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A STUDY OF THE IMPACT OF POWER SUPPLY PARAMETERS ON METAL FLOW VELOCITY IN THE CHANNEL OF A DEVICE FOR WASHING OUT PRECIOUS METALS FROM OF THE AUTOMOTIVE CATALYTIC CONVERTERS

BADANIE WPŁYWU PARAMETRÓW ZASILANIA NA PRĘDKOŚĆ PRZEPŁYWU METALU W KANALE URZĄDZENIA DO WYPŁUKIWANIA METALI SZLACHETNYCH Z KATALIZATORÓW SAMOCHODOWYCH

The lifetime of a catalytic converters is limited. Today's environmental regulations require that used converters should be properly recycled as a valuable source of precious metals, Al_2O_3 and steel scrap. The precious metals used in the devices perform catalytic functions. They are suspended in a ceramic or metal carrier. This paper deals with the recovery of precious metals from automotive converters using a metal-collector method. In order to speed up the washout of the precious metals from the capillary structure of the converter, the movement of the liquid metal-collector was forced by the electromagnetic field. The research was aimed at improving the effective velocity of the liquid metal flow through the carrier by means of a device with a double windings. Various ways of power supply were considered. The calculation experiment was performed as a weakly coupled analysis of the electromagnetic field and flow field.

Keywords: PGM recovery, HHD pump, metal-collector method

Czas życia katalizatorów samochodowych jest ograniczony. Dzisiejsze przepisy środowiskowe wymagają aby były one poddawane procesowi recyklingu jako cenne źródło platynowców, Al_2O_3 i złomu stalowego. Metale szlachetne stosowane w tych urządzeniach pełnią funkcje katalityczne, naniesione są na ceramiczny lub metalowy nośnik. Artykuł ten dotyczy procesu odzyskiwania metali szlachetnych ze zużytych katalizatorów samochodowych przy wykorzystaniu metody metalu-zbieracza. W celu przyspieszenia procesu wymywania metali szlachetnych ze struktury kapilarnej katalizatora, przepływ ciekłego metalu-zbieracza zmuszony został przez pole elektromagnetyczne. W pracy przedstawiono wyniki modelowania mające na celu poprawę skuteczności przepływu ciekłego metalu przez nośniki katalizatora za pomocą urządzenia z podwójnym uzwojeniem. Przeanalizowano także różne sposoby zasilania urządzenia. Eksperyment obliczeniowy został zrealizowany jako słabosprzężona analiza pola elektromagnetycznego i pola przepływu.

1. Introduction

An automotive catalytic converter is built mainly of a metal or ceramic carrier with a porous surface into which the elements from the platinum family (Pt, Pd, Rh) are incorporated. The carrier is coated with fibrous material (that prevents shifting) and enclosed in a casing made of stainless sheet. The platinum metals are usually suspended into a ceramic carrier (Al_2O_3 with addition of other oxides, e.g. CeO_2) with a honey-comb structure, that is a dense net of rectangular hollow cells [1]. These construction increase the surface contact area of exhaust gases with the precious metals that are the catalysts of the reaction and significantly speed up the reactions of oxidization for carbon oxides and hydrocarbons and reduction for nitrogen oxides [2]. As a result, the substances appearing at the outlet of the converter, like carbon dioxide, water and nitrogen, are neutral to the environment [3].

Used catalytic converters containing precious metals are very attractive recyclable material [4] as the devices have to be periodically renovated and eventually replaced. Used converters can be processed pyro- and hydrometalurgically; mixed methods are also adopted. [5-8]. A single catalytic converter contains at most a few grams of platinum metals and they are captured in the capillary structure of its usually ceramic carrier. For this reason, in order to make the whole procedure economic, the cost of processing a single converter should be maximally reduced. The authors suggested and patented a technology based on washing out the platinum metals from the converter structure with the use of liquid metals. This technique does not require the ceramic carriers to be ground, which reduces the costs. As the mechanically forced flow of such an aggressive medium as a molten metal is practically impossible in a large-scale recycling process, the authors suggested a non-contact method exploiting eddy current electromagnetic field and magnetohydrodynamic phenomena. Unfortunately, this way of setting the metal in motion additionally complicates the whole issue, as the electromagnetic field acts on the metal only beyond the area of the converter, that is be-

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yond the area where we the flow is needed. The solution would be to achieve a pressure difference at the two ends of the converter that would be sufficient to overcome the resistance of the capillary structure of the carrier. The researches so far have used a three-phase inductor placed inside the channel [9-12]. Since in the case of an inductor operated on mains frequency the electromagnetic field penetrated only from the outside part of the channel, the resulting non-homogenous distribution of the forces generated eddy currents between the converters placed in the channel instead of forcing the flow through their structures. In effect only the external part of the core was flushed by the liquid metal. The changes in the strength of the current and power supply frequency did not improve the effectiveness of flushing the converters cores. Only bigger distances between the converters quickened the flow through the structure but at the cost of significant decrease in electrical efficiency of the device [4]. There are very sophisticated devices which allow to produce almost any configuration of the traveling and rotating field [13], but it involves high costs (especially of power supplies).

The paper presents a series of numerical experiments for a device with two coils, inner and outer one (Fig. 1). The supply frequency and the ways of supplying power to the inductors were modified so that the running field generated by the coils was either a transverse or longitudinal one. The calculations were conducted for the liquid lead as a medium washing out the precious metals out of the converter.

2. Calculation model

The model of the process requires the coupling of electromagnetic and hydrodynamic fields. Creating numerical model of any process usually requires a number of simplifications to make its implementation technically possible. Because the magnetic Reynolds number has small value and the temperature during the process and electric conductivity do not change significantly, it is possible to use a weak, one-way coupling, which allows a separation of electromagnetic and hydrodynamic calculations.

The creation of a three-dimensional model precisely mapping each capillary is technically impossible. That is why, the created two-dimensional model of the process uses further simplifications. Since the direction of the induced current is orthogonal to the direction of the catalyst capillaries, it was possible to assume a zero electric conductivity in the area occupied by the catalyst. For this reason, the only cause of the flow of the metal through the capillaries is the pressure difference between their inlet and outlet.

3. Electromagnetic field modelling

The first step was to analyze the calculations of the electromagnetic field. Computational model was two-dimensional and based on the solution of Eq.1. The description of the electromagnetic field in symbolic form using vector potential $\boldsymbol{A}$ allows an analysis of electromagnetic phenomena in the steady state for linear systems.

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

where: $\boldsymbol{A}$ – magnetic vector potential; μ – permeability; ω – angular frequency; σ – electrical conductivity; J_s – surface density of forcing current.

In the analyzed model, the non-linearity (with respect to the electromagnetic field) can be found only in the core (Fig. 2), but as shown in [12] if the core is designed properly, it should not go into saturation. Thus, it also satisfies the characteristics of linearity and therefore it could be modelled as ideal (non conductive with high relative permeability). The analysis of the electromagnetic field in symbolic form is advantageous because it allows a significant reduction of computation time [14,15]. Calculations were carried out using a professional program Flux. The calculation model is limited to 1/8 (due to the electric anti-periodicity) given in the form of a suitable boundary condition at the edges *ab* and *ac*. The model for electromagnetic field analysis was coupled with the electrical circuit, which enabled the calculations for different configurations of the inner and outer coil power supply.

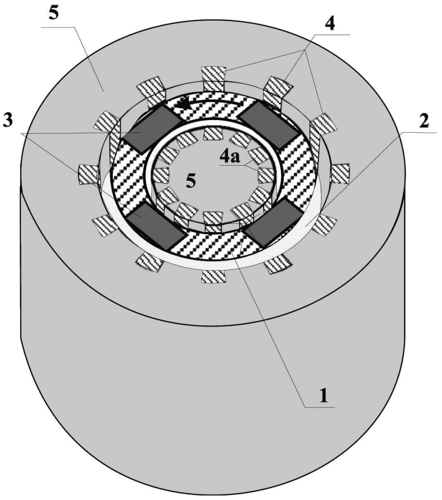

Fig. 1. Outline of the device for washing the precious metals out of automotive catalytic converters 1 – liquid metal, 2 – air gap, 3 – automotive catalyst, 4 – outer windings, 4a – inner coils, 5 – magnetic cores

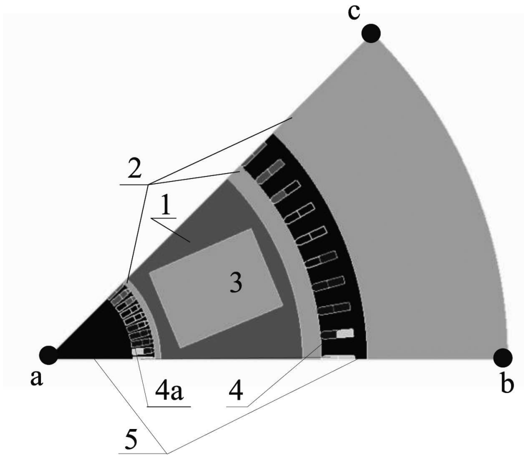

Fig. 2. Model of the system for electromagnetic calculations: 1 – liquid metal, 2 – air gap, 3 – automotive catalyst, 4 – outer coils, 4a – inner coils, 5 – magnetic cores

The determination of the vector potential ***A*** allows the calculation of the magnetic induction component (2), the components of the current density (3) and on this basis (using its own procedure) the average volume density of the component forces (4) acting on the liquid metal.

$$\underline{\mathbf{B}} = \nabla \times \underline{\mathbf{A}} \tag{2}$$

$$\underline{\mathbf{J}} = \mathrm{j}\omega\sigma\underline{\mathbf{A}} \tag{3}$$

$$\begin{aligned} f_x &= -\tfrac{1}{2}\left(Re(J)Re(B_y) + Im(J)Im(B_y)\right); \\ f_y &= \tfrac{1}{2}\left(Re(J)Re(B_x) + Im(J)Im(B_x)\right) \end{aligned} \tag{4}$$

where: fx, fy – volume density of electromagnetic forces; J – surface density of eddy current;

The volume density components of the forces, calculated at points on a rectangular grid with a mesh 1×1 mm, in the flow field analysis in the Fluent program became part of Eq. 5.

4. Flow field modelling

The flow field was modelled basing on the solution of Navier-Stokes equation and continuity for incompressible fluids equations. The calculations were made by using the finite volume method in two-dimensional space and were carried out using the Ansys Fluent software. In the channel which was not occupied by the carrier of catalytic converters, Navier Stokes equation received the form of Eq. 5. The value f represents the effect of the electromagnetic field on the liquid metal. In this area, the commonly used standard *k-epslion* model of turbulence [10,16] was assumed. Although this model may give less accurate MHD flow distribution outside the catalysts than the model LES, the calculations based on it are significantly shorter [11].

$$\rho_f\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \eta_e\nabla^2\mathbf{v} + \mathbf{f} \tag{5}$$

where: v –velocity, p – pressure, ηe – effective viscosity, f – electromagnetic force density.

The areas occupied by the carrier of the catalyst was modelled as anisotropic porous medium, in which the laminar flow and pressure drop occurred consistent with the Hagen-Poiseuille equation [12]:

$$\frac{\Delta p}{L} = \frac{28.5}{d^2}\eta v \tag{6}$$

where: Δp – pressure drop, L – unit length, d – hydraulic diameter of the capillary, η – viscosity of metal, v – velocity

In the case of the catalyst, a module which represents the resistance of porous media was based on Eq. 6 appears in the Navier-Stokes equation, however the impact module of electromagnetic force field disappears.

$$\rho_f\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \eta\nabla^2\mathbf{v} - \frac{28.5}{d^2}\eta\left(\mathbf{n}\cdot\mathbf{v}\right)\mathbf{n} - \infty\left(\mathbf{m}\cdot\mathbf{v}\right)\mathbf{m} \tag{7}$$

where: n – a unit vector parallel to the direction of catalyst channel, m – vector perpendicular to the direction of the channel in 2D space.

In order to enable numerical simulations (in the last term of equation responsible for the resistance of capillary structure in the perpendicular direction to the channels), instead of the ∞ value, the number several orders of magnitude bigger than the structure resistance in the channels direction was inserted.

5. Numerical experiments

As mentioned before, the research was conducted for six different frequencies and two different ways of supplying power to the coils (generating either longitudinal or transverse field). The calculations were performed for a channel filled with liquid lead, with the inner radius of 62 mm and the outer radius of 139 mm. The assumed dimensions of a single converter were 60x40 mm. In order to obtain a symmetrical distribution of the forces at the outer and inner walls of the channel, the outer coil was supplied with the current of 37A, and the inner one with 23 A for frequency of 50 Hz and the longitudinal field. Such selection of the current parameters yields approximately similar values of electromagnetic forces for both inner and outer coil. For the remaining frequencies and configurations the current strength was adjusted so that the power released in the core was the same as in the case. Fig. 3 presents the distribution of the magnetic flux obtained for the case of transverse and longitudinal fields at the frequency of 25 Hz.

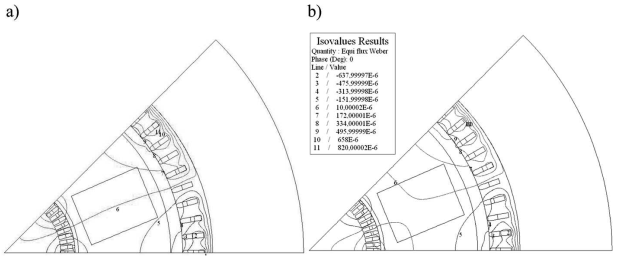

Fig. 3. Magnetic flux isolines for frequency 25 Hz for transverse field (a) and longitudinal field (b)

Although for the case of the transverse field the field penetration is evident in the entire cross-section of the liquid metal, it does not necessarily translates into an increase of the forces and in turn, improvement of the metal flow, which is shown in the subsequent pictures. (Fig. 4-8). This is probably due to the big part of the channel being filled with the converter, where the electromagnetic forces do not act on the liquid metal. Fig. 4 presents, in cross-section, the distribution of electromagnetic forces acting on the liquid metal in the area between the flushed converters. The type of eddy rotating field (transverse or longitudinal) did not influence the structure of the field acting on the liquid metal in any significant way.

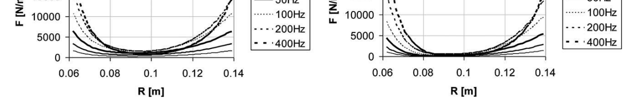

Fig. 4. The distribution of electromagnetic forces in cross section of the channel obtained for the transverse field (a) and longitudinal field (b) at different frequencies

Both for transverse and longitudinal fields (Fig. 5) an increase in frequency causes an increase in maximum values of the forces acting on the liquid metal at the walls of the device. However, an increase in frequency above 200 Hz at the stated level of the power supplied (8kW) does not increase an average force acting on the metal (in the area beyond the porous structure of the converters).

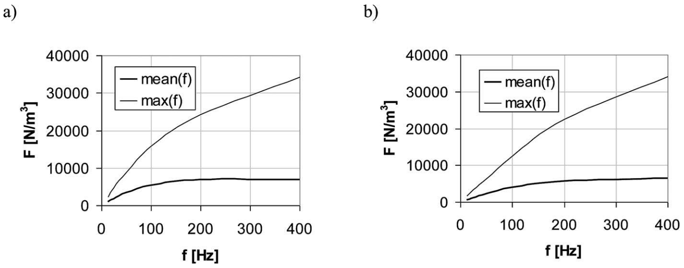

Fig. 5. Influence of frequency on average and maximum values of the forces for transverse (a) i longitudinal (b) fields

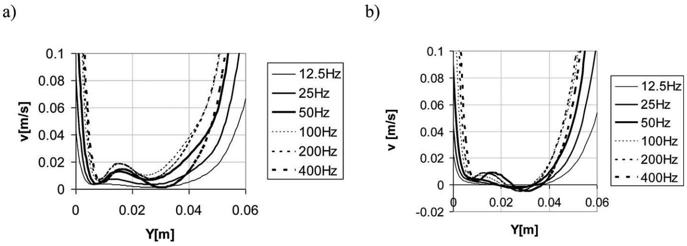

Fig. 6. Velocity distribution in the capillary structure of the converter for transverse (a) i longitudinal (b) fields

The distributions of velocities in the structure of the converter presented in Fig. 6 indicate that the longitudinal field causes the appearance of some areas with zero or reverse flow, which means loss of the precious metals that are not washed out of these areas. The last stage of the experiment was to examine the influence of the frequency on the distribution of medium and minimum flow velocities in the flushed core.

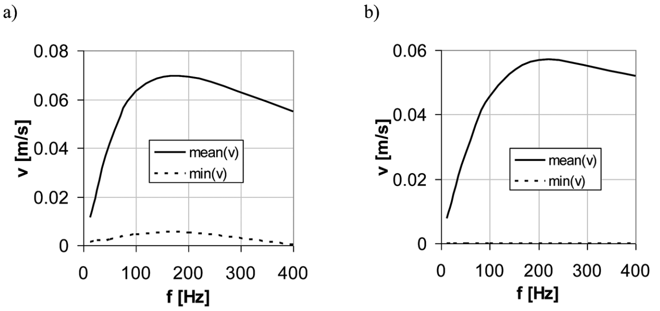

Fig. 7. Influence of frequency on minimum and medium flow velocity in the converter, a – transverse field, b – longitudinal field

Both for transverse and longitudinal fields the greatest intensity of the flow in the converter structure was obtained for the frequency of about 200 Hz. However, the longitudinal field caused a decrease in the average flow velocity compared with the transverse field (at the same power consumption level of 8kW). The areas with zero or reverse flow through the capillaries occurred for the whole range of the analysed frequencies, which is presented in Fig. 7a-b. Fig. 8 shows the force field (a) and velocity filed (b) for the best of the cases under consideration, that is for the frequency of 200 Hz and the longitudinal field. The catalytic converters cause vortices in the areas among them, which disturbs the flow of the liquid metal through their carriers and thus reduces the rate at which the precious metals are dissolved in the metal-collector.

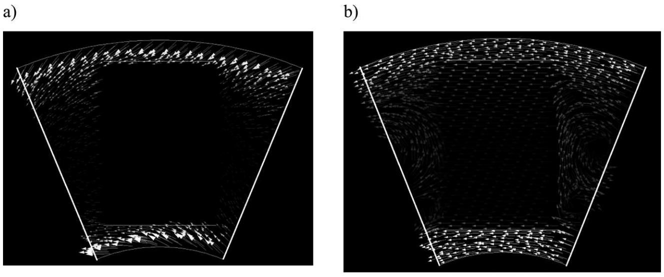

Fig. 8. Distribution of the force field (a) and the velocity field (b) for the optimum variant – the transverse field at frequency of 200 Hz

6. Summary and conclusion

The presented numerical experiment concerns the recovery of precious metals from used automotive catalytic converters. Precious metals are washed out of the capillary structure of the converter by a liquid metal-collector, which in the case under consideration is liquid lead. In order to increase the efficiency of dissolving the precious metals, the liquid metal-collector must flow through the capillaries of the converter. The movement of the liquid is forced by the electrodynamic forces. The previous researches have not achieved satisfactory efficiency in this respect. The research presented here was an attempt to intensify the flow of the liquid metal by means of double windings used at both ends of the converter that were supplied in two configurations with currents of different frequencies. The power supplied to the coils generated either transverse or longitudinal field. It was expected that for lower frequencies the configuration generating a transverse field would be more effective, while for higher frequencies both configurations would yield comparable results, with a slight advantage of the one generating a longitudinal field.

The conducted calculations show that more effective flow velocities are achieved for transverse field, irrespective of frequency. It is true for both maximum and medium velocities (Fig. 7). A more intense flow can be achieved when the number of converters that are washed simultaneously is lowered, which influences the efficiency of the process. Another direction of the research aiming to improve the structure of the flow could be to control the values of the current in particular coil (inner and outer one) or to apply a divider that would steer the flow inside the channel.

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