Application of computer simulation methods in the studies of air flows in a vacuum–assisted installation

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Abstract
Vacuum installations are currently used in moulding machines for flaskless as well as for flask moulding processes. The basic aim of using such installation is the improvement of compaction effects due to the intensification of the course of processes in the main compaction method (eg. by shooting) or also realizing of the initial compaction before squeezing. In moulding machines using of this type installations the stable and high compaction state, good imprint of difficult pattern shape are achieved. The low level of noise during the operation of such machines is also the advantage of their using. The correct selection of design and operation parameters of pneumatic moulding machines can be easier with the modeling of air flow process in workspaces of the machine. In the article the mathematical model and example-results of the air flow process simulation in the system of the stand for vacuum assisted moulding investigation have been presented. The simulation results were compared with measurements results of basic parameters describing the course of air flow process.

Keywords: Foundry Engineering; Moulding Processes; Moulding Machine; Vacuum Process; Simulation.

1. Introduction
Vacuum-assisted compaction processes are now widely applied in moulding machines in foundries, they are treated as the initial moulding stage aimed to obtain uniformly compact moulding sand, particularly in the case of difficult-to-handle models. Advantages of this technology include good mapping of the model’s contours and little wearing of models[10]. This moulding method might also support the main moulding operation [12]. Manufacturers of vacuum-assisted installations provide only little technical data in catalogues, which are rather commercial brochures. Despite a widespread interest in this technology, universal solutions are still lacking that would permit optimisation of the vacuum-assisted process parameters. It is reasonable to suppose that providing scientific backgrounds should enable the process optimisation. The optimisation procedure might be formalised by using the simulation approach to the description of the very structure of the process, in order to effectively control the parameters that affect the process efficiency. This study summarises an attempt to apply the computer simulation methods to the performance evaluation of a vacuum-assisted installation. Simulation data are then verified by experimental tests.

2. Model of airflow in a vacuum installation
The main objective of the simulation procedure is to optimise the involved processes through the control of relevant parameters. In the case of vacuum installations, these parameters include the design parameters, such as the cross-section of the piping installation, capacity (volume) of vacuum tanks, valve opening area, vent area and time of process duration, the required vacuum pressure and others. Actually, any optimisation before the advent of computer simulation methods would help design a machine and select the control parameters only by a trial and error method, which proved time-consuming and cumbersome. Thanks to computer simulations, the stage of trials is vastly minimised,
consisting in extensive tests to yield the machine design and simulation and experimental data can be reliably compared. When the test results are positive, the machine is to be manufactured. Simulation methods are useful not only in testing new solution but also in optimising the existing ones. In order to fully utilise the potentials of computer simulation methods, its is required that a relevant mathematical model be developed to support the simulations.

A thorough scrutiny of the literature on the subject reveals that underlying the existing vacuum-assisted processes [1,2,3,4] is the fundamental Saint Venant- Wantzel equation. In order that models can be further developed and improved, it is required that technological particulars of the given process be duly taken into account. No matter how detailed the identification of process components, the models should be sufficiently universal to adapt to different operating conditions that must be expected in various types of installations. Underlying the mathematical model given in the present study is the theory of quasi-stable 1D flows [5], applied to air flows in vacuum installations. Equations governing the variations of the state of air inside the vacuum installation, based on the Saint Venant- Wentzel formulas, yield the air flow rate and describe the valve defined by linear equations. The key principles adopted by the Authors of the pressurised -gas installation models [1,2,4,6] are still applicable.

The mathematical model is written as:

\[
-\kappa RT \frac{dm_{1/2}}{dt} = V_1 dp_1
\]

(1)

\[
\kappa RT (\frac{dm_{1/2}}{dt} - \frac{dm_{2/3}}{dt}) = V_2 dp_2
\]

(2)

\[
\kappa RT \frac{dm_{2/3}}{dt} = V_3 dp_3
\]

(3)

\[
dm_{1/2} = G_{1/2} \cdot d\tau
\]

(4)

\[
dm_{2/3} = G_{2/3} \cdot d\tau
\]

(5)

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

(6)

\[
G_{1/2} = C_2 \cdot \mu_1 \cdot A_1 \cdot \frac{p_1}{\sqrt{T}}, \quad \text{for} \quad \frac{p_2}{p_1} \leq 0,528
\]

(7)

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

(8)

\[
G_{2/3} = C_2 \cdot \mu_2 \cdot A_2 \cdot \frac{p_2}{\sqrt{T}}, \quad \text{for} \quad \frac{p_3}{p_2} \leq 0,528
\]

(9)

\[
A_2(\tau) = a^* \tau \quad \text{for} \quad A_2(\tau) < A_2^{\text{max}}
\]

(10)

\[
A_2(\tau) = A_2^{\text{max}} \quad \text{for} \quad A_2(\tau) = A_2^{\text{max}}
\]

(11)

Where:

- $p_{1,2,3}$- air pressure in a given volume
- $\kappa$- exponent in an adiabatic equation
- $V_{1,2,3}$- volume of the given space
- $A_{1,2}$- flow ratio for the vent and valve, respectively
- $D_{\text{air}}$- differential form of the air mass change within the given space
- $G_{ij}$- flow rate between the two spaces
- $T$- temperature
- $\tau$- time

These equations are most complicated, that is why basic solution methods are impracticable. Computer assistance is fully recommended and this simulation procedure is supported by MatLab- Simulink. The package MatLab-Simulink (version 7.0) allows the process parameters to be promptly changed (vacuum, valve opening area, vent area, flow rate, and space volumes within an installation). Simulation data are exported to Microsoft Excel to be graphically compared with the experimental data.

The model yields the parameters of the airflow processes as subsequent equations govern the energy balance for particular spaces (Eq 1-3), the mass flux (Eq 4-5), flow conditions in the supercritical and sub-critical regimes taking into account the Saint Venant- Wentzel equation (Eq 6-9) and fluctuations of valve opening area (Eq 10-11). Simulation data might be utilised to evaluate the efficiency of the vacuum installation parameters in the conditions required for moulding. Besides, the model enables the selection and control of relevant parameters.

The model exhibits the behaviour of open models and can be further extended to incorporate equations governing the sand compaction and air filtering processes.
3. Selected simulation and experimental data

Experiments were performed on the laboratory facility for vacuum-assisted moulding tests, designed and engineered in the Laboratory of Mechanisation, Automation and Design for the purpose of the research program [11]. The experimental setup is shown in Fig 1.

![Fig.1. View of investigation stands](image)

The measuring circuit incorporates vacuum pressure transducers MPX 2100 (Motorola), connected via flexible cables at four points of the installation:
- vacuum installation ahead of the valve
- collection chamber carrying the air stream flowing through the venting openings
- vacuum tank
- process chamber (mould)

Data from pressure transducers are registered by a digital recording system implemented on a Atmel microprocessor. This circuit, connected to the computer via an interface RS232, enables real-time data transmission to the computer.

Tests were run on an empty mould (without moulding sand) [9]. They were aimed to evaluate the moulding performance in the function of process intensity and airflow rate and with respect to design parameters of the moulding installation. Furthermore, the effects the moulding sand might have on the final results could be eliminated, so the comparison with simulation data was more reliable.

Experiments tests were run for four vacuum levels. The volume of the vacuum tank remained constant (14.17 dm³). The volume of the mould was fixed, too (6.16 dm³). Tests showed the dynamics of pressure fluctuations in time, revealed the impacts of pressure and the dimensions of the process chamber (mould), associated with the vent areas in the model board. Thus obtained data were digitally handled and compared with simulation results.

Selected simulation results and experimental data for various vacuum levels are shown in Figs 3-6.

![Fig 3. Simulated and experimental pressure fluctuations in particular points of vacuum-assisted moulding installation (for a-0.03, b-0.04, c-0.05, d-0.06 MPa)](image)
Plots in Figs 3-6 reveal that the created mathematical model well portrays pressure fluctuations at the selected points of the installation, both in qualitative and quantitative terms. The graphs yield the time of airflow duration at the instant the largest pressure gradient should occur in the mould, which is the major determinant of the moulding sand compaction in the system. Knowledge of this time allows for its precise control to adapt to the conditions required for particular moulding processes. For the laboratory installation, the optimal time would range from 0.14 to 0.08 s, depending on the initial pressure level. As the best compaction effects are achieved when the pressure difference is minimised. Nowadays optimisation by the trial and error method installation, and hence the costs of experimenting are vastly reduced. This study is a part of the AGH-UST research program no 10.10.170.219.

4. Conclusions

Modelling of air flow in a vacuum-assisted moulding installation facilitates the control of its basic parameters. Simulation data permit a qualitative and quantitative analysis of the effects that variations of design parameters and process parameters might have on airflow conditions within the foundry machine, affording us the means to prognosticate the compaction effects. Experimental and simulation data presented in this study reveal that the underlying mathematical model well emulates the airflow conditions in the moulding installation.

The mathematical model might become the starting point for optimisation of the vacuum-assisted processes and of the existing moulding machines and vacuum-assisted installations used at the stage of moulding sand compaction. When designing moulding machines that utilise vacuum-assisted compaction processes, regarded as the initial moulding stage, care must be taken to optimise particular parameters. Applying the simulation procedure to each separate case enables the optimal selection of the relevant parameters, without having to construct the installation, and hence the costs of experimenting are vastly minimised. Nowadays optimisation by the trial and error method is no longer economic.

Acknowledgements

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References

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