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ANALYSIS OF BASIC PHENOMENA OCCURRING IN THE VACUUM-ASSISTED MOULDING PROCESS

ANALIZA PODSTAWOWYCH ZJAWISK ZACHODZĄCYCH W PROCESIE FORMOWANIA PODCIŚNIENIOWEGO

Variant of vacuum-assisted moulding process, proposed by the authors, can be used (as the initial stage of moulding) either in new moulding machines or during modernization of existing moulding machines as well. In the article analysis of basic phenomena in the vacuum-assisted moulding process was based on: high speed imaging technique, dynamic air pressure measurements in the working space of the prototype moulding machine, as well as typical compaction effect measurements. The exemplary results of the simulation of the air flow process in the working space of the moulding machine prototype, can be useful in making the proper choice of basic machine parameters.

Keywords: foundry engineering, moulding processes, moulding machine, vacuum process, compaction

Proces formowania podciśnieniowego, w wariancie zaproponowanym przez autorów, może być wykorzystany jako wstępny etap zagęszczania, w nowych maszynach formierskich, jak również przy modernizacji użytkowanych maszyn. W artykule przedstawiono analizę podstawowych zjawisk zachodzących podczas formowania podciśnieniowego. Analizę oparto o wyniki badań procesu formowania podciśnieniowego wykorzystujące: technikę szybkiego filmowania, dynamiczne pomiary ciśnienia w przestrzeniach roboczych prototypowej formierki oraz o typowe pomiary efektów zagęszczania. Przedstawiono przykładowe wyniki symulacji procesu przepływu powietrza w przestrzeniach formierki podciśnieniowej, przydatne w doborze podstawowych parametrów maszyny.

1. Introduction

During the production of castings, the phenomena that take place in moulding sands during the manufacturing of moulds are of interest for the R&D centers, [6, 7, 11, 13] as well as for the producers of foundry machines and equipment [10]. The conditions under which foundry moulds are made should be selected based on the scientific aspects of the theory on mould compaction, while being fully conscious of changes that take place in the technological properties of foundry sand mixture [12] and with its ability to provide faithful shape reproduction and the most effective use of compaction energy. All these issues, when properly solved, should make the moulding process economically competitive.

When classifying the processes of making foundry moulds by pneumatic methods, two main variants are distinguished:

– the techniques which use positive air pressure; these are the stream and impulse moulding methods, both being capable of ensuring the required degree of sand compaction in the mould,
– the techniques which use negative air pressure.

The first technique is widely used in current moulding machines. There are many publications concerning investigations of the moulding process [1, 2, 4, 7], as well as theory and modeling (simulation) of the process or moulding machines operating [3, 6, 7, 11, 13].

The data concerning the second technique has rather technical aspects (not scientific) and has been published by machine manufacturers. It should be noted that there is a lot of data concerning the vacuum assisted moulding process with moulding sand transportation (from the moulding sand hopper to the technological chamber). The earlier publications of the authors [8, 9] maintain that the compaction of moulding sand in a vacuum-assisted process without moulding sand transport can be effectively realized in flask moulding as preliminary compaction.

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2. The basis of the vacuum-assisted moulding process

Contrary to the moulding methods which use positive air pressure, the vacuum-assisted method is mainly applicable in the preliminary compaction of moulding sand. The two variants differing in this mode, during which the vacuum is operating on the moulding sand, are the possible versions of this method. The first variant includes the process where sand is handled in a flask, the second includes the process where the sand is not handled within a flask space [9].

The pressure gradient induced by the effect of air-sand stream flowing between the vacuum vessel and the flask is the factor which causes sand compaction. In the method discussed here, the effect of sand compaction depends on a number of different factors, and mainly on the technical parameters of moulding machines, on the design of vacuum installation and on its performance characteristics, on the properties of moulding sand and parameters of the tooling (dimensions of flasks, patterns configuration, layout of vents). Figure 1 shows a diagram with all of the above mentioned parameters included.

The subject of this paper is vacuum-assisted technology, applied in preliminary sand compaction, as well as in the variant without sand transport to a technological space.

The preliminary sand compaction is an outcome of the effects which take place in the moulding sand subjected to the air pressure drop operating within the entire mould volume. All these relationships are shown in the diagram in Figure 1, as well.

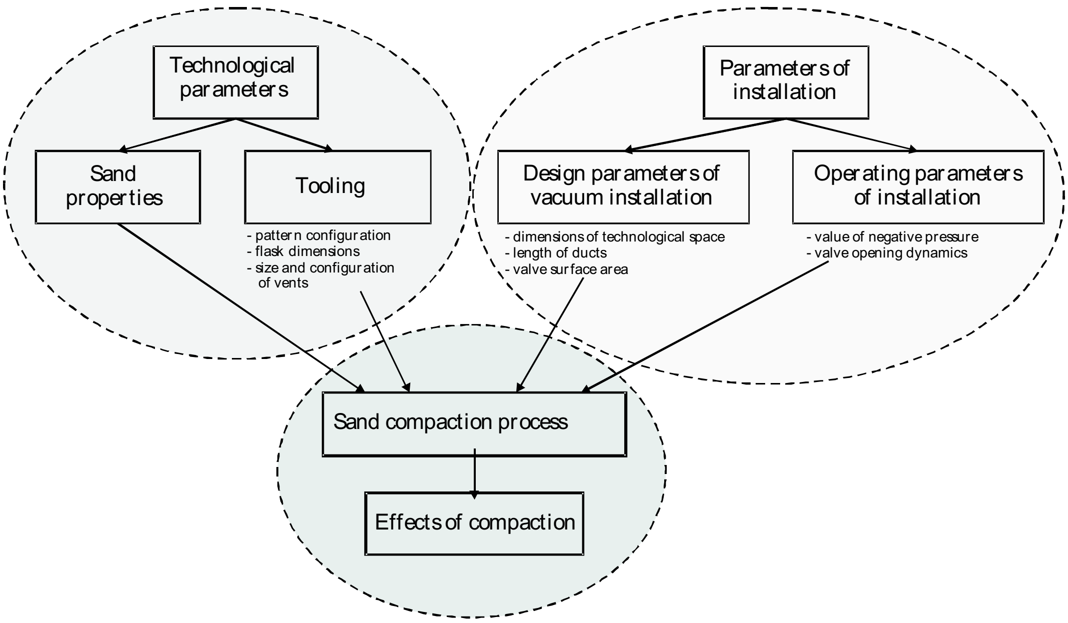


Fig. 1. Flow chart of vacuum-assisted moulding

The vacuum-assisted sand compaction process is of a complex character and results from the dynamic and kinematic effects taking place in a mould system. It is assumed that the mechanism of changes taking place in the sand volume between the pattern and flask include the following phenomena:

- sand compaction resulting from difference in static pressures acting on the sand layers distributed across the flask height and defined as an upper layer and lower layer directly contacting the pattern plate
- change in the layers' configuration resulting from kinetic-dynamic movement of the air jet flowing through intergranular spaces of the sand
- change in the sand layer's density resulting from the dynamic effect of the first acceleration, followed by impeded, movement on the pattern plate of sand layers distributed across the flask height.

The above assumptions regarding the phenomena that take place during vacuum-assisted moulding determine the research procedure that should be followed to establish a theoretical approach to these problems.

3. The air flow process and sand compaction in vacuum-assisted installations

One of the first studies on the problem of flow modeling in machines for pneumatic sand compaction was analysis of the air-blow process conducted by P.N. Aksionov [1], based on the model shown in Figure 1a. In an extended version, these models were used by J. Dańko for the calculation of the air stream impact in blow machines [2] and by J. Bast for the description of the Seiatsu process [3]. The developed equation enables quick determination of the main parameter describing this process, i.e. the rate of pressure increase in technological space [1].

Besides the above mentioned models, in the description of the impulse moulding process models of a quasi-steady flow are also used [5]. This can an example of the application of various pneumatic elements in the analysis of the operation of these processes, which can serve the studies done by the authors of [4, 6, 7]. Special attention should be dedicated to the fact that [6] the discussed theory has been adapted to the description of the flow process taking place in different pneumatic moulding machines [2, 5, 6, 14].

The description of the air flow process in the vacuum machine can be also based on quasi-steady one dimensional flow [4]. It should be noted that the model of ideal gas is better for air description in low pressure conditions [15]. The basic equations for each machine chamber describe the changes of pressure and temperature. In general cases the change of the volume of the chamber and inflow and outflow source of air can be taken into account:

$$\kappa R\left(\sum_{k=1}^{n} T_{i,k}dm_{i,k} - \sum_{l=1}^{m} T_{j,l}dm_{j,l}\right) = V_j dp_j + \kappa p_j dV_j \tag{1}$$

$$R\left[m_j dT_j + T_j\left(\sum_{k=1}^{n} dm_{i,k} - \sum_{i=1}^{m} dm_{j,l}\right)\right] = V_j dp_j + p_j dV_j \tag{2}$$

where: κ – adiabatic exponent, R – gas constant of air, p_j – absolute pressure in given chamber, V_j – volume of chamber, $T_{j,k}$ – air temperature in inflow stream (from source k to chamber j), T_j – air temperature in given chamber j, dm_i, dm_j – differential increament of air mass connected with inflow and outflow stream.
The increment of mas- dm in increment of time- $d\tau$ can be expressed as:

$$dm = G \times d\tau \tag{3}$$

Where G is calculated from well known Saint Venant-Wantzel formulas for air flow rate (for supersonic and subsonic flow).

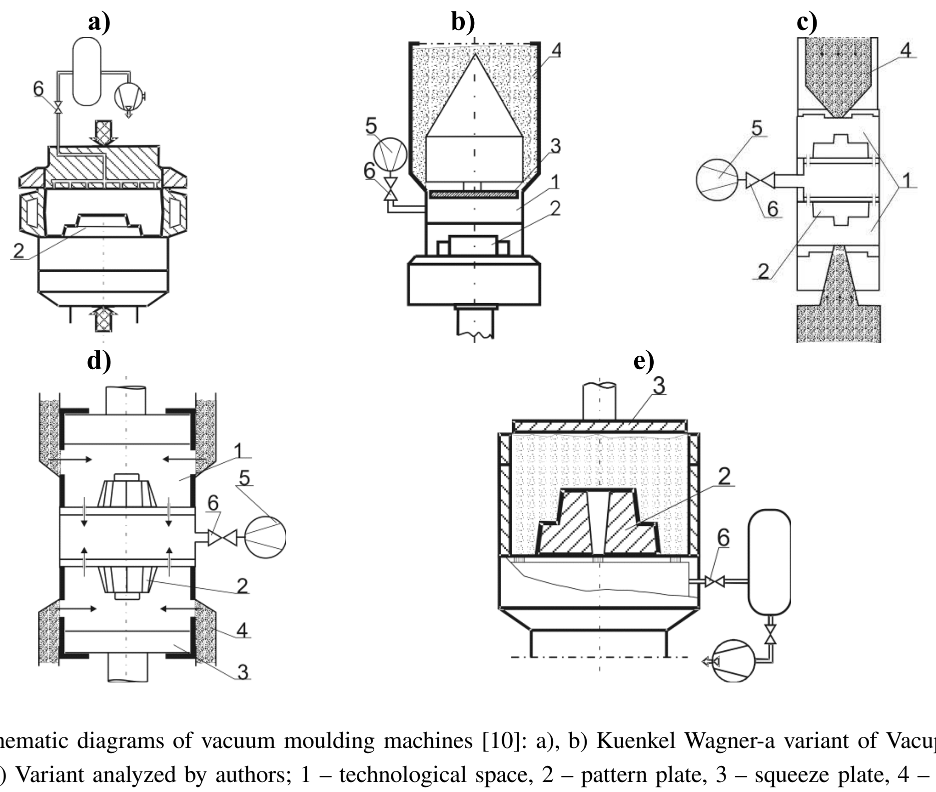


Fig. 2. Simplified schematic diagrams of vacuum moulding machines [10]: a), b) Kuenkel Wagner-a variant of Vacupress system c) Disa Forma, d) Haflinger, e) Variant analyzed by authors; 1 – technological space, 2 – pattern plate, 3 – squeeze plate, 4 – sand bin, 5 – vacuum system, 6 – valves

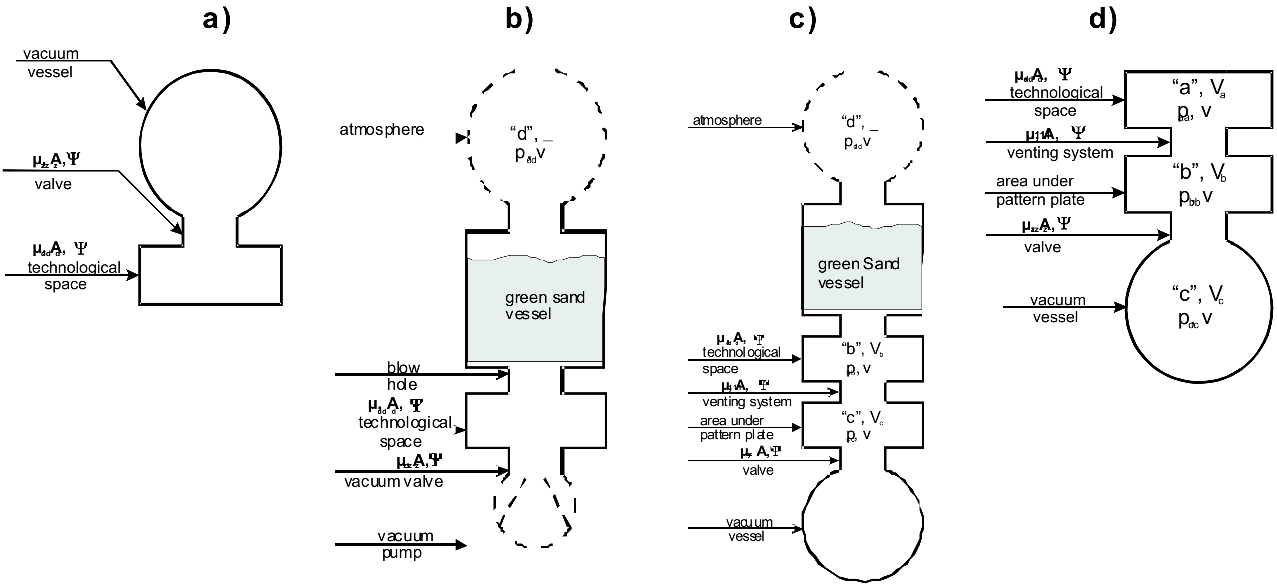


Fig. 3. Models of flow in vacuum moulding machines corresponding to the design diagrams in Fig. 2: a) Figs. 2a, b) Fig. 2b, c) Fig. 2d, d) Fig. 2e

The above mentioned equations must be completed by movement equations for volume changing and valve elements displacements. These equations system (solved numerically) has been verified for air flow processes in impulse moulding machines [6, 8].

During the procedure of modeling the air flow in vacuum moulding machines, the relationships describing process-related phenomena were based on an analysis of machine operating diagrams, the designs of which are shown in Figure 2.

Using these diagrams, a few simplified models of the flow process were developed in which the symbols proposed by the authors mentioned in [1, 2] were used. The models (Fig. 3) were created according to the principle of increasing shape intricacy and number of the physical phenomena taken into consideration.

In spite of the fact that these advanced practical solutions and theoretical models have already been developed, offering some practical effects, the research and work has been continued by the author of this paper, among others. The aim of the research is to design high capacity moulding machines, which enable manufacturing of high quality moulds.

The majority of the presented equations include parameters difficult to determine by the theoretical route. Therefore, practical supporting investigations are needed to examine, e.g., the flow ratio, the operating characteristics of valves, etc. The theory of another compaction process like impulse moulding, shooting, impact moulding, squeezing are in the most advanced state and there are some sophisticated models of the process, which use the complicated numerical algorithms [4, 10, 12, 17]. The investigations of the moulding sand properties useful for the compaction process calculation are also on the higher level [3, 4, 11].

For the initial analysis of the main factor influenced by the vacuum-assisted moulding process, S. Ergun's and A. Orning's equation (cited in [16]), which determines gas pressure drop Δp during flow through granular material of height H, can be applied:

$$\frac{\Delta p}{H} = 150\frac{v_0 \times \mu\ (1-\varepsilon)^2}{d^2 \times \varepsilon^3} + 1{,}75\frac{\rho_g \times v_0(1-\varepsilon)}{d \times \varepsilon^3},\quad \text{Pa/m} \tag{4}$$

where: Δp – pressure drop [Pa], H – height of granular material layer [m], μ – absolute viscosity of gas (air), ρ_g – density of fluidising agent (air) [kg/m^3], v_0 – gas (air) flow rate [m/s], d – grain diameter in compacted material [m], ε – porosity of layer.

During the process description, the following effects influencing the change in compaction degree have been taken into consideration:

– the effect of air flow resistance in sand layers
– the process running simultaneously on the entire mould height
– the effect of upper sand layers acting on the lower layers and thus increasing the degree of their compaction
– the effect of atmospheric pressure acting on the upper layers and making them, in turn, act downwards on layers placed beneath them

- sand movement and simultaneous arresting of successive layers done by the pattern plate acting on the entire mould height
- the effect of the forces of inertia with vector pointing downwards, which initiates change of stresses in individual sand layers, increasing in direction towards the pattern plate.

The proper description of the effects that occur during vacuum-assisted moulding needs new experimental researche. This elaboration can serve as a scientific basis for the process in the form of an equation adequate to the condition of vacuum moulding.

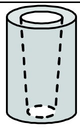
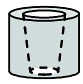
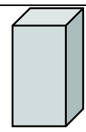
4. Investigation's results and discussion

The investigations were conducted on a test stand equipped with adequate tooling. The loose medium, in which the phenomena take place during the vacuum moulding, was investigated, and was found to be synthetic bentonite sand with coal dust, assigned for the manufacturing of iron castings. The properties of the sand used for investigations were as follows: $R_c^w = 0.12$ MPa, $P^w = 2.04\ m^2/MPa\cdot s$, $W = 3.2\%$. The parameter that required stabilization was sand humidity. The parameters that were measured to determine the sand compaction ratio included hardness and strength; the measurements were taken with instruments commonly used in foundry laboratories.

The model characteristics and respective data are compiled in Table 1, while the schematic representation of a test stand is shown in Figure 4. The compaction effects were recorded by an optical method using a FAST-CAM Super 10KC quick digital camera. The object of recording was the sand movement effect during compaction.

TABLE 1

Characteristics of the pattern used in tests

Type	High cylinder: h = 150 mm, Φ_z = 71 mm, Φ_w = 45 mm	Low cylinder h = 50 mm, Φ_z = 69 mm, Φ_w = 48 mm	High cubicoid h = 150 mm
Schema			

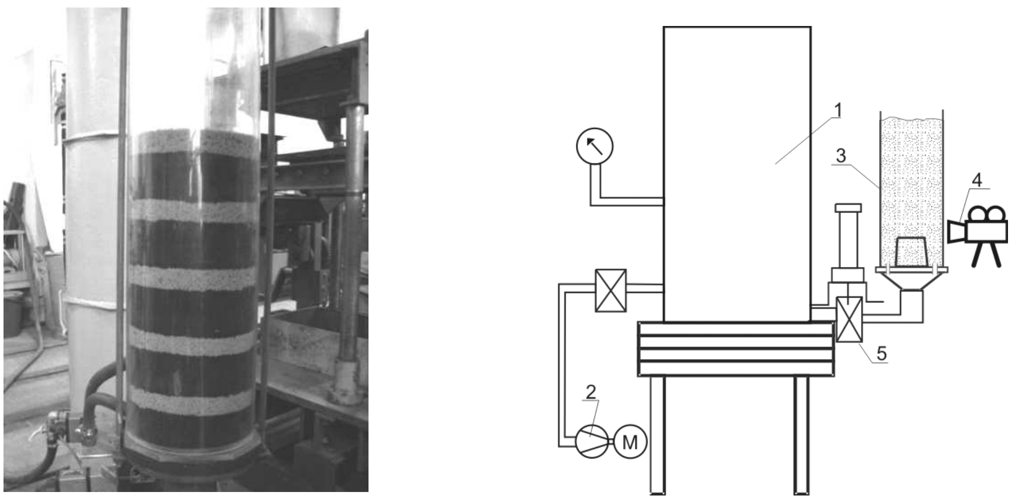


Fig. 4. General view and schema of a test stand for investigation of the vacuum moulding process: 1 – vacuum vessel, 2 – vacuum pump with drive, 3 – PMM mould, 4 – high speed camera, 5 – valve

The design and construction of the test stand enabled the conduction of investigations in two variants of the compaction process, i.e. with and without the sand transport to the technological area. In the latter case, the sand was introduced to the technological area before the start of the process (Fig. 4). As was stated in the introduction to this paper, since the vacuum compaction process can be used for preliminary compaction of the sand, complementary studies were made with additional compaction by squeezing. The results of the measurements obtained in investigations are shown in Figures 5, 6 and 7. Following the compilation of the results, it is shown that a much better compaction degree is obtained by the application of a squeeze after the preliminary compaction of the sand.

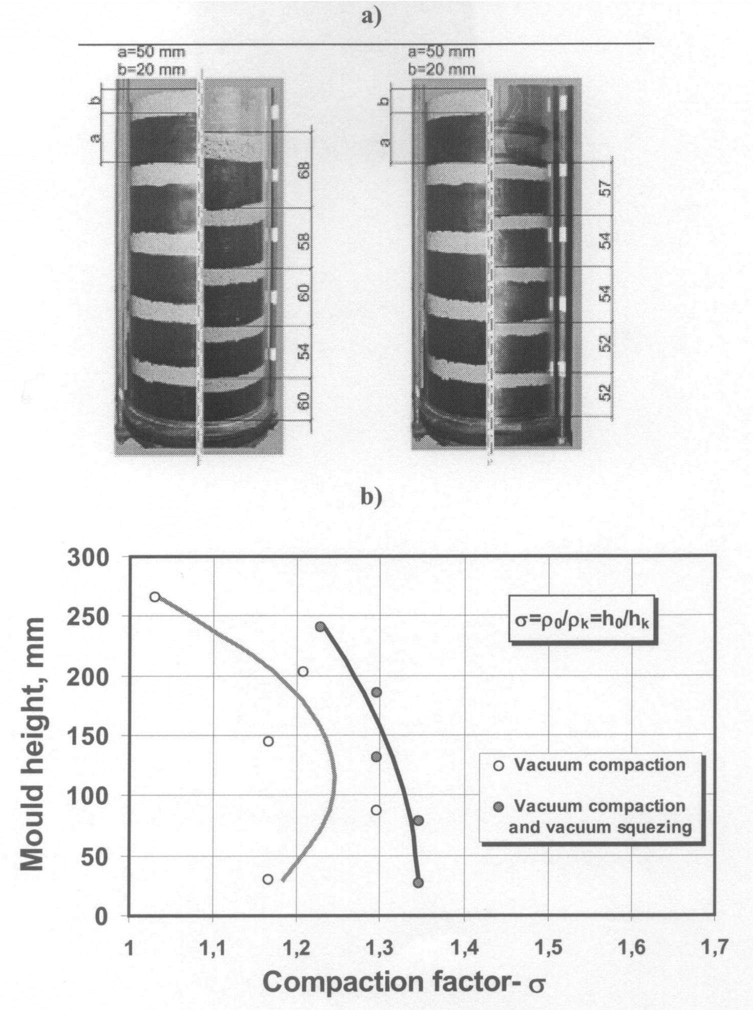


Fig. 5. View of compacted test moulds – a and the results of compaction distribution along the mould height – b

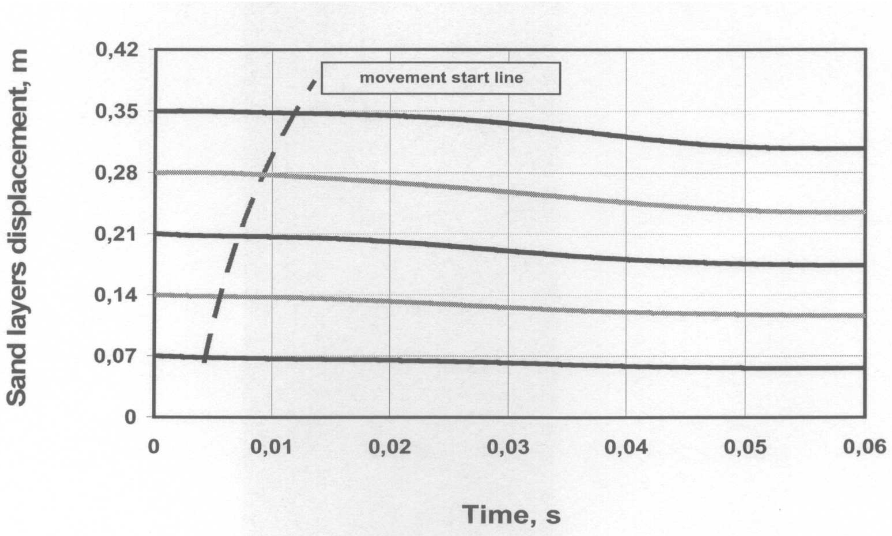


Fig. 6. The results of sand layers displacements (data obtained from analysis of high speed images). Vacuum preliminary compaction.

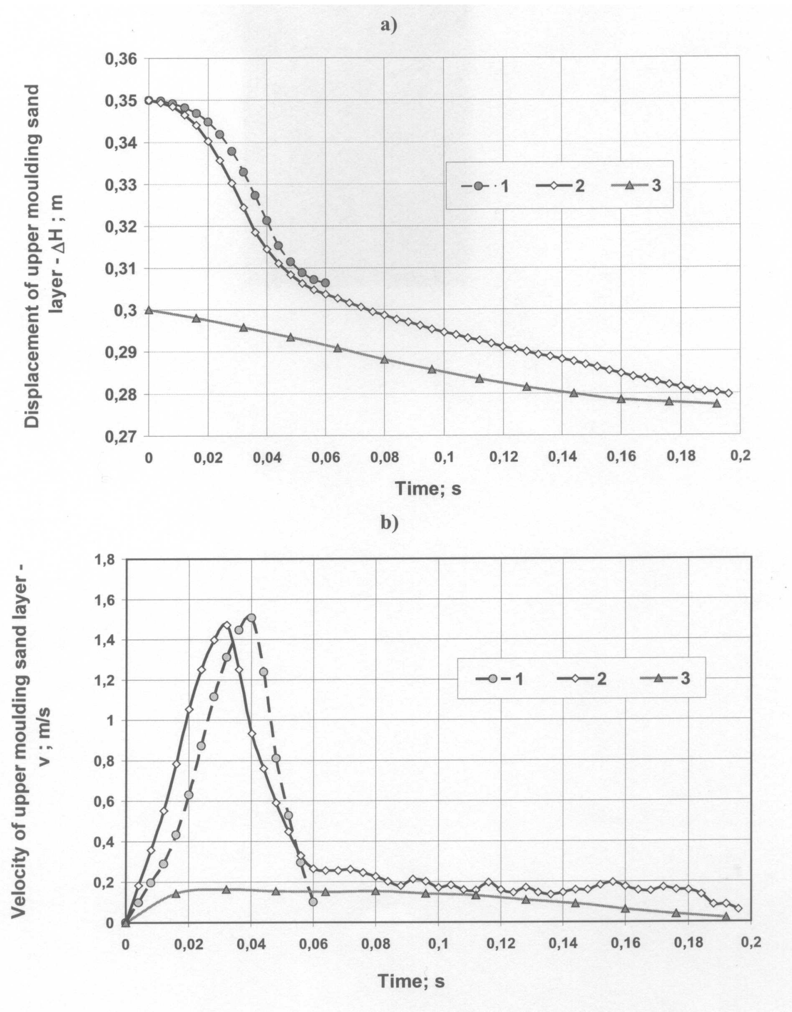


Fig. 7. Displacement – a) and velocity – b) of upper sand layer in selected variants of the vacuum-assisted moulding; 1st stage; 1 – vacuum compaction, 2nd stage; 3 – vacuum after-squeeze, 2 – vacuum squeeze

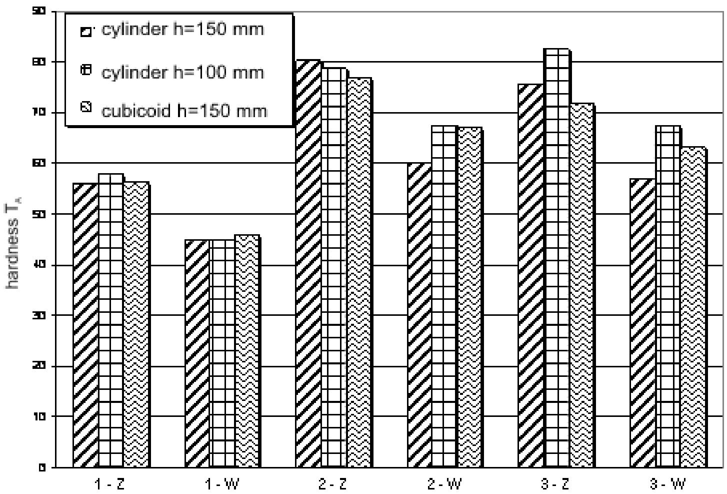


Fig. 8. The results of hardness measurements T_A in moulds compacted by: vacuum – 1, vacuum with squeeze – 2, and squeeze – 3; areas of hardness measurements : Z – area outside the model contour, W – area inside the model contour

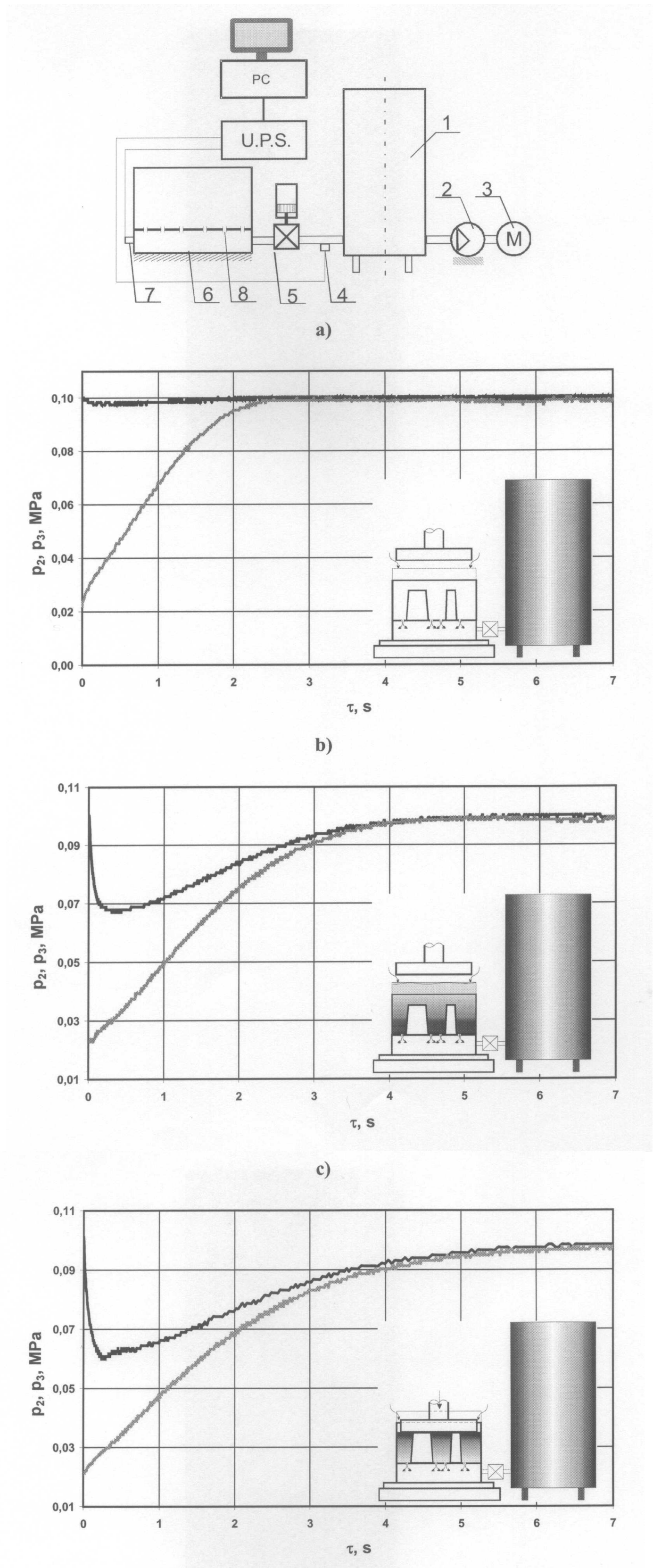


Fig. 9. Schemes of investigation stands for vacuum assisted moulding based on the jolt-squeezing machine FKT 54 type and results of pressure recording in given chamber – a), b), c); 1 – vacuum receiver, 2, 3 – vacuum pump with drive, 4 and 7 – pressure gauges, 5 – valve, 6 – moulding flask with frame, 8 – vents

The results of the analysis of the recorded films are presented in graphical form on the diagrams plotted in Figures 6 and 7. Due to the way of decreasing the pressure (on the side of the pattern plate through the vents) the start of the movement of sand layers has begun in the space near the mould bottom and wave of compaction has been directed to the upper region- fig. 6. This vacuum compaction differs from other compaction methods, for example from impulse moulding (the compaction wave has been propagated from upper to lower layers of moulding sand). The situation creates useful conditions for better compaction in the deep pocket area of the pattern (see also fig. 8).

The results from fig. 7 proved that nearly the same results of compaction can be obtained in one stage or two stage processes. The limitation of air flow from atmosphere to moulding sand by using compaction disc (fig. 5) increase the compaction force due to a higher pressure drop on the sand layers (more uniform density distribution has been obtained in that case – fig. 5).

The configuration of the diagrams indicates a dynamic nature of the processes taking place in spite of a relatively low pressure gradient, if compared with other stream methods. The effect of the squeeze obtained due to the presence of a pad placed on the sand surface enables additional compaction of the upper sand layers. The 1st stage of the process remains unchanged – similar values of the velocity; the 2nd stage - "vacuum squeeze" – is much slower. The final effect of compaction was similar for both the 1st stage vacuum compaction with the application of a pad and the 2nd stage process, along with the vacuum compaction followed by the vacuum squeeze with the application of a pad. All this, of course, is valid under certain predetermined conditions of research (fig. 5, 7).

In investigations, the technologically intricate patterns of the high slenderness ratio of the internal cavity (h/d ~ 3) were used. The effect of preliminary compaction was also observed to bring some beneficial changes to the sand when absolute pressure was reduced in the vacuum vessel.

The experiments have been conducted not only on model stands but also on moulding machine prototype, where vacuum installations were added to the industrial moulding machine (schemes in fig. 9). In this case the evaluation of the run of the machine operating the pressure measurements in the defined chamber of machine has been done. The influence of realized compaction process (described by the additional schemes) on pressure run and pressure decreasing rate (obtained by differentiation the pressure function) – fig. 10 have been presented in Figures 9 and 10. Similarly like the experiments on the model stand (fig. 4 and 5) the limitation of air flow to the upper sand layer has lead to the increase of the dynamics of the vacuum process (fig. 9c) – faster decrease of pressure.

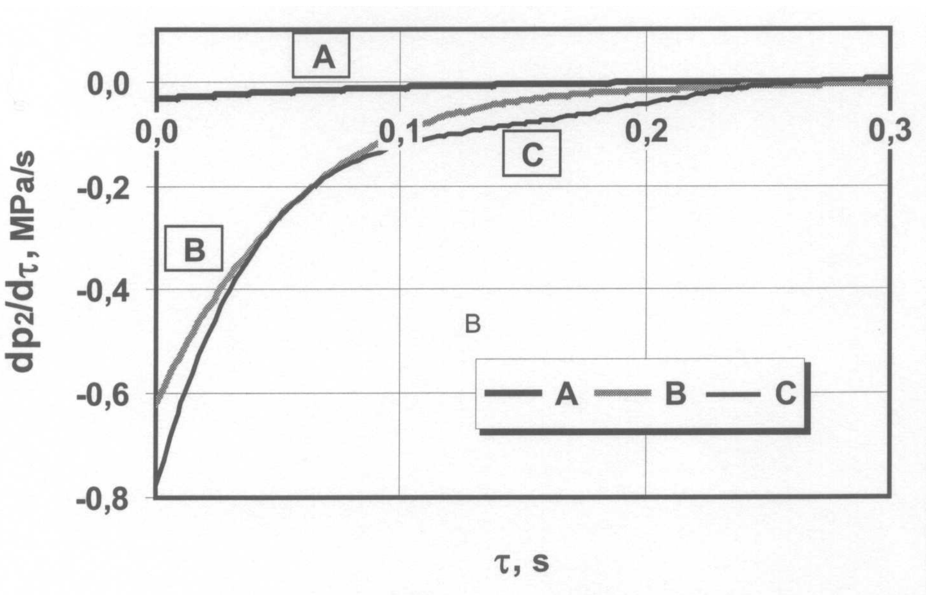


Fig. 10. The time run of the rate of pressure decreasing in vacuum process variants; the letters A, B and C correspond with designation of the vacuum process variants on the fig. 9

5. Simulation of air flow in vacuum moulding machine prototype

The equations system described air flow model in each chamber of the vacuum system corresponds to the scheme from figure 11 and basic equations (1), under the initial assumption that the temperature is constant. The change of temperature has of course occurred but its influence on flow is lower than in the impulse process. The equations system with boundary condition is presented below. The initial condition can be observed on simulation results on figures 12 to 15. The solutions have been obtained using Matlab-Simulink.

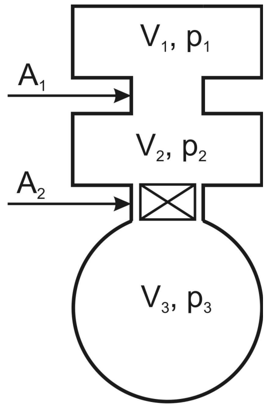


Fig. 11. Schematic diagram of vacuum system

$$-\kappa \mathrm{RTd}m_{1/2} = V_1 \mathrm{d}p_1 \tag{5}$$

$$\kappa \mathrm{RT} \left(\mathrm{d}m_{1/2} - \mathrm{d}m_{2/3}\right) = V_2 \mathrm{d}p_2 \tag{6}$$

$$\kappa \mathrm{RTd}m_{2/3} = V_3 \mathrm{d}p_3 \tag{7}$$

$$\mathrm{d}m_{1/2} = G_{1/2} \cdot \mathrm{d}\tau \tag{8}$$

$$\mathrm{d}m_{2/3} = G_{2/3} \cdot \mathrm{d}\tau \tag{9}$$

$$G_{1/2} = C_1 \cdot \mu_1 \cdot A_1 \cdot \frac{p_1}{\sqrt{T}} \cdot \sqrt{\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}}}, \quad \text{for} \quad \frac{p_2}{p_1} > 0,528 \tag{10}$$

$$G_{1/2} = C_2 \cdot \mu_1 \cdot A_1 \cdot \frac{p_1}{\sqrt{T}}, \quad \text{for} \quad \frac{p_2}{p_1} \leqslant 0,528 \tag{11}$$

$$G_{2/3} = C_1 \cdot \mu_2 \cdot A_2 \cdot \frac{p_2}{\sqrt{T}} \cdot \sqrt{\left(\frac{p_3}{p_2}\right)^{\frac{2}{\kappa}} - \left(\frac{p_3}{p_2}\right)^{\frac{\kappa+1}{\kappa}}}, \quad \text{for} \quad \frac{p_3}{p_2} > 0,528 \tag{12}$$

$$G_{2/3} = C_2 \cdot \mu_2 \cdot A_2 \cdot \frac{p_2}{\sqrt{T}}, \quad \text{for} \quad \frac{p_3}{p_2} \leqslant 0,528 \tag{13}$$

$$A_2\ (\tau\ ) = a * \tau \quad \text{for} \quad A_2\ (\tau) < A_2^{\max} \tag{14}$$

$$A_2\ (\tau\ ) = A_2^{\max} \quad \text{for} \quad A_2\ (\tau) >= A_2^{\max} \tag{15}$$

$$a,\ C_1,\ C_2 - \text{constants}$$

The data concerning the design of the vacuum system included: volumes, vents area, valve openings corresponds the prototype installation presented on fig. 9. The simulation has done for empty technological space (without moulding sand) and for the closed system. Such calculations also have been presented for air- flow (Seiatsu process) and impulse moulding [6, 14], as well as for shooting compaction [2]. The simulation results in this case represens the dynamic possibilities of the machine and can be useful for comparison of different machines (of given type) and also for the machines parameters optimization.

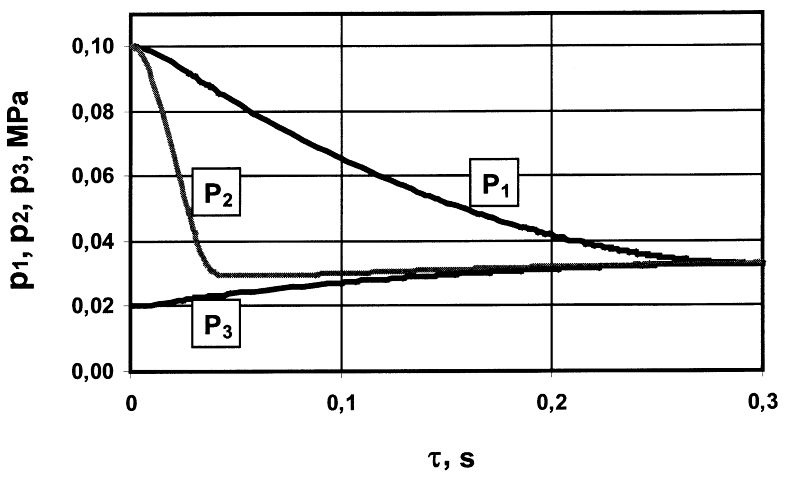


Fig. 12. Simulation results of air flow in vacuum process. Basic parameters

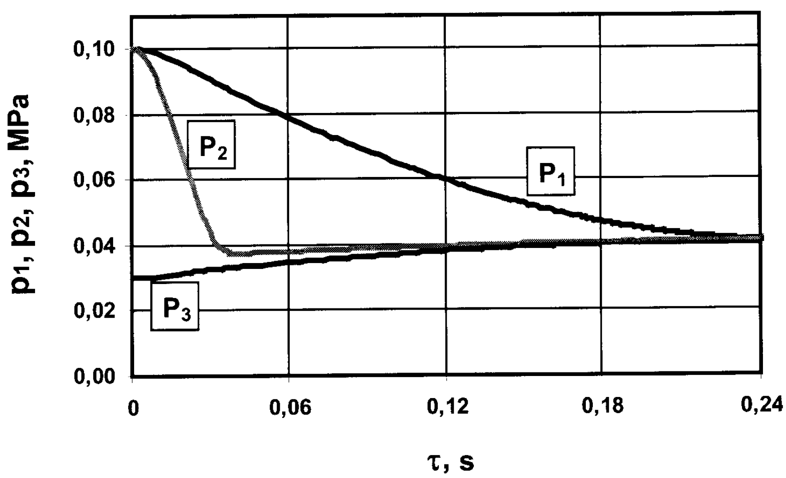


Fig. 13. Simulation results of air flow in vacuum process. Initial values p_3 are increased

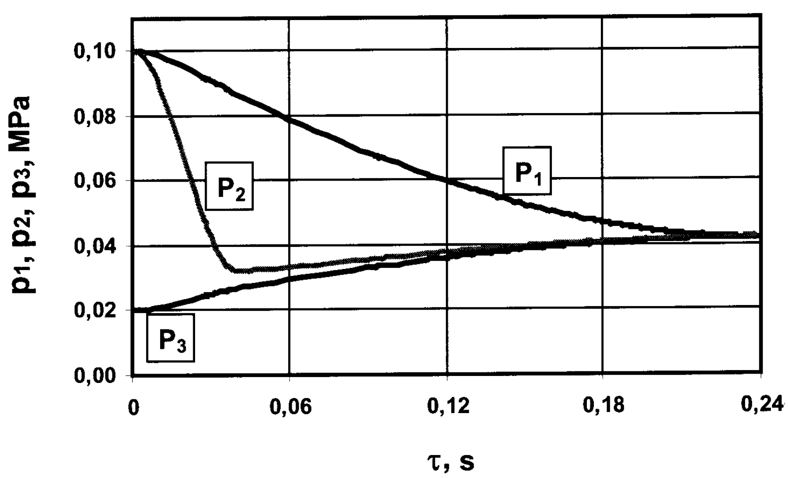


Fig. 14. Simulation results of air flow in vacuum process. Vacuum receiver volume V_3 is decreased (two times)

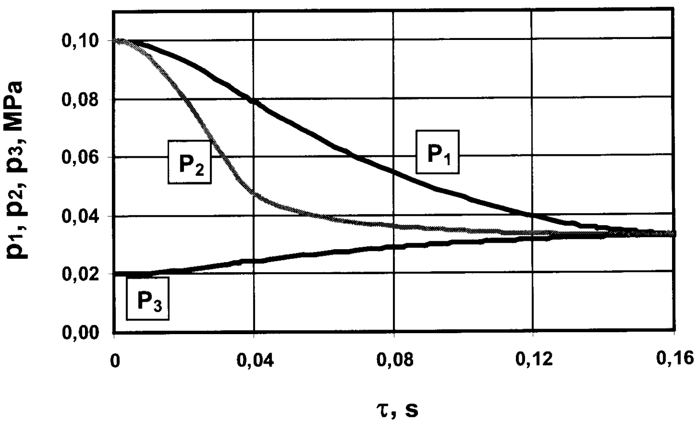


Fig. 15. Simulation results of air flow in vacuum process. Openings area of vents – A_1 is increased (two times)

The simulation has been run in such a way that only one parameter from initial data (fig. 12) has changed. The comments are given under the figures 13–15. These make it easier for the observation of the influence of given parameters. For example the increase of the initial pressure in the vacuum tank (fig. 13) is connected with higher equilibrium pressure in the system, but the equilibrium state is achieved much quicker.

The decreasing of the receiver volume – fig. 14 has also resulted with higher equilibrium pressure in the system, and with the decreasing of the rate of the process.

It has been stressed that, for example, that two of the analyzed above parameters: initial value of pressure in vacuum receiver and its volume are important factors of energy consumption during the process.

Well known technological conditions of good compaction in several pneumatic methods are the proper arrangement of vents and the proper choice of their size. On fig. 15 it shows that above mentioned parameters strongly influenced the air flow during the vacuum process.

On the basis of the analysis of the simulation results and pressure measurements the test stand has been modernized.

6. Summary

From the investigations carried out by the authors of this paper so far and from the data given in reference literature, it has been deduced that sand compaction by a vacuum-assisted process conducted by stages has the potential necessary to satisfy the imposed requirements. An innovation in this process of compaction is a division into the stage of sand feeding and preliminary compaction, and the stage of squeezing, which is generally regarded as the main one. The methods applied so far include sand transport to the technological space. An advantage of this solution is the effective use of the energy of a multi-step stream. The drawback is higher energy input and certain requirements regarding the type of the moulding flask, as well as the necessity to provide an air-tight system.

The preliminary sand compaction as an effect of the pressure drop gives a uniform distribution of the sand layers. Due to this, it is possible to obtain a uniform and beneficial density distribution in the most critical areas of pattern and between the pattern and the flask walls – all of this is irrespective of the pattern wall surface development. This is a very important technological effect. A non-uniform distribution of sand may cause surface defects, no matter how effective the final sand compaction is. With the proper value of negative pressure and the sand amount adjusted to the mould volume, the compaction is carried out during one single cycle and proceeds simultaneously on the entire mould height. During this process, an interrelation between the individual sand layers in direction towards the pressure gradient occurs. The highest degree of compaction acquires the layers adjacent to the pattern plate. Moreover, due to a resistance offered by the pattern plate surface, the movement of the sand layers is impeded. This leads to a further increase of the stresses in the lower layers, which has a beneficial effect on the sand density distribution in the lower and central part of the mould.

The obtained results can be improved by optimization the parameters of vacuum installations. The presented results of measurements, as well as simulation results, have shown that possible parameters, like negative pressure values and its decreasing rate, can be changed at the stage of machine design.

The simplified, presented model of air flow in the vacuum chamber system could be completed with another equations expressed for example the model of the compaction process.

In spite of the fact that the vacuum-assisted process is used on moulding machines of a certain design (in variant with the sand transport), the full and comprehensive designs and solutions, which would in a consistent way identify the potentials of this technology, are still not available. It is necessary to establish the principles of operation of this method and relate it to a varied assortment of the castings made, followed by investigations that look into the possibility of the mechanization and design of fully integrated automatic moulding plants.

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