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ANALYSIS AND ASSESSMENT OF FOUNDRY MOULDING SAND PREPARING PROCESS USING THE DYNAMIC POWER MEASUREMENT METHOD

ANALIZA I OCENA PROCESU SPORZĄDZANIA ODLEWNICZYCH MAS FORMIERSKICH METODĄ DYNAMICZNEGO POMIARU MOCY

Preparation of moulding sand is a key process, determining the final quality of casting products. Special requirements are imposed at stabilising and optimising the parameters of the moulding sand so that it should maintain its properties required for moulding. These requirements can be satisfied as long as specialised mixing systems are used to prepare and control the sand mixing processes. The key elements of the system include sand mixers supported by dedicated measuring equipment operating in accordance with the approved control methods. Methods employed to determine the key properties of sand mix include the methods applied in on-line mixing control systems. The author's research to date has led to the development of a method whereby the sand quality indicator is defined by a dynamic power demand signal from the mixer system. This study provides the selected measurement data, showing power consumption by the driving units in a prototype turbine mixer, used in laboratory conditions. The experimental programme utilises a state-of-the-art microprocessor system for measuring the parameters having relevance to power consumption by the mixer drive. Measurement signals of power demand by a paddle stirrer and a rotor are analysed. Testing was done for variable moisture content in moulding sands containing different kind of bentonite and for variable mixer pan loads. The methodology is supported by measurements of sand properties by conventional methods. The complete set of data and interrelations holding between them is utilised to describe the investigated processes in terms of dynamic systems, in accordance with the rules of automation. Attention is given to practical applications of the power measurement method in the analysis of mixing dynamics, in control of water-feeding system and in evaluation of energy demand for the process. The proposed methodology enables the comprehensive evaluation and selection of constructional parameters of devices of sand preparation systems.

Keywords: foundry processes, preparing of moulding sand, dynamic power measurement of mixer's drive systems

Istotnym procesem w technologii wykonania odlewów, decydującym o ich jakości, jest sporządzanie masy formierskiej. Szczególne wymagania dotyczą stabilizacji i optymalizacji parametrów masy, określających jej właściwości i przydatność do wykonania form odlewniczych. Spełnienie tych wymagań zależy od zastosowanych systemów sporządzania i sterowania procesem mieszania składników masy oraz konstrukcji zastosowanych mieszarek. Podstawowym układem w systemie są mieszarki mas oraz współpracujące oprzyrządowanie pomiarowe, działające według określonych metod badawczych. Spośród metod służących do określania istotnych właściwości mas formierskich, wyróżnia się metody stosowane w układach sterowania on-line zasadniczym procesem mieszania mas. Na podstawie autorskich badań zdefiniowano metodę, w której miernikiem oceny jakości masy jest dynamiczny sygnał poboru mocy przez układy mieszające masę. W artykule przedstawiono wybrane wyniki pomiaru poboru mocy przez zespoły napędu prototypowej, laboratoryjnej mieszarki wirnikowej. W badaniach wykorzystano nowoczesny mikroprocesorowy system do pomiarów zbiorów parametrów charakteryzujących pobór mocy przez napęd mieszarki. Przeprowadzono analizę uzyskanych sygnałów pomiaru mocy napędu mieszadła łopatkowego oraz wirnika. Badania wykonano przy zmianie stopnia nawilżenia mieszanych mas formierskich z bentonitem (różne gatunki) oraz przy zmiennym napełnieniu misy mieszarki. Dopełnieniem metodyki badawczej były pomiary właściwości masy metodami klasycznymi. Pełny zbiór danych i ich wzajemnych zależności posłużył do opisu badanych procesów w ujęciu systemów dynamicznych zgodnie z regułami automatyki. Zwrócono uwagę na praktyczne możliwości wykorzystania sygnału poboru mocy: w analizie dynamiki procesu mieszania, w sterowaniu procesem dozowania wody do masy formierskiej oraz w ocenie energochłonności procesu. Zaproponowana metodyka umożliwia także kompleksową ocenę i dobór parametrów konstrukcyjnych urządzeń systemów sporządzania masy.

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1. Introduction

Most systems used in control of sand preparation processes are based on the relationships between sand parameters and its moisture content. Moisture measurements are taken with various types of sensors placed inside the mixer or also at selected points of the sand preparation line [2, 3, 4, 5, 9, 17, 21]. Besides, there are automatic systems for measuring the sand's technological parameters used for online monitoring of the sand being prepared and for process control (online updating of the amounts of ingredients to be fed). An example here is the Multicontroller system SMC-PRO [21].

The concept of measuring the selected parameters of power demand during the mixing process is not entirely new. The method was already described in earlier source materials [8, 20, 22], yet recent development of microprocessor systems offers new opportunities in this field [3, 7, 14]. Older publications lack the profound analysis of measurement data, chiefly because of limited accuracy levels and long response times of measurement devices used previously. Applications of the measurement signals of the mixer drive's power components to the assessment of the sand condition and to the control of sand preparation processes were explored in previous publications by the authors [e.g. 7, 12, 13, 14], which present the newly-designed original microprocessor system for implementation of such measurements and explore the basic relationships associated with power demand parameters to be handled by the dedicated software [14]. Power measurements of the mixer's drive are given below, tests were run on a turbine mixer based on a paddle mixer MS 75 [16], used in laboratory applications. The test rig is intended for testing the system for measurements of power components. One has to bear in mind, however, that each measurement method has its advantages and limitations [2, 4, 9,12, 14]. Combining several methods may improve the accuracy of sand quality assessment and help in monitoring of the sand preparation system. This study shows the measured power demand parameters of the drive unit in a laboratory mixer incorporating a paddle stirrer MS 75 [16]. The experimental setup was designed to test the measurement system. Besides, detailed analysis of previously collected data [7, 11, 12, 13], supported by new experimental results enables the identification of processes involved in moulding sand mixing.

2. Evaluation of selected parameters of sand preparation processes basing on dynamic power measurements

The tested mixer was engineered by providing a paddle mixer MS 75 [16] with a rotor and drive and with a water feeding system. The design of the rotor's drive allows for varying the inclination angle of the rotor axis and the rotor can be replaced by that having a different shape. In terms of its functional features, this mixer is an equivalent of the turbine mixer WM, manufactured by Kunkel Wagner [20]. Variations of the rpm speed of the paddle stirrer's drive and of the rotor are made possible by the use of frequency converters. The diagram of the measurement and control system is shown in Fig. 1.

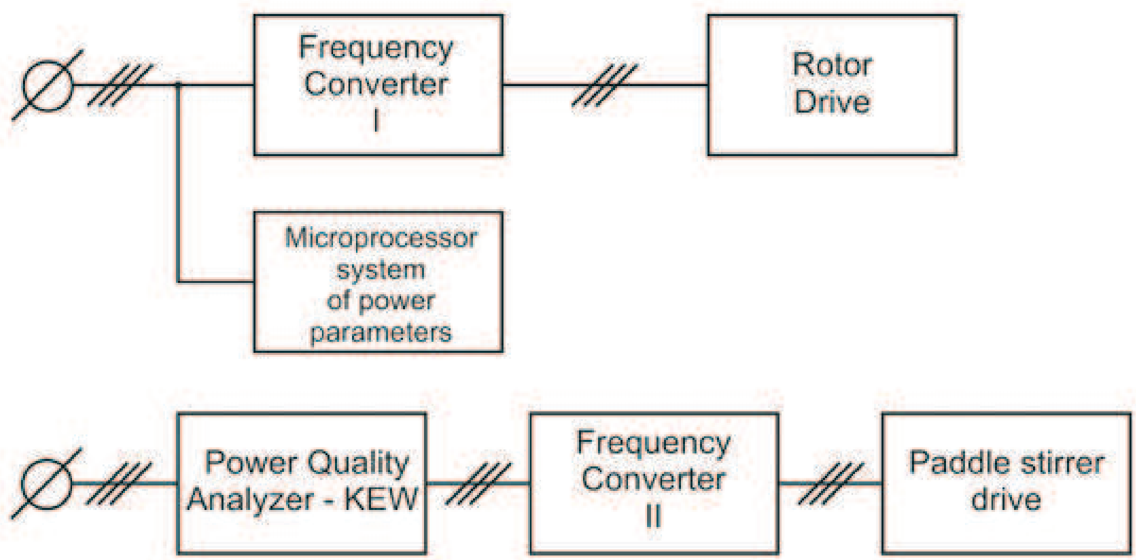

Fig. 1. General block diagram of control and measuring system of prototype laboratory mixer drives parameters

In the early stage of the test procedure, the characteristics are explored between the rpm speed of the rotor and stirrer in the function preset accordingly on the frequency converter. Measurements were taken with an optical speed meter Testo 460. It is found out that the degree of the mixer's charging has little bearing on the rpm speed of the mixer in stable- state conditions. Selected results are shown in Fig. 2.

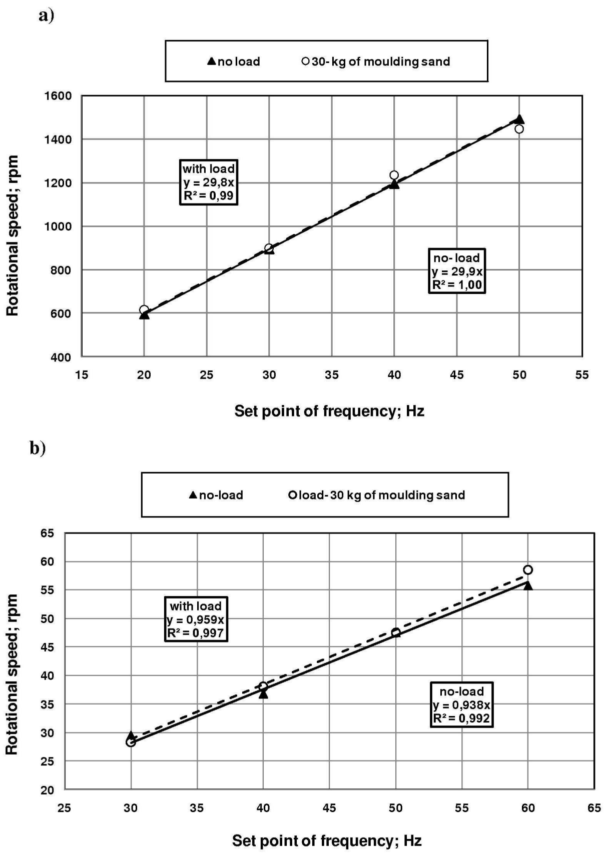

Fig. 2. Rotational speed of rotor – a) and paddle stirrer – b) versus set point of frequency

The novel feature is introduced by a prototype microprocessor system which enables the recording of several parameters associated with power demand. The dedicated software allows for graphic representation of registered data and for data transfer to other programs or spreadsheets (Excel).

For comparison, the measurement procedure uses also the power quality analyser KEW 6310, manufactured by Kyoritsu, enabling the simultaneous recording of selected power demand parameters of the drives in the rotor and paddle stirrer.

The purpose of this testing program was to evaluate how the variations of sand parameters associated with moisture content should affect the power demand by the mixer's drive throughout its duty cycle.

Synthetic sand used during the tests contained bentonite, designated as M1 (silica sand- 100 parts by weight, bentonite – 8 parts by weight) and sand mix (M2) from the foundry, containing bentonite and a lustrous coal carrier. Figure 3 shows the vital properties of sand mix M1 and M2 in the function of moisture content.

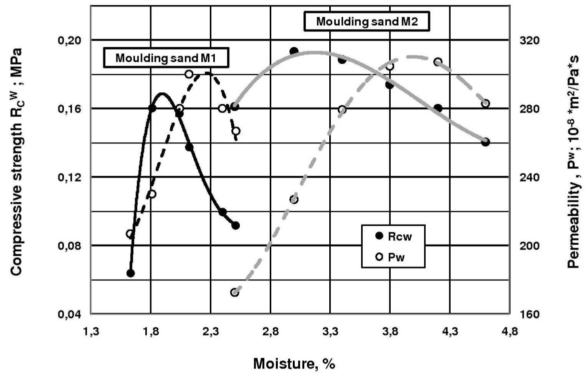

Fig. 3. Basic parameters of moulding sand – M1 prepared in laboratory roller mixer and moulding sand – M2 (each points represent mean value for series of measurements)

The window in Fig. 4 shows data registered during the power measurements of the mixer's rotor in laboratory conditions during the experimental program.

The plot of the registered signal of instantaneous power (an active components) reveals that the instantaneous values tend to oscillate round the mean value in a lesser degree during the early stages of mixing in relation to the final stage (Figs. 4, 5). When interpreting the plots, variations of rheological properties and associated technological parameters (moisture content) of moulding sand are of particular importance [4, 13, 15]. The apparent density of moulding sand changes considerably from low moisture content (of the order or 1%) to about 2%. It is well apparent (see Fig. 3) that the moisture content of the tested sand mix M1 is associated with the compression strength R_c^w nearing the maximal value.

Variations of apparent density of the moulding sand during the mixing process had an effect on position of its free surface and hence the level of rotor's immersion in the moulding sand. In the consequence, the registered power signals changed, too. A thorough analysis reveals periodic changes of power consumption in the system, associated with cyclic displacements of the paddle stirrer underneath the rotor. Each passage of one of its two arms causes the local elevation of the sand level, so the rotor was immersed more deeply, leading to increased mixing resistance.

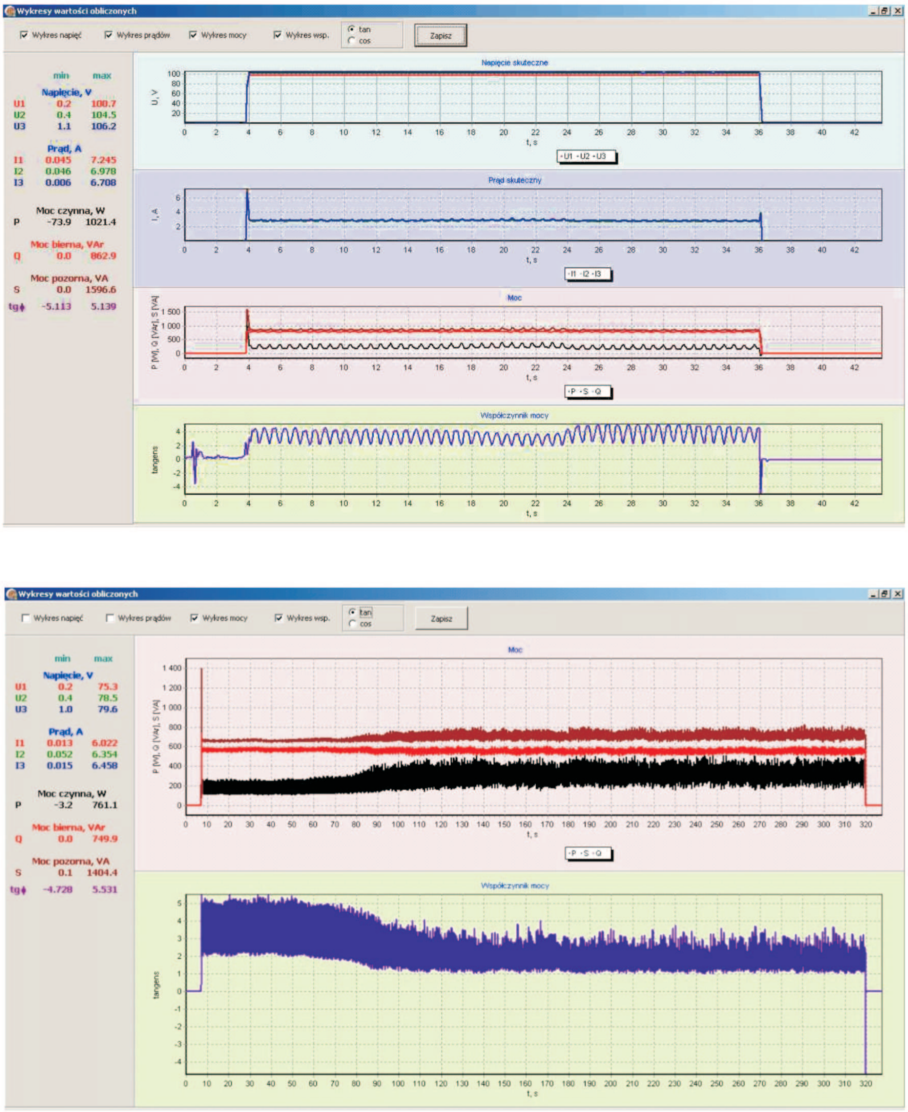

Fig. 4. Exemplary view of windows in a program of recording of selected power parameters values during mixing period

Pulsating power signals correspond to the frequency associated with the stirrer's arm passing under the rotor, related to the rpm speed of the stirrer.

A sine function with frequency associated with the rpm speed of a two-armed stirrer is superimposed on the selected time sections in the plot of the power signal. Selected time sections correspond to the period of mixing sand with low moisture content – power pulsation is decidedly smaller (Fig. 5a), and after moistening in the final stage of the mixing cycle (Fig. 5b). Enhanced power pulsation at that time might be attributable to cyclic, intensive motion of moistened sand in the radial direction (towards the mixer's axis). This kind of sand circulation is associated with the presence of vertical strips on the pan's side surfaces in the paddle mixer MS 75 [1, 6, 16]. Intensity of motion is closely associated with the moisture content of the moulding sand. Frequency of power signal pulsation throughout the entire measurement cycle changes very slightly whilst major variations of amplitudes of power pulses are revealed during the final stage, as explained above (Fig. 5).

In order to better capture the trends in variations of active power consumed by the rotor drive due to impulsive water dosing, the effective parameters of the signal were computed (by the trapezoids method) during the time periods associated with the obtained frequency of signal pulsation. Results are shown in Fig. 6. Measurement and computation data collected within the first 10 seconds after switching the mixer's drive are neglected, assuming it to be the start-up period. Besides, Fig. 6 shows an approximated flow rate of water dosed into the system (in the shape of square pulse).

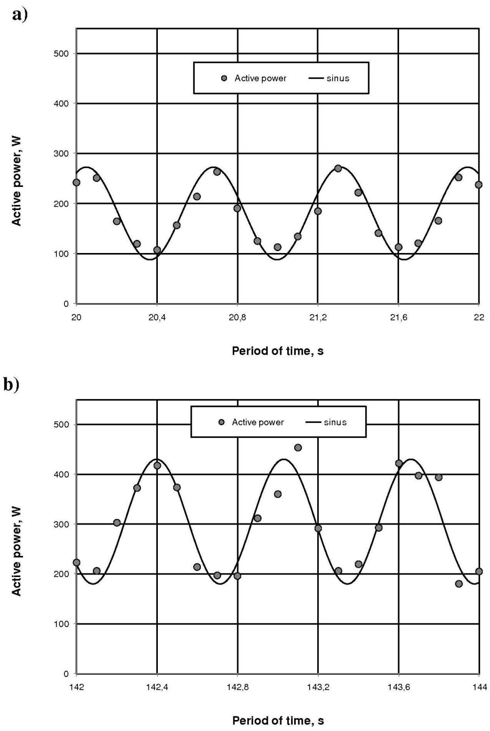

Fig. 5. Variations of active power demand of mixer rotor in different period of mixing time; a) near after the end of water dosing, b) in the period of stabilization of average value of power signal; moulding sand M1

When the process is treated as dynamic, it can be described in the simplest terms by a SISO (Single Input-Single Output) model. Taking into account the object's response to the present excitation, the transmittance function governing the model is given as [7]:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{k \cdot e^{-\tau_0 \cdot s}}{s \cdot (T_1 \cdot s + 1)(T_2 \cdot s + 1)} \qquad (1)$$

The model of the process is proposed in the form of the series connection of the integrating element and II order inertial element with time delay (model II in Fig. 6). The exciting signal x(τ) is the flow rate of the flux of dosed water, and the response y(τ) is the increment of the effective active power of the rotor's drive.

Alternatively, the transmittance function can be given as:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{k \cdot e^{-\tau_0 \cdot s}}{s \cdot (T \cdot s + 1)^n} \qquad (2)$$

In this case the process is modelled by the serial connection of an integrating element and n inertial elements of the I order and the delaying element (model III in Fig. 6).

The response patterns were obtained for both transmittance functions by the following methods:

- graphical method for the model governed by Eq (1)
- graphical – analytical method developed by V. Strejc, for the model governed by Eq (2)

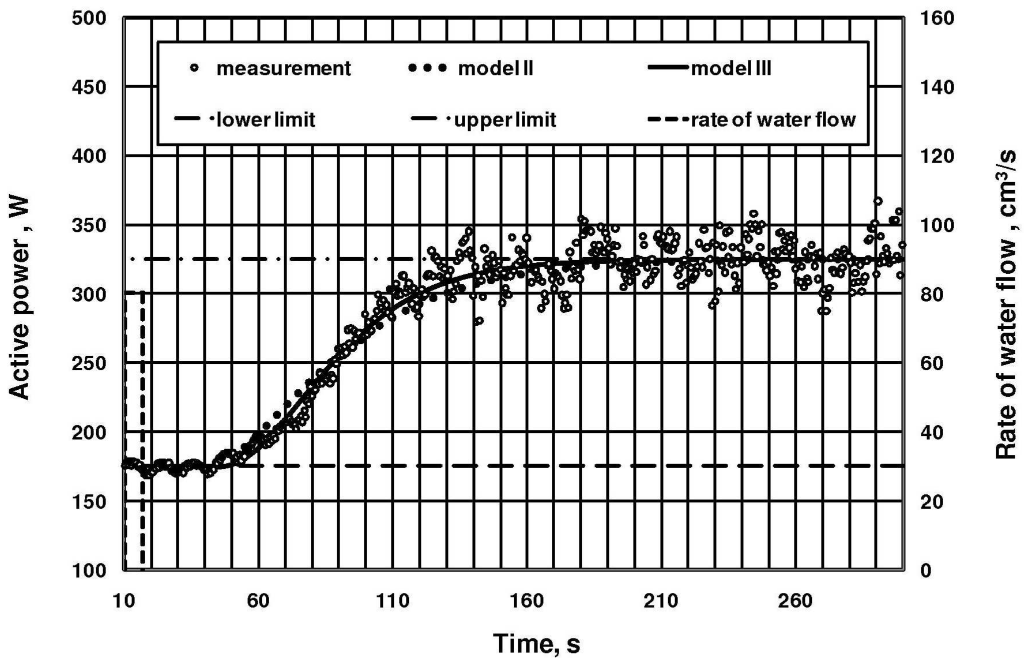

Fig. 6. Active power signal response of rotor drive for impulse input signal – rate of water flow in mixing process; moulding sand M1, pan load- L = 30 kg

The time delay readily apparent in Figs. 6 and 7 might be attributable to the operation of the water dosing system and intensity of the mixing process (delay in transport). In the presented series measurements the value of τ_0 falls in the interval between 30 and 40s (Fig. 6). Inertial terms present in the transmittance function are associated with the reaction of the binding agent to moisture, with parameters of the mixing process and constructional parameters of the mixer and its drive (for instance time constants present in the transmittance of the motor). In the case of Eq (1) and (2), impulse excitations lasting for a comparatively short time in relation to the whole process can be treated as a product of ideal excitation signal (Dirac impulse) and a constant, when such signal passes through the integrating element, a step signal is obtained at the output. The form of the final response after the signal's passing through further transmittance components is typical of inertial plants of the higher order. In Fig. 6 time response lines are indicated for the two models described above, determined by widely employed methods of the theory of control. A slightly better agreement between the experimental and predicted data is achieved when the second method is employed as the transmittance involves an inertial object of the III order, treated as a serial connection of three identical inertial elements of the I order for n=3. The model III is indicated with continuous line on the plot in Fig. 6.

It has to be emphasised that knowing the equation of static characteristic:

$$\Delta P = f(\Delta V) \quad (3)$$

where:

ΔP – increment of the drive's effective power

ΔV – the amount of water fed to the given quantity of moulding sand (mass) as well as the time response equation, one can easily control the water dosing process basing on power signal measurements.

Due to disturbances in industrial processes of sand preparation, such as deviations of the sand temperature [18, 20, 22] and to the fact that other ingredients are fed as well, the model of the mixing process has to be more complex [10, 11, 14].

Effective solution to such an intricate problem requires that all processes involved in sand preparation in turbine mixers should be identified [7,10, 14].

A similar plot of the power signal is obtained for the paddle stirrer's drive. In this case the measurement are taken with the KEW 6310 analyser while water is dosed in an impulse manner. Measurements of the active power signals are registered with the sampling time 2 s. The increase the pulsation of the active power signal (Fig. 7) with the increase in moisture content is explained above. Figure 8 shows the results of similar measurements (sampling time – 1 s) taken during the mixing (with water addition) of the moulding sand M2.

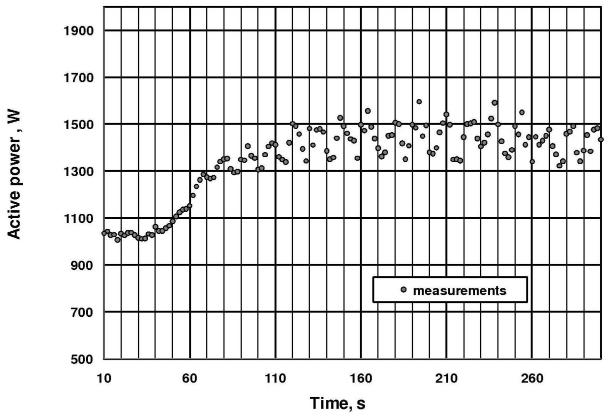

Fig. 7. Active power signal response of paddle stirrer drive for impulse input signal – rate of water flow in mixing process; measurement with KEW analyser, moulding sand M1, pan load – L = 30 kg

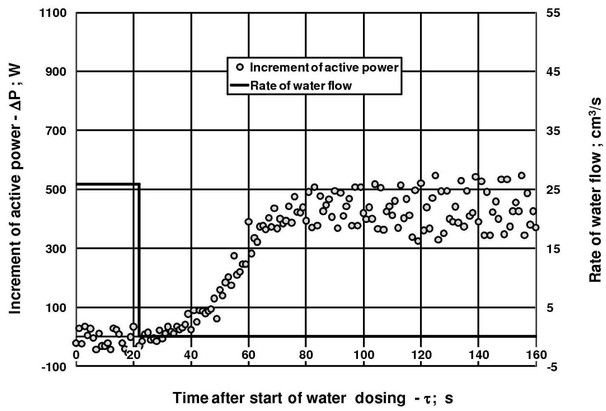

Fig. 8. Increment of active power signal response of paddle stirrer drive – P for impulse input signal – rate of water flow in mixing process; measurement with KEW analyser, moulding sand M2, pan load – L = 40 kg

The plot shows an idealised pattern of water jet flow rate in the form of an square pulse. The longer duration time of that pulse in relation to that shown in Fig. 6 is associated with the altered construction of the water dosing tank. Instead of absolute power values (Fig. 7), on the ordinate axis in Fig. 8 we get increment of measured power data with respect to the mean value computed for the period before signal variations caused by water dosing. That is why we get negative values of the signal, too. The stirrer's power signal shown in Fig. 7 and 8 follow a similar pattern, which is explained above. Like variations of rotor's power signal, the variations of stirrer's power signal are governed by Eq (1) or (2).

When compared to Fig. 8, it appears that the results correspond well with those shown in Fig. 9a, revealing the variations of basic properties of sand mix samples collected during the mixing process. The first four samples were collected with the time interval of 30s. The first sample was collected after 30s from the moment the water dosing was ended. Plots in Fig. 9a reveal a slight increase, corresponding to the pattern of the mean value of the active power increment signal. To better capture the period of intensive power increase, the sampling interval ought to be shortened, which would be difficult as the samples have to be collected manually. Fig. 9b summarises similar measurement data obtained for variable initial moisture content whilst the amount of dosed water remained the same. The plots of investigated parameters are similar to those shown in Fig. 9a, though the compressive strength of the moulding sand is slightly lower. Given the measurement accuracy, these variations are too insignificant to demonstrate a decidedly falling trend.

Measurements taken in accordance with the proposed methodology confirm the relatively fast (of the order of 30-40s) change of sand mix parameters during the mixing process in the rotor mixer and the fact that they are well correlated with dynamic measurements of drive power.

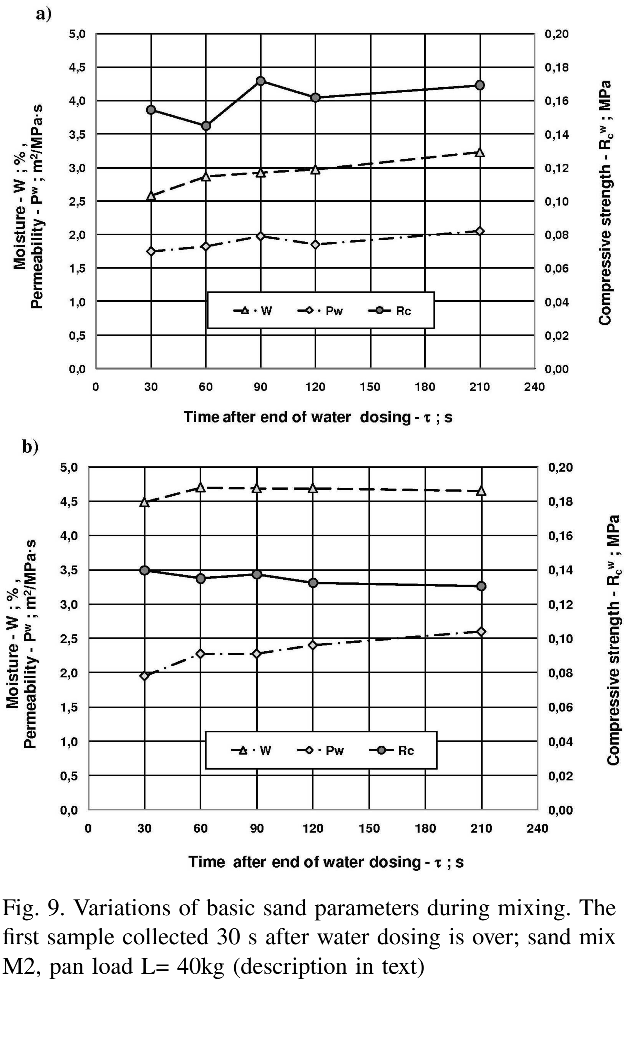

Fig. 9. Variations of basic sand parameters during mixing. The first sample collected 30 s after water dosing is over; sand mix M2, pan load L= 40kg (description in text)

Apart from sand mix properties, the pan load is another major factor affecting the power consumption by the mixer drive [12, 13, 14]. The pan load curve is obtained for the sand mix M2 with the moisture content 1.7%. Fig. 10 shows the measurement results of the paddle stirrer's active power for various pan loads. The effective power P_{av} is indicated with continuous line, expressing the pan load computed over the time interval of 50s and taking into account the standard deviation s, expressed in percentage points (standard deviation computed in relation to the constant effective value over the interval 50s).

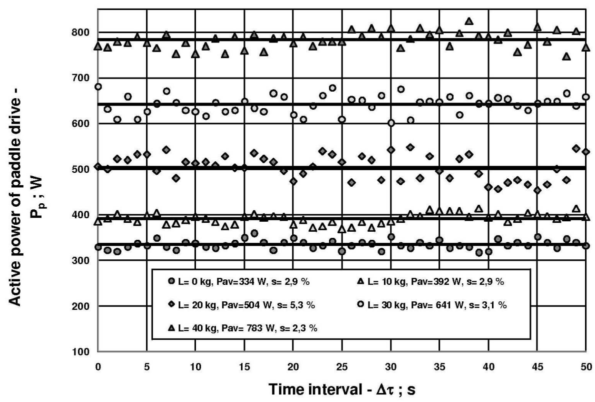

Fig. 10. Variations of active power of paddle drive – P_p for different pan load – L; P_{av} – average values of power over time interval – $\Delta\tau$ = 50s, s- standard deviations; moulding sand M2, moisture W = 1.7%

These results indicate that power demand tends to increase with increased pan loads. Only when the pan load 20 kg is applied, the standard deviation of measured active power increases in relation to the effective value (over the given time interval), which is probably associated with the beginnings of the rotor's operation under the applied loading. One has to bear in mind, however, that deviations from the effective value also involve the uncertainty of measurements, associated with the accuracy of the measurement system (of the order or 1.5%). That applies also to data given in Figs. 6-7.

Recalling the quoted data and the power demand factor C_{pd} [14], we get:

$$C_{pd} = \frac{P - P_0}{L} \tag{4}$$

where:

C_{pd} – coefficient of mixing power demand, W/kg

P – active power of the mixer, W

P_0 – idle run power of he mixer, W

L – load of the mixer pan, kg of moulding sand
Accordingly, the plot is graphed in Fig. 11.

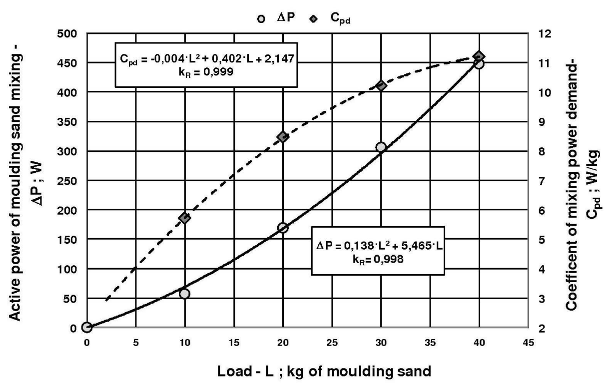

Fig. 11. Active power of moulding sand mixing for paddle drive – $\Delta P = P - P_0$ and coefficient of mixing power demand – C_{pd} versus load of mixer pan – L; moulding sand M2, moisture content $W \approx 1.7\%$

The product of C_{pd} and the time interval enables us to compute the unit energy demand over the given time interval. Summing up the values obtained for particular mixer's drives over the specified time intervals associated with the mixer's duty cycle we get the total unit energy demand (J/kg of moulding sand), specific to the mixer's construction and its duty cycle.

For pan load ranging from 20 to 40kg, the relationship between the power demand and pan load might be treated as linear (the correlation factor in excess of 0.9), which implies power increase proportional to the load increase. That observation is confirmed by dynamic power measurement data representing the power signal response to the sand flux signal in the form of a square pulse.

Measurement data are compiled in Fig. 12. Throughout the test program the initial pan load was varied (m_p) whilst the amount of dosed sand mix remained the same = 10kg ($m_k = m_p + 10$kg) over the time period of 1s. All registered time patterns are shifted to the point representing the time instant (τ = 50s) when the power demand begins to change. Similar to Fig. 8, Fig. 12 shows the increment of measured signal in relation to the steady effective value computed before the intensive increase of the power signal, that is why the plot reveals some points where the ordinate values are negative.

When the power increment signal is treated as the response to impulse excitations (rapid change of pan loading), the process can be described in terms of automatics by the transmittance formula given by (2). The initial values of involved factors are: $\tau_0 = 0$ and n=1 (transmittance of a real, integrating object, with no delay) and the approximate time response of the object is indicated with continuous line in Fig. 12.

The process description is adequate (in terms of mean values of signals). In measurements taken on industrial plants equipped with automatic sand dosing systems the time patterns of the input signal (the flux of sand mix to be fed) can be precisely determined making the process identification more accurate. Determining the response parameters would be more accurate if the KEW analyser were replaced by a prototype measurement system, shown in Fig. 1. The vital point is that the equivalent time constant used in the description of the sand dosing process is decidedly smaller than the time constant in the process of power change associated with sand moisturising (Fig. 6).

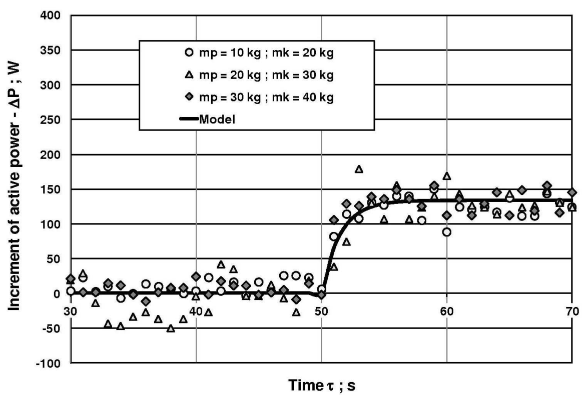

Fig. 12. Time run of increment of active power of moulding sand mixing for paddle drive – ΔP for different initial load of mixer pan at impulse dosing of 10 kg of moulding sand; moulding sand M2, moisture content $W \approx 1.7\%$

3. Summing up

The methodology of measurements of power consumption by the mixer's drive is outlined. In the light of treatment and interpretation of measurement data, further work is merited to develop the system to effectively monitor the power consumption in control of sand preparation processes. Test results reveal major variations in the mixer's drive's loading in the consequence of water feeding. Variations of power demand during the mixing process due to changes in sand parameters are considerable. At that stage further research works are underway, involving the application of more advanced identification algorithms and development of the dedicated software to enable the analysis of a vast body of measurement data obtained even from a single procedure. The form of thus obtained time responses confirms that the time of the mixer's duty cycle can be controlled basing on measurements of parameters of power uptake by the mixer's drive. That applies to the drives of both the rotor and the paddle stirrer. Results can be utilised to investigate the individual processes during the mixing operation, which are influenced by the mixer's design and technological parameters. It is reasonable to apply this measurement methodology to optimisation of turbine mixer's design and selection of their operating parameters. Measurements based on the proposed methodology enable the evaluation of the mixer's performance in the context of energy efficiency. Systems based on the proposed principles can well support the existing systems of sand monitoring and mixer control.

Acknowledgements

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