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Analysis of temperature distribution in electromagnetic mill

Abstract. *The article presents the method of technical condition control for electromagnetic mill by means of thermal imaging camera. The principal areas of high temperature occurrence and the reasons of its presence have been determined. Furthermore the methods of interpretation of obtained results have been described. Thanks to the analysis of obtained results, it was possible to develop the thermal model using the equivalent thermal diagrams method. Presented research makes it possible to qualify the electromagnetic mill for operation in continuous or ad hoc mode as well as to determine its operation parameter in terms of obtained temperature increments for individual structure elements.*

Streszczenie. *W artykule przedstawiono metodę kontroli stanu technicznego młyna elektromagnetycznego z wykorzystaniem kamery termowizyjnej. Określono główne miejsca występowania wysokiej temperatury oraz przyczyny jej powstawania. Zaprezentowano także sposoby interpretacji uzyskanych wyników. Analiza otrzymanych wyników pozwoliła na opracowanie modelu cieplnego wykorzystującego metodę zastępczych schematów cieplnych. Przedstawione badania dają możliwość zakwalifikowania młyna elektromagnetycznego do pracy ciągłej lub dorywczej, a także określenia parametrów jego pracy z punktu widzenia uzyskiwanych przyrostów temperatury poszczególnych elementów konstrukcyjnych.* ***Analiza rozkładu temperatury w młynie elektromagnetycznym***

Keywords: electromagnetic field, rotating field inductor, IR radiation, thermal imaging camera.
Słowa kluczowe: młyn elektromagnetyczny, wzbudnik pola wirującego, termogram, podczerwień, kamera termowizyjna.

Introduction

The grinding consists in the destruction of internal structure of grain under the influence of an external force applied to a material [1, 2]. The grinding process can be subdivided into two phases: crushing and milling. Usually the both phases take place simultaneously but devices used for fractions processing belong to two different groups.

The grinding processes mechanics is complex and despite long lasting period of use of various facilities used for milling, the knowledge in this field is based mainly on empirical research. The mathematical descriptions based on scientific theories can be found in reference studies in only a slight degree. This situation is caused by the lack of formalized description of phenomena occurring in the grain being grinded [3, 4]. As observed by the author, the principal issue associated with this situation is the impossibility to precisely determine the value of energy required to achieve proper grain size and to determine the grinding process effectiveness. This effectiveness depends on dynamically varying properties of media and loads occurring in specified structure of the mill. Therefore the knowledge in the scope of designing process systems in milling plants and the knowledge of forces occurring there is based mainly on empirical research.

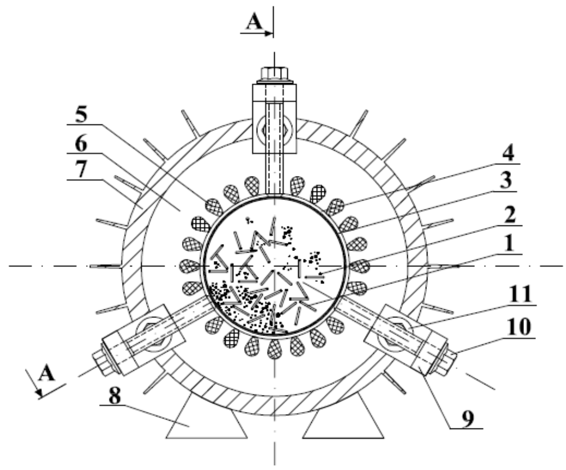
Structure of an electromagnetic mill

The stator of a 3-phase asynchronous general purpose motor is used as the basis for the construction of tested laboratory model. As a result of proper configuration of the working circuit incorporating the working chamber with milling elements, it was possible to adapt the stator for operation in the role of rotating field inductor of the mill.
The electromagnetic mill with the inductor with non – salient poles consists of the following basic elements (Fig. 1):

- 3-phase rotating field inductor with non – salient poles built on the basis of an asynchronous motor with single pair of poles;
- working chamber made of non-magnetic material;
- ferromagnetic elements - grinding media which are located in working chamber and are moving under the influence of rotating electromagnetic field;
- cooling system enabling effective transfer of large amount of heat generated in course of grinding process.

The inductor windings in presented solution are adapted for operation in delta or star configuration. The tests were carried out for inductor windings in delta configuration.

a)



b) A-A

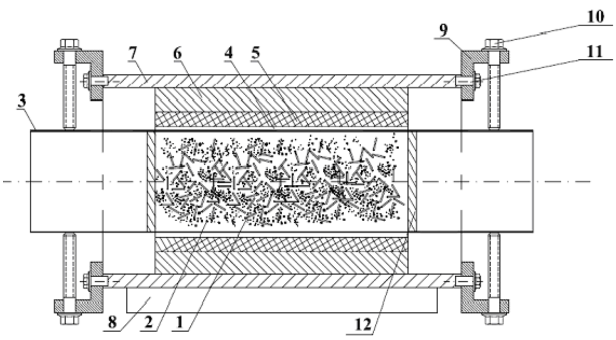


Fig.1. Cross – section of electromagnetic mill [5]:
a) view from the face windings end, b) view from the aluminium housing end – cross - section A-A (without cooling system); 1 – grinding media, 2 – material being grinded, 3 – working chamber, 4 – air gap,5 – inductor winding in grooves, 6 – inductor magnetic core, 7 – inductor housing, 8 – supporting arms, 9 – connecting elements, 10 – working chamber adjustment bolt, 11 – connecting element fastening bolt, 12 – working chamber sealing element

Laboratory tests

The use of electromagnetic mill in materials grinding process is characterized by large amounts of heat generated mainly in excitation windings and working chamber as a result of dynamic collisions of grinding elements with material being ground and as a result of induction heating under the influence of field generated by the mill inductor. Also electric and magnetic losses contribute to the total temperature value in electric machines including the electric mill described herein.

Thermovision measurements have been performed for the model being tested in order to enable heat distribution analysis. It is particularly important when qualifying specified equipment for operation in continuous or ad hoc mode. The selection of testing method was determined by its non – invasiveness, accuracy and wide experience gained by the author in the scope of tests using thermal imaging cameras.

The accuracy of thermal imaging research depends mainly on applied method, device calibration and on the accuracy of the thermal imaging camera itself. The most important issue are the following errors of applied method [6, 7, 8]:

- emissivity estimation errors;
- errors caused by geometry of the object being tested (Lambert cosine law);
- errors caused by impact of ambient radiation reflected by the object (e.g. solar radiation, street lighting);
- errors caused by radiation transmission through atmosphere;
- errors caused by IR radiation transmission through the camera;
- errors caused by impossibility of results averaging.

a) b)

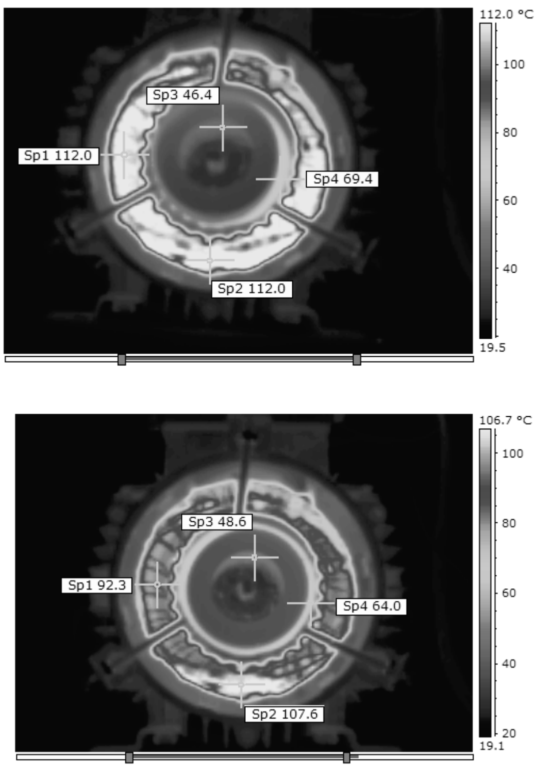


Fig.2. Temperature distribution in face part of inductor windings in course of electromagnetic mill operation: a) without cooling (t=6 minutes, I=13 A), b) with cooling (t=16 minutes, I=13 A)

Because these errors may reach several percent, they should be prioritized in case of thermovision measurements. The greatest measurement errors are associated with the determination of emissivity. In the tests presented herein, this value has been determined individually for each element of the mill. This measurement has been completed by means of the material with known high emissivity and good thermal conductivity, which has been adhesive bonded onto element under test [9].

In order to minimize the influence of other errors, the tests have been completed in a normal direction, along the mill axis. Furthermore, the impact of atmospheric radiation and radiation reflected from the device under tests was also minimized because the measurements have been carried out in the room with shaded windows without electric lighting.

Owing to the fact that various structural materials characterized by diversified emissivity, the starting point was the determination of the inductor windings temperature in course of long lasting work – due to possibility of their thermal damage (Fig. 2).
The test have been completed for two values of the inductor supplying current: 10,8 A and 13 A.

The use of rubber elements as the working chamber sealing prevents the temperature visualization in the working chamber where its value may reach about 100 °C. The impact of high temperature in the chamber is favourable because the material is additionally dried.

The electromagnetic mil being presented herein has been adapted for continuous operation thanks to properly designed cooling system. It is important in terms of technological processes because each downtime brings economical losses. The temperature in inductor windings is stabilized after about 15 minutes achieving maximum value lower than 120 °C for current value of 13 A (Fig. 3). Owing to the fact that the inductor windings are provided with insulation in F class withstanding the maximum permanently permissible temperature of 155°C, the mill is not endangered by damage as a result of windings overheating. In case of necessity of electromagnetic mill operation in an environment preventing sufficient heat transfer or in case of high outside temperatures, it is possible to apply windings insulation in H (180°C) or C class (220°C). However it is associated with the necessity to change the inductor structure due to the factor of grooves filling with thicker insulation. It should be also emphasized that the service life of windings is reduced in case of increased temperature. Therefore, the designing of optimal cooling system is of extreme importance in terms of the mill operation.

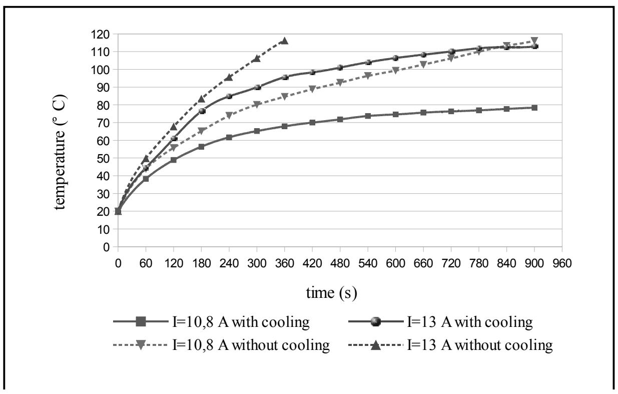


Fig.3. Temperature distribution in face part of inductor windings in course of electromagnetic mill operation with and without cooling for inductor current of 10,8 A and 13 A

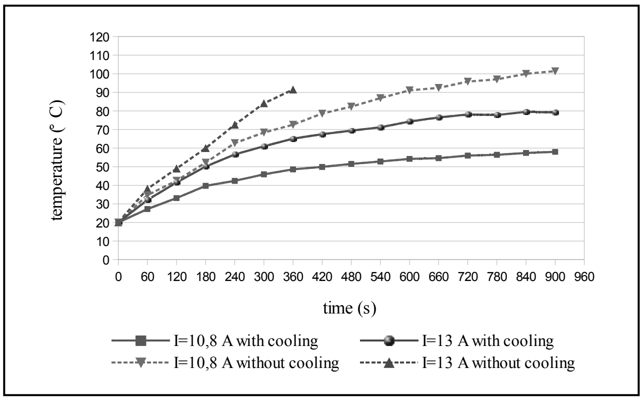
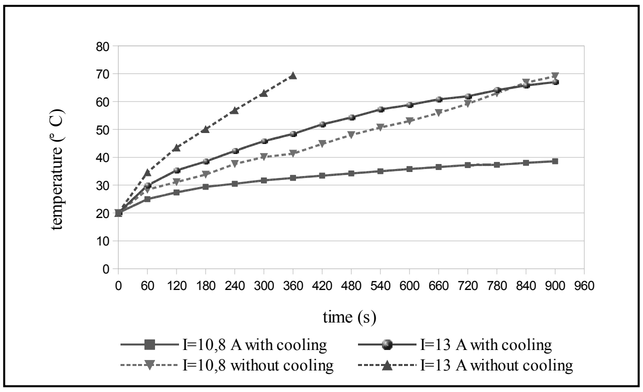


Fig.4. Maximum temperature distribution in the inductor magnetic core in course of electromagnetic mill operation with and without cooling for inductor current of 10,8 A and 13 A



Rys.5. Maximum temperature distribution in the working chamber in course of electromagnetic mill operation with and without cooling for inductor current of 10,8 A and 13 A

The figures No 4 and 5 illustrate maximum temperatures in the inductor magnetic core and in working chamber. The tests in the configuration without cooling with current of 13 A have been interrupted after 6 minutes due to possibility of thermal damage of inductor windings. In such case, the Mill could be operated in ad hoc mode – operation S3. From the characteristics presented for configuration with enforced air circulation, it appears that achieved value of temperature increase is equal to about 100°C. Therefore we can found that the load condition are optimal and corresponding to F insulation class. Therefore the structural elements of the mill will not reach the temperature which could prevent its correct operation and result in thermal damage. After about 15 minutes, the temperature is stabilized at a constant level.

Analysis of laboratory tests results

The inductor windings and working chamber are the principal areas of the electromagnetic mill where the thermal energy is generated. This energy mainly comprises of energy losses. Active winding losses (losses in copper) and inductor iron losses are the basic component of losses. The power losses in individual structural elements of the mill are the basic values used for thermal and ventilation calculations of the machine.

The power losses in the inductor windings depend mainly on rms current value in this winding. They are called basic losses and determined by means of the following equation:

(1) $$P_w = n \cdot R_d \cdot I_{ph}^2$$

where: P_w – power dissipation in the inductor windings [W], n – number of phases, R_d – DC resistance of phase winding *at temperature* ϑ *[Ω], I_{ph} - rms phase current value* [A].

The total losses in the inductor consist additionally of losses in core occurring as a result of losses in material and magnetic field distribution vs. frequency. Eddy currents are induced in course of the magnetic flux flow in ferromagnetic material. These losses can be determined by means of the following equation:

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

where: P_{Fe} – power dissipation in the inductor core [W], k_t – design and technological coefficient of the inductor core, $\Delta p_{B,f}$ - losses in material determined for B_p and f_p [W/kg], f_{Fe} - frequency in the inductor core [Hz], B_{Fe} - induction in the inductor core [T], m_{Fe} –mass of the inductor core [kg].

In more precise calculations, hysteresis losses and Eddy current losses occurring in core are considered separately. Most often, the losses in metal sheets are measured at the values of magnetic induction and frequency similar to intended operation parameters of the machine. The manufactures usually specify the value $\Delta_{p1,50}$. In the teeth with cross – section varying along height, the inductor losses can be determined by means of the following equation: [10, 11, 12]:

(3) $$P_{ds} = k_{td} \cdot k_{Bd} \cdot \Delta p_{1,50} \cdot \left(\frac{f}{50}\right)^{\frac{4}{3}} \cdot B_{ds}^2(0) \cdot m_d$$

where: P_{ds} – power dissipation in the inductor teeth [W], k_{td} - design and technological coefficient of the inductor teeth, k_{Bd} – coefficient determining tooth shape, $\Delta p_{1,50}$ - losses in material determined for 1 T and 50 Hz [W/kg], $B_{ds}(0)$ – induction in teeth cross - section for coordinate y=0 [T], m_d – teeth mass [kg].

In the active area of electromagnetic mill, the principal reason of high thermal energy generation is the friction and collisions between grinding elements as well as with material subjected to grinding and working chamber walls. Furthermore the rotating electromagnetic field with frequency of 50 Hz causes inductive heating of working chamber tube with ferromagnetic grinding media. Due to chaotic movement of grinding media and material to be ground placed in the chamber, the value of thermal energy generated by grinding elements in course of electromagnetic mill operation can be determined only by means of laboratory tests concerning the power transferred to the ambient area in the form of heat. Analytic determination is problematic because it is necessary to assume several simplifications contributing to significant errors in obtained results.

The analysis of these phenomena indicates to the fact that the greatest thermal energy is generated under the influence of active losses in the inductor windings. It is also confirmed in laboratory tests performed by means of physical model. However this method creates several problems with large amounts of heat to be transferred from the windings. Therefore it is the critical issue in case of evaluation of continuous operation possibility.

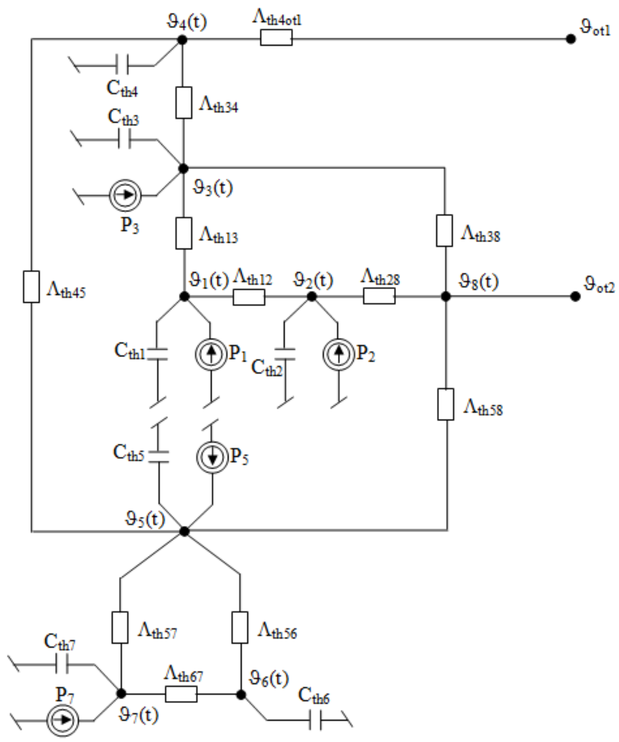


Fig.6. Equivalent thermal diagram of electromagnetic mill: $\vartheta_1(t)$ - temperature of groove part of inductor windings, $\vartheta_2(t)$ - temperature of face part of inductor windings, $\vartheta_3(t)$ - temp. of inductor core $\vartheta_4(t)$ - temp. of mill housing, $\vartheta_5(t)$ - temp. of working chamber, $\vartheta_6(t)$ - temp. of material subjected to grinding or temperature of raw material, $\vartheta_7(t)$ - temp. of ferromagnetic grinding media $\vartheta_8(t)$ - temp. of air in air gap of the mill, $\vartheta_{ot1} = \vartheta_{ot2}$ – ambient temperature, P_i - losses generated in individual elements, C_i – thermal capacity of individual elements, Λ_{ij} – equivalent thermal conductivity of individual elements (i,j = 1,2,3,...,8)

In order to perform precise analysis of thermal phenomena occurring electromagnetic mill, a thermal model has been created to determine temperature distribution in individual elements of the machine. The equivalent diagrams method has been used for this purpose [13, 14, 15, 16]. Determination of temperatures distribution gives the possibility to develop the equipment monitoring the mill operation in terms of its reliability in future.

In the equivalent thermal model developed by the author and modelled on the electric diagram (Fig. 6), individual structural elements of the mill are allocated to measurement nodes determining their temperature.

Conclusions

The prototype of electromagnetic mill presented herein is characterized by high output in comparison with conventional machines commonly used for materials grinding. Furthermore the mill operation is many times faster and makes it possible to achieve several processing effects which are unachievable by means of other methods and be means of different machines. The electromagnetic mill presented herein is characterized by the simultaneous impact of electric, magnetic and thermal field as well as high pressure and friction on the material subjected to grinding.

On the basis of the research presented herein, we can found that the properly designed cooling circuit makes it possible to operate the electromagnetic mill in continuous mode e.g. on processing line with the need of bulk materials grinding with high effectiveness and output. In such case any thermal damage of the machine under the impact of thermal field occurring in the inductor windings and working chamber is impossible. Optimally designed cooling system makes it possible to operate the electromagnetic mill in continuous mode S1 without downtimes which is justified from economic point of view.

The tests describe herein have been also demonstrated that the thermal imaging methods can be easily and rapidly used for diagnostics of selected elements or the whole systems of electromagnetic mill. Proper interpretation of obtained results – thermograms is the determinant of their use.

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