# DESCRIPTION OF UNSTEADY FLOWS IN THE CUBOID CONTAINER CAUSED BY LORENTZ FORCES

Kateřina Horáková*, Karel Fraňa*

*Leading topic of this article is description of Lorentz forces in the container with cuboid shape. Inside of the container is an electrically conductive melt. This melt is driven by rotating magnetic field. Numerical simulations of these unsteady flows were performed in commercial software Ansys Fluent (version 13). Input data (Lorentz forces in the container with cuboid shape) were also obtained from the computing program NS-FEM3D, which uses DDES method of computing as a turbulent approach. Related velocity field of the melt inside the container was displayed and described as well.*

Keywords: *MHD, Lorentz forces, velocity field, rotating magnetic field, secondary flow*

## 1. Introduction

A theory of flow behaviour under magnetic field effect is called magnetohydrodynamics (MHD). First mentions about MHD appeared in relation to astrophysics and geophysics. Nowadays the magnetic field is used in technical practice. Rotating magnetic field generates eddy flow in electric conductive melt. This effect is used to e.g. for non-contact electromagnetic stirring of the melt in metallurgy and for crystal growing, when rotating magnetic field homogenize of varied metal alloy and fine metal. The melt flow positively affects metallographic structure of casts. For more details about electromagnetic stirring see [1], [2].

This process is possible to simulate by commercial software Ansys Fluent (version 13) using MHD module for computing MHD processes. Contours of Lorentz forces are also possible to obtain by computing code NS-FEM3D, which uses DDES method of computing as a turbulent approach. This code was validated by several studies [3] especially for cylindrical container. Several articles for unsymmetrical container were published over the last years [4]. Contours of Lorentz forces obtained by these two methods are described in this article.

## 2. Problem formulation

This work could be interpreted as a flowing melt inside the container. The melt inside the container is an electrically conductive and melt flowing is driven by rotating magnetic field (Fig. 1). Shape of the container could be various. In my previous works analytical formula of Lorentz forces in cylindrical container was inferred [5]. Comparing of Lorentz forces in cylindrical container (used analytical formula) and cuboid container (simulated

* Ing. K. Horáková, doc. Ing. K. Fraňa, Ph.D., Technical University of Liberec, Faculty of Mechanical Engineering, Department of Power Engineering Equipment, Studentska 2, Liberec 1

by computing program NS-FEM3D) was published in [6]. Comparing Lorentz forces (and caused unsteady flows) obtained by analytical formula and simulated by software Ansys Fluent was performed in [7]. In this article will be descripted unsteady flows caused by rotating magnetic field in cuboid container. In Navier-Stokes equations for flow calculations the external forces are occurred. In the flow of melt driven by a rotating magnetic field these forces are the Lorentz forces. Contours of these forces could be simulated by commercial software Ansys Fluent (version 13) or in computing code NS-FEM3S.

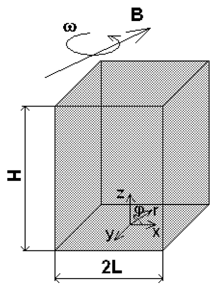


*Fig.1: Description of the electromagnetic stirring*

## 3. Solutions in software Ansys Fluent

The Magnetohydrodynamics (MHD) module is provided as an additional module with the standard ANSYS FLUENT licensed software. The ANSYS FLUENT MHD model allows analysing the behaviour of electrically conducting fluid flow under the influence of constant (DC) or oscillating (AC) electromagnetic fields [8]. Equations of MHD are solved through user-defined scalar (UDS) transport equations. Other model-related variables such as the external magnetic field data, current density, Lorentz force and Joule heat are stored as user-defined memory (UDM) variables [8]. Computing of MHD in Fluent is possible by two different methods – solving magnetic induction equation or scalar potential equation. Both methods are solved by scalar transport equations. Solution by magnetic induction uses two or three transport equations (2D or 3D solution). Solution by electric potential uses only one transport equation. MHD module is relatively new and some computing limits and other parts (solidification, simulation of free surface etc.) will be added to upgraded version. Some computing limits are: computing program is set for the melt with sufficient conductivity, it can be set up only magnetic induction value (no current density), it is assumed that frequency is low etc.

### 3.1. Ansys Fluent set-up

Mesh of the cuboid container was created in Ansys meshing. Boundary conditions are set as wall. Number of mesh elements is c. 700 000 (including refinement in the area of boundary layers). This mesh was exported to Ansys Fluent. Because of AC electromagnetic field unsteady computing was chosen. Computing code NS-FEM3D uses DDES method of computing as a turbulent approach. Because of comparable results, that model (with RANS model Spalart – Allmaras) was chosen in Fluent as well. Taylor magnetic number of this flow is $1{\times}10^6$, turbulent approach is necessary. MHD module was unloaded and magnetic induction computing method was chosen. Solving MHD equations was extended for Lorentz forces computing. Physical values of density, electric conductivity and viscosity were set the same as in NS-FEM3D (density $\varrho = 6361\,\mathrm{kg\,m^{-3}}$, kinetic viscosity $\nu = 3.4\times10^{-7}\,\mathrm{m^2\,s^{-1}}$, electric conductivity $3.3\times10^{6}\,\mathrm{S}$). The cover of the container was chosen as insulated walls. The values of external magnetic field was chosen – AC field with angular velocity of the field $\omega = 439\,s^{-1}$ and amplitude of magnetic induction in $x$ and $y$ direction $B_0 = 4.478\times10^{-3}\,\mathrm{T}$. Magnetic induction has only components $B_\mathrm{x}$ and $B_\mathrm{y}$ because is assumed that vertical size of bipolar inductor is bigger than the height of the melt in the container. Time step is very small – $10^{-6}\,\mathrm{s}$ in the begging of computing, $5\times10^{-5}\,\mathrm{s}$ passing the initial problems. Value of time step is small because of bad convergence and angular velocity of the field $\omega = 439\,\mathrm{s}^{-1}$. Total time is c. 2 s.

### 3.2. Postprocessing

Lorentz forces in Fluent are possible to display only in Cartesian coordinate system and only as instantaneous values but Lorentz forces are changed because of AC field (Fig. 2).

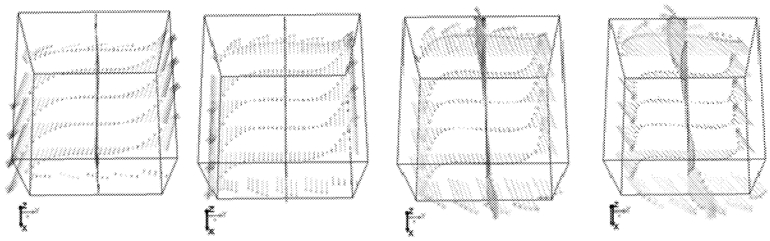

*Fig.2: Vectors of Lorentz forces in different computing time*

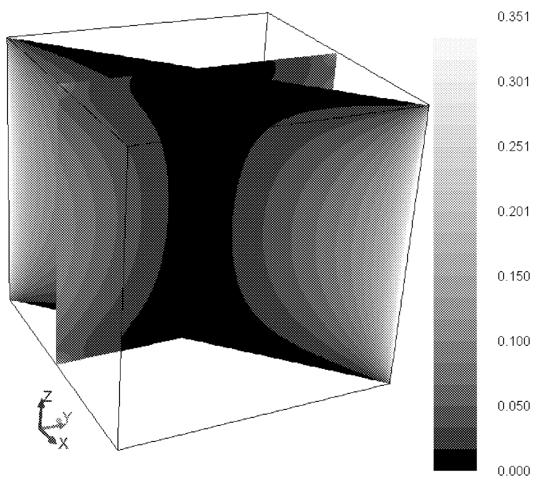


*Fig.3: Contours of Lorentz forces in Fluent*

Contours of Lorentz forces (in Newton) are displayed in Fig. 3. These contours in Fluent include forces in $x$, $y$ and $z$ directions. In NS-FEM3D (and analytical formula for Lorentz forces in cylindrical container) part of Lorentz forces in $z$ direction is zero. It is caused by some simplifications in boundary conditions (scalar potential $\Phi_2 = 0$ – see [5]) and $B_\mathrm{z} = 0$. Maxima of these forces are occurred on the outer walls of container in the half of container

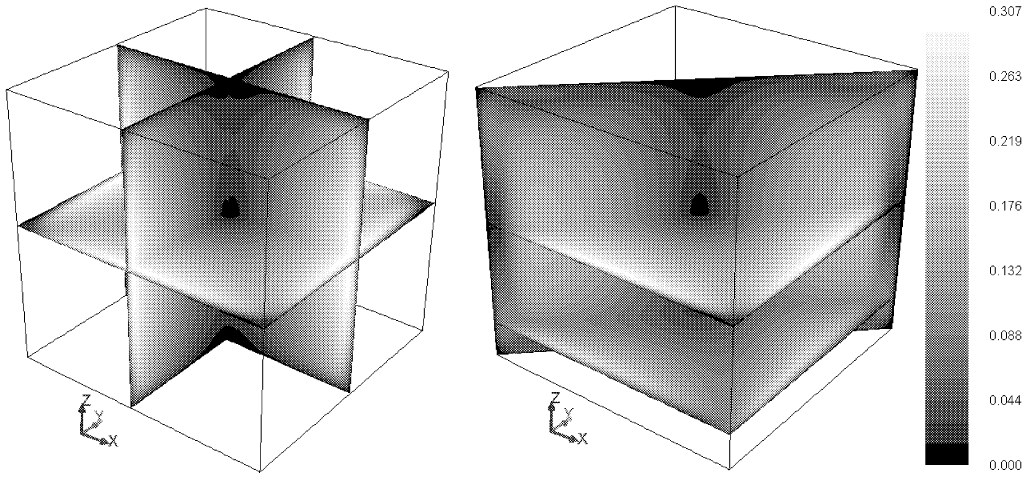


*Fig.4: Contours of mean velocity field in Fluent*

high. On the contrary minima of magnetic forces are in the axis of container and on upper and lower base (based on boundary conditions).

Contours of mean velocity field are displayed in Fig. 4. Maxima of these velocities are appeared near the outer walls of container. In horizontal plane in half of the container height four areas of maximum velocity are occurred. These areas could be found for every intensity of magnetic field (for every Taylor number), only positions of these areas are changed [4]. For laminar flow (smaller Taylor number) these four areas are placed farther from outer walls of container. For turbulent flow (higher Taylor number) these four areas are displaced closely outer walls. The melt moved in azimuthal direction decelerated and accelerated in dependence on container position. Near container edges the melt decelerated and then accelerated. Minima of velocities are in the axis of container, edges and on container walls (based on boundary conditions). Near container edges small eddies are formed. These eddies have much lower energy than mean flow and they are absorbed by it. This effect is visible also from energy spectrum of these areas [9].

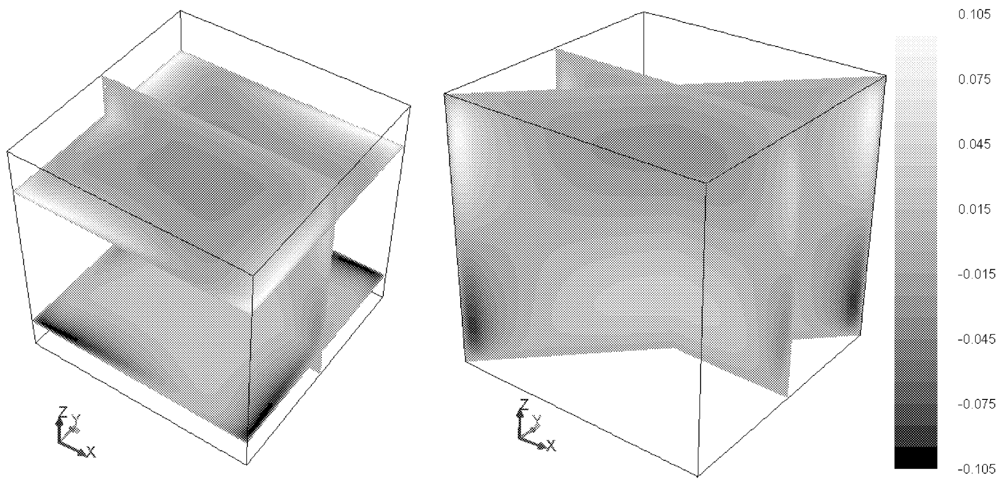


*Fig.5: Contours of axial velocity field in Fluent*

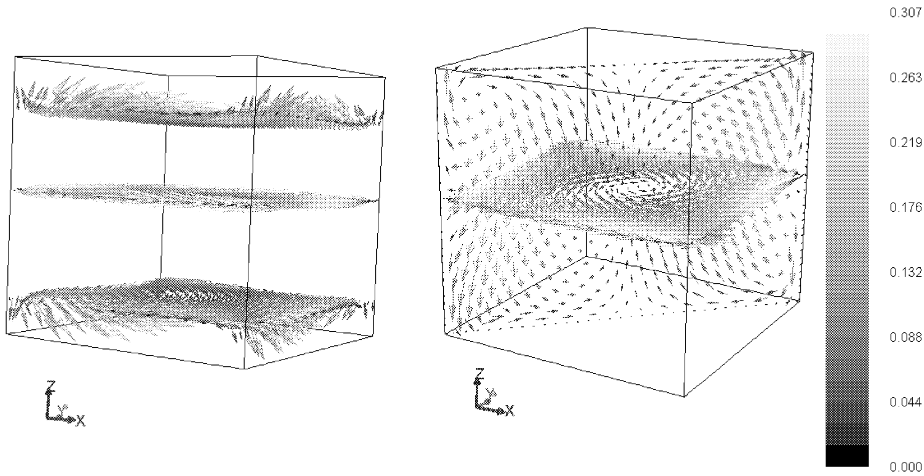


*Fig.6: Vectors of velocity field in Fluent*

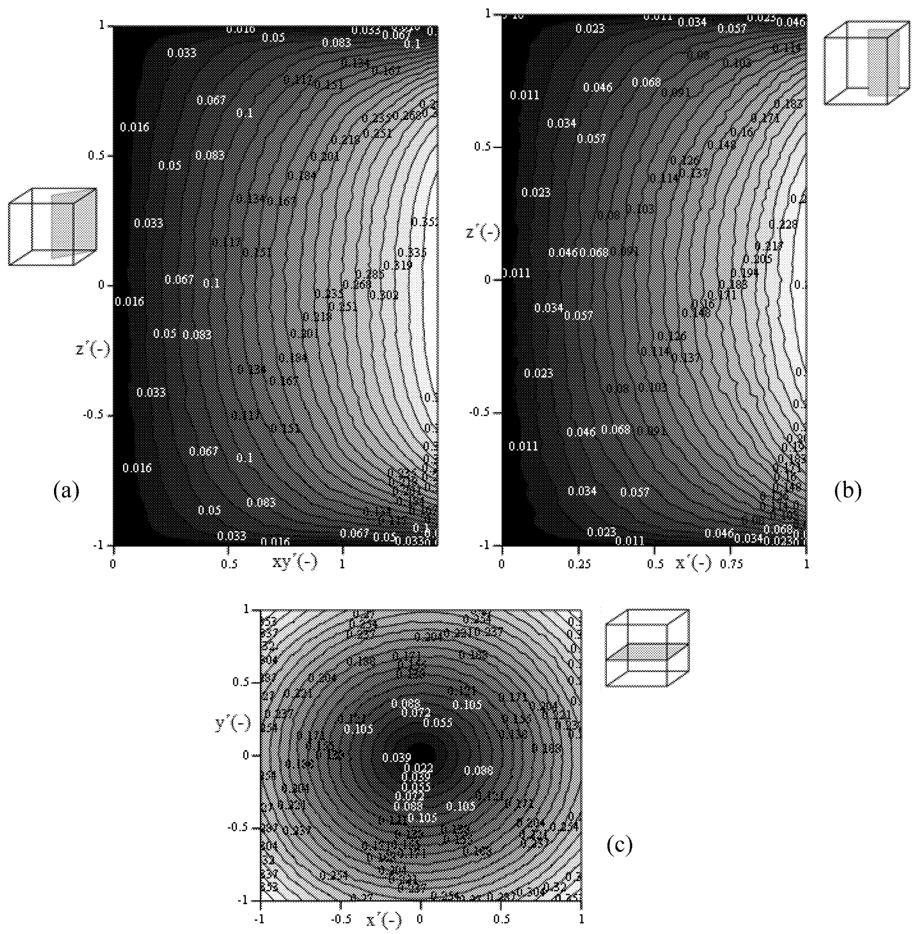


*Fig.7: Contours of Lorentz forces in NS-FEM3D: a) in central plane, b) in angular frame, c) in horizontal plane*

Primary flow of the melt is in the azimuthal direction, but secondary flow is important as well. Secondary flow is formed from pressure gradient in Ekman layer. Secondary flow is composited mostly from two large vortex structures. Blending melt is caused mostly by secondary flow. Axial velocity field is displayed in Fig. 5. Melt in the half of the container is minimum affected. On the contrary melt near the outer walls. Radial velocities are even smaller than axial velocities (c. half). Maxima are occurred near upper and lower bases. Vectors of instantaneous velocities (Fig. 6) show directions of flowing. Melt in the half of the container is least affected. The melt is moved in azimuthal direction. Secondary flow is significant mostly near outer walls of the container and container edges

## 4. Solutions in computing code NS-FEM3D

Input data for comparing Lorentz forces in the container with cuboid shape were obtained from the computing program NS-FEM3D which uses DDES method of computing.

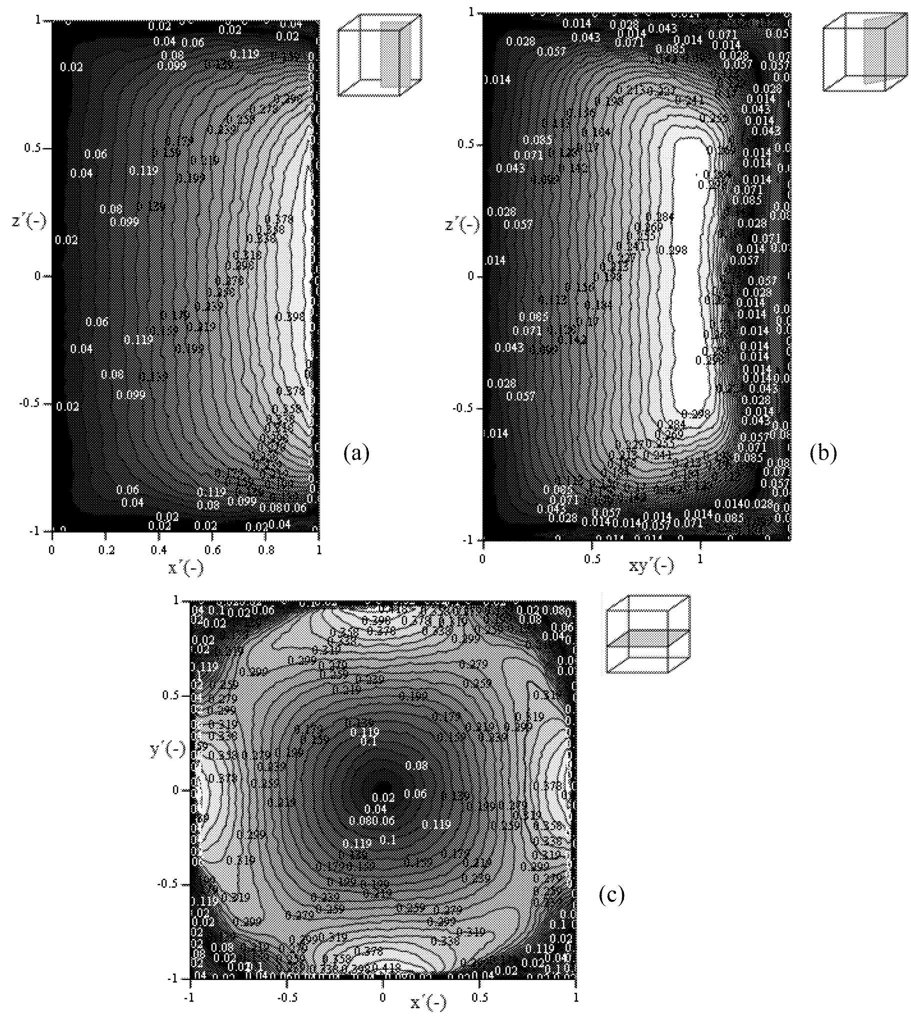


*Fig.8: Contours of mean velocities: a) in central plane, b) in angular frame, c) in horizontal plane*

The Delayed Detached Eddy Simulation model has been applied as a turbulent approach. This approach was implemented for higher Taylor number. Without any turbulent approach study of unsteady flows driven by magnetic field was limited only for lower Taylor number. Complete summary of applied mathematical model and validations see in [3], [4]. The grid of container was unstructured. Whole grid has over 2 200 000 elements. Database from this computing code were created by data matrix – coordinates of grid node points, values of Lorentz forces component in the Cartesian coordinate system. And this database was processed in software MathCad (version 15). MathCad displayed maxima and minima (colour list) only for one figure. Colour list is different for each figure. Contours of Lorentz forces (time averaged) are displayed in Fig. 7a, b, c. These contours include forces only in $x$ and $y$ direction. Maxima of Lorentz forces are occurred in container edges of vertical walls. Minima of Lorentz forces are appeared near vertical axis of the container and on upper and lower bases.

Time averaged velocity fields in vertical and horizontal plane are displayed in Fig. 8a, b, c. Primary flow – in azimuthal direction, is dominant. Values of velocities are c. about one order bigger. The melt moved in azimuthal direction decelerated and accelerated in dependence on container position. The effect of the container shape is evident. Near container edges and upper and lower bases small eddies are formed.

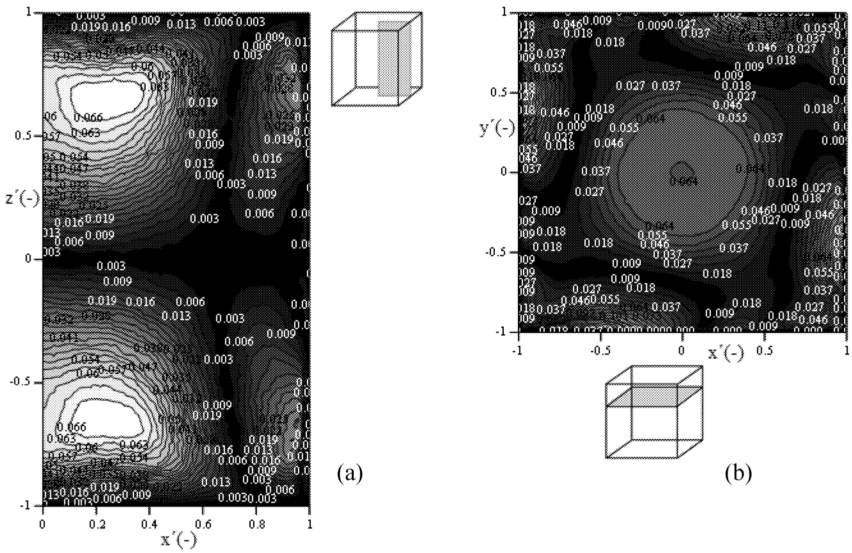


*Fig.9: Contours of axial velocity field in NS-FEM3D*

In Fig. 9 there are contours of velocity field in axial direction. Velocities are displayed in absolute value. These velocities are c. about one order smaller then velocities in azimuthal direction. Two large counter eddies appeared in the melt. Melt in the half of the container is least affected.

## 5. Conclusions

Contours of Lorentz forces were displayed in Fluent and in MathCad (from NS-FEM3D data). They are placed at the same area and values are similar (exact values are not comparable because of only instantaneous forces in Fluent). Maxima of Lorentz forces are in area of bigger distance from axial axes (because of large melt mass). Velocity contours answers to contours of Lorentz forces. Differences are in area near corners. Moving melt (dominantly in azimuthal direction) accelerates and decelerates. As a result relatively significant turbulent coherent structures are appeared. Near upper and lower base the melt is affected edges and friction. Values from Fluent are slightly smaller. Fluent has many limits for computing MHD. Edges and corners of the container have strong effect on computing.

**Acknowledgements**

This work was financial support from the particular research student grant SGS 28000 at the TU Liberec.

**References**

[1] Davidson P.A.: An Introduction to Magnetohydrodynamics, Cambridge, 2001
[2] Doležal I, Musil L.: Moderní průmyslové technologie založené na procesech v tekutých kovech řízených elektromagnetickým polem, č. 11/2003, Praha, 2003
[3] Fraňa K., Honzejk V., Horáková K..: A Numerical Simulation of the Magnetically Driven Flows in a Square Container Using the Delayed Detached Eddy Simulation, Computational Fluid Dynamics 2010, Springer-Verlag Berlin Heidelberg 2011
[4] Fraňa K., Stiller J.: A numerical study of flows driven by a rotating magnetic field in a square container, European Journal of Mechanics – B/Fluids, Issue 4, Vol. 27, pp. 491–500, 2008
[5] Horáková K., Fraňa K.: Lorentz forces of rotating magnetic field, Mechanical Engineering Journal Strojárstvo, Slovak Republic, 2009
[6] Horáková K., Fraňa K.: Lorentz forces in the container, World Academy Of Science, Engineering And Technology (WASET), Issue 59, Venice Italy, November 2011
[7] Horáková K., Fraňa K.: CFD Solution of MHD, Journal of applied science in the thermodynamics and fluid mechanics, No. 2/2011
[8] Ansys Fluent 12.0 Magnetohydrodynamics (MHD) Module Manual, April 2009
[9] Horáková K., Fraňa K.: Energetic spectra of unsteady flows, Journal of applied science in the thermodynamics and fluid mechanics, No. 1/2011

*Received in editor's office*: August 31, 2012
*Approved for publishing*: May 30, 2013