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Analysis of electromagnetic and flow fields in the channel of a device used for precious metals leaching from auto catalytic converters

Abstract. *The article presents the results of coupled analysis of the electromagnetic and flow field calculations. The aim of conducted research was to design a device for precious metals leaching from used auto catalytic converters. The aim the calculations was to determine the velocity field distribution of liquid metal, the movement of which was forced by the electromagnetic field. Computational experiment was conducted to obtain the relation between the metal velocity distribution and the inductor supply parameters.*

Streszczenie*. Artykuł zawiera wyniki sprzężonej analizy pola elektromagnetycznego i pola przepływu. Celem przeprowadzonych badań było zaprojektowanie urządzenia do odzyskiwania metali szlachetnych z zużytych katalizatorów samochodowych. Obliczenia przeprowadzono w celu wyznaczenia pola prędkości ciekłego metalu poruszanego z wykorzystaniem oddziaływań elektrodynamicznych. Obliczenia wielowariantowe przeprowadzono, aby uzyskać zależności rozkładu pola prędkości od parametrów zasilania wzbudnika urządzenia. (****Analiza pola elektromagnetycznego i pola przepływu w kanale urządzenia służącego do wymywania metali szlachetnych z katalizatorów samochodowych****).*

Keywords: magneto-hydro-dynamics, precious metals leaching, catalytic converters.
Słowa kluczowe: magnetohydrodynamika, wymywanie metali szlachetnych, katalizatory samochodowe.

Introduction

Environmental requirements forced car producers to reduce emissions and control of the combustion quality. This task is achieved in two ways: through more efficient and precise construction of motors and change of the exhaust gases composition through their catalytic combustion. The auto catalytic converters used in motor vehicles are constructed primarily of metal or ceramic carrier. Catalytic carrier is wrapped in a fibrous material (to prevent slipping) and closed in stainless steel shell. It has the porous structure of the honeycomb (the dense net of square holes). Such construction increases the active surface which is the contact zone of precious metals with fumes. Platinum metals act as catalyst for the combustion reaction. Usually these are: platinum, rhodium and palladium. Typically, the platinum layer is applied on a ceramic carrier (Al_2O_3 additions of other oxides such as CeO_2). The content of platinum metals in auto catalytic converter depends not only on the construction and its utilization (an average of about 2 grams of platinum), but also on the car producer. Catalytic converters are devices that should be periodically regenerated, and eventually replaced. The increasing number of catalysts (coming from the exchange and from vehicles withdrawn from using) goes to the landfills. The need for the waste management and high prices of precious metals contained in these wastes, make the recovery of platinum group metals from used auto catalytic converters profitable. The main problem of platinum recovery from catalysts is its low content in a single catalyst. The research on dissolving the platinum group metals from used auto catalytic converts in metal-collector and flushing out many of these catalysts by the same metal has been carried out in this work. Obtained metal collector with platinum will be treated in hydrometallurgical way in order to obtain pure platinum and other precious metals.

The article discusses the issue of flushing used auto catalytic converters by liquid metal. There are plans to use the magneto-hydro-metallurgical device to force circulation of liquid metal under the influence of electromagnetic fields. The movement of the collector metal speeds up leaching of precious metals. Use of collector metal closed cycle increases the concentration of precious metals in collector metal. This paper presents the preliminary calculations of the coupled analysis of an electromagnetic field and a flow field. The purpose of these calculations is to determine the relation between the basic electrical parameters and velocity and flow structure. The effect of power frequency on the flow parameters is analysed in that study.

Calculation model

The model of the device for which calculations were carried out consists of a three-phase inductor (1 - Figure 1) placed inside the magnetic core (2) and channel (5) made of a thin non-magnetic steel filled with liquid lead (3). Scheme of this device is shown in Figure 1. The working version of the device is shown in Figure 2.

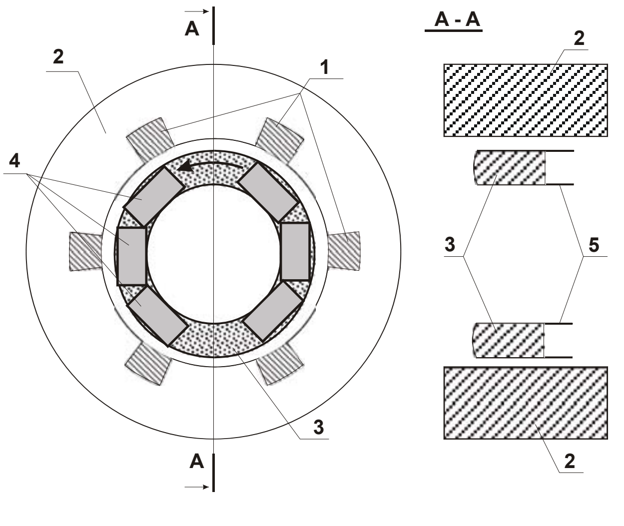

Fig.1. Model of the device for platinum leaching from used auto catalytic converters 1 - winding, 2 - magnetic core, 3 - molten metal, 4- catalytic converters, 5 – channel

Inductor produces a rotating magnetic field and it induces eddy currents in a liquid metal interacting with the inductor's electromagnetic field. This interaction generates electromagnetic forces cause metal spin. In a stream produced on that way, used auto catalytic converters (4) are placed in the molten metal and this allows the platinum, palladium and rhodium flush from the capillaries. The continuous movement of the metal significantly enhances leaching. Application of the same melt in leaching large number of catalysts will let to obtain a high concentration of precious metals to the value which ensures the profitability of their extraction from the molten metal. The use of closed circuit liquid metal reduces harmful influence of the process on the environment.

Fig.2. Working version of the device for platinum leaching from used auto catalytic converters

Analysis of the phenomena, occurring in the device, requires numerical modelling of electromagnetic field [1-3], flow field, and at the final stage of the platinum recovery using hydrometallurgical methods.

Analysis of electromagnetic field

The presented work is the first stage of the research. That is why, simplified, two-dimensional model was used to analyse electromagnetic field (as shown in Figure 3). Due to the geometrical and electrical symmetry, the circuit model was reduced to 1/8 of the entire device. The presence of used auto catalytic converters and bathtubs (made of nonmagnetic steel) was omitted in the discussion.

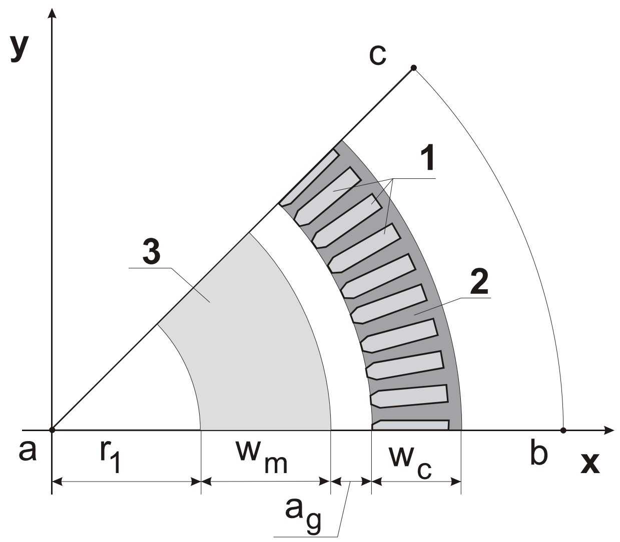

Fig.3. Model used for electromagnetic field analysis. 1 - winding, 2 - magnetic core, 3 - molten metal

The electromagnetic field analysis was carried out in a symbolic form. Discussion on the analysis of specific areas of physical fields and the associated advantages and disadvantages was carried out in [4 - 6]. Analysis of the electromagnetic field was based on the equation (1) [7].

$$\nabla\times\left(\frac{1}{\mu}\nabla\times\underline{\boldsymbol{A}}\right)+\mathrm{j}\omega\sigma\underline{\boldsymbol{A}}=\underline{\boldsymbol{J}}_s \tag{1}$$

where:
$\underline{\mathbf{A}}$ - magnetic vector potential;
μ - permeability;
ω - angular frequency;
σ - electrical conductivity;
$\underline{\mathbf{J}}_s$ –surface density of forcing current.

After determining the distribution of the vector potential, the average (per period) value of electromagnetic forces on the basis of relations (2) and (3) using the eddy current density expressed by the relation (4) and induction determined from the relation (5) was calculated.

$$\boldsymbol{f}_m=\frac{1}{2}\mathrm{Re}\left(\underline{\boldsymbol{J}}\times\underline{\boldsymbol{B}}^*\right) \tag{2}$$

$$\begin{aligned} f_x &= -\frac{1}{2}\left(\mathrm{Re}(J)\mathrm{Re}(B_y)+\mathrm{Im}(J)\mathrm{Im}(B_y)\right)\\ f_y &= \frac{1}{2}\left(\mathrm{Re}(J)\mathrm{Re}(B_x)+\mathrm{Im}(J)\mathrm{Im}(B_x)\right)\end{aligned} \tag{3}$$

$$\underline{\boldsymbol{J}}=\mathrm{j}\omega\sigma\underline{\boldsymbol{A}} \tag{4}$$

$$\underline{\boldsymbol{B}}=\nabla\times\underline{\boldsymbol{A}} \tag{5}$$

where:
f – volume density of electromagnetic forces;
$\underline{\mathbf{J}}$ – surface density of eddy current;
$\underline{\mathbf{B}}^*$ - value conjugate to the magnetic induction.

The calculation model was supplemented by necessary boundary conditions. For edge and due to the geometric symmetry and electrical antisymmetry anti-cyclic condition was assumed, while for the edge Dirichlet condition (expressed by equation (6)) was adopted.

$$\boldsymbol{A}=0 \tag{6}$$

To analyse the electromagnetic and flow field (due to the lack of consistency between digitalisation grids) [4] volume density of electromagnetic forces was determined on a rectangular grid with a density two times bigger than the grid for the flow field analysis. For the electromagnetic fields analysis, the program Flux 2D was used. This model was completed with author's procedures, allowing to determine an average volume density (for the period) of electromagnetic forces [4].

Calculation model for the flow field analysis

The electrodynamic forces, determined during the analysis of electromagnetic field, are included in the equation used to analyse the flow field. Flow field was modelled using the Navier – Stokes equation (7). These equations were supplemented by the continuity stream equation (8) [8], [9]. Due to the fact that as a liquid metal was used, the equation model for incompressible centers was assumed.

$$\rho\left[\frac{\partial\boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}\right]=-\nabla p+\eta_d\cdot\Delta\boldsymbol{v}+\boldsymbol{f}_m \tag{7}$$

(8) $$\nabla \cdot \rho \mathbf{v} = 0$$

where: ρ – density; $\mathbf{v}$ – velocity; p - pressure; f_m – electrodynamics forces; g - gravitational acceleration; η_d - dynamic viscosity coefficient.

The analysed flow field model was limited only to the area of liquid metal. Geometry was limited to a quarter due to the symmetry of the system. As in the case of the electromagnetic field analysis, the capillary structures presence of the catalysts in the melt were neglected. Solution of the Navier - Stokes equation allowed to determine important parameters of the fluid flow in a channel: flow velocity and its structure. Fluent program was used for flow calculations. It was supplemented by its own functions in order to introduce electromagnetic forces.

Computational experiment

The multi-variant calculations were carried out to determine the relation between frequency of current supply of the model and the structure and flow velocity in the channel. A detailed description of the options is presented in table 1.

Table 1. Description of the computational variants

Variant	Frequency, Hz	Current, A	a_g, mm
v1	12.5	40	10
v2	25	40	10
v3	50	40	10
v4	100	40	10

The results of the simulation are shown in Figures 4-9. Figure 4 and Figure 5 presents the distribution of electromagnetic forces for variants v1 and v4 respectively. Clearly decreasing penetration depth of electromagnetic field with maintained shape of the field can be observed. Increase of value of forces and increase of radial component of electromagnetic forces can be observed (maximum value of forces for v1 is about 2000 N/m^3, for variant v4 about 13000 N/m^3). It should be remembered, that the calculations were carried out for fixed value of inductor current, not for a constant value of power dissipated in charge.

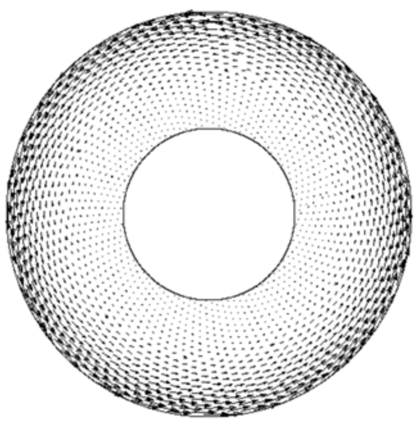

Fig.4. Electromagnetic forces distribution for variant v1

In Figure 6 and Figure 7 distribution of tangential components of magnetic forces and velocity along the radial cross section of the channel are presented. The greatest values of velocity are observed near the outside wall of the channel (r = 125.0 mm for v1 and 125.8 mm for v2 – v4). It means that, in such a system, the viscosity and a friction has greater influence on velocity distribution then forces distribution.

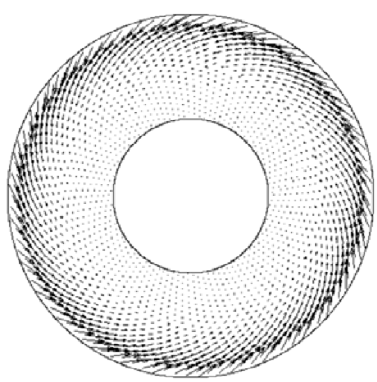

Fig.5. Electromagnetic forces distribution for variant v4

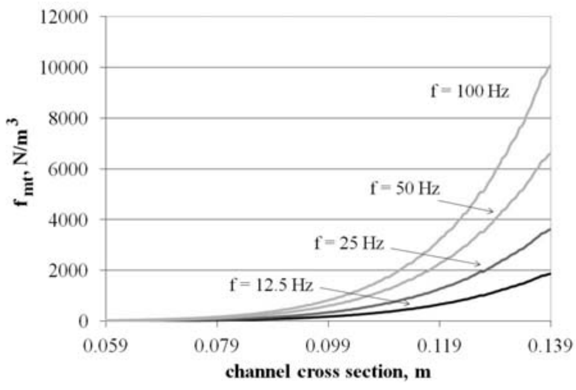

Fig.6. Distribution of tangential component of electromagnetic forces on the radial cross section of channel

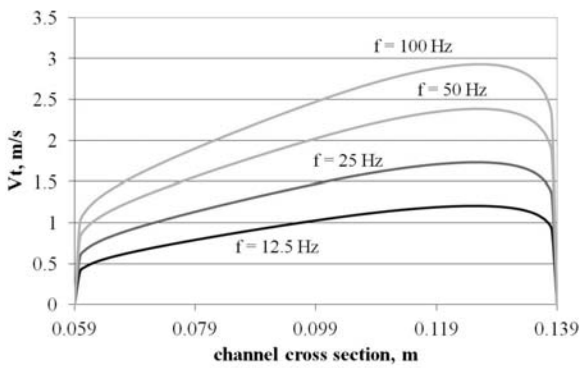

Fig.7. Distribution of tangential component of velocity on the radial cross section of channel

Flow structure of liquid lead is illustrated in Figure 8. The structure of flow is similar for all considered cases.

Dependency of maximal and average velocity on frequency is presented in Figure 9. Increase of frequency results in similar increase of average and maximum liquid metal velocity. Increase of velocity is asymptotic (in logarithmic kind) and bigger for low frequencies.

The results obtained in the calculations will be verified. Metal speed value in the channel will be measured by the Prandtl tube.

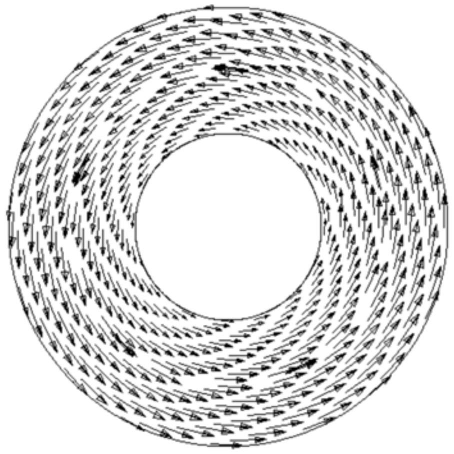

Fig.8. Velocity vectors distribution for variant v3

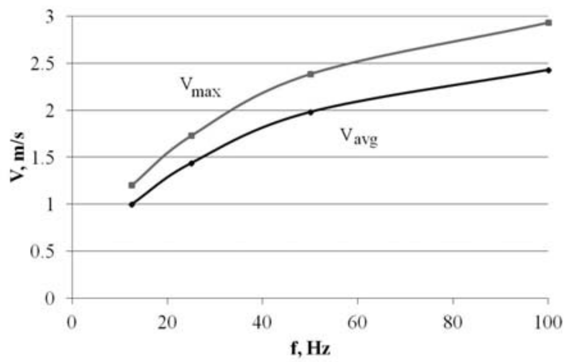

Fig.9. Dependency of velocity on frequency

Conclusion

The aim of the calculations was to determine the velocity field distribution of liquid metal, the movement of which was forced by the electromagnetic field. Computational experiment was conducted to obtain the relation between metal velocity distribution and the inductor supply frequency. The analysis was conducted as a two-dimensional for both the electromagnetic and flow fields. During the analysis, the weak coupling between the electromagnetic and the flow field was used. In total, 4 variants of computations were analysed. The aim of conducted research was to design a device for precious metals leaching from used auto catalytic converters. Forced movement of liquid metal intensifies the leaching process.

On the basis of carried out calculation it can be concluded for system in question that:

- Maximum velocity of liquid metal is obtained for frequency 100 Hz (variant v4) and the value of velocity is about 3 m/s.
- Maximum average velocity of liquid metal is obtained for frequency 100 Hz (variant v4) and the value of the velocity is about 2.5 m/s.
- The most uniform velocity distribution in the channel is obtained for frequency 25 Hz (variant v2), differences between maximum and average velocity is about 20.5 % for this case, but for other cases the values are in similar range.
- Liquid metal velocity obtained in the experiment seems to be too high, but it should be remembered that calculation model do not take into account presence of capillary structures of catalytic converters. Their presence will reduce the velocity of liquid metal in channel.

Further studies will be conducted to verify the influence of other parameters of the device for precious metals leaching from used auto catalytic converters on the structure and fluid flow velocity in the device channel.

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