XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

SOME PRACTICAL ASPECTS OF EXCITATION COIL DESIGN FOR ELECTROMAGNETIC FLOW METER

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Abstract – Paper presents some practical aspects of excitation coil design for electromagnetic flow meter dedicated for open channels. Two types of coil is discussed, saddle type and double deck type. Some minor and major differences are discussed.

Keywords: excitation coil design, magnetic field, electromagnetic field.

1. INTRODUCTION

Measuring flows is very well known and described problem in current metrology. The problem becomes much more difficult if we are trying to measure the flow rates in open channels. If the relationship between flow rate and liquid levels is not known, the classical methods that calculate flow rates from area and fluid velocity are useless. Only electromagnetic and ultrasonic methods can make satisfactory measurements of flow rates in such situations. This situation can be very often found in a wastewater treatment plants or irrigation system. This paper is focused on electromagnetic methods in application to the artificial, rectangular flow channel. Artificial channel means that the channels banks are nonconductive and because the rectangular cross section, the excited magnetic field should be homogenous [1].

Faraday's law is the principle behind electromagnetic flow meters. It associates an electric potential φ induced in the measurement zone with both the liquid velocity vector $\vec{\vartheta}$, and the magnetic flux density $\vec{\boldsymbol{B}}$.

The voltage between the electrodes, which are placed on the opposite sides of a flow channel, is proportional to the mean velocity of the flow in the area between the electrodes. The measured voltage can be described as follows:

$$U = \int_V \vec{W} \cdot \vec{\vartheta} dv \qquad (1)$$

where: $\vec{W}$ is the weight vector introduced by Bevir [1,2] ($\vec{W} = \vec{B} \times \vec{J}$, where $\vec{J}$ - is the virtual current density vector, $\vec{B}$ - is the magnetic flux density vector, U is the voltage across electrodes, V is the flow volume and $\vec{\vartheta}$ is the velocity vector of the water.

The measuring head of an electromagnetic flow meter dedicated for small artificial channels comprises a part of a flow channel, an excitation coil and a pair of electrodes [2]. The main design problem is to ensure a high level of uniformity in the magnetic flux distribution across the measurement zone by a specific design of an excitation coil.

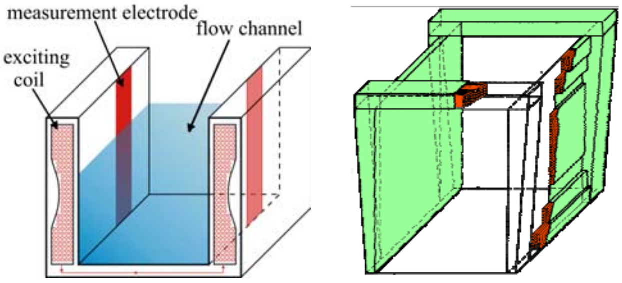

Fig. 1. Primary transducer for electromagnetic flow meter.

One of the classical approach to the excitation coil is presented in Fig. 1.

2. PRACTICAL APROACH TO COIL DESIGN

The main goal of design analysis were, from one side, the magnetic field homogeneity in a measurement zone and the expected magnetic field distribution in a border region of the exciting coil, from the other side. In a border region is observed the fast vanishing of magnetic field what can be a source of disturbing electric field (side effects) [3, 4]. The side effects are a result of the finite length of the excitation coil. This phenomenon seriously reduces the measured signal. The simplest way to eliminate this problem is to lengthen the excitation coil in the flow direction [3].

Additional problem which should be also solved during analysis is the ability to wind the exciting coil according to the final results of design procedure.

Two versions of the excited coils were taken into consideration, saddle type and double deck type. Two analysed coils differ, among other things, in a type of coil joints between two opposite side of excitation coil and the way of coil winding.

To simplify the analysis, the shape of the excitation coil's cross-section was not optimized.

ISBN 978-963-88410-0-1 © 2009 IMEKO

2.1. Saddle type of exciting coil

The saddle type coil is presented in Fig. 2.

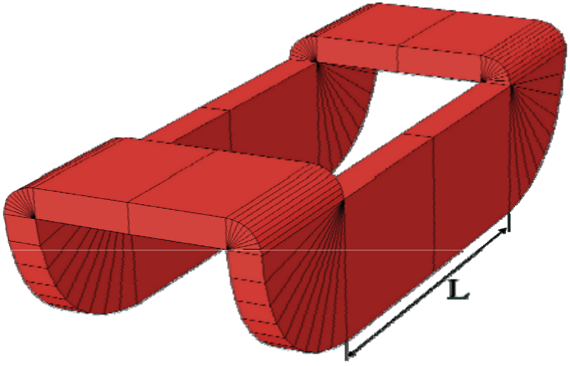

Fig.2. The idea of saddle type coil.

This type of exciting coil is very similar to the classical coil described in [3], but the upper joints between both sides of the flow channel are different. The exemplary spatial magnetic field distribution excited by a described coil in a flow channel is presented in Fig. 3.

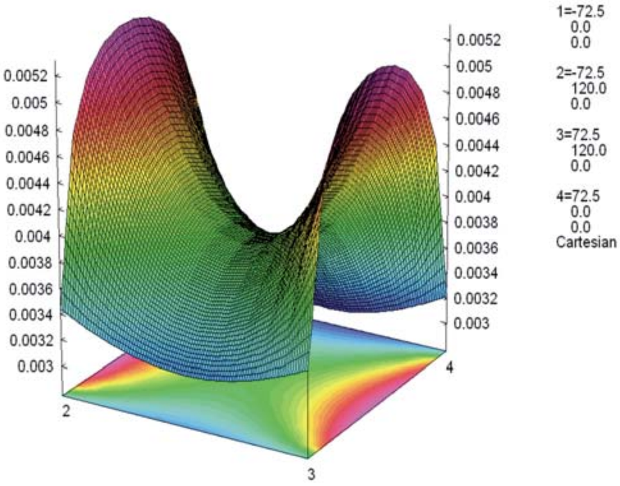

Fig. 3. Magnetic field distribution in a flow channel. (saddle type coil)

The above picture shows the magnetic field in the middle of the coil, in the plane where measurement electrodes are located. This plane is defined by vertices 1,2,3 and 4, as presented in Fig.4.

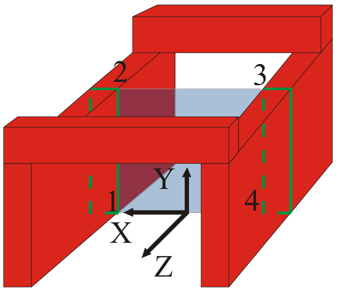

Fig. 4.The chosen X-Y measurement plane where the magnetic field distribution is calculated

The shape of the upper joints substantially affected the magnetic field distribution in a border region. From the side effect point of view, the most important is the magnetic field distribution in a border region. The exemplary magnetic field distribution for this type of coil is shown in Fig. 5.

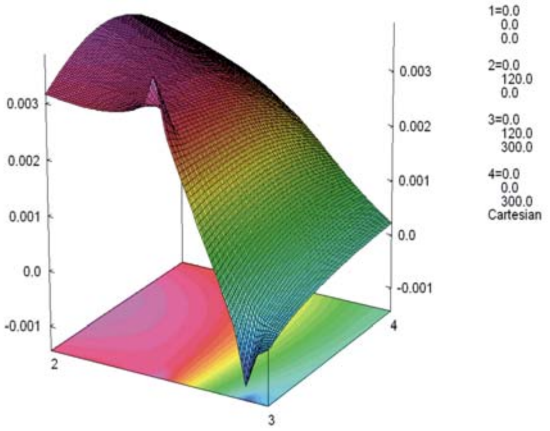

Fig. 5. Magnetic field distribution in a border region (saddle type coil).

The above distribution of a magnetic field was calculated in the middle of the flow channel, in the plane parallel to the flow velocity vector. This plane is defined by a rectangle with vertices 1, 2 ,3 and 4, as shown in Fig.6.

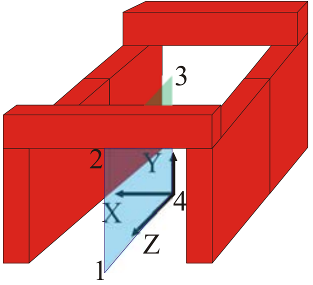

Fig.6. The chosen Y-Z measurement plane where the magnetic field distribution is calculated

2.2. Double deck type of exciting coil.

The main goal of double deck type coil was to improve the ability to wind the excitation coil. From this point of view, the double deck type coil (Fig. 7.) is much better than saddle type.

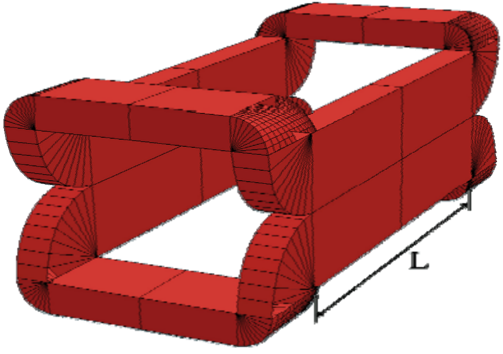

Fig.7. The idea of double deck type coil.

The magnetic field distribution excited by described coil in a flow channel is very similar to the distribution excited by saddle type coil (Fig. 8).

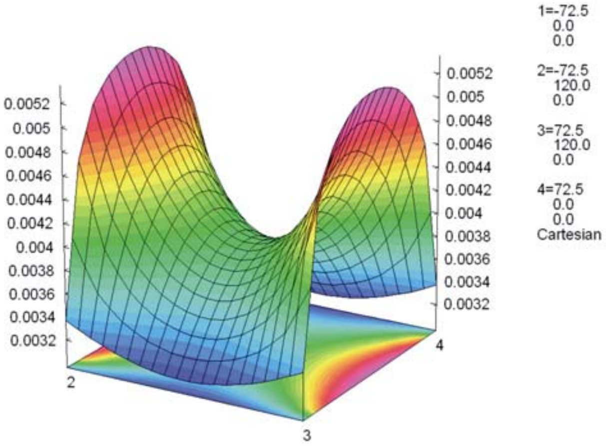

Fig. 8. Magnetic field distribution in a flow channel. (double deck type coil)

The main difference between two described coils can be shown in a border region of the coil. The exemplary view of magnetic field distribution in a border region is shown on Fig. 9.

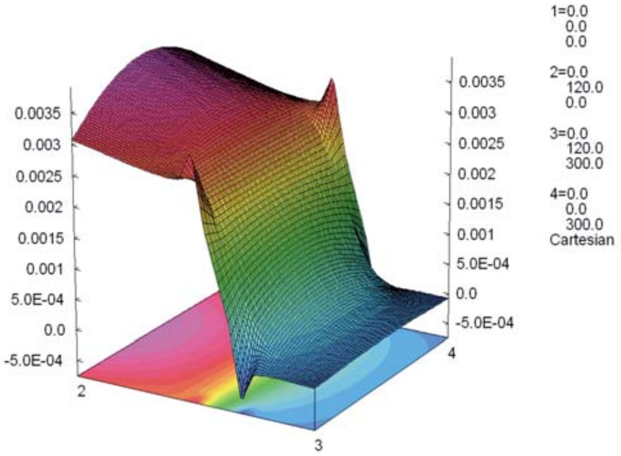

Fig. 9. Magnetic field distribution in a border region (double deck type coil)

In such view it is very difficult to weight up the homogeneity of the magnetic field in a measurement zone. More useful estimation in comparative analysis can be done using root mean square deviation calculated for cross-section of the measurement zone.

2.3. Comparative analysis

The comparative analysis of the both coils will be curry out according to the two main problems, magnetic field homogeneity in a measurement zone and the shape of vanishing magnetic field in border region.

As a criteria for the assessment of the quality of the coil design, three chosen, characteristic distributions of magnetic field were analyzed:

- distribution in the X-Y plane perpendicular to the flow, in the middle of the coil's length (Z=0, as shown in Fig. 4).
- distribution in the Y-Z plane parallel to the flow, in the middle of the coil's width (X=0, as shown in Fig. 6).
- distribution along the straight line of chosen length, parallel to the flow and located in the middle of the channel's width, for different channel filling (Y=var).

The analyzed excitation coils were designed for the same flow channel. The designs differ mainly in the layout of upper joints, but the dimensions of a central, straight part of the coil is identical in both cases. The coil's sidewall is 120 mm high, 25 mm wide and its straight (L), rectangular part is 300 mm long. The total length of the coil is 420 mm for double deck and 540 mm for saddle type coil. During numerical calculations only the half of the total coil was analyzed, due to symmetry of the problem. For the clarity of comparison , the selected results obtained for both coils are presented together. Fig.10. shows the values of B_y component of magnetic flux density calculated along the parallel line segments in the vertical symmetry plane. All segments started at coordinates (X=0; Z=0) and ended at coordinates (X=0; Z=300) behind the upper joints. Y-coordinates for the analyzed segments equaled 0, 30, 60, 90 and 120 mm, respectively.

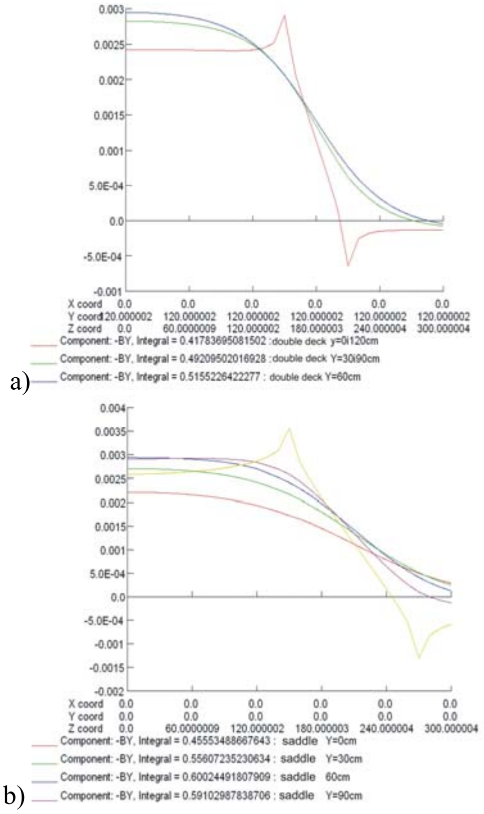

Fig. 10. B_y component of magnetic flux density calculated along the channel in the middle of its width, at different heights: a) double deck coil b) saddle type coil

Fig. 11 presents the B_y component of magnetic flux density calculated for both coils along the line segments 150 and 300 mm in length, along symmetry axis (Y=60).

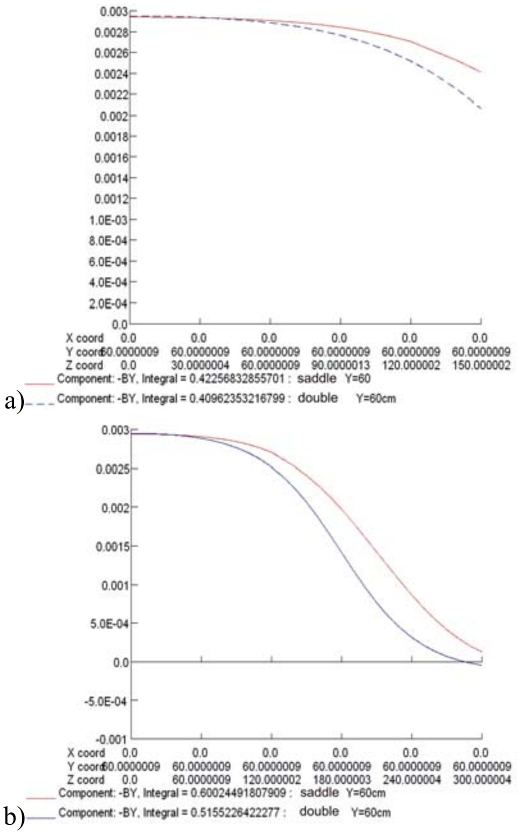

Fig. 11. B_Y component of magnetic flux density calculated along the channel in the middle of its width and height: a) 150 mm b) 300 mm.

In order to present more clear and explicit comparison of the two coil designs, the mean values and standard deviations of magnetic flux density distributions were calculated for analyzed line segments and areas. The results for both coil designs are summarized in Tables 1 and 2.

Tab.1 Magnetic flux distribution along chosen line segment

Line segment coordinates (1-start 2-end) [mm]	Double deck coil		Saddle type coil	
	Mean value [mT]	Standard deviation [mT]	Mean value [mT]	Standard deviation [mT]
1. X=0;Y=60;Z=0 2. X=0;Y=60;Z=150	**2,731**	0,246	**2,817**	0,145
1. X=0;Y=60;Z=0 2. X=0;Y=60;Z=300	**1,718**	1,127	**2,000**	0,967

The presented data show, that double deck coil provides better field uniformity in its middle part, in the X-Y plane across the electrodes. Mean value of magnetic flux density is higher and the standard deviation is smaller than in case of saddle type coil, for the same electric current density supplying both coil designs.

Considering magnetic field distribution in the Y-Z plane (along the flow channel) it can be seen that from the middle of the coil to the upper joints region the saddle type coil provides higher value of magnetic flux density, but worse field uniformity than double deck coil. In the next analyzed area covering the upper joints region, the saddle type coil provides both higher mean value of magnetic flux density and better field uniformity (smaller standard deviation).

It can be seen, from the presented, calculated distributions of the magnetic field in the X-Y plane, that by moving the upper joints away from the area of analysis, the magnetic field distribution is affected for both coil designs. These changes in the mean value of magnetic flux density and standard deviation as a function of coil's length were further investigated and the distributions of magnetic field were calculated as a function of the length of the central, rectangular parts of the coils.

Tab.2 Magnetic flux distribution on chosen planes inside the channel

Coordinates of boundary vertices 1, 2, 3 and 4	Double deck coil		Saddle type coil	
	Mean value [mT]	Standard deviation [mT]	Mean value [mT]	Standard deviation [mT]
Across the channel X-Y plane 1.X=-72.5; Y=0;Z=0 2.X=-72.5; Y=120;Z=0 3. X=72.5; Y=120;Z=0 4. X=72.5; Y=0;Z=0	**3,032**	0,286	**3,014**	0,310
Along the channel Y-Z plane 1. X=0; Y=0;Z=0 2. X=0; Y=120;Z=0 3.X=0; Y=120;Z=150 4. X=0; Y=0;Z=150	**2,628**	0,213	**2,680**	0,261
Along the channel Y-Z plane 1. X=0; Y=0;Z=0 2. X=0; Y=120;Z=0 3.X=0; Y=120;Z=300 4. X=0; Y=0;Z=300	**1,609**	1,145	**1,875**	1,000

The half length of the rectangular part of the coil's sidewall was changed from 150mm to 450 mm, whereas the shape of upper joints region was unchanged. The following figures present the influence of the length of the rectangular part of the coil on the mean value and standard deviation of magnetic flux density and for both coil designs. Fig. 12 shows the results calculated on the X-Y plane in the middle of the coil, as defined in Fig.4.

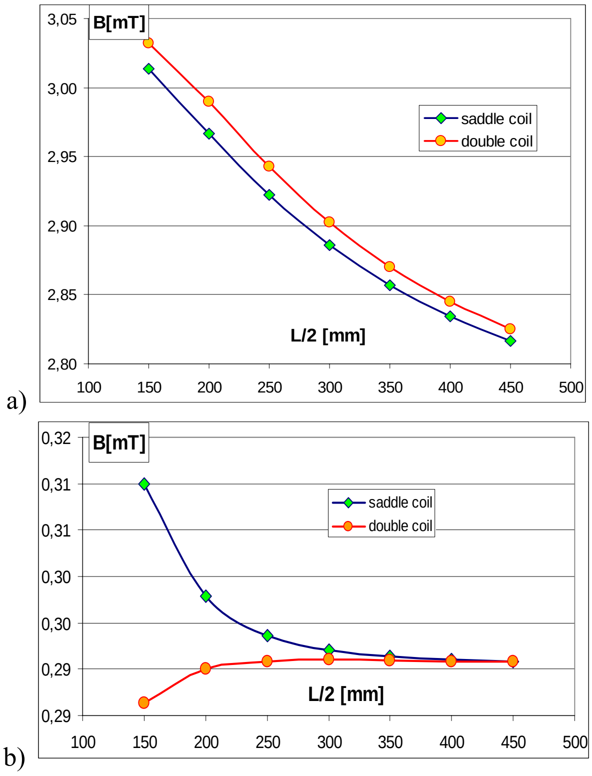

Fig.12. Mean value of magnetic flux density (a) and standard deviation (b) in the middle of the coil (X-Y plane) as a function of coil's dimensions.

The presented plots show that the mean value of magnetic flux density on X-Y plane is in every case (for every analyzed length of the coil) slightly higher for double deck coil. The calculated values of standard deviation also favor this particular coil design. The saddle type coil achieves the same level of standard deviation values for much greater overall length. It should be mentioned that standard deviation diminishes for a double deck coil when the coil is shortened. So, short double deck coil provides better magnetic field uniformity. It is very important feature, because it reduces the cost of the coil itself. The opposite effect can be observed for a saddle type coil. It must be twice as long as the double deck one to achieve similar field uniformity. Taking into account solely field uniformity it can be said that double deck coil should be as short as possible and saddle type coil as long as possible.

Fig.13 shows the mean value and standard deviation of magnetic flux density calculated on Y-Z plane situated in the middle of the channel, as shown in Fig. 4a. In spite of changing the length of the coil, the length of the analyzed plane was always 150mm in the direction of the flow velocity vector.

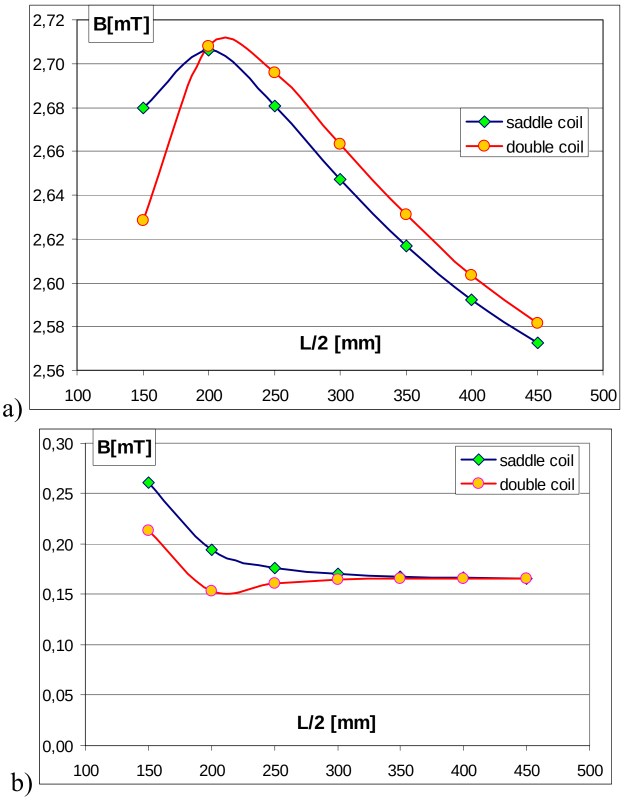

Fig.13. Mean value of magnetic flux density (a) and standard deviation (b) in the middle of the coil (Y-Z plane) as a function of coil's dimensions.

The results are similar to those presented in Table 2 and show that short saddle type coil provides higher mean value of magnetic flux density. By extending the coil (moving the joints away from the center) by 100 mm the double deck coil gains advantage. The opposite relation is with standard deviation. In this case, even the short the double deck coil ensures better magnetic field uniformity. The difference vanishes as the length of the coils is enlarged. It should be pointed out that the minimal value of standard deviation is obtained for the half-length of the coil of 200mm. It means, in practice, that 60mm long joints are 50 mm away from the measurement zone, which extends 150 mm from the centre of the coil. Such proportions of the coil design, where the rectangular part of the coil's sidewall is by 1/3 longer than the measurement zone ensure the maximal mean value of magnetic flux density and best possible field uniformity. Further lengthening of the coil slightly reduces the value of By component of magnetic field and worsens the field uniformity.

Fig.14. presents the mean value and standard deviation of magnetic flux density calculated along line segment located in the middle of the channel, on its symmetry axis. The coordinates of the beginning and the end of this line segment are: (X=0,Y=60,Z=0;X=0,Y=60,Z=150). This line segment is located in the middle of previously analyzed Y-Z plane.

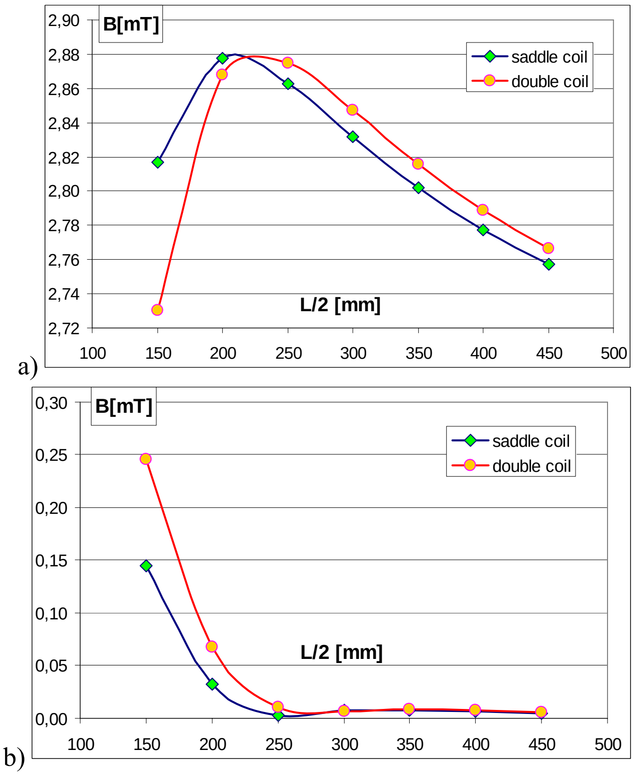

Fig.14. Mean value of magnetic flux density (a) and standard deviation (b) along the line segment in the middle of the Y-Z plane.

The results of numerical calculations and analysis show the advantage of double deck coil design over previous saddle type solution, especially when short coils are considered. The designers generally opt for the short coils, as it reduces the costs, but without negative impact on the magnetic field uniformity in the plane perpendicular to the flow (X-Y). Double deck coil is additionally simpler to make and ensures better repeatability of magnetic field distribution.

CONCLUSIONS

The decision to change the type of the exciting coil from saddle type to double deck one was initially based only on technological reasons. The carried out analysis proved also its superiority over previous design when the uniformity of magnetic field distribution is considered.

Double deck coil basically consists of two saddle type coils connected back to back. The parting of the same total number of windings between two identical coils reduces twice the length of upper joints. The length of the rectangular, working part of the coil is the same in both designs, but the total length of double deck coil is shorter than saddle type one by one length of upper joints. The double deck coil design makes the manufacturing process much easier and coils can be easily replicated using the developed set of templates.

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