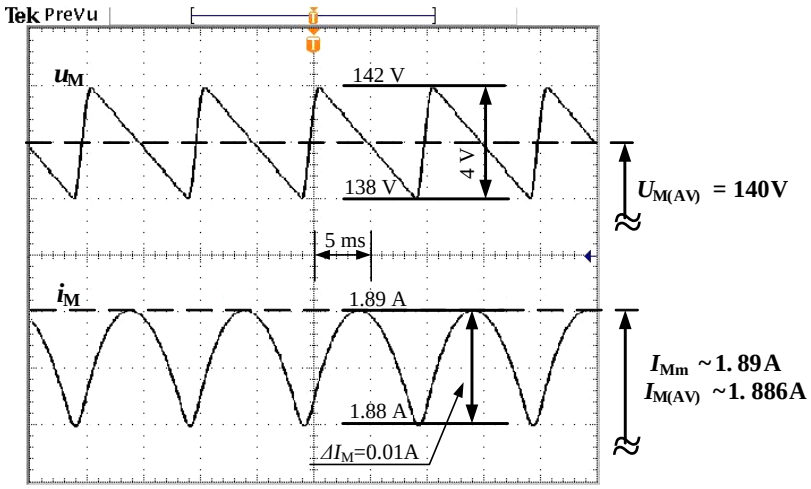


Fig. 3. Oscillogram of the ripple of voltage and current of the coil for $U_{s(RMS)}$ = 232V
Rys. 3. Oscylogram składowych zmiennych napięcia i prądu cewki dla $U_{s(RMS)}$ = 232V

The capacitance filter is equipped with short circuit and over-voltage protection system. Short circuit protection consists of fuse F_2 (= 3.15 A). Over-voltage protection is R-15-3PDT relay (Relpol) which turns off the supply when the average voltage $U_{M(AV)}$ on the coil clamps is higher than 160 V [6]. Since the nominal voltage of the relay coil is U_{REL} = 24 V, additional series resistor R_d = 2 kΩ is needed.

The process of adjusting the amplitude of the magnetic field is based on the adjusting of the average value of current i_M what is achieved by adjusting the output voltage of autotransformer u_{TR}. The magnetic field density B_{SUM} vs. voltage of the coil $U_{M(AV)}$ for two locations (X = 0, Y = 0 and X = 50 mm, Y = 0) is presented in fig. 4 (SUM indicates vector sum of Y and X components; $\overrightarrow{B_{SUM}} = \overrightarrow{B_X} + \overrightarrow{B_Y}$). The magnetic field density for these two points is equal correspondingly 49 mT and 51 mT. The polymeric membrane placed in the center of the coil is exposed to the magnetic field of assumed homogeneity. The requirement of ΔB_{SUM} = 2 mT is fullfilled (since Y components in these points are very small and can be neglected – fig. 8).

The measurements were done for the thermal steady-state and the ambient temperature T_{AIR} = 25°C. The equipment used for the measurement of B_{SUM} was the magnetic field strength meter FH54 [7] with the axial Hall probe HS-AGB5-4820 [8]. Measurements were carried out in two places (X = 0, Y = 0, Z = 0) and (X = 50 mm, Y = 0, Z = 0). The accuracy of measurements of FH 54 is ±0.3% and the accuracy of axial Hall probe is ±0.25%. The uncertainty of the probe location is ΔX = ΔY = ΔZ = ± 1 mm. The fluctuation of the magnetic field density in time generated by current ripple equals $\Delta B_{SUMt} = (\Delta I_M/I_{M(AV)} \cdot B_{AV}) = (0.01/1.886) \cdot 50$ mT = 0.27 mT. (B_{AV} defined in sec.2).

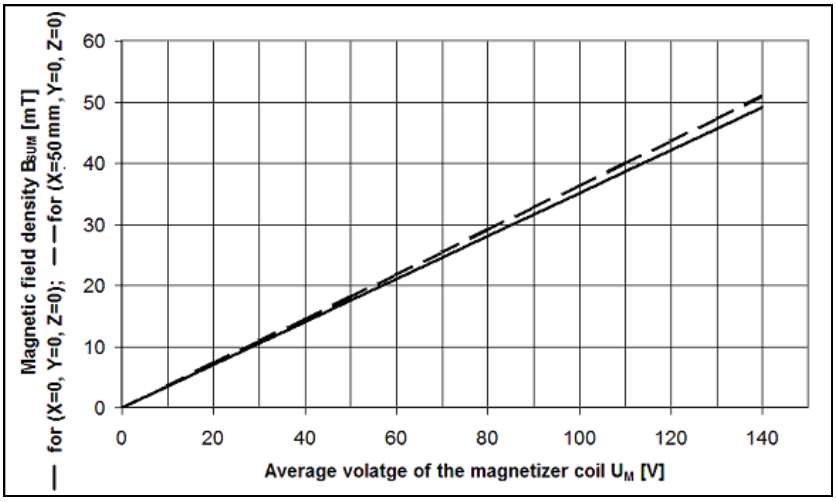
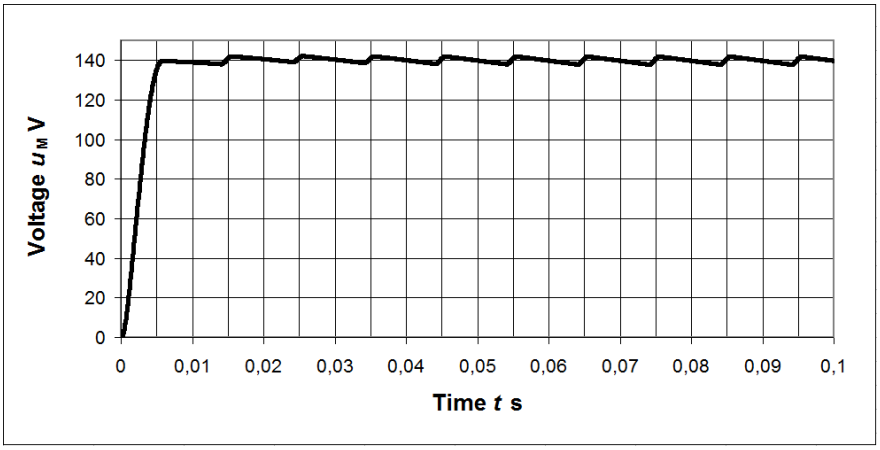


Fig. 4. Measured magnetic field density B_{SUM} vs. supply voltage $U_{M(AV)}$ for (X = 0, Y = 0, Z = 0) and for (X = 50 mm, Y = 0, Z = 0)

Rys. 4. Zmierzona zależność pola magnetycznego B_{SUM} od napięcia zasilania cewki $U_{M(AV)}$ dla (X = 0, Y = 0, Z = 0) oraz (X = 50 mm, Y = 0, Z = 0)

The waveform of the coil voltage u_M and current i_M vs. time for switching on u_{TR} are given in fig. 5. Because of high value of the coil time constant ($\tau_M = L_M/R_M \approx 0.018$ s) the transient of current is relatively long.

a)



b)

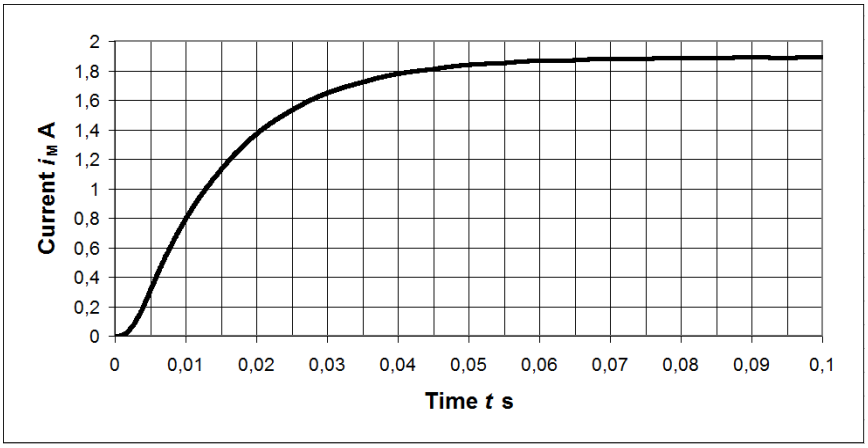


Fig. 5. Measured trasients of: a) voltage u_M, b) current i_M, after circuit breaker is on
Rys. 5. Pomiar stanu nieustalonego: a) napięcia u_M, b) prądu i_M; po załaczeniu wyłącznika „circuit breaker”

4. FEM ANALYSIS OF THE MAGNETIC FIELD DISTRIBUTION

The FEM analysis of the magnetic field distribution inside the static magnetizer coil was done using software ANSYS, [9]. The analysis results in optimized shape and dimensions of the coil that was carried out having assumed homogeneity of magnetic field density in the middle of the coil where membrane is placed.

The analyzed model is presented in fig. 6 – it depicts ¼ of the overall model. It consists of areas corresponding to the following components: coil, magnetized membrane sample and

surroundings. The model of the coil is simplified to one turn with cross area of all turns in the real coil. The coil fill factor of the winding is equal k = 0.7.

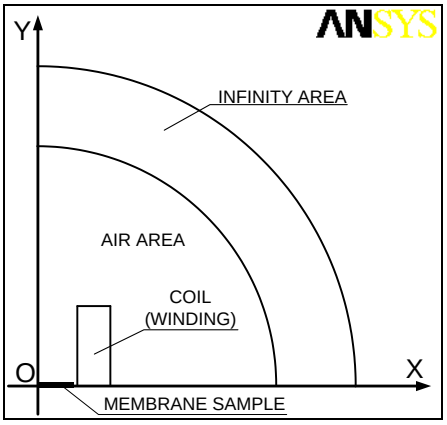


Fig. 6. The analzed model of the static magnetizer coil (infinity area: R_{in}=300 mm; R_{out}=375 mm)
Rys. 6. Analizowany model cewki magneśnicy statycznej (obszar nieskończoności: R_{in}=300 mm; R_{out}=375 mm)

The magnetic field distribution together with the flux lines is depicted in fig. 7. The highest value of average magnetic field density B_{SUM} is in the middle of the coil. For the supplying voltage ($U_{M(AV)}$ = 140 V) and current (I_{Mm} = 1.9 A) the generated magnetic field is B_{SUM} = 51 mT, what meets requirements. The value of the magnetic field outside of the coil is much lower (10% of the maximal value) and is equal B_{SUM} = 5 mT. In fig. 8 the perpendicular B_X and parallel B_Y components of the magnetic field density are depicted.

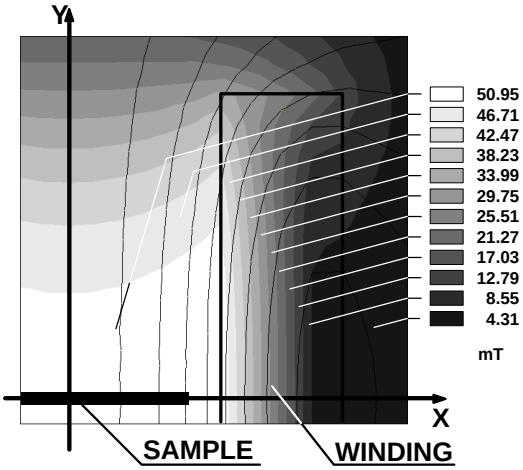


Fig. 7. The magnetic field density distribution B_{SUM} with the flux lines for I_{Mm}=1.9 A
Rys. 7. Rozkład indukcji pola magnetycznego B_{SUM} z liniami sił pola dla I_{Mm}=1.9 A

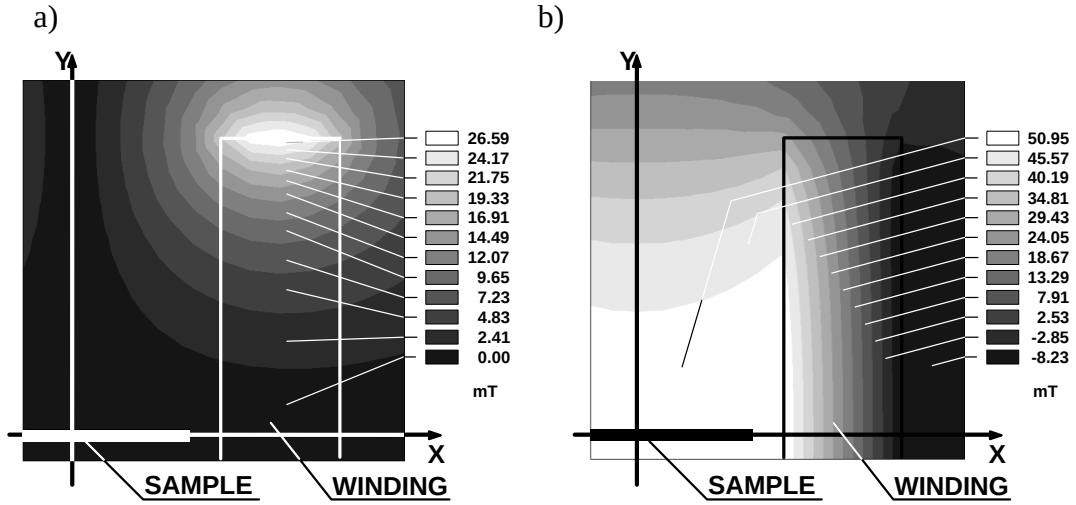


Fig. 8. The components of the magnetic field distribution: a) perpendicular B_X, b) parallel B_Y for I_{Mm}=1.9 A

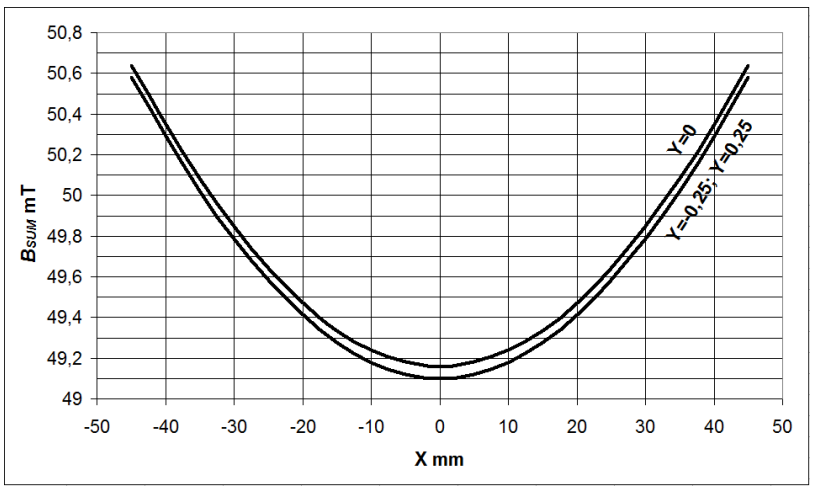
Rys. 8. Składowe indukcji pola magnetycznego: a) prostopadła B_X, b) równoległa B_Y dla I_{Mm}=1.9 A

The magnetic field density B_{SUM}, the perpendicular B_X and the parallel B_Y components inside the magnetizer coil in the place where the sample is placed are presented in fig. 9.

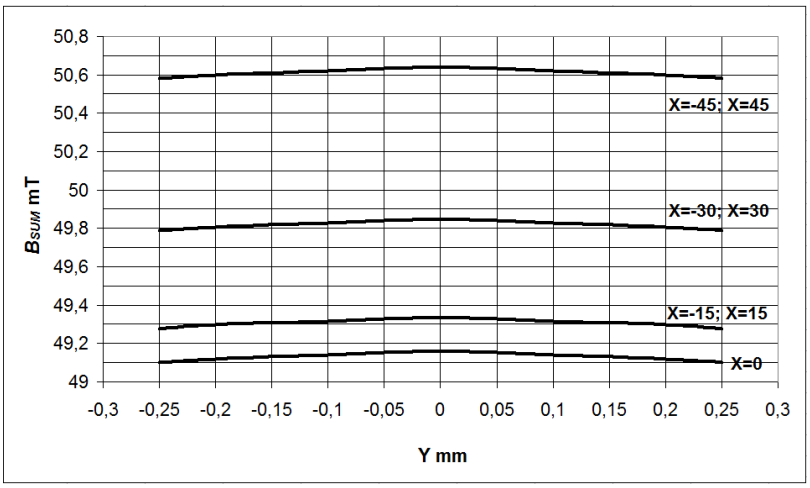
Inside the coil the magnetic field density along OX axis (parallel component of the magnetic field B_Y) has high homogeneity level. The lowest magnetic filed is in the geometrical middle of the coil and is growing up along OX axis. Finally, the variation of the magnetic field density along OX axis is ΔB_{OX} = 1.6% B_{SUM}.

The value of the magnetic field density along OY axis (perpendicular component of the magnetic field B_X) is very small (about 20 μT) and finally can be neglected. The requirement of $\Delta B(x,y)$ is fullfilled.

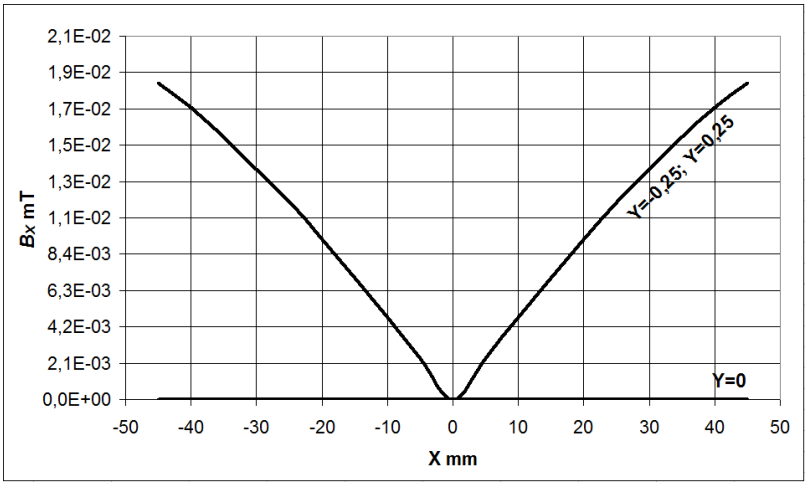
a)



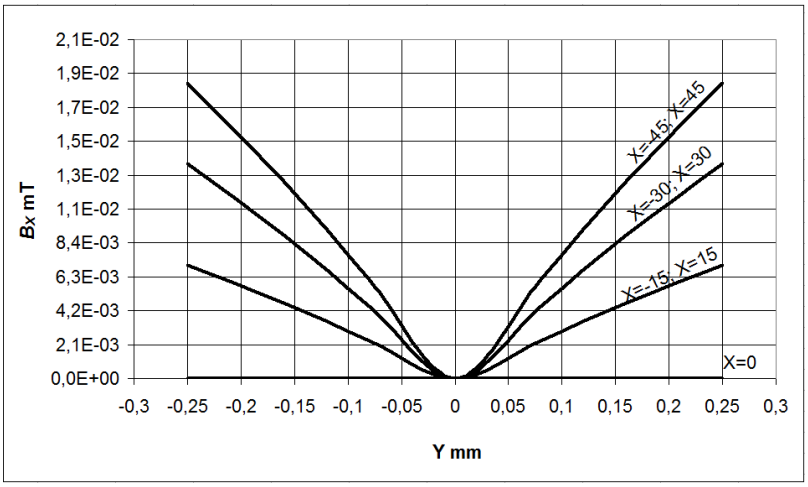
b)


50,8
50,6
50,4
50,2
50
49,8
49,6
49,4
49,2
49
BSUM mT
X=-45; X=45
X=-30; X=30
X=-15; X=15
X=0
-0,3 -0,25 -0,2 -0,15 -0,1 -0,05 0 0,05 0,1 0,15 0,2 0,25 0,3
Y mm

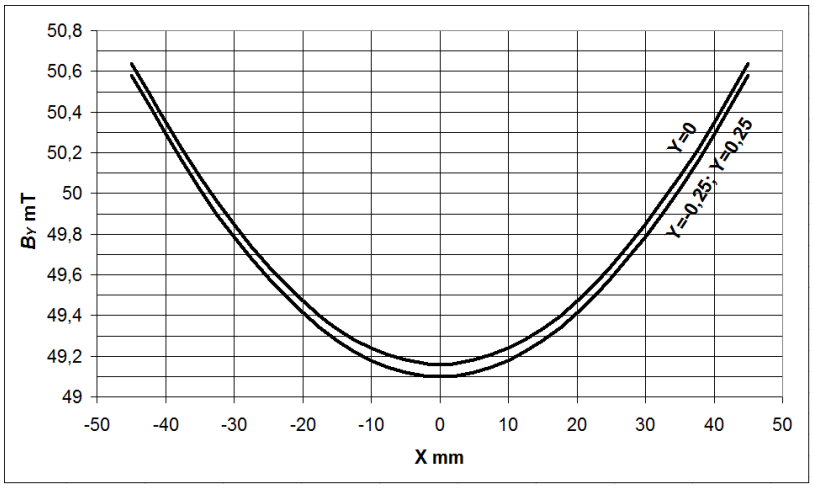
c)


2,1E-02
1,9E-02
1,7E-02
1,5E-02
1,3E-02
1,1E-02
8,4E-03
6,3E-03
4,2E-03
2,1E-03
0,0E+00
Bx mT
Y=0,25; Y=0,25
Y=0
-50 -40 -30 -20 -10 0 10 20 30 40 50
X mm

d)


2,1E-02
1,9E-02
1,7E-02
1,5E-02
1,3E-02
1,1E-02
8,4E-03
6,3E-03
4,2E-03
2,1E-03
0,0E+00
Bx mT
X=-45; X=45
X=-30; X=30
X=-15; X=15
X=0
-0,3 -0,25 -0,2 -0,15 -0,1 -0,05 0 0,05 0,1 0,15 0,2 0,25 0,3
Y mm

e)



f)

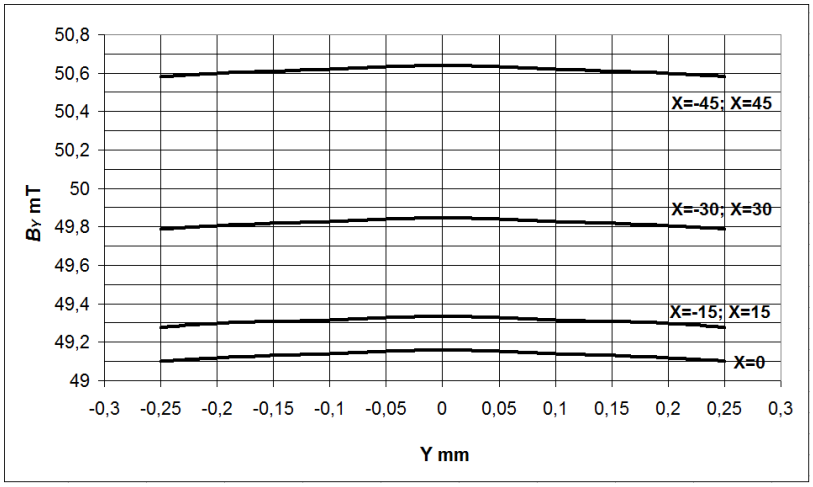


Fig. 9. Distributions of the magnetic field B_{SUM} along axis: a) OX, b) OY; the perpendicular component B_X along axis: c) OX, d) OY; the parallel component B_Y along: e) OX, f) OY axis

Rys. 9. Rozkład indukcji sumarycznej B_{SUM} wzdłuż osi: a) OX, b) OY; składowej prostopadłej B_X wzdłuż osi: c) OX, d) OY; składowej równoległej B_Y wzdłuż osi: e) OX, f) OY

5. CONCLUSIONS

1. FEM method of analysis proved to be very useful in design of the coils with assumed magnetic field distribution.
2. For the analyzed coil the highest irregularities of the magnetic field are along OX axis ΔB_{OX} = 1.6% B_{SUM} =0.8 mT (for X = 0, Y = 0, Z = 0). The irregularities along OY axis can be neglected because of very low thickness of the sample (ΔB_{OY} = 0.04% B_{SUM}). The magnetic field generated in the magnetizer coil can be considered as a homogeneous one.

3. The filter with capacitance C = 4000 μF together with coil inductance L_M = 1.38 H provides assumed time fluctuation of magnetic field ΔB_{SUMt} = 0.27 mT (for ΔU_M = 2.86 % $U_{M(AV)}$ = 4V, ΔI_M = 0,5% $I_{Mm} \approx$ 0.01 A).
4. The total irregularity of the magnetic field along OX axis (ΔBOX), together with fluctuation (ΔB_{SUMt}) is equal $\Delta B_{SUM} = (\Delta B_{OX} + \Delta B_{SUMt})$ = (0.8 mT + 0.27 mT) ≈ 1.1 mT that fullfils assumed value.
5. The power losses, generated in the resistance of the coil, in the case of maximal current I_{Mm}=1.9 A are ΔP_M = 267 W and are dissipated by the natural heat convection for ambient temperature of ~25°C.
6. The future works should embrace the following problems: i) stabilization of the current i_M in the case of voltage fluctuations in the power grid and ambient temperature, ii) influence of different shape of the coil than typical solenoid (e.g. Helmholtz coil) on the homogeneity of the magnetic field, iii) the temperature distribution in the area the sample is placed.

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Omówienie

W artykule przedstawiono analizę rozkładu pola magnetycznego we wnętrzu cewki magneśnicy statycznej służącej do magnetyzacji membran polimerowych zawierających sproszkowany neodym. Analizę ukierunkowano na zagadnienie równomierności rozkładu pola w obszarze oddziaływania na membranę. Zagadnienie to zostało kompleksowo przeanalizowane teoretycznie (analizy FEM, ANSYS) oraz eksperymentalnie. Uwzględniono dwa aspekty wpływające na niejednorodność wytwarzanego pola magnetycznego, mianowicie: I) zmianę indukcji wzdłuż osi OX oraz OY oraz II) wpływ tętnień napięcia i prądu cewki pochodzących od układu zasilania.

Analizowana cewka umożliwia wytworzenie pól magnetycznych o regulowanej wartości w zakresie $B_{SUM(\mathrm{AV})} = 0 - 50$ mT. Przeprowadzone analizy pozwalają określić niejednorodność wytwarzanego pola magnetycznego w różnych punktach magnesowanej membrany i potwierdzają, że przyjęta konstrukcja spełnia założone kryteria.

W artykule omówiono także zagadnienie zasilania cewki magneśnicy statycznej z sieci elektroenergetycznej przez przekształtnik AC/DC. Opisano parametry przekształtnika spełniającego przyjęte kryteria oraz przeanalizowano wpływ tętnień napięcia i prądu cewki na zmiany wytwarzanego pola magnetycznego. Przeprowadzono analizę cewki ze względu na straty mocy projektując ją tak, aby możliwe było chłodzenie powietrzne z wykorzystaniem konwekcji naturalnej.