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Examination of an electromagnetic mill structure by means of infrared radiation

Abstract. *The method proposed in the present article consists in the use of thermovision camera in order to check the technical condition of an electromagnetic mill. The article presents the problems occurring in course of such type of tests as well as the methods to be applied to increase the accuracy of their performance. The analysis of obtained results makes it possible to easily and quickly indicate the areas of hazards which may lead to the equipment failures. Furthermore the article presents the procedure to be followed in course of such type of tests as well as the ways to interpret obtained results.*

Streszczenie. *W artykule zaproponowano metodę kontroli stanu technicznego młyna elektromagnetycznego z wykorzystaniem kamery termowizyjnej. Przedstawiono problemy podczas przeprowadzania tego typu badań oraz metody zwiększenia dokładności ich wykonania. Analiza otrzymanych wyników pozwala w szybki i łatwy sposób wskazać miejsca występowania zagrożeń, które mogą być przyczyną uszkodzeń urządzenia. W artykule zaprezentowano ponadto procedurę postępowania podczas tego typu badań, a także przedstawiono sposoby interpretacji uzyskanych wyników. (**Badanie konstrukcji młyna elektromagnetycznego z użyciem podczerwieni**).*

Keywords: electromagnetic mill, rotating field inductor, thermogram, thermovision camera.
Słowa kluczowe: młyn elektromagnetyczny, wzbudnik pola wirującego, termogram, podczerwień, kamera termowizyjna.

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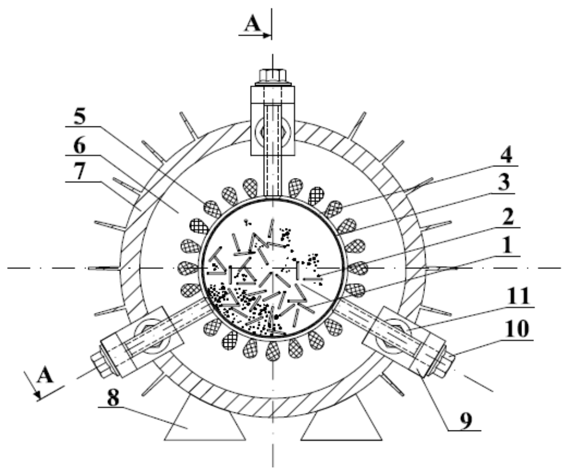
Introduction

The milling process consists in material disintegration under the influence of a force sufficient for that purpose. Said process consists in material crushing and milling. A properly designed mill should be used in order to obtain grains with diameter under 1 mm. From the review of Polish and foreign literature it appears that there are many machines used for disintegration of loose material. They are characterized by diversified output, construction, energy consumption and application [1-3]. Machines used for milling are individually selected for specified applications. One thing is for certain: disintegration is an extremely energy consuming process and the mills components are subject to wear and tear deteriorating their efficiency.

Characteristic of model under test

In comparison with other design solutions described in literature [4, 5], the mill presented in the present study is called an electromagnetic mill for its operation principle i.e. an synchronous motor stator playing the role of an inductor. Instead of a rotor, its interior contains a working chamber with milling elements (Fig. 1). The task of the inductor with hidden poles is to generate a rotating electromagnetic field which moves the milling elements. Due to their collisions with the material to be disintegrated, the dimensions of the material or raw material are reduced.

a)



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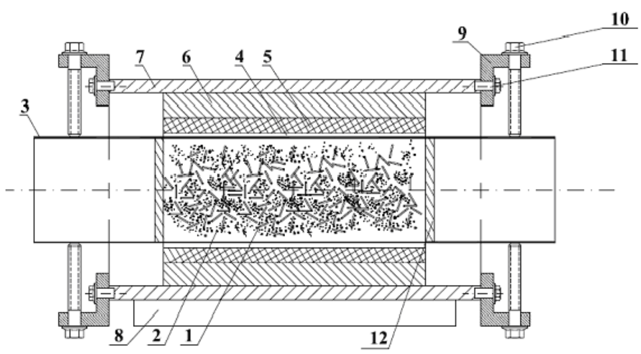

Fig.1. Cross – section of an electromagnetic mill [6]: a) view from the inductor winding, b) view from the side of the body; 1 – grinding media, 2 – material being disintegrated, 3 – working chamber, 4 – air gap, 5 – inductor winding in grooves, 6 – magnetic core of the exciter 7 – exciter housing, 8 – mill feet, 9 – connecting element, 10 – working chamber adjustment bolt, 11 – bolt fastening the element connecting element, 12 – working chamber sealing element

The electromagnetic mill is characterized by a simultaneous impact of electric, magnetic and thermal field as well as high pressure and friction on the material being disintegrated. Therefore the electromagnetic mill operation is many times faster in comparison with conventional milling machinery commonly used for disintegration. It makes it also possible to achieve several effects in the scope of materials processing which are unachievable by means of other methods and other equipment. For example the following processes are possible by means of an electromagnetic mill: dry and wet disintegration of materials, mixing of loose, liquid and gaseous materials, grinding of elements and grains, volatile dusts processing, production of composite materials in mechanical alloying process, obtainment of substances with proper physical and chemical properties.

There are several energetic transformations occurring in the working chamber. One of them consists in the creation of thermal field characterized by high temperature gradients and causing the heating of structural elements of the mill. Moreover it is necessary to apply appropriate cooling systems required for the inductor windings conducting high density current in order to avoid their damage. The thermovision examinations by means of IR cameras are used as one of the methods for analysis of temperature distribution between individual structural elements and its influence on the electromagnetic mill operation.

Thermovision measurements accuracy

The thermovision examinations [7-10] are more and more frequently used for the diagnostics associated with machines, including electrical machinery to which the electromagnetic mills belong. Due to relationship between the temperature and specified physical parameter, it was possible to create the fast and non-invasive methods for the evaluation of technical conditions of selected equipment or the components thereof.

The thermovision measurements are based upon visualization of infrared radiation invisible to human eye, radiated by a body the temperature of which is higher than absolute zero. This property is termed as emission factor consisting in ability of a body to give up energy. The emission factor depends on physicochemical properties and is an unique feature of each object. The thermovision camera is used for temperature measurement and analysis; the image obtained is called thermogram.

Due to their advantages e.g. versatility and possibility of contactless temperature measurement, the thermovision examinations are perfectly suitable for the analysis of elements generating certain amount of heat in course of their operation. The accuracy depends mainly on applied method, calibration of the device and on the accuracy of thermovision camera. The errors associated with applied method are of the highest importance, i.e. the following [11-15]:

- emission factor assessment errors;
- errors caused by examined object geometry;
- errors caused by the impact of radiation reflected by the object;
- errors caused by radiation transmittance through the atmosphere;
- errors caused by infrared radiation transmittance through the camera;
- errors caused by impossibility of averaging the results.

A/m errors may reach the level even higher than 10%. Therefore they are given priority in course of thermovision measurements. In course of examinations described in the present article, a/m errors have been minimized, because appropriated measurement procedure has been used, as described in the chapter entitled „Examinations methodology".

Examinations methodology

The examinations described in the present article have been performed by means of ThermaCAM E45 thermovision camera supplied by FLIR company. The following criteria have been applied in order to minimize the inaccuracies associated with measurement method:

1. Due to the lack of information about the materials which have been used to make the insulation of the electromagnetic mill windings and other parts of the machine, each examined element was provided with an adhesive bonded black tape with known emission factor and good heat conductivity every time in order to determine the correct value of the emission factor. The radiation intensity of examined element depends on the emission factor in accordance with Stefan-Boltzman law:

$$M(T) = \varepsilon \cdot \sigma_0 \cdot T^4 \quad (1)$$

where: ε – emissiveness, σ_0 –Stefan-Boltzman constant for black body, T – temperature.

2. The examinations have been completed in the direction perpendicular to the surface of the machine under test in accordance with Lambert cosine law:

$$M(\alpha) = M(T)_{\perp} \cdot \cos\alpha \quad (2)$$

where: ε – emissiveness, σ_0 –Stefan-Boltzman constant for black body, T – temperature.

3. The measurements have been performed in a dark room without electric lighting in order to minimize the impact of atmospheric radiation and the impact of radiation reflected from the object under test.
4. The measurements were performed in 1 minute intervals at the distance of 2m from the object under test and at air humidity of 45%. In case of wrong determination of any parameter, it is possible to correct them in course of computer analysis of obtained results.

Due to compliance with the criteria presented above, it was possible to obtain the objective results and to meet the condition of measuring error minimization.

Results obtained from thermovision examination

The determination of actual working temperature of an electromagnetic mill is of extreme importance for the mill to be qualified for continuous operation mode (S1), occasional operation mode (S2) or periodical interrupted operation mode (S3). Moreover it is required to determine the impact of temperature on individual machine elements in order to select proper construction materials, particularly the selection of mill inductor windings insulation. Presented thermovision examinations can be also used as diagnostic symptoms in order to determine the technical condition of the mill and to plan the dates of technical inspections of the machine.

Figure No 2 and 3 illustrates the thermograms of an electromagnetic mill in course of long lasting operation. The rated current was conducted by the inductor windings in course of machine operation. The examinations have been carried out for two cases: mill operation without any additional cooling circuit, mill operation with forced air flow – an additional cooling circuit. The forced air circulation has been provided by means of an efficient fan and properly designed distribution circuit contributing to significant reduction of the mill components temperature.

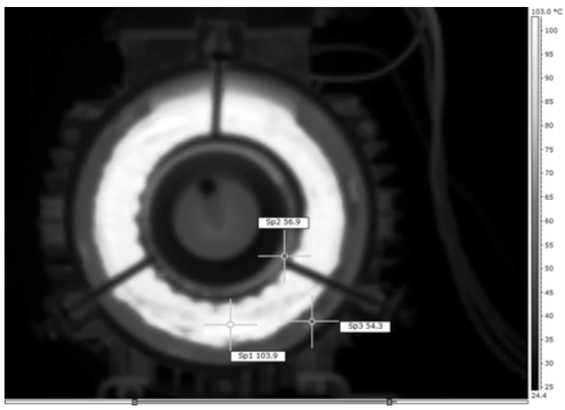

Fig.2. Thermogram in course of electromagnetic mill operation without cooling (time t=720 s.)

The following locations have been analysed in course of examinations by means of a software:

- inductor windings (point Sp1, Fig. 2-3);
- working chamber (point Sp2, Fig. 2-3);
- inductor core (point Sp3, Fig. 2-3).

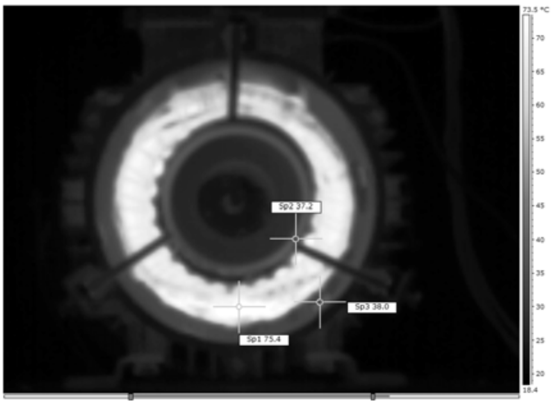

Fig.3. Thermogram in course of electromagnetic mill operation with cooling (time t=720 s.)

Figure 4-6 illustrates the average temperature distribution curves in the basic structural elements of an electromagnetic mill. From the examinations it appears that the largest amount of thermal energy is generated by the inductor windings. Said thermal energy mainly consists of the basic losses in copper, losses associated with eddy currents and equalizing currents between the windings. Further losses occurring in the inductor are caused by power losses, power supply frequency, magnetic field distribution and magnetic circuit reluctance changes [16, 17].

The power losses in inductor windings depend mainly on RMS current in those windings and can be determined by means of the following equation:

$$P_w = n \cdot R_d \cdot I_{ph}^2 \tag{3}$$

where: n – number of phases, R_d – DC resistance of phase winding at temp. ϑ, I_{ph} – RMS phase current.

The total losses in the inductor additionally consist of losses caused by eddy currents generated in the conductors as well as between parallel wires and branches, losses in core occurring as a result of power losses and magnetic field distribution vs. frequency. Generally, said losses can be calculated from the equation:

$$P_{Fe} = k_t \cdot \Delta p_{B,f} \cdot \left(\frac{f_{Fe}}{f_p}\right)^{\frac{4}{3}} \cdot \left(\frac{B_{Fe}}{B_p}\right)^2 \cdot m_{Fe} \tag{4}$$

where: k_t – design – technological factor, $\Delta p_{B,f}$ – power losses determined for Bp and f_p, f_{Fe} – frequency in core, B_{Fe} – induction in core, m_{Fe} – core mass.

The working chamber is the next source of heat occurring in an electromagnetic mill. Moving milling elements are heated as a result of collisions and friction giving up their thermal energy to the walls of working chamber and to the material being disintegrated. Furthermore the induction heating of grinding media and the walls of working chamber is caused by the rotating magnetic field generated by the inductor circuit. The value of tube temperature on thermograms illustrated in the present article is low as a result of the insulation material used for the working chamber sealing. The phenomenon consisting in post- drying of material or raw material being ground is a positive effect resulting from thermal energy generated in working chamber and contributes to further increase of an electromagnetic mill operation efficiency.

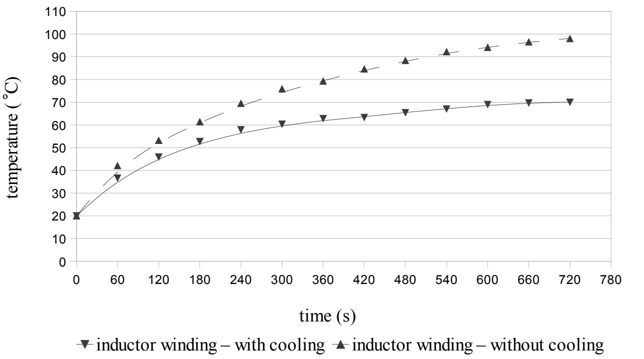

Fig.4. Average temperature distribution on inductor winding of an electromagnetic mill without/with cooling

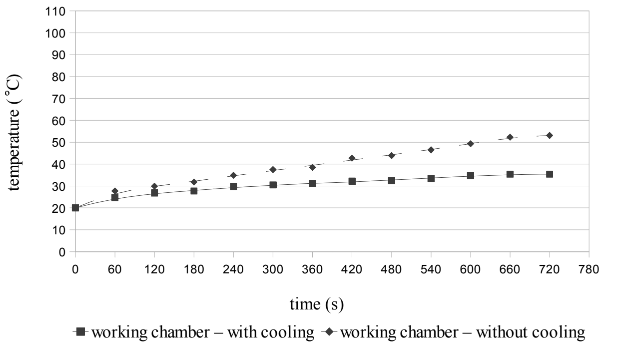

Fig.5. Average temperature distribution on working chamber of an electromagnetic mill without/with cooling

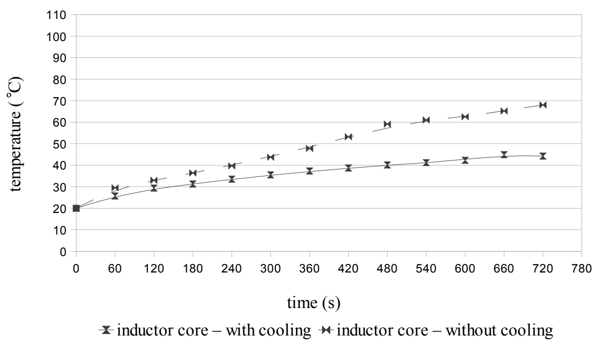

Fig.6. Average temperature distribution on inductor core of an electromagnetic mill without/with cooling

The use of an additional enforced air circulation by means of dedicated mechanical ventilation significantly reduces the temperature of inductor windings enabling the long term mill operation without shutdown periods and contributing to the extension of failure free operation of the machine due to extended period of structural elements ageing under the influence of significant temperature changes. The heat transfer coefficient (for conduction and convection to ambient area) is improved as a result of applied enforced air circulation and contributes to the reduction of mutual impact of individual mill elements.

Conclusions

1. From obtained characteristics it can be stated that the application of properly designed cooling circuit makes it possible to operate the electromagnetic mill in continuous mode e.g. in a processing plant where the loose materials must be disintegrated with high

efficiency and output. In such case there will be no thermal damage of the machine under the influence of thermal field occurring in the inductor windings and working chamber.
2. Optimally designed cooling circuit makes it possible to operate the electromagnetic mill in continuous mode (S1) without any shutdowns which is justified from economical point of view.
3. From presented examinations it appears that the thermovision methods can contribute to the diagnostics for selected elements or for the whole systems of an electromagnetic mill in a very easy and fast manner. The correct interpretation of obtained results – thermograms is a determinant for their use.
4. The use of a thermovision camera makes it possible to evaluate the condition of insulation on the inductor supply windings and to indicate the areas potentially exposed to damages. This method makes it possible to detect the mill faults in the scope of operation, design and technology.
5. Comprehensive computer analysis of obtained results (thermograms) makes it possible to qualify an element or the whole system (circuit) as inefficient. The thermovision photos are the diagnostic symptoms ensuring the fast and reliable detection of damaged area.
6. The thermovision examinations are an objective, non-invasive and contactless method used for evaluation of technical condition of the structural elements of an electromagnetic mill enabling the obtainment of diagnostic information without the necessity to dismantle its individual parts.
7. Moreover it is possible to use the thermovision photos as database useful for designing of new solutions, increasing the reliability and output of electromagnetic mills. They make it also possible to perform the analysis of thermal phenomena occurring in course of mill operation.

REFERENCES

[1] Ciszek T., Układy Technologiczne młynowni. Cz. 1, *Magraf,* Bydgoszcz 2009

[2] Drzymała Z., Badania i podstawy konstrukcji młynów specjalnych, *PWN*, Warszawa 1992

[3] Flizikowski J., Rozdrabnianie tworzyw sztucznych, *Wydawnictwo Uczelniane Akademii Techniczno – Rolniczej w Bydgoszczy*, Bydgoszcz 1998

[4] Polechoński W., Najzarek Z., Wielopolowy reaktor i jego zastosowanie w procesach wytwarzania paliw z odpadów chemicznych, *I Międzynarodowa Konferencja „Paliwa z Odpadów '97" Ustroń*, 15-17 październik 1997, 61-66

[5] Sosiński R., Szczypiorowski A., Szymanek P., Nowak W., Problematyka zastosowań młyna elektromagnetycznego, *XIV Międzynarodowa Konferencja „Popioły z energetyki", Międzyzdroje*, 17-19 październik 2007, 95-105

[6] Styła S., Pietrzyk W., Zgłoszenie patentowe na wynalazek pt.: Młyn elektromagnetyczny z trójfazowym wzbudnikiem pola wirującego nr. P.395321 [WIPO ST 10/C PL395321] z dnia 2011-06-17

[7] Orzechowski T., Technika pomiarów termowizyjnych w diagnostyce maszyn, *Pomiary Automatyka Kontrola,* 4 (2002), 18-20

[8] Poloszyk S., Różański L., Thermographic Diagnosis Station of Machines, *7th International DAAAM Symposium*, Wienna 1996, 351-352

[9] Poloszyk S., Różański L., Termowizyjna diagnostyka maszyn technologicznych, *PAK 1/2000*, Warszawa 2000, 15-18.

[10] Więcek B., Lis M., Zwolenik S., Danych R., Wajman T., Zastosowanie termowizji w badaniach nieniszczących i w mikroelektronice, *Pomiary Automatyka Kontrola,* 11 (2002), 8-12

[11] Madura H. (praca zbiorowa), Pomiary termowizyjne w praktyce, *Agenda Wydawnicza PAKu,* Warszawa 2004

[12] Maldague X., Non destructive evaluation of materials by Infrared thermography, *Springer-Verlag*, London 1993

[13] Minkina W., Pomiary termowizyjne – przyrządy i metody, *Wydawnictwa Politechniki Częstochowskiej*, Częstochowa 2004

[14] Minkina W. A., Rutkowski P., Wild W. A., Podstawy pomiarów termowizyjnych. Część II – Współczesne rozwiązania systemów termowizyjnych, błędy metody, *Pomiary Automatyka Kontrola*, 1 (2000), 11-14

[15] Wesołowski M., Niedbała R., Kucharski D., Wiarygodność termowizyjnych technik pomiaru temperatury, *Przegląd Elektrotechniczny*, 85 (2009), nr 12, 208-211

[16] Dąbrowski M., Projektowanie maszyn elektrycznych prądu przemiennego, *WNT* Warszawa 1994

[17] Mitew E., Maszyny elektryczne. Tom 1, *Zakład Poligraficzny Politechniki Radomskiej*, Radom 2005

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