ELECTROMAGNETIC DOSING DEVICE OF MOLTEN METAL

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ABSTRACT

The paper deals with the analysis of operation electromagnetic doser of molten metal in periodical regime. The doser is driven by three-phase current. There is presented the mathematical model and also the computer model. The focus of the work is to discuss the results of the numerical examples that enable to choose an optimal arrangement and operational mode of the doser.

Keywords: *electromagnetic doser, mathematical model of doser, numerical analysis of doser*

1. INTRODUCTION

Forces effects of electromagnetic fields are used in various technical systems whose parts can be:

- Solid (e.g. rotating and linear electro- motors, levitation systems [1], various actuators and accelerators, [2], [3]), or
- Liquid (blenders and homogenizers of molten metals [4], or pumps, either continual [5] or discontinual, pacing ones, functioning as dosers).

The presented paper deals with the analysis of operation and optimal design of electromagnetic doser of molten metal fed by three-phase electric current and operating in periodical regime. The principle of operation of this doser is described here as well as its mathematical model and also a computer model. The focus of the work is to discuss the results of the numerical example that enable to choose an optimal arrangement and operational mode of the doser.

2. PROBLEM DEFINITION

The principle of electromagnetic doser of molten metal is evident from Fig. 1.The doser consists of a ceramic pipe **2**, which serves as a duct of circular cross-section filled with molten metal **1**. This duct is connected with the storage tank of molten metal **6** and is inserted into a ferromagnetic coat **3**, in which three-phase or two-phase winding **4** is placed. Into the pipe **2** a flat valve **5** is inserted, which in one position enables free flux of liquid metal through the pipe (Fig. 1a, Fig. 1b), in the second one prevents the flux and brings the metal into outlet duct **7** (Fig. 1c).

This basic scheme was improved by the fact that instead of one outer shielding **3** a system (Fig. 6) of two concentric ferromagnetic coats **3a**, **3b** was used, between which there was a system of two concentric ceramic pipes **2a**, **2b**. In the flow duct with intercircular diameter that is filled with liquid metal a magnetic field acts whose shape is more favorable than in simple arrangement accord. Fig. 1.

The doser operates in three subsequent regimes:

- 1. *Preparation regime* (Fig. 1a): working area of the doser is filled with molten metal from the storage tank **6**, in winding **4** there is no current

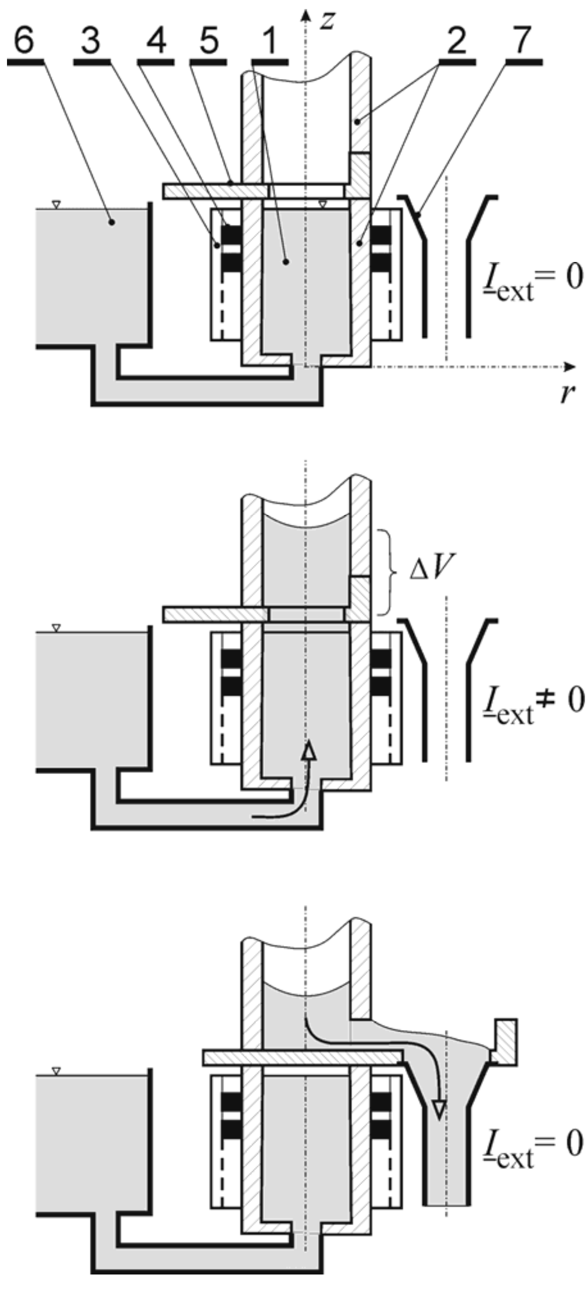

Fig. 1 Scheme of electromagnetic doser of molten metal: a) preparation regime, b) operation regime „feeding " c) operation regime „outlet"; **1** molten metal, **2** ceramic pipes, **3** ferromagnetic coat, **4** winding, **5** valves, **6** storage tank of molten metal, **7** outlet duct

(I_{ext} = 0) and the metal in the working area is only influenced by its own weight F_{g0}.

- 2. *Operation regime „feeding "* (Fig. 1b): valve **5** is in the starting position, enabling the flux of molten metal **1** through an annular duct formed by pipe **2** (or a system of pipes **2a**, **2b)**. Winding **4** has harmonic current I_{ext} with frequency *f.* In electrically conductive metal **1** in the working area of doser V_1 inside ferromagnetic coat **3** (or **3a**, **3b**) eddy current are induced with current density $J_{eddy}(r,z,t)$ and specific Lorentz forces occur operating in direction *z* (Fig. 1a). The final Lorentz force $\boldsymbol{F}_L$,or its constant component $\boldsymbol{F}_{LS}$ opera- ting on molten metal in area V_1, pushes above this area metal volume ΔV, for which force balance $F_{LS} = F_G = \int_{\Delta V} \rho_1 \, dV$ is valid, where ρ_1 is specific mass of molten metal **1**.

- 3. *Operation regime "outlet "(*Fig. 1c): there is no current (I_{ext}= 0) in winding **4** and valve **5** is in the position which brings molten metal of volume ΔV to the outlet duct **7**.

These regimes repeat periodically according to the movement of moulds under the outlet duct **7** , to which molten metal is brought in doses ΔV.

The aim of the work is to evaluate particular parameters that influence the work of the doser and create conditions for its optimal design.

3. MATHEMATICAL MODEL OF THE DOSER

The mathematical model of the molten metal doser is defined in a cylindrical coordinate system (*r,z*). Regarding time-harmonic current I_{ext} we use complex representation.

3.1. Definition area consists of five sub-areas (Fig. 2), bound by fictional boundary {A, B, C, D, A}.

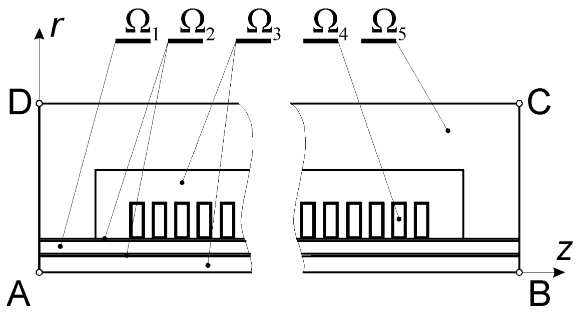

Fig. 2 Definition area of the mathematical model of the doser.

Sub-areas:

Ω_1 … molten metal of electrical conductance γ_1 and permeability μ_0 ;

Ω_2 … electrically non-conductive ceramic pipes **2a**, **2b** of permeability μ_0 ;

Ω_3 … outer and inner ferromagnetic coats **3a** , **3b**, with magnetizing curve $B(H)$;

Ω_4 … conductors of the winding **4**, with currents I_{ext} of frequency f ,and with current density $\boldsymbol{J}_{ext}$. The conductors have electric conductivity γ_4 and permeability μ_0 ;

Ω_5 … surrounding air with permeability μ_0 and other non-ferromagnetic and electrically non- conductive elements of the doser.

Physical qualities of the sub areas are in Tab 1.

Table 1 Physical parameters of the doser components

positron	element of doser	material	conductivity γ_{el} [S/m]	relat. permeability μ_r [-]
1	molten metal	Al	3.4 10^7	1
2a, **2b**	ceramic pipe	tech. porcelain	0	1
3a, **3b**	feromagnetic coat	steel 12 042	5 10^6	relation *B*(*H*) see Fig. 3
4	excitation winding	Cu	5.7 10^7	1
5	flat valve	tech. porcelain	0	1
6	storage tank	Al	3.4 10^7	1
7	outlet duct	tech. porcelain	0	1

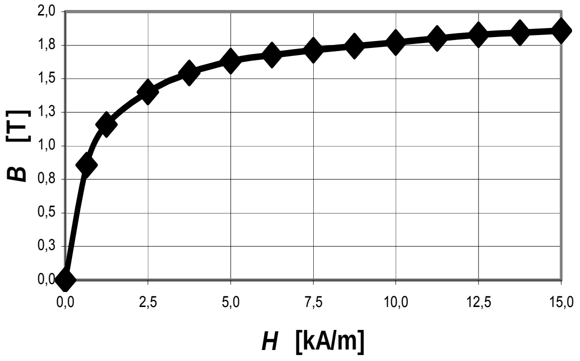

Fig. 3 Magnetizing characteristics $B(H)$ of the ferromagnetic coat

3.2. Differential equations of time-varying electromagnetic field in non-linear environment is described by vector potential $\boldsymbol{A}(r,z,t)$ (e.g. [6], [7]):

$$\mathrm{rot}\ \frac{1}{\mu}\ \mathrm{rot}\,\boldsymbol{A} + \gamma\ \frac{\partial \boldsymbol{A}}{\partial t} = \boldsymbol{J}_{\mathrm{ext}} \tag{1}$$

For linearized environment with complex expres- sion of current I_{ext}, or its current density $\boldsymbol{J}_{\mathrm{ext}}$ it chan- ges into a simpler Helmholtz equation:

$$\mathrm{rot}\,\mathrm{rot}\underline{\boldsymbol{A}} + \mathrm{j}\omega\gamma\mu\ \underline{\boldsymbol{A}} = \mu\,\underline{\boldsymbol{J}}_{\mathrm{ext}} \tag{2}$$

Concrete forms for Eq. (2) for definition sub-areas Ω_1 to Ω_5 result from the values of corres- ponding parameters γ, μ, see Tab. 1.

Phasor of eddy currents vector $\underline{\boldsymbol{J}}_{\mathrm{eddy}}(r,z)$, induced by time-varying electromagnetic field in conductive environment is

$$\underline{\boldsymbol{J}}_{\mathrm{eddy}} = -\,\mathrm{j}\omega\gamma\,\underline{\boldsymbol{A}} \tag{3}$$

and phasor $\underline{\boldsymbol{B}}(r,z)$ of magnetic inductance vector is

$$\underline{\boldsymbol{B}} = \mathrm{rot}\,\underline{\boldsymbol{A}} \tag{4}$$

The entire Lorenz force $\boldsymbol{F}_{\mathrm{L}}(t)$ operating on molten metal in area V_1 is

$$\boldsymbol{F}_{\mathrm{L}}(t) = \int_{V1} (\boldsymbol{J}_{\mathrm{eddy}}(r,z,t) \times \boldsymbol{B}(r,z,t))\,\mathrm{d}V \tag{5}$$

for $t \in \langle 0, T_{\mathrm{P}} \rangle$, where $T_{\mathrm{P}} = \dfrac{1}{f}$ is the time of one period of current I_{ext}. This force has a constant component $\boldsymbol{F}_{\mathrm{LS}} = \dfrac{1}{T_{\mathrm{p}}} \displaystyle\int_0^{T_{\mathrm{p}}} \boldsymbol{F}_{\mathrm{L}}(t)\,\mathrm{d}t$ and ripple component

$$\Delta\boldsymbol{F}_{\mathrm{L}}(t) = \boldsymbol{F}_{\mathrm{L}}(t) - \boldsymbol{F}_{\mathrm{LS}}\,.$$

Note. Definition sub-area Ω_3, in which non-linear dependence $B(H)$ is valid (Tab. 1 and Fig. 3) was divided in sub-sub-areas. The solution in this sub-sub-area was carried out in the same way as for linear environment while the permeability values were corrected in the iterative way.

3.3. Boundary conditions guarantee uni- queness of the solution of equation (1) or (2). Because of anti-symmetry of magnetic field on the axis $\overline{\mathrm{AB}}$ and because of continuity of vector $\boldsymbol{B}(r,z,t)$ in points A, B, C, D of the boundary A-B-C-D (Fig. 2), boundary conditions can be expressed in the form

$$r\,\boldsymbol{A}(r,z,t) = 0 \tag{6}$$

or

$$r\,\underline{\boldsymbol{A}}(r,z) = 0 \tag{7}$$

4. COMPUTER MODEL AND OBTAINED EXACTNESS OF THE SOLUTION

Mathematic model is solved numerically using the method of finite elements (FEM), by professional programme *Quick Field*, [8]. In calculation the numerical convergence was observed. To obtain exactness of three non-zero digits for calculation $\boldsymbol{F}_{\mathrm{L}}$ it was necessary to use network with 80 to150 thousand nodes according to the used winding and frequency f of current I_{ext}.

For illustration in Fig. 4 there is a distribution of the calculated magnetic field in the doser (winding $W1$, see Tab. 2, f = 50 Hz). Regarding the intensity of force $\boldsymbol{F}_{\mathrm{L}}$ the shape of lines of force in the area of molten metal **1** is appropriate. From Eq. (5) it is obvious that force $\boldsymbol{F}_{\mathrm{L}}$ will be the bigger the more perpendicular the lines of force will be to the movement of the metal, which is in this case well met.

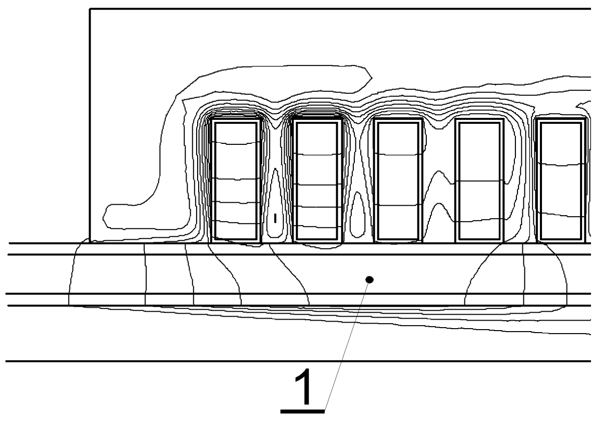

Fig. 4 Distribution of magnetic field in the doser (winding W1, f = 50 Hz)

5. ILUSTRATIVE EXAMPLE

5.1. Assignment

The arrangement and basic dimensions of the molten metal doser are evident from Fig. 5 and 6; Physical qualities of its com- ponents are in Tab. 1.

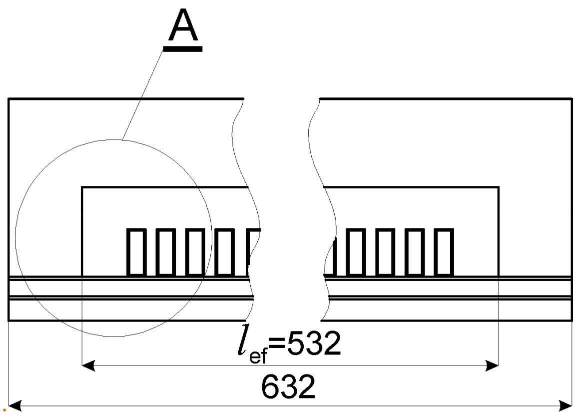

Fig. 5 Basic arrangement of the doser (winding W1)

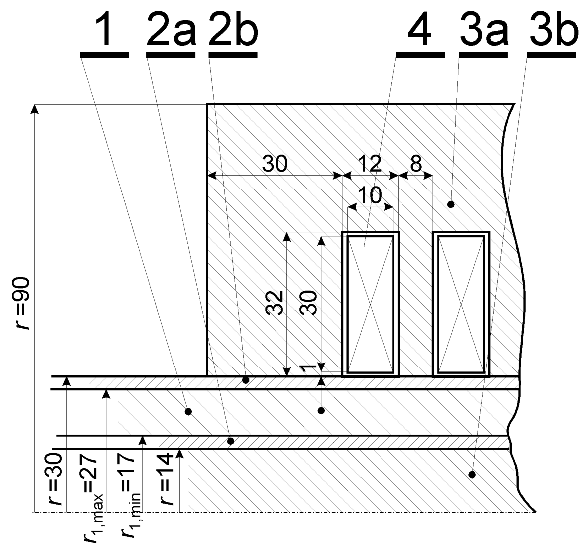

Fig. 6 Detail arrangement of the grooves of the doser – see Fig. 5, detail A (winding W1)

<u>The aim of the solution</u> is to evaluate parti- cular parameters influencing operating of the doser and so to create conditions for its optimal design. It means above all to evaluate:

- type of winding **4**,
- influence of the cross-section of the conductor (thick or thin wires),
- value of current I_{ext} and its frequency f.

Four types of one-layer exciting winding are considered.

5.2. Results and their discussion

5.2.1. The influence of realization of winding 4 is evident from Tab. 3, where is:

l_{ef} [m] …the length of effective area (Fig. 5) of the doser,

$V_{ef} = \pi\,(r^2_{1,max} - r^2_{1,min})\, l_{ef}$ [m^3] …the volume of liquid metal affected by the magnetic field induced by winding **4**,

$F_{g,ef} = 9.81 V_{ef} \rho$ [N] …weight of molten metal (for Al is $\rho = \rho_{Al} = 2.699\ 10^3$ [kg/m^3]) in volume V_{ef},

$F_{LS}/F_{g,ef}$ …ratio of constant component F_{LS} of Lorentz force in area $V_{1,ef}$ to $F_{g,ef}$ of molten metal **1** in the same area. If the ratio is > 1, volume ΔV is pushed up until equilibrium is reached: $F_{LS} = F_g = \int_{\Delta V} \rho_1 \,\mathrm{d}V$, where

F_g is the weight of pushed metal **1** of volume ΔV. If FLS/$F_{g,ef}$ ≤ 1, metal is not pushed up and thus the doser does not work.

From Tab.3 these conclusions can be reached:

- From the point of view of intensity of force F_{LS} in all cases thin-wire winding is more suitable than thick-wire one. It oppresses eddy currents in winding and increases magnetic field in area V_{ef}, in which F_{LS} occurs.
- The most favorable is winding W 1, which provides biggest force F_{LS} ($I_{ext\,=}$ 900 A ≈ J_{ext} = 3 10^6 A/m^2 , f = 25 Hz). In this case is $F_{LS} / F_{g,ef} > 1$, and only then the required pushing up of the metal **1** occurs.
- Force F_{LS} depends on the frequency f and thus it is possible to find an optimal frequency value.

5.2.2. The influence of the frequency on the inten- sity of force F_{LS} and the ratio $F_{LS} / F_{g,ef}$ is evident from Fig. 7. It is obvious that there is certain optimal frequency: high frequency leads to high value of vector $\boldsymbol{J}_{eddy}(r,z,t)$ but only in a thin layer, whereas in low frequencies the values $\boldsymbol{J}_{eddy}(r,z,t)$ are smaller, but are more evenly distributed. This influence can be practically neglected as low-frequency sources of high currents are no commonly available. It is more favorable to regulate values F_{LS} and $F_{LS} / F_{g,ef}$ by the current I_{ext} for f = 50 Hz.

Table 2 Considered types of winding

	type of winding							
	W 1		*W* 2		*W* 3		*W* 4	
slot	phase	orientation	phase	orientation	phase	orientation	phase	orientation
1	X	x	X	●	X	●	Y	x
2	X	x	X	●	X	●	Y	x
3	Z	●	Y	●	Y	●	Y	x
4	Z	●	Y	●	Z	x	Y	x
5	Y	x	Z	x	X	x	X	●
6	Y	x	Z	x	X	x	X	●
7	X	●	X	x	Y	x	X	●
8	X	●	X	x	Z	●	X	●
9	Z	x	Y	x	X	●	Y	●
10	Z	x	Y	x	Y	●	Y	●
11	Y	●	Z	●	Z	x	Y	●
12	Y	●	Z	●	Z	x	Y	●
13	X	x			X	x	X	x
14	X	x			Y	x	X	x
15	Z	●			Z	●	X	x
16	Z	●			Y	●	X	x
17	Y	x			X	●		
18	Y	x			Z	●		
19	X	●			Z	x		
20	X	●			X	x		
21	Z	x			Y	x		
22	Z	x			Y	x		
23	Y	●			Z	●		
24	Y	●			X	x		
25					Y	●		
26					Y	●		
27					Z	x		
28					X	x		
29					Y	x		
30					Z	●		
	winding							
	three-phase		three-phase		three-phase		two-phase	
	number of slots							
	24		12		30		16	
	coils							
	lap		lap		concentric		lap	

5.2.3. The influence of current intensity on the intensity of F_{LS} and on the ratio $F_{LS} / F_{g,ef}$ is obvious from Fig. 8. Both observed parameters increase substantially with the increasing values J_{ext}. It is in accordance with the theory and in given example it has also a practical meaning. If there is a doser or a device operating in time intervals, higher values J_{ext} ($\approx 10^7$ A/m^2) are acceptable, as for interrupted operation the winding can cool easily. It would be also possible to cool externally the outer shielding **3b** (Fig. 6), using e.g. cooling ducts with water.

Table 3 Influence of winding type 4 ($I_{ext} = 900$ A $\approx J_{ext} = 3\ 10^6$ A/m^2).

		masive conductor	conductor from thin wire (suppresed skin effect)				
winding	f [Hz]	F_{LS} [N]	F_{LS} [N]	l_{ef} [m]	V_{ef} [m^3]	$F_{g,ef}$ [N]	$F_{LS}/F_{g,ef}$ [-]
W 1	50	6,980E-01	1,028E+01				
	100	3,670E-01	5,082E+00				
	25	1,323E+00	**2,023E+01**	0,532	7,352E-04	1,946E+01	**1,039E+00**
W 2	50	1,197E+00	4,695E+00				
	100	6,280E-01	2,311E+00				
	25	2,234E+00	9,183E+00	0,292	4,035E-04	1,068E+01	8,590E-01
W 3	50	6,474E-02	1,251E+00				
	100	4,795E-03	6,354E-01				
	25	1,833E-01	3,601E+00	0,652	9,01E-04	2,39E+01	1,510E-01
W 4	50	2,118E-01	3,047E+00				
	100	1,143E-01	1,570E+00				
	25	4,188E-01	6,357E+00	0,372	5,14E-04	1,36E+01	4,670E-01

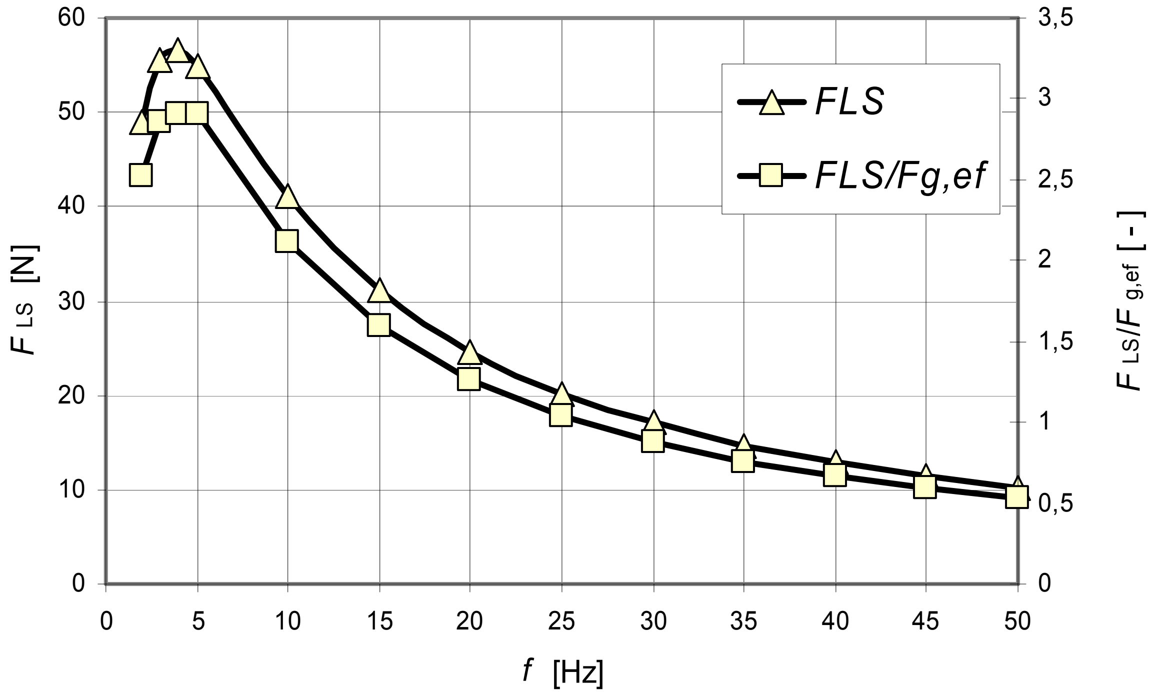

Fig 7. Dependence of $\boldsymbol{F}_{LS}$ and $\boldsymbol{F}_{LS}/\boldsymbol{F}_{g,ef}$ on frequency f. (Winding W1 is from thin wire, $I_{ext} = 900$ A $\approx J_{ext} = 3\ 10^6$ A/m^2 , $\boldsymbol{F}_{g,ef} = 19.46$ N).

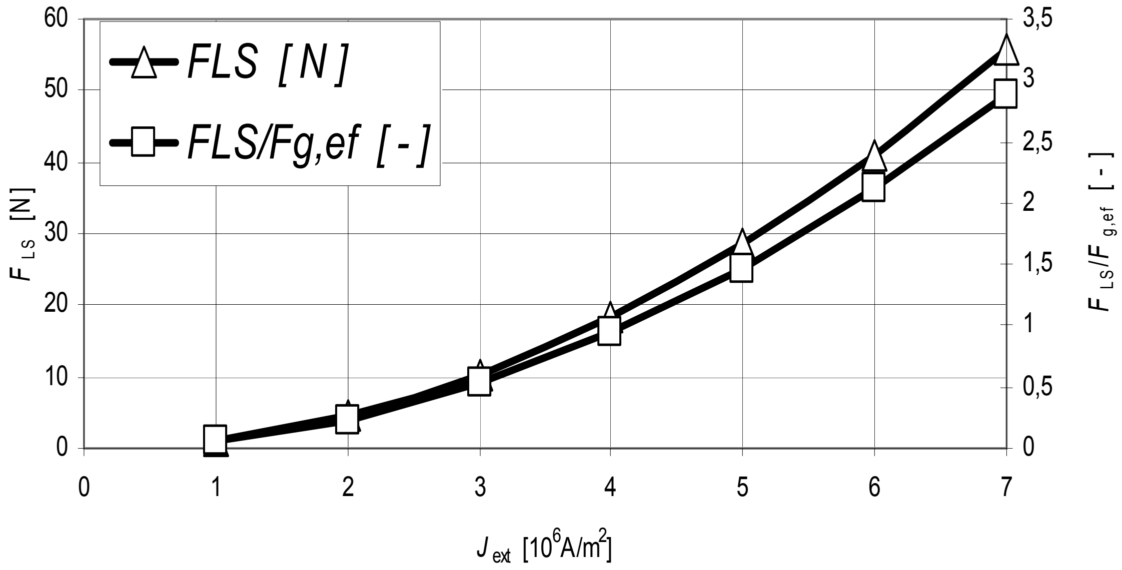

Fig. 8 Dependence FLS and $\boldsymbol{F}_{LS}/\boldsymbol{F}_{g,ef}$ on current density J_{ext} of current I_{ext}. (Winding W1 is from thin wire, I_{ext} = 900 A ≈ J_{ext} = 3 10^6 A/m^2, f = 50 Hz, $\boldsymbol{F}_{g,ef}$ = 19.46 N).

6. CONCLUSION

From the given paper it is obvious that electromagnetic doser can be technically easily realized and is capable of dosing molten metal in a wide scope. Stated facts can be used for optimalized design of the doser. Further development of the design of the doser can be seen in the choice of winding, which in the areas of molten metal induces the most suitable magnetic field to obtain the biggest force $\boldsymbol{F}_{LS}$.

ACKNOWLEDGEMENT

Financial support of the Grant Agency of the Czech Republic (project No. 102/070147) is highly acknowledged.

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Received February 2, 2007, accepted April 11, 2008

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