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THE ENERGY CONSUMPTION ASPECTS IN THE VACUUM ASSISTED MOULDING PROCESS

ASPEKTY ENERGOCHŁONNOŚCI W PROCESIE FORMOWANIA PODCIŚNIENIOWEGO

In the current manufacturing of foundry sand moulds, various methods of moulding sand compaction are used. Researchers are still looking for the optimal methods of mould manufacturing not only in terms of achieving the best technological effects, but also in terms of energy consumption. The article presents selected results of research of their own variant of the synthetic moulding sand compaction process using a vacuum. The measurements were also designed for evaluation the energy consumption in this method. The results were compared with other air flow moulding methods which are widely used. The study was performed on the original design test stand, which allows the visualization of the compaction process.

Keywords: sand mould casting, moulding machines, energy consumption

W wytwarzaniu piaskowych form odlewniczych są stosowane obecnie różnorodne metody zagęszczania. Nadal poszukiwane są metody wytwarzania form optymalne nie tylko pod względem uzyskiwanych efektów technologicznych, ale również pod względem ważnego parametru- energochłonności procesu. W artykule przedstawiono wybrane wyniki badań własnego wariantu procesu zagęszczania podciśnieniowego syntetycznej masy formierskiej oraz pomiarów zmierzających do oceny metody w aspekcie energochłonności. Wyniki porównano z wynikami badań innych metod zagęszczania strumieniowego – powszechnie obecnie stosowanych w wytwarzaniu form odlewniczych. Badania wykonano na oryginalnym stanowisku badawczym własnej konstrukcji, umożliwiającym wizualizację procesu zagęszczania.

1. Introduction

Currently the green sand moulding is still the most popular in the casting manufacturing process. Modern foundries generally use the moulding machines which compact the moulding sand by direct action of air stream. It can be denominate as air stream moulding machines [1]. Air stream moulding machines have included impulse machines (air impact), impulse-squeezing machines, as well as performing the Seiatsu process (air flow moulding machines of Sintokogio Company, Japan and Heinrich Wagner- Sinto in Europe). These machines use positive air pressure. The parting line of the air stream process of the Seiatsu type and of impulse process is not precisely definite, nowadays it is also offered by the Künkel-Wagner Company the machines about the intermediate dynamics – the solution Airpress plus [2]. There is also an offer of solutions bringing together air stream moulding (Seiatsu type) and impulse moulding (at present such machines are offered by the EMI Inc.). To the air stream moulding machines one can include also the vacuum assisted and squeezing moulding machines which use negative air pressure [3, 4].

This method has two main variants differing in a mode. The first variant includes the process where moulding sand is handled in a flask due to the gravitational forces and forces induced by vacuum in the technological space. The second one includes the process where the sand is dosed only gravitationally to the flask and then compacting forces are induced by connecting the technological space to the vacuum chamber [1, 3, 4]. In both systems the final step of compaction is squeezing.

The most important criterion of the evaluation of the given moulding machine are technological effects of its operation [1, 4, 5, 6, 7, 8]. Energy-consumption can be treated as the supplementary criterion of foundry machines assessments but currently also very important [1, 9, 10, 11, 12, 13, 14]. To such criterion one can also include, in example, the level of automation or the process reliability. Wide aspects of the assessment of the moulding machines can make easier the proper choice from the group of moulding machines with similar technological possibilities.

In the article the problems of energy-consumption of the above and the one of certain vacuum moulding machine have been discussed [1, 3, 11, 13]. This factor is all-important from the point of view of ecologies and running costs of the machine operation. In the case of processes occurring in air stream moulding machines there is also existing the relationship between operation parameters e.g. initial pressure (connected with energy-consumption) and with the level of the noise emission.

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2. Energy aspects of the moulding sand compaction process

The specification of energy demand in moulding sand compaction is a very complicated problem due to the different varieties of realised compaction processes [1, 6, 7, 8, 9]. The basic division of compaction methods relates to the dynamics of the compaction process. The air stream moulding may be attributed to the dynamic methods. Usually the duration time of the compaction process does not exceed 1 second. Opinions on the subject of the influence of the stress growth rate in the moulding sand on compaction effects are diverse. According to some authors [6, 7] the increasing of the speed of the stress growth causes the improvement of the compaction degree- this is explained by occurrences (among others) of thixotrophy phenomenon, the diminution of the viscosity of the moulding sand, the decreasing of internal friction. According to others [5, 8, 9] the effect is inverse. The Fig. 1 shows calculations results of the moulding sand compaction process according to the nonclassical rheology model described in [8]. For the compaction process of moulding sand Orlov [8] has take into account only the plastic and viscous parts and he has allowed omission of the elastic part of the deformation. The main differential equation describing this model in such simplified form is:

$$\frac{\rho}{\rho_{01}} = \left[\frac{1}{\sigma_{01}}\left(\sigma - \frac{\lambda}{\rho} \cdot \frac{\partial \rho}{\partial \tau}\right)\right]^{\mu} \tag{1}$$

wherein: ρ – apparent density of moulding sand, ρ_{01} – density after acting the initial (small) stress- denominated as σ_{01}, σ – stress, λ – coefficient of dynamic viscosity, μ – compressibility factor, τ – time.

The solution of this differential equations leads to dependence between the stress (showing its growth rate) and the strain in compacting elementary volume of moulding sand. It is easy to link the strain change with the change of apparent density of moulding sand. The increasing of the stress growth rate- $\mathbf{d}\sigma/\mathbf{d}\tau$ leads to the smaller final density and of course the increasing of the rate of density changes- $\mathbf{d}\rho/\mathbf{d}\tau$ (Fig.1).

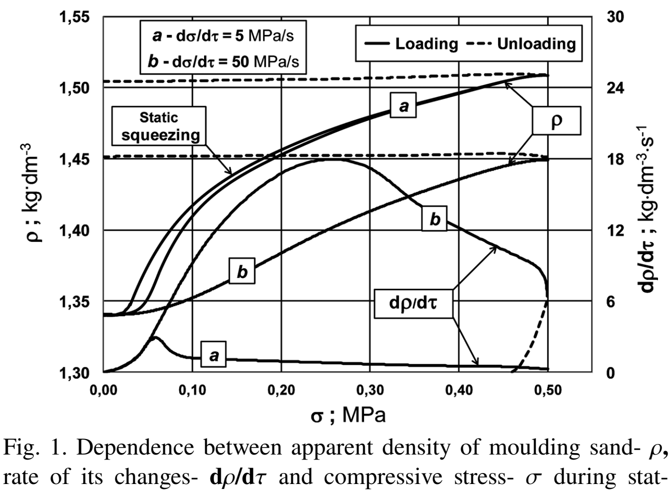

Fig. 1. Dependence between apparent density of moulding sand- ρ, rate of its changes- $\mathbf{d}\rho/\mathbf{d}\tau$ and compressive stress- σ during static squeezing and dynamic loading (at different stress growth rate- $\mathbf{d}\sigma/\mathbf{d}\tau$). Data for calculation from [8]

It should be noted that the rate of the tensions growth used in calculation (5 MPa/s and 50 MPa/s – Fig. 1) are the same order as rate of the pressure growth in the Seiatsu process (or Airpress process) and in the classical impulse process. During the unloading period, within the range of analysed compressive tensions, takes place the comparatively small elastic deformation of the moulding sand [8].

On Fig. 2 there are presented test results of the impulse moulding [9] compared with the calculations of the squeezing process according to well-known empirical Aksjonov equations (for the static squeezing) and to the equations with the Saltykov correction coefficient [5]. The transformation of mentioned above equations gives:

$$\Delta\rho = \rho_k - \rho_0 = 0.68 \cdot H_0^{-0.19} \cdot (k \cdot p)^{0.25} \tag{2}$$

wherein: ρ_0 – the initial density; g/cm^3, ρ_k – the average, final density; g/cm^3, H_0 – the initial height of the moulding sand layer; m, p – squeezing pressure; MPa, k – the corrective coefficient taking into account the speed of the stress growth (at speeds of the stress growth of milliseconds order k $\approx$ 0,2). The acceptance of the coefficient k<1 makes for diminutions of the increase of the final density in spite the same values of squeezing pressure.

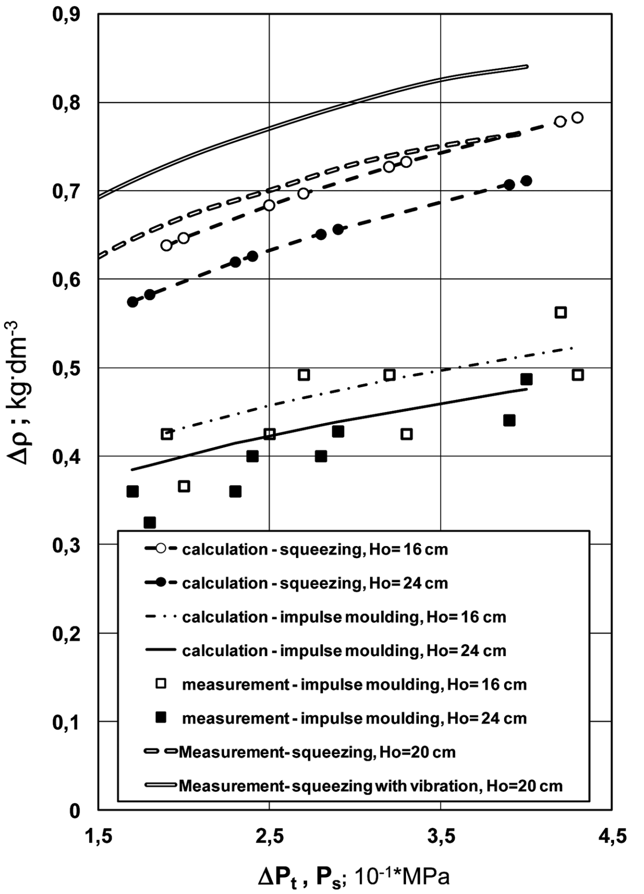

Fig. 2. Dependence between increment of mean mould density – $\Delta\rho$ and maximal overpressure value – $\Delta\mathbf{P_t}$ (at impulse moulding) or squeezing pressure- Ps (at squeezing): initial height of moulding sand layer $\mathbf{H_0}$ = 16 cm- ρ_0 $\approx$0.94 kg/dm^3, initial height of moulding sand layer $\mathbf{H_0}$ = 24cm- ρ_0 $\approx$0.97 kg/dm^3. Calculation acc. eq. (1) at $\mathbf{k}$=0,2 for impulse moulding and $\mathbf{k}$=1 for static squeezing. Measurement data for squeezing and squeezing with vibration from [5]

From the Fig. 2 one can see the good agreement of measurement with the calculations results according to eq. (1). Results of calculations and measurements for the static squeezing

(Fig. 2) confirm the opinion represented by the second group of researchers [among other 8, 9].

The equation (1) evaluates the average value of mould density. In the impulse process it occurs when the air flow inside the moulding sand layers is present – thus the effective air-pressure causing compaction of the moulding sand is different from the value Δ Pt (Fig. 2) [1, 8, 9]. There appears the large differentiation of the density along the height of the mould. Effective pressures in the region of the pattern – plate have exceed the value of the pressure over the upper surface of the moulding sand in the flask. The effect of the compaction in near pattern plate region is better in the case of the enlargement of the dynamics of the compaction – what is the result of the higher kinetic energy of accelerated moulding sand layers in their downwards motion. This phenomenon leads to the occurrence of higher values of efficient pressures in definite mould areas than the value of the maximum overpressure Δ Pt in the space over the moulding sand, consequently the better compaction have been obtained in these areas [7, 8, 9, 15]. It is especially important at the usage of complicated patterns- the realization of such moulds by squeezing method would be then very difficult (or even impossible). In this case the additional vibration can improve the compaction effects – Fig. 2. With stream-oriented methods one can perform moulds even in the case of slim pockets in pattern [1, 2, 3, 8, 15]. The obtainment of the profitable distribution of the compaction degree on the mould height is connected however with enlarged energy demand.

and the vacuum tank. It induces the air stream action (from the atmosphere) on the moulding sand and consequently initializes the compaction process. The compaction level in this method are not as good as in Seiatsu process or impact moulding [1, 2].

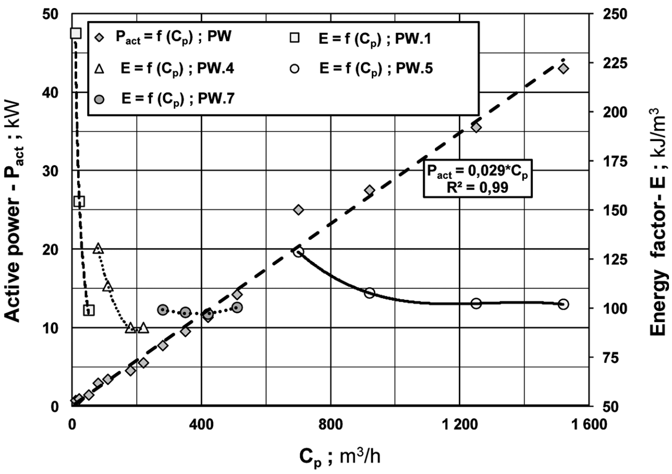

Fig. 3. Dependence between drive active power- **P** and vacuum pump capacity- $\mathbf{C_p}$ (sucked air at 213 hPa) and dependence between energy factor- **E** and vacuum pump capacity- $\mathbf{C_p}$. Series of vacuum pumps (with liquid ring) – PW of Hydro-Vacuum S.A.; (data from [16])

3. Power measurements in vacuum installation of model moulding stand

Vacuum technology is widely used in foundry industry [2, 8]. In the area of mould manufacturing the most known is V process, still in use in many foundry plants on the world. In green sand flask moulding one can indicates the Vacupress machines of Künkel Wagner Company or in flaskless moulding HFM of Haflinger GmbH or vacuum module in Disamatic [2]. The main problem of vacuum assisted moulding is the proper choice of vacuum installation parameters. The basic parameters of vacuum devices are the level of obtained vacuum, pump system capacity and power of the pump drive. The typical relationship between the power of a vacuum pump drive and pump capacity is near linear – Fig. 3. These two parameters determine the unit energy demands in vacuum installations (ratio of drive power to capacity of pump). It should be noted that values of energy factor for vacuum pumps is near such values for compressors [1, 9]. Generally such energy coefficients are more beneficial for larger pumps [11, 16] and it is especially beneficial for the Roots type pump. In practise the demand of energy for vacuum installation also depends on the operation cycle of the devices (i.e. duration of idle run, the level of pump load etc.). The relationship between the technological operation parameters and energy consumption of vacuum installation of moulding devices can be evaluated precisely by adequate power measurements. In the investigated variant of vacuum-assisted moulding process (Fig. 4) the moulding sand is gravitationally dosed to the moulding chamber. The quick valve connects the space beneath the pattern plate (with vents)

The compaction distribution in narrow pattern pockets of the mould is very suitable and useful for obtaining a good level of compaction in the next step of moulding- squeezing. The proper choice of: vacuum level in vacuum tank, its volume, open area of vents, and parameters of the quick valve are very important for the compaction process. Selection of the parameters of the vacuum pump system is decisive for the energy-efficiency of suction installation. The model test stand (Fig. 4) was a process analogy to solutions in large scale. It has the following systems: a vacuum installation system with pumps, tanks and valve system, moulding chamber, pressure measurement and recording system. Additionally it is possible to connect the compressor with the tank and vacuum generator (with a Laval type nozzle). For measuring the absolute pressure four differential pressure transducers MPX2100, manufactured by Motorola have been used. Analogue signals are further amplified by signal amplifiers MC33272A. Pressure transducers are connected to a certain point of vacuum installation via an elastic pipe conduit. The recording system incorporates a microprocessor-based digital recorder. Sampling frequency was 300 Hz for each transducer system. Transmission to the computer is via the RS232 and USB ports, at a variable speed of data transfer [3, 4, 11, 12]. The pressure in the compressor tank was measured by a Honeywell transducer and the data was transferred to the digital recorder and via USB ports to the computer. The power measurements have been done with a digital multimeter VC940 (VOLTCRAFT), also connected to the PC. The most sophisticated power measurement with instantaneous values recording has been described in an earlier paper of the authors [10, 11, 12, 13].

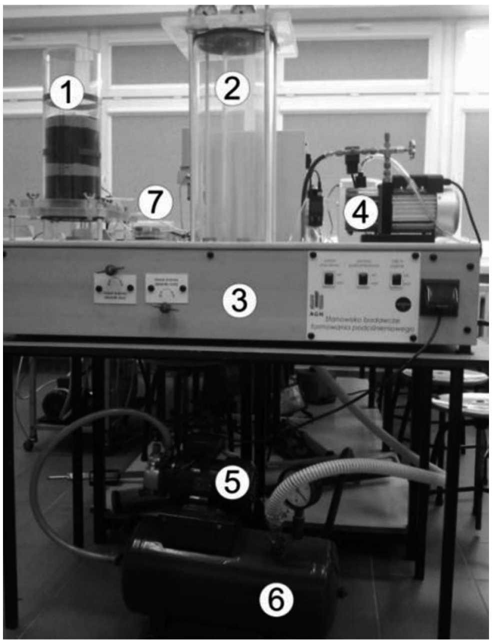

Fig. 4. Model stand for investigating vacuum moulding [3]: 1- moulding chamber, 2- vacuum tank, 3- control unit, 4- vacuum pump No.1, 5- vacuum pump No.2, 6- additional vacuum tank, 7- pressure transducers

The experimental program involves the measurements of electric power parameters whilst the vacuum is being generated in the installation connected to the pumps or to the vacuum generator. The plots of active power of pump drive and power factor – cos φ are shown in Fig. 5. The short period after switch on of the vacuum pump (connected with the disturbances of the voltage) has been omitted. Due to one measurements channel in VC 940 for the measurements of power factor and voltage the measurements of active power must be interrupted at a certain time point. But the regular shape of time function of active power and power factor allows the evaluation of these parameters in each point of the operation cycle period (by using the trend line equations). On the registered graphs of active power one can observes the maximum point. The power factor – cos φ has the adverse value (~0.5) which is characteristic for not fully loaded small electric motor.

The simultaneous measurements of absolute pressure and active power of drive of vacuum pump (or overpressure in compressor tank and active power of drive of compressor) allows to correlate these parameters in one diagram – Fig. 6. The data from Fig. 5 and 6 (or Fig. 7 and 8) allows also the calculation of the energy consumption connected with the achievement of certain levels of pressure in the vacuum tank.

$$E = \int_{\tau_1}^{\tau_2} P_{act}(\tau) d\tau \tag{3}$$

where:

E – energy consumption connected with emptying of vacuum tank from absolute pressure P_{abs1} to P_{abs2} (or with the filling compressor tank from overpressure – P_{ov1} to P_{ov2}),

$P_{act}(\tau)$ – time function of active power during vacuum tank emptying (or compressor tank filling) (Fig. 5, 7),

τ_1, τ_2 – time point connected with the achieving the values of overpressure in tank: P_{ov1} and P_{ov2} during tank filling.

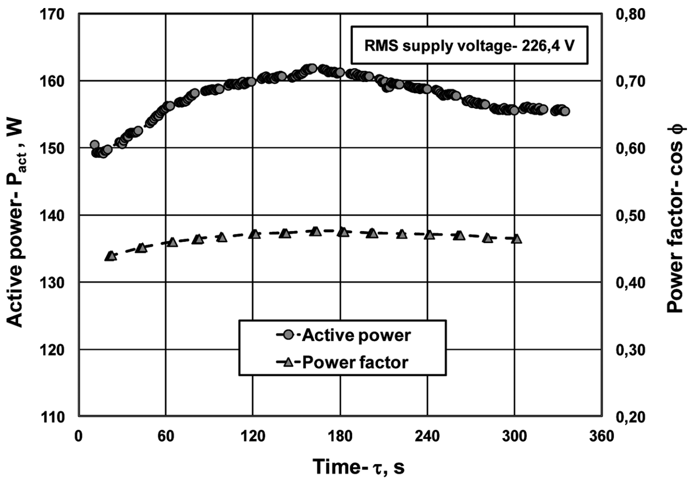

Fig. 5. Time runs of active power – $\mathbf{P}_{act}$ of vacuum pump drive and power factor – cos φ during vacuum tank emptying

Combining data from Fig. 5-6 (Fig. 7-8) and using eq. (3) it is possible to evaluate the energy consumption connected with the process of achieving certain levels of vacuum in the tank with using a vacuum pump or using a vacuum generator.

The second possibility of vacuum creation is using the vacuum generator (with Laval nozzle). For operation of such devices it is necessary the access of compressed air source of given efficiency.

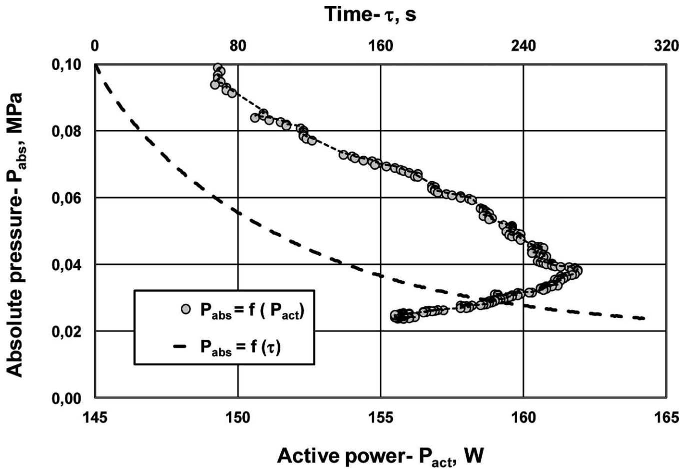

Fig. 6. Dependence between absolute pressure – $\mathbf{P_{abs}}$ in compressor tank and active power – $\mathbf{P_{act}}$ of vacuum pump drive; time run of absolute pressure in vacuum tank

Such a role may also fulfil the system: compressor (with a relatively low capacity) with the tank of adequate volume. On Fig. 7 is presented the change of active power and power factor during filling of the compressor tank and on Fig. 8 the relation between active power and overpressure in compressor tank (the maximum value of achieved pressure is 0.48 MPa).

As one can see the increasing of overpressure in the compressor tank leads to the increasing of active power (of compressor drive) and increasing of power factor.

This volume of compressed air is enough for creating the vacuum on the level of 0.064 MPa (absolute pressure) in the vacuum tank – Fig. 9.

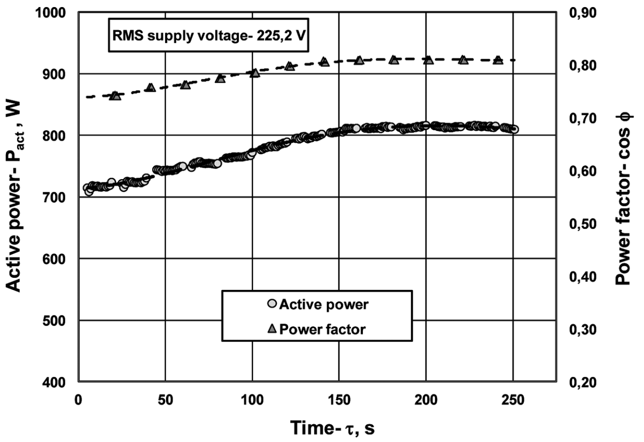

Fig. 7. Time runs of active power – $\mathbf{P}_{act}$ of compressor drive and power factor – cos φ during filling the compressor tank

This is connected with an overpressure drop in the compressed tank from 0.48 to 0.27 MPa. The calculation of energy input (connected with compressor work) is about 107 kJ. The same effect- obtaining the vacuum level of 0.064 MPa, while using the vacuum pump can be achieved with energy input – 9,2 kJ.

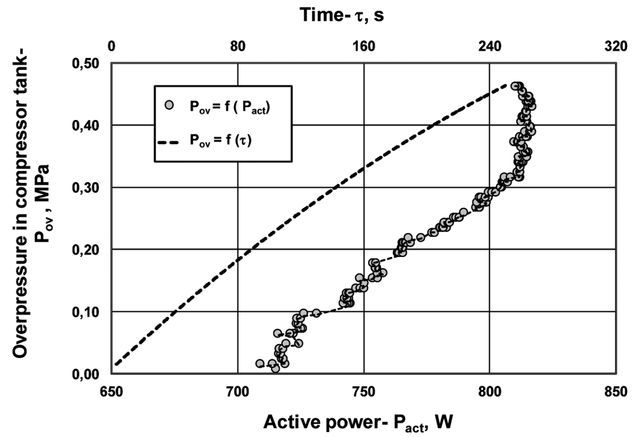

Fig. 8. Dependence between overpressure – $\mathbf{P}_{ov}$ in compressor tank and active power – $\mathbf{P}_{act}$ of compressor drive; time run of overpressure in compressor tank

The comparison of necessary time for achieving the absolute pressure – 0.064 MPa in the vacuum tank in both cases indicates that with the vacuum pump it is about 70 s and with vacuum generator it is about 147 s (including time of compressor tank filling – 132 s and short time for vacuum tank emptying – 15 s).

With the stable source of compressed air with a suitable efficiency level the relation between the energy input in the above two mentioned cases of vacuum creation can be improved. However the vacuum generator being used needs several times more energy input in comparison of the vacuum pump being used [16, 17]. But with the efficient source of compressed air the emptying process with the vacuum generator being used can be shorter than with the vacuum pump being used.

Vacuum creation with the vacuum generator using is so less effective in comparison of vacuum pump using, from the energy consumption point of view. But the use of the vacuum generator in industrial systems has significant advantages.

Such devices have no movable parts, they are simply in operation and they have a wide range of efficiency (in producers offer). Additionally there is no problem to connect them to a supply net of compressed air which is usually used in every mechanised foundry plant.

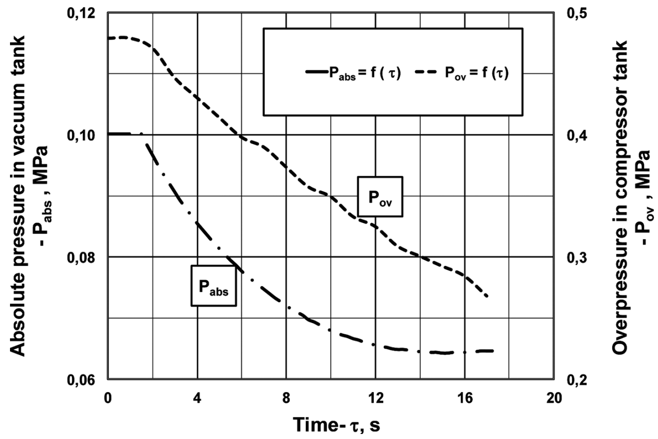

Fig. 9. Time runs of absolute pressure – $\mathbf{P}_{abs}$ in vacuum tank and overpressure – $\mathbf{P}_{ov}$ in compressor tank during vacuum generation with using vacuum generator VADMI (Festo)

There is also no problem of creating the vacuum level comparable to that during vacuum pump operation, but for this the efficiency of air supply must be on a suitable level. The filling of the compressor tank from compressed air net (compressor with much powerful drive) to the 0.7 MPa of overpressure can create the vacuum of the 0.02 MPa absolute pressure in the vacuum tank. For such a vacuum level the small compressor in the model stand would have to operate too long from an exploitation point of view. From Fig. 10 it is evident that the absolute pressure 0.03 MPa is enough for reaching the maximum level of mean indicators of moulding sand compaction – apparent mould density and mould hardness. In some cases of moulding, for example when the pattern with narrow pockets are in use – Fig. 11, the vacuum level must be near 0.02 MPa of absolute pressure. It is the lower limit of absolute pressure that is enough for moulding processes in machines which use vacuum assisted methods [3,4].

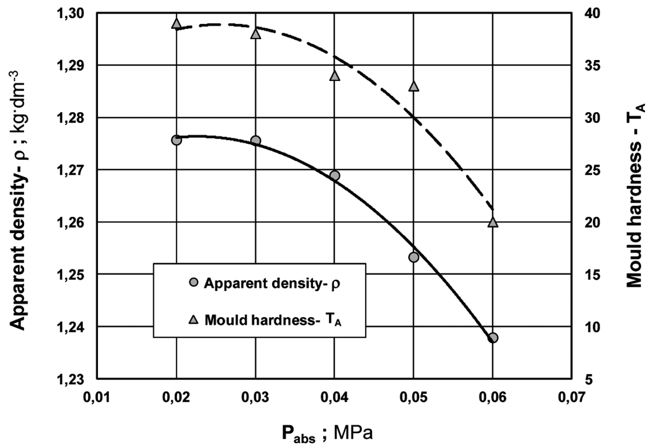

Fig. 10. Dependence between apparent density of the mould – ρ or surface hardness of the mould – T_A and initial values of absolute pressure in vacuum tank – P_{abs}. Vacuum assisted compaction

Presented on Fig. 11 data shows that even while using the difficult pattern the two stage moulding process can improve the compaction in critical areas, which is confirmed by other sources [3,4,8,15].

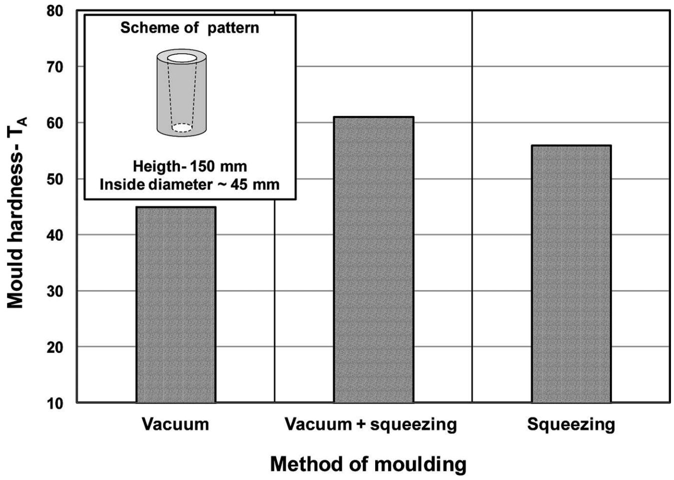

Fig. 11. The results of hardness measurements T_A inside the pattern contour (on the pattern plate level) in moulds compacted by different methods (vacuum only, vacuum with squeezing, squeezing only)

According to estimated calculations [1] for the compaction process with using a vacuum, energy consumption factor is about 1.4 kJ/kg (for 1 kg of compacted moulding sand), at the pressure 0.02 MPa. In comparison, such factor for impact (air impulse) moulding is in range 1-2.5 kJ/kg and for moulding by squeezing: only 0.01-0.05 kJ/kg [1].

4. Summary

There are two possibilities of vacuum creation in vacuum assisted moulding machines: use of the vacuum generator or use of the vacuum pump. The second one is the better from an energy efficiency point of view. On the other hand the connection of the vacuum generator with a compressed air supply system of moulding machines is technically very simple. Combining the pressure measurements with electric power measurements and their suitable interpretation can confirm the adequacy of the parameters choice in the vacuum assisted moulding process. It allows for assessment of proper run of compaction process and simultaneous evaluation of energy demand. Due to technique development the measurements of electric power parameters are currently much easier and more effective. Electric power measurements can also be used for identification of operation malfunctions of foundry machines and devices. Measurements of vacuum pressures in model installations and combining its results with efficiency indicators of compaction will support the proper choice of moulding processes parameters on an industrial scale.

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