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EVALUATION OF VACUUM ASSISTED COMPACTION PROCESSES OF FOUNDRY MOULDING SAND BY THEORETICAL AND EXPERIMENTAL METHODS

TEORETYCZNA I DOŚWIADCZALNA OCENA PROCESU ZAGĘSZCZANIA ODLEWNICZYCH MAS FORMIERSKICH METODĄ PODCIŚNIENIOWĄ

Vacuum-assisted compaction processes are now widely used in flask moulding and flaskless moulding installations. Vacuum-assisted method improve the compaction performance through the application of dynamic action in the early stage of the process.

In vacuum-assisted methods, the constructional and operational parameters of vacuum installations are of primary importance. The compaction level can be easily controlled and improved, making the process cost-effective.

Underlying the theoretical analysis is the mathematical model of airflow developed by the Author. The model yields the key process parameters required for the design, operation and potential optimisation of the vacuum- assisted moulding installation.

This study outlines the methodology of experimental testing of mould compaction performance in the laboratory conditions. Experimental data and simulation results are used in evaluation of conventional compaction processes of sand mix containing bentonite. The methodology enables an analytical and theoretical verification, taking into account the requirements of the foundry practice.

Keywords: foundry production, moulding machines, vacuum moulding, mathematical model, computer simulation

Proces formowania podciśnieniowego jako metoda zagęszczania masy, jest obecnie powszechnie stosowana w maszynach formierskich wykonujących formy skrzynkowo i bezskrzynkowo. Zastosowanie tej metody ma na celu poprawę efektów zagęszczania masy formierskiej poprzez wspomaganie dynamiczne w początkowej fazie procesu.

W metodzie podciśnieniowej istotną rolę odgrywają parametry konstrukcyjne instalacji oraz parametry eksploatacyjne. Prawidłowy dobór parametrów jest podstawą do optymalizacji procesu formowania. W konsekwencji następuje wzrost efektów zagęszczania masy formierskiej oraz czyni proces bardziej ekonomicznym.

Podstawą oceny teoretycznej jest opracowany przez Autora model matematyczny przepływu powietrza umożliwiający obliczanie istotnych parametrów procesu, niezbędnych dla prawidłowego projektowania, eksploatacji oraz perspektywicznej optymalizacji systemu formowania podciśnieniowego.

W artykule przedstawiono metodykę doświadczalnego badania efektów zagęszczania masy formierskiej na stanowisku laboratoryjnym. Wyniki badań doświadczalnych oraz badań symulacyjnych posłużyły do oceny procesu zagęszczania odlewniczej masy formierskiej. Przedstawiona metodyka umożliwia weryfikację analityczno-teoretyczną z uwzględnieniem wymagań zależnych od praktyki przemysłowej.

1. Introduction

New requirements imposed on the foundry engineering industry, including the product quality, cost-effectiveness and environmental considerations, prompt the development of more effective, precise and less time-consuming methods of moulding, particularly as the casting products become more and more intricate [4,5].

Processes taking place in moulds during the moulding operations have received a great deal of attention from numerous researchers and manufacturers of foundry machines. The moulding process should be supported by extensive expertise in the area of sand compaction, variations of technological properties of sand mix, supplemented by the ability to contour the model shape and utilise the compaction energy.

The author's research to date [13] supported by a scrutiny of literature data [4,15,17] lead us to the conclusion that vacuum-assisted compaction processes involving subsequent stages can potentially satisfy the imposed requirements. Accordingly, the process should consist in two stages: initial com-

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paction by a gradient-induced air flow and the stage of sand compaction by squeezing [13,16].

In wet greensand technologies, methods using automatic process lines allow for application of under-pressure action in the area where aerated moulding sand is stored, to achieve the satisfactory initial compaction performance and hence to improve the final compaction effect. Vacuum-assisted processes are applied with great success in automatic flask moulding and flaskless moulding lines. Both in flask moulding and in flaskless moulding installations, vacuum assisted processes help in blowing the solid particles (core or sand mix) together with the compressed air stream towards the processing zone. Because of relatively low pressure gradients in sand layers, the initial compaction performance is not very high yet the compaction levels can be vastly improved in hard-to-access mould regions (in relation to squeezing methods). This technology is now used with great success and will certainly continue to be used in flask-moulding and flaskless moulding installations [10].

Theoretical evaluation of vacuum-assisted processes and experimental research enable the optimisation and selection of parameters of the vacuum installations. Future test results will be used to formulate design objectives to improve the construction of moulding machines enabling the wider range of moulding operations than now.

2. Theoretical backgrounds of airflow in vacuum- assisted moulding installations

Regardless of the actual pressure or negative pressure value, processes induced by the flow of a stream of air take place in a specific installation. The key components of compaction installations using airflow stream include:

- a source of air and the piping system;
- an equalising tank (in pressure installations) or a vacuum tank (in vacuum installations);
- an internal container of sand or, alternatively, a charge chamber in blower installations;
- a mould or a core box in the area where the initial compaction takes place.

In terms of operational parameters, an assumption is made for the purpose of analytical modelling that the power source is the first element of the installation and the moulding box or a core box is located in its end section, where the airflow energy is converted into work of sand compaction. Between the energy source and the conversion point in the analysed pneumatic installations are other elements that impact on the airflow dynamics. Each element has specific constructional parameters, for example a piping system is defined by its spatial configuration, diameter, effective cross-section area, length, surface conditions. Key parameters of impulse valves include the cross-section of flow channel, opening mode and rate, parameters of internal chambers are: volume, shape, position in the process line, the amount of vents and their layout and others [3,11,13].

The main operational parameters include: air pressure, the rate of pressure increase or decrease, and sand flow rate. These parameters affect the dynamic behaviour of the flowing air [16] and airflow-induced effect, defined by the compaction value and its distribution within the sand volume.

These factors clearly show that the airflow in the vacuum-assisted compaction installation is most complex and involves a number of processes that are variable and probabilistic in nature. These processes can be investigated by a theoretical method supported by computer modelling. Underlying the method is the theoretical model of airflow in particular sections of the installation incorporating a specified sequence of material elements of precisely defined geometry and flow-related parameters.

Underlying the author's mathematical model of vacuum-assisted moulding processes are theoretical backgrounds of blowing system operations, supplied first by P.N.Aksonov [1] and developed by J.Dańko, in a form that allows a number of simplifying assumptions to be eliminated [3]. Underlying the mathematical model given in the present study is the theory of quasi-stable [6] flows applied to air flows in pressurised -gas installations [2,7,8,9]. Application of general equations based on that theory to the description of flows in impact zones of foundry machines is given elsewhere [12].

Equations governing the gas transformations during the air flow in particular sections of the pneumatic installation have to be supported by equations describing the motions of elements that cause the volume change in the analysed region and by equations of motion of the valves. The total number of equations describing the process depends on the level of complexity of the model, defined by the number of working spaces, known as working chambers, within the investigated installation.

The model presented in this study uses three working chambers comprising the relevant volumes and the ascribed pressure levels:

1) working space V_a, of the pressure p_a

2) space beneath the model plate, of volume V_b and pressure p_b

3) vacuum-tank, of the volume V_c and pressure p_c

Parameters governing the flow of air between particular chambers (as shown above) include: cross-section areas of the conduits and valves (designated as A), the characteristic flow number (symbol ψ) and flow ratio for openings on subsequent airflow stages (symbol μ).

Accordingly, the mathematical model is written as:

$$-\kappa \mathrm{RT} \mathrm{d}m_{1/2} = V_1 \mathrm{d}p_1 \quad (1)$$

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

$$\kappa \mathrm{RT} \mathrm{d}m_{2/3} = V_3 \mathrm{d}p_3 \quad (3)$$

$$\mathrm{d}m_{1/2} = G_{1/2} \cdot \mathrm{d}\tau \quad (4)$$

$$\mathrm{d}m_{2/3} = G_{2/3} \cdot \mathrm{d}\tau \quad (5)$$

$$G_{1/2} = C_1 \cdot \mu_1 \cdot A_1 \cdot \frac{p_1}{\sqrt{T}} \cdot \sqrt{\left(\frac{p_2}{p_1}\right)^{\frac{2}{\kappa}} - \left(\frac{p_2}{p_1}\right)^{\frac{\kappa+1}{\kappa}}}, \quad \text{for } \frac{p_2}{p_1} > 0.528 \quad (6)$$

$$G_{1/2} = C_2 \cdot \mu_1 \cdot A_1 \cdot \frac{p_1}{\sqrt{T}}, \quad \text{for } \frac{p_2}{p_1} \leqslant 0.528 \quad (7)$$

$$G_{2/3} = C_1 \cdot \mu_2 \cdot A_2 \cdot \frac{p_2}{\sqrt{T}} \cdot \sqrt{\left(\frac{p_3}{p_2}\right)^{\frac{2}{\kappa}} - \left(\frac{p_3}{p_2}\right)^{\frac{\kappa+1}{\kappa}}}, \quad \text{for } \frac{p_3}{p_2} > 0.528 \quad (8)$$

$$G_{2/3} = C_2 \cdot \mu_2 \cdot A_2 \cdot \frac{p_2}{\sqrt{T}}, \quad \text{for } \frac{p_3}{p_2} \leqslant 0.528 \quad (9)$$

$$\mathrm{A}_2(\tau) = \mathrm{a}^{*}\tau \quad \text{for} \quad A_2(\tau) < \mathrm{A}_2^{\max} \quad (10)$$

$$\mathrm{A}_2(\tau) = \mathrm{A}_2^{\max} \quad \text{for} \quad A_2(\tau) >= \mathrm{A}_2^{\max} \quad (11)$$

C_1, C_2 – constants
where:
$p_{1,2,3}$ – air pressure in a given volume,
κ – exponent in an adiabatic equation,
$V_{1,2,3}$ – volume of the given space,
$\mu_{1,2}$ – flow ratio for the vent in the working space and valve, respectively,
$A_{1,2}$ – opening areas in the vent and valve, respectively,
$\mathrm{dm}_{i/j}$ – differential form of the air mass change within the given space,
$\mathrm{G}_{i/j}$ – flow rate between the two determined spaces,
T – temperature,
τ – time.

Simulations yields the key flow parameters, such as instantaneous flow rates at the specific point, the rate of pressure increment and instantaneous airflow rates [12,13,17]. Simulation data can be further utilised to evaluate the efficiency of the vacuum installation parameters, to support the selection procedure and the design of new machines where compaction processes should be directly based on compressed air.

3. Simulation of airflow in vacuum installations and experimental verification

The main purpose of simulations and the experimental verification procedure is to check the adequacy of the theoretical description based on the analytical mathematical model and to verify it on a physical model emulating the vacuum installation and the phenomena that can be witnessed in various flow conditions.

The simulation and verification program involved two stages:

1) simulation of a virtual vacuum installation, being an equivalent of the mathematical model
2) experimental testing done on a physical model of the vacuum-assisted moulding installation, made as a laboratory stand in a reduced scale.

Schematic diagram of experimental testing on a vacuum-assisted moulding installation is shown in Fig. 1 in a graphic format.

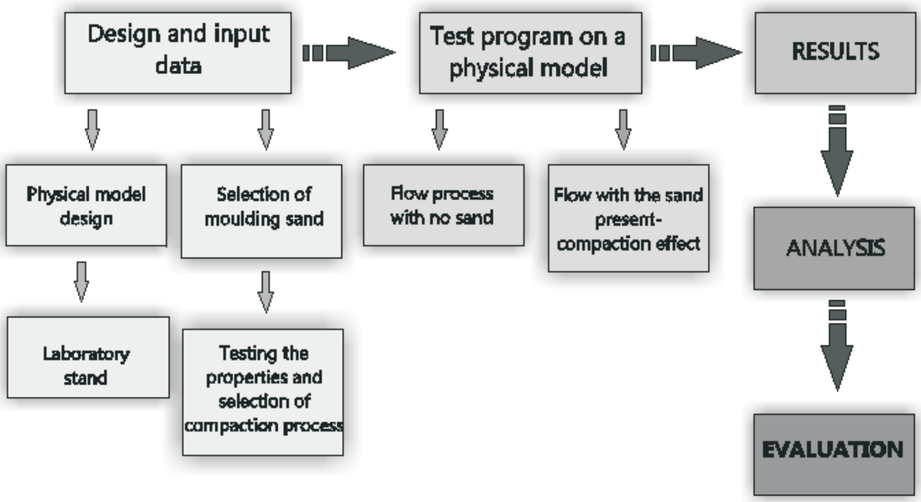

Fig. 1. Schematic diagram of experimental testing of a vacuum moulding process [16]

Simulations were done for identical conditions as in the physical model of a vacuum installation, characterised by the following constructional and process – related parameters:

– pressure tank volume 14.17 dm^3
– large mould volume 6.15 dm^3
– total vent area – 965.1 mm^2
– flow ratio μ_1= 0.9
– flow ratio μ_2= 0.6
– opening area of vents A_1=507 mm^2
– opening area of a valve A_2=231 mm^2
– valve opening time = 0.13 s
– the average speed of valve opening = 0.5 m/s

Simulation testing of the mathematical model was supported by programs Matlab 7.5 and Simulink 7.0.

Tests on a real model were done in the experimental setup adapted to handle vacuum moulding processes. Parameters of the vacuum installation correspond to the design objectives assumed for the purpose of simulations. The experimental setup (Fig. 6a) incorporates the following systems:

a) vacuum-assisted installation representing a functional physical model of the moulding machine;
b) measurement system;
c) recording system.

Experimental testing on physical model of a vacuum assisted moulding installation was done in the working space free from moulding sand [14,15]. The absence of moulding sand in the process chamber allowed for evaluating how constructional parameters of the installation should affect the airflow. Experimental and simulation tests were done for four levels of vacuum pressure, assuming the constant volume of the vacuum tank, equal to 14.17 dm^3. Simulation data and verification results are shown in Figs. 2-5.

Testing was also done on an experimental stand, in accordance with the relevant procedure and assuming that the following parameters should remain constant:

a) volume of the vacuum tank;
b) location of points of precisely controlled vent cross section area;
c) volume of the process chamber filled with a specified amount of sand.

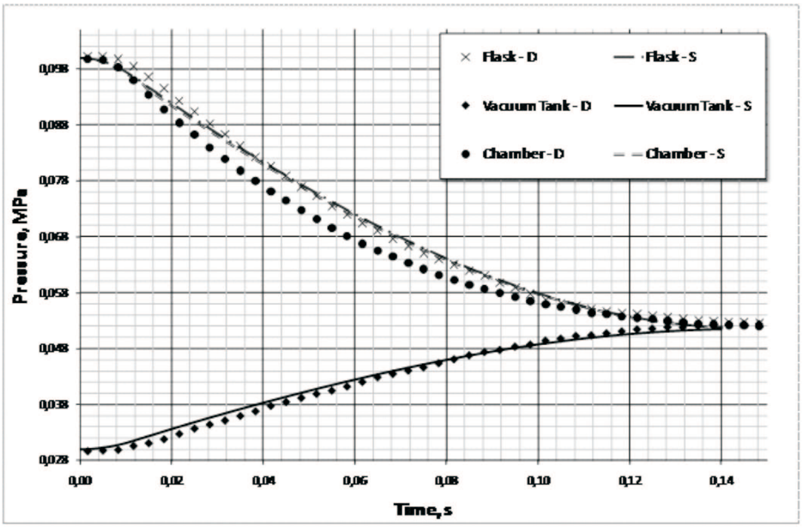

Fig. 2. Simulated (S) and experimental results (D) of testing airflow in particular section of the experimental vacuum-assisted moulding installation. Vacuum level – 0.03 MPa

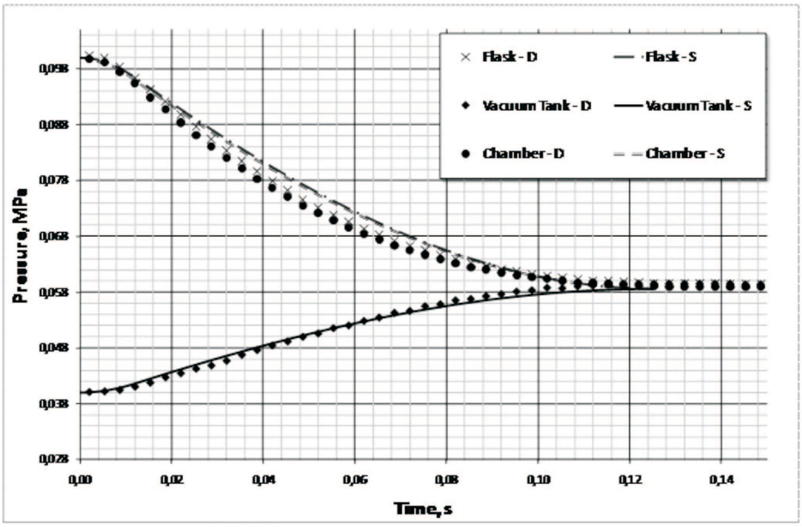

Fig. 3. Simulated (S) and experimental results (D) of testing airflow in particular section of the experimental vacuum-assisted moulding installation. Vacuum level – 0.04 MPa

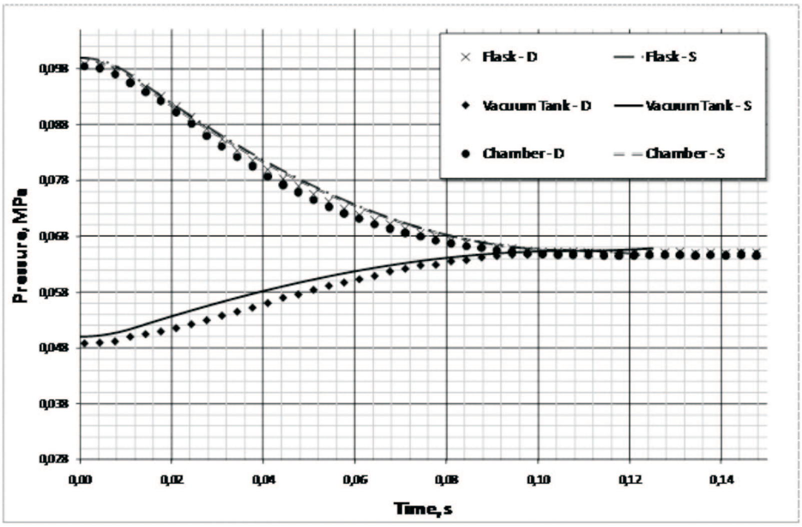

Fig. 4. Simulated (S) and experimental results (D) of testing airflow in particular section of the experimental vacuum-assisted moulding installation. Vacuum level – 0.05 MPa

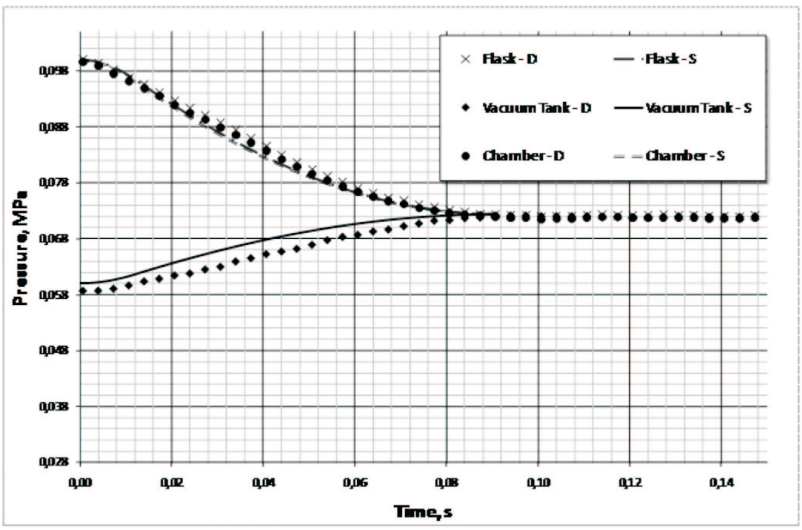

Fig. 5. Simulated (S) and experimental results (D) of testing airflow in particular section of the experimental vacuum-assisted moulding installation. Vacuum level – 0.06 MPa

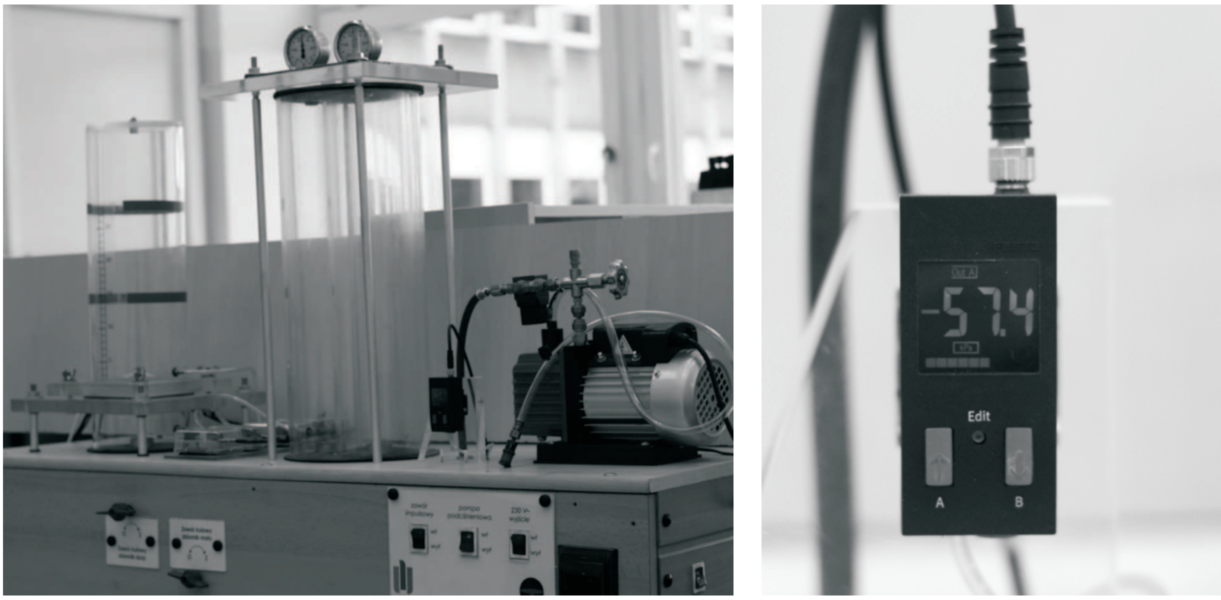

Fig. 6. Tested stand (a) and an electronic vacuum sensor (b)

Pressure in the vacuum tank was the variable parameter. This is a most important parameter, determining the potential energy of sucked-in air used for compaction. Pressure measurements were taken by a direct method, using an electronic vacuum sensor (Fig. 6b) of the measuring range 0-0.1 MPa.

The main purpose of the test was to find the optimal pressure level ensuring the best compaction performance under the specified conditions imposed by the construction of the installation and sand mix parameters.

Research data suggest that good compaction performance is achieved at under pressure level 0.03 MPa. The plot of pressure in the vacuum installation reveals that application of negative pressures below that level is not justified, both in terms of process requirements and cost-effectiveness. That is why the vacuum pressure in further tests remained on the level of 0.03 MPa.

Pressure patterns registered in particular sections of the vacuum-assisted moulding installation are given in Figs. 7-10.

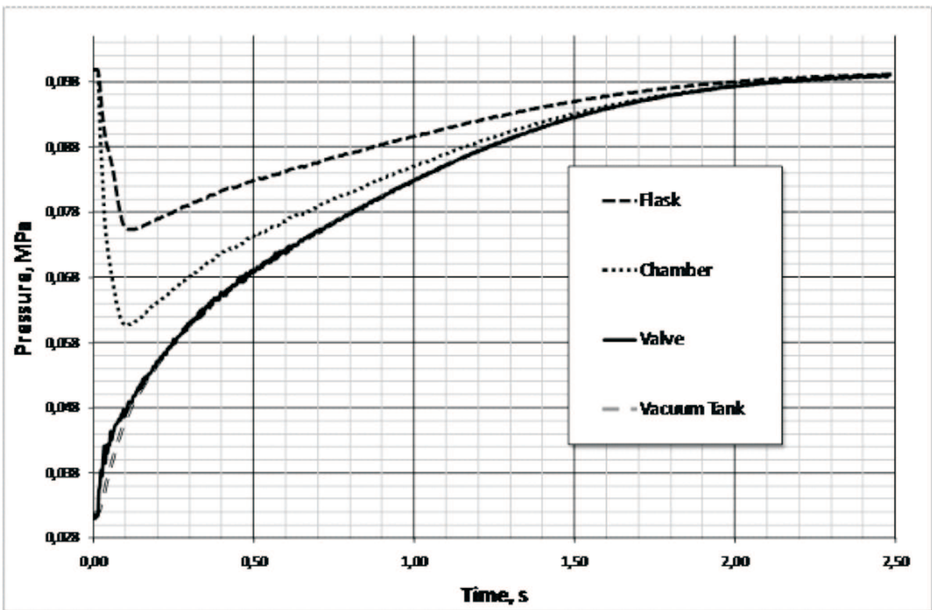

Fig. 7. Pressure in a vacuum installation during the sand compaction process – initial value of the pressure 0.03 MPa

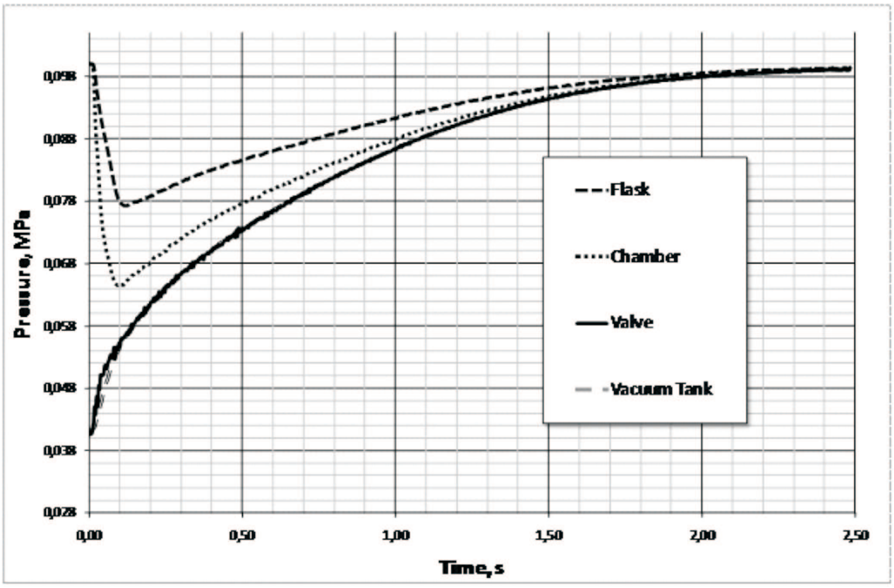

Fig. 8. Pressure in a vacuum installation during the sand compaction process – initial value of the pressure 0.04 MPa

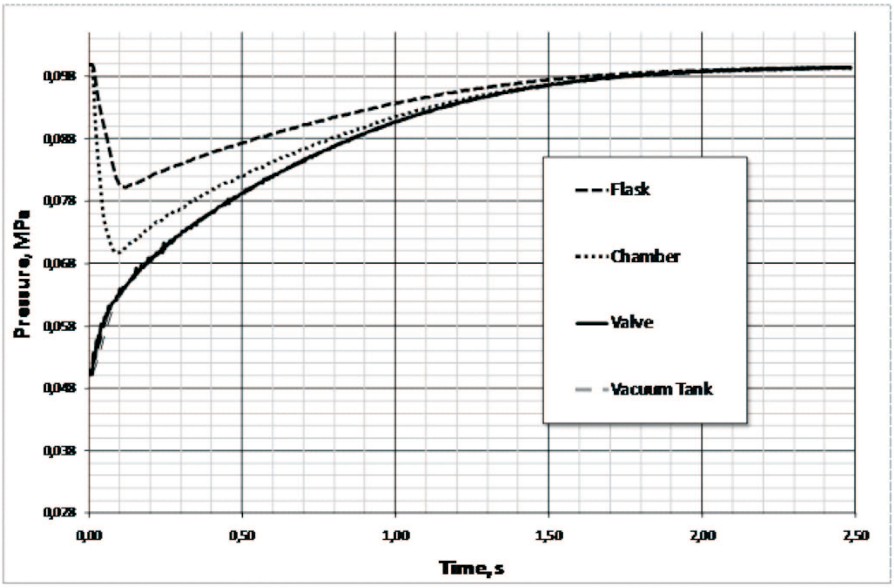

Fig. 9. Pressure in a vacuum installation during the sand compaction process – initial value of the pressure 0.05 MPa

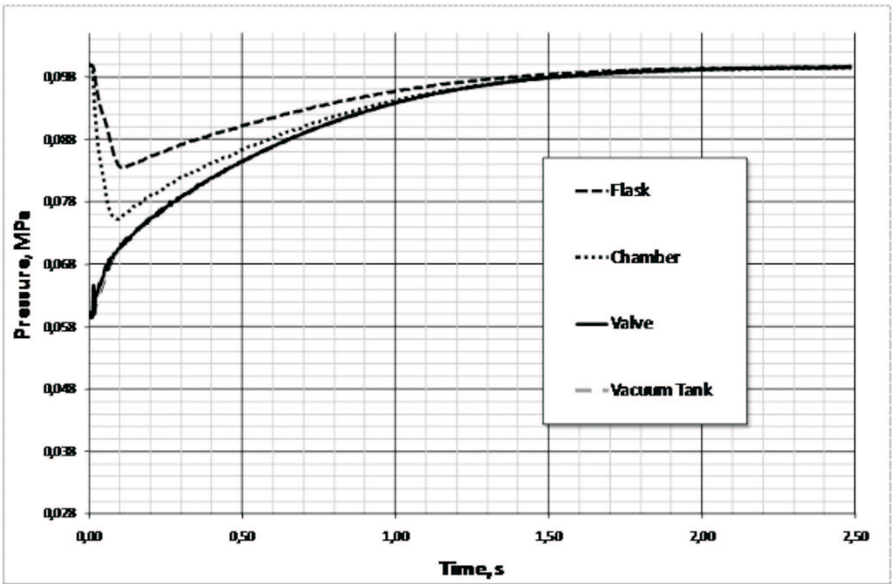

Fig. 10. Pressure in a vacuum installation during the sand compaction process – initial value of the pressure 0.06 MPa

4. Conclusions

Simulation results and experimental data confirm the adequacy of the theoretical model in describing the initial moulding sand compaction by vacuum-assisted methods. One has to bear in mind, however, that the process is highly complex and hence requires further testing to take into account the specific features of the vacuum-assisted moulding processes. Better understanding of the process will allow for developing the method of the vacuum-assisted moulding in box moulding processes that should be used in initial compaction and to foresee new applications of moulding installations.

Vacuum assisted moulding ensures the uniform compaction of sand mix in technologically difficult mould regions, such as long, narrow and slender slits. It would be worthwhile to get a better insight into the mechanism of the compaction process, caused by air filtration due to pressure gradient, which is one of the controllable parameters of the process. That would ensure the uniform sand mix distribution in the lower and medium mould section and the capturing of the model, owing to satisfactory sand compaction in the by-model zone. That allows for application of models with deep slits and for increasing the dimensioning accuracy. The vacuum-assisted initial compaction technique produces very little dust in the moulding stand (air-tight process) and is characterised by low-level pattern wear and low noise emissions, below 85 dB.

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