Humidity Migration in Surface Layers of Sand Moulds During Processes of Penetration and Drying of Protective Coatings

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Abstract

The results of investigations of humidity migration in near surface layers of sand mould during processes of penetration and drying of protective coatings are presented in the hereby paper. The process of the humidity exchanging between surroundings and moulding sands as porous materials, is widely described in the introduction. In addition, the humidity flow through porous materials, with dividing this process into stages in dependence of the humidity movement mechanism, is presented. Next the desorption process, it means the humidity removal from porous materials, was described. Elements of the drying process intensity as well as the water transport mechanisms at natural and artificial drying were explained. The innovative research stands for measuring resistance changes of porous media due to humidity migrations was applied in investigations. Aqueous zirconium coatings of two apparent viscosities 10s and 30s were used. Viscosity was determined by means of the Ford cup of a mesh clearance of 4mm. Coatings were deposited on cores made of the moulding sand containing sand matrix, of a mean grain size $d_L = 0.25$ mm, and phenol-formaldehyde resin. Pairs of electrodes were placed in the core at depths: 2, 3, 4, 5, 8, 12 and 16 mm. Resistance measurements were performed in a continuous way. The course of the humidity migration process in the core surface layer after covering it by protective coating was determined during investigations. Investigations were performed in the room where the air temperature was: T = 22 ºC but the air humidity was not controlled, as well as in the climatic chamber where the air temperature was: T = 35 ºC and humidity: H = 45%. During the research, it was shown that the process of penetration (sorption) of moisture into the moulding sand is a gradual process and that the moisture penetrates at least 16 mm into the sand. In the case of the drying (desorption) process, moisture from the near-surface layers of the moulding sand dries out much faster than moisture that has penetrated deeper into the sand.

Keywords: Core, Sand mould, Porous medium, Humidity migration, Protective coatings, Resistance measurement

1. Introduction

Moulding sands as well as core sands, being porous materials, have the ability of exchanging humidity with surroundings.

The intensity of absorbing and giving up the humidity by these materials depends on the following factors [1,2]:
* relative humidity of surroundings,
* temperature of a material,

- material porosity.

A process of absorbing humidity is called a sorption. A water vapour sorption by porous materials can occur by means of two ways [3-5]:
- adsorption – accumulation of water vapour particles on surfaces of pores,
- absorption – penetration of water vapour particles into solids and their solution there.

A flow of the humidity in porous materials is a complex effect since it is unequal in the total humidity range of a material due to this material unorganised structure. The process of the humidity sorption into porous materials can be divided into several stages dependent on the mechanism of the humidity movement [4].

Stage 1 – at a low humidity content, water is adsorbed on surfaces of porous materials. A general pressure gradient causes water transfer by means of the surface diffusion and water vapour movement in the mixture of water vapour and air. When a temperature gradient occurs in such mixture, the water vapour - as a heavier gas - flows in the direction of heat flux, while the air - as a lighter gas - in the opposite direction [6,7].

Stage 2 – a humidity increase in a material causes filling of pores and capillaries of the medium. Clusters of liquids, called 'islands of liquids', are formed. They are not transporting masses of liquids since they are immobile. Cross-sections of channels are decreasing, and the transport of liquids occurs by means of condensation and evaporation of water on sides of 'islands of liquids' [4,7].

Stage 3 – a further humidity increase causes increases of islands of liquids. A condensation - evaporation mechanism increases its importance, while a humidity movement caused by the water vapour diffusion and humid air convection decreases [4,8].

Stage 4 – porous materials obtain the so-called critical humidity H^{cr}, liquid threads are formed due to joining of clusters of liquids. Liquid phase is moving under an influence of capillary forces, which causes a significant increase of sand flux and equilibration of the humidity within micro-zones of porous media [4,7].

Stage 5 – humidity increases above H^{cr}, porous materials become saturated by water. Capillary movements stop, water flows by means of convectional movements [4,8,9].

As a result of the surrounding conditions changes the process of humidity sorption into porous materials turns away and the humidity removal process - called desorption - starts. This process intensity depends on the difference of partial pressures of water vapour on the porous material surface (p_p) and in the drying air (p_g).

The following condition must be satisfied for the occurrence of desorption [10,11]:

$$p_p > p_g \tag{1}$$

A partial pressure of water vapour on a material surface must be higher than in the air. In the moment when the humidity equilibrium state is obtained, it means when these partial pressures are the same, the desorption process will stop [10,11].

According to the references a drying process can be natural of artificial. Natural drying is a self-active process, in which water vapour from drying material enters the atmosphere. On account of

the transport mechanism of water two stages can be separated [12,13]:
- Physical evaporation of humidity from the surface of material. The evaporation intensity depends on the difference of vapour pressures above the material surface and in surrounding air as well as on the air movements above the material;
- Convectional-diffusive humidity transport from inside of the material. The intensity of this transport depends on the material structure, since various capillary forces are exerted by pores of various sizes and shapes.

In case of artificial drying the process of water vapour removal is accelerated by supplying an additional heat. This process can be divided into three periods [14-17]:
- The heating period – beginning of drying – a temperature of drying material as well as a pressure of water vapour increases. The drying rate is fast increasing;
- The period of the constant drying rate – the equilibrium between heat exchange and water mass occurs. This period lasts up to the total humidity removal from a surface. The period ends when the critical humidity point is obtained, it means in the moment when the obtained humidity, is of such value at which water is not behaving as free water;
- The period of decreasing drying rate – the humidity migration to the surface slows down, mass transfer does not counterbalance a heat exchange, drying occurs inside the material.

On account of the process simplicity and low costs natural drying is still applied method. Sometimes, due to dimension of moulds or cores, it is the only possible way of a humidity removal. Drawbacks of the process constitute: low possibility of controlling the drying process, dependence on weather conditions and long drying time [17-20].

During the process of covering the surface of a core or mould by protective coatings the effects of a humidity sorption followed by it desorption occur in surface layers of moulding sands. Protective coatings are applied in order to [21]:
- improve the surface quality of a mould or core, which allows to obtain the smooth casting surface,
- increase the strength of the surface layer of the mould,
- limit reactions between the mould and liquid metal,
- protect against surface defects,
- improve the quality of the casting surface layer.

Protective coatings can be deposited by spraying, painting by brushes or rolls, pouring or dipping. Each of these methods has its good points and flows and also certain limitations in applications [22]. After depositing the coating on a core or mould this coating is subjected to drying to remove diluents from it. In case of small cores the artificial drying, e.g. in the horizontal drying stove, can be applied. However, in case of large moulds and cores only natural drying can be used. Not properly dried coating can be the reason of casting defects formation, especially on the surface or in the near surface layer. The most often occurring defects of a gaseous origin are: skin holes, pinholes, surface blowholes and pitted skin [21-23].

In case of the foundry industry, there is a lack of complex information concerning the sorption and desorption process

courses in surface layers of moulding sands of cores and moulds. An attempt to determine the course of the humidity migration processes in the surface layer of the sand mould, during penetrating/soaking and drying of protective coatings, was undertaken in the hereby paper.

Investigations of a drying process of protective coatings can be carried out by a few methods such as gravimetric, ultrasound or resistance [22,24]. However, the best way to record the humidity sorption and desorption processes, in a surface layer of a sand mould, is to utilise the effect of resistance changes of the medium, after the introduction of electrolyte - water into it [24]. The innovative research stand for measuring resistance changes of porous media, occurring due to the humidity migration, is presented in this paper. The concept described in the authors solution (patent of Zych, Snopkiewicz, PL 228373 B1), is also used [25].

2. Own investigations

2.1. Aim and the investigation methodology

In order to record the course of resistance changes in the porous medium during the humidity migration process 7 pairs of electrodes were used, in the construction of the research core. Electrodes were placed at distances of: 2, 3, 4, 5, 8, 12 and 16 mm from the work surface of the core. The distance between pairs of electrodes was constant and equalled 13 mm. The scheme of the electrodes distribution in the core is presented in figure 1, while the core with the mounted electrodes in figure 2. The moulding sand, of which the core was made, contained the sand matrix „Szczakowa" and phenol-formaldehyde binder in the following proportions:

- Sand matrix – 100 w.p – sand BK50 - $d_L = 0,25$ mm, main fraction Fg = 80,9 % (0,2/0,16/0,32)
- Binder – 1,2% in relation to the amount of the matrix
- Hardener - 50% - in relation to the amount of binder

A protective coating was deposited on the prepared core. The aqueous zirconium coating of two kinematical viscosities was applied in investigations:

- $v = 16 \cdot 10^{-6} \, m^2/s$ (10 s);
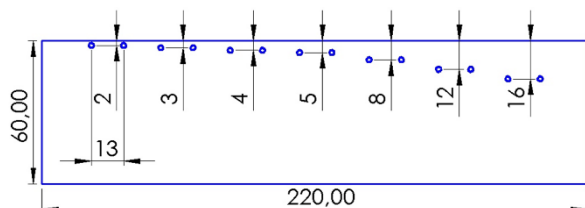- $v = 122 \cdot 10^{-6} \, m^2/s$ (30 s)

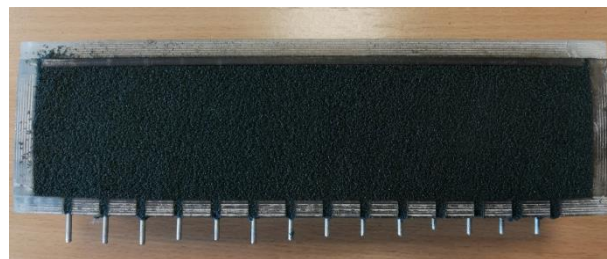Fig. 1. Scheme of electrode arrangement in the test core

Fig. 2. Test core with formed electrodes

The protective coating was deposited on the core by two ways:
- by dipping – thickness of the coating layer formed on the core depended on the coating viscosity;
- by pouring – thickness of the coating layer formed on the core was controlled and equal, regardless of the applied viscosity.

The core with the protective coating layer deposited by dipping is presented in figure 3, while the core with the layer deposited by pouring in figure 4. Limiters, seen on the core sides, allowed to scrap the coating excess and to have always the same thickness of layers. For the coating applied to the core by dipping, the coating thickness was approximately 0,2 mm for coating viscosity L = 10s, and 0,5 mm for L = 30s. For the coating applied by pouring, the coating thickness was constant at 0,8 mm.

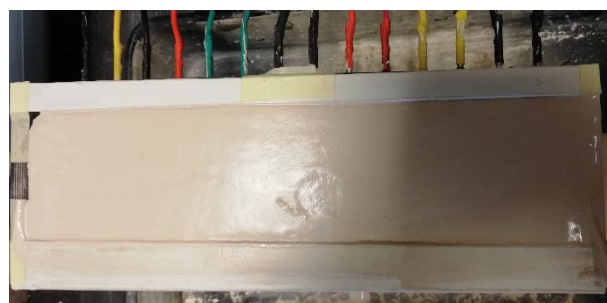Fig. 3. Core with protective coating applied by dipping

Fig. 4. Core with protective coating applied by pouring

Measurements were performed in a continuous way. Sets of electrodes were connected to the Keysight recorder. Resistances were measured every 5 minutes and the obtained results were saved in a computer. The Keysight recorder with a connected computer is seen in figure 5. A certain part of investigations of the humidity migration was performed in the climatic chamber, in which there was the possibility to control both the humidity and temperature of the air. The core placed in the climatic chamber is shown in figure 5.

The course of the humidity migration process in the surface layer of the core after the protective coating was deposited on it, was determined during investigations. Measurements were performed on the core placed in:

- a room with air temperature T = 22 °C and no humidity control
- climate chamber with air temperature T = 35 °C and humidity H = 45%

Fig. 5. Keysight recorder with computerized data logging (left), climate chamber (right)

2.2. Results of investigations

The course of the humidity migration process in the surface layer of the sand is seen in figure 6. Investigations were performed in a chamber of a temperature T = 22 °C but without controlling the air humidity. The coating of an apparent viscosity of 10s was deposited on the core by dipping. The process course recorded in all measuring points is presented in the diagram. The moulding sand resistance is changing during the humidity migration to the core and from it. The resistance of the dry core was above 120 MOhm, and the measuring device recorded precisely 9.9E+37 Ohm. The course of the migration process can be divided into 3 phases.

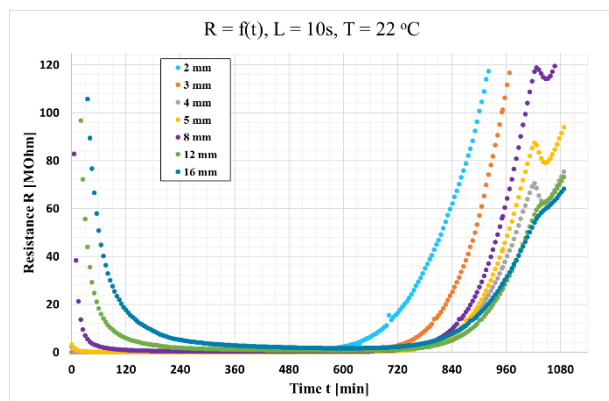Fig. 6. Process of moisture migration in the surface layer of the sand mould, coating viscosity L =10s, air temperature T = 22 °C

The first phase, the damping (sorption) occurs up to approximately 240 minutes of a measurement (figure 7). In case of

electrodes placed at the depth of 2, 3, 4 and 5 mm very low resistance - below 1MOhm - is, in practice, recorded in the moment of the coating deposition. This means that humidity from the coating very fast penetrates the moulding sand layer. For the depth of 8 mm only after 5 minutes the resistance equal 84 MOhm was recorded. For the depth of 12 mm after 20 minutes resistance of 96 MOhm was measured, while for the depth of 16 mm after 35 minutes the resistance was 106 MOhm. As time goes by the moulding sand resistance at the depth of 8, 12 and 16 mm gradually decreases, which means that the humidity is gradually penetrating the moulding sand. The process course is not linear but exponential.
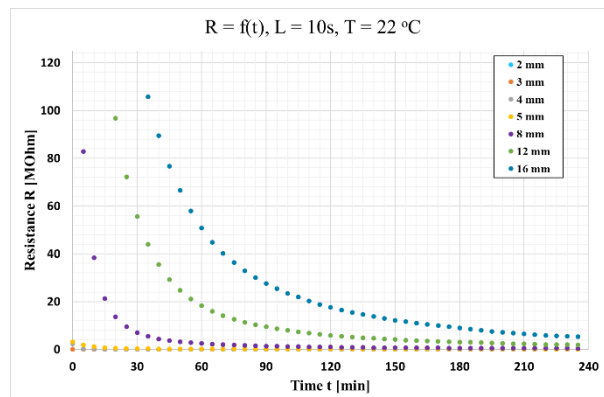

Fig. 7. Process of moisture sorption in the surface layer of the sand mould, L = 10s, T = 22 °C

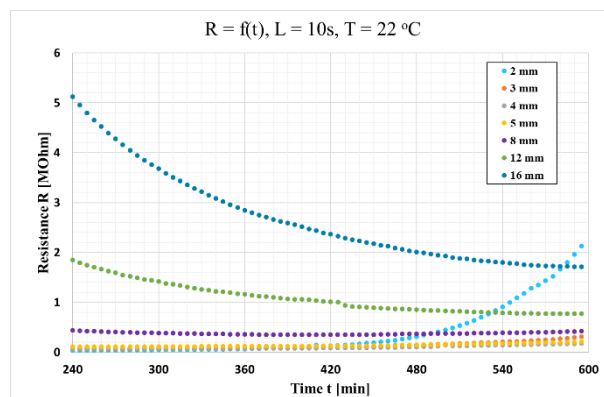Fig. 8. Transition phase of the moisture migration process in the surface layer of the sand mould, L = 10s, T = 22 °C

The second phase – temporary – which lasts to approximately 600 minutes of the process, is presented in figure 8. During this phase, a humidity content in a moulding sand is - in practice - not changing. In measurements at the depth of 16 mm and 12 mm a slow decrease of the resistance is observed up to achieving the value of approximately 2 MOhm for 16 mm and approximately 1 MOhm for 12 mm. At the depth of 8 mm the resistance equals approximately 0.5 MOhm. For the remaining measuring points, the resistance is at the level of 50 kOhm. The lower resistance the higher humidity content in the moulding sand. In case of measurements at the depth of 2 mm, the measured resistance starts to increase from approximately 480 minutes. This should be interpreted as a humidity decrease in the moulding sand.
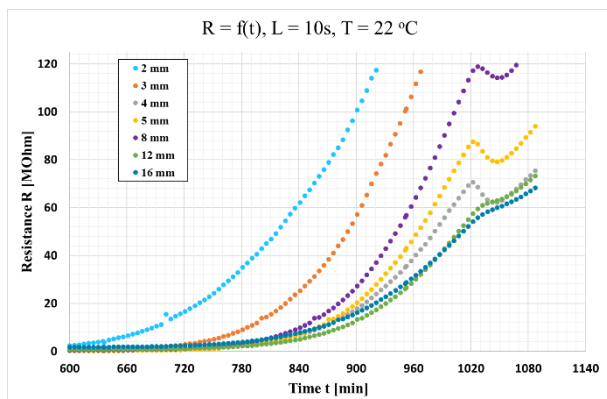
Fig. 9. Process of moisture desorption in the surface layer of the sand mould, L = 10s, T = 22 °C

The third phase of the process - drying (desorption) – which starts after approximately 600 minutes of the measurement, is presented in figure 9. Gradually in all measuring points the measured resistance is increasing until reaching the value above 120 MOhm. The fastest water evaporation is from the layer being at the depth of 2 mm. The maximum resistance was measured after 930 minutes of measuring, while at the depth of 3 mm, only after 970 minutes. Investigations of the humidity migration process were finished after 1090 minutes. It was noticed, that after this time the resistance in the remaining measuring points was lower than 120 MOhm. This means that the humidity desorption process was not finished in these points. It was also noticed, that after 1020 minutes the tested resistance started to decrease and after approximately 30 minutes it was again increasing. Probably during this time there was a change of the air humidity in the measuring place.
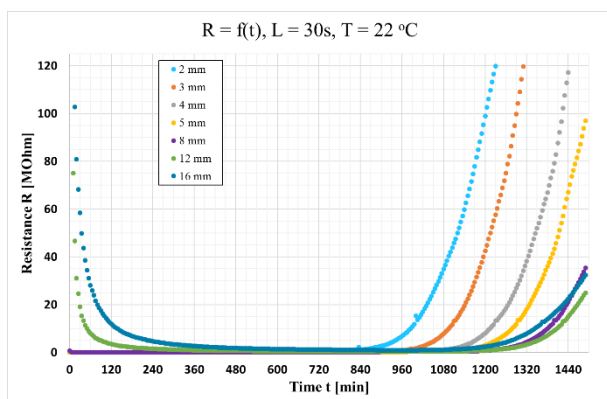

Fig. 10. Process of moisture migration in the surface layer of the sand mould, L = 30s, T = 22 °C

In case when the core was covered by a coating of an apparent viscosity 30s the humidity migration process was similar (Fig. 10). During the first phase – damping of a moulding sand – the process occurs nearly 2 times faster than for the apparent viscosity coating of 10s. On the other hand, the desorption process, in case of the coating of an apparent viscosity 30s, starts later, only round 840 minutes. Therefore the moulding sand drying at the depth of 2mm, (it means the measured resistance above 120 MOhm), occurs only after 1230 minutes of a measurement. For the remaining depth, the

drying process lasts even longer. This prolongation of the humidity migration process in the surface layer, when the coating deposited on the core was of an apparent viscosity 30s, can be a result of a larger amount of water contained in the coating layer formed on the core. The coating of an apparent viscosity 30s, contains, in percentage terms, less diluents (water) than the coating of an apparent viscosity 10s. However, the thickness of the coating formed on the core depends on the viscosity of this coating. The higher viscosity the higher thickness of the layer. Thus, the mass content of a diluent in the coating deposited on the same surface will depend on the thickness of the formed layer. The thicker layer the higher mass content of a diluent. In addition, thicker layers of the coating render difficult the evaporation of water from moulding sand layers. Coatings are of a low porosity, and this is the reason that changes in drying rates occur in such direction
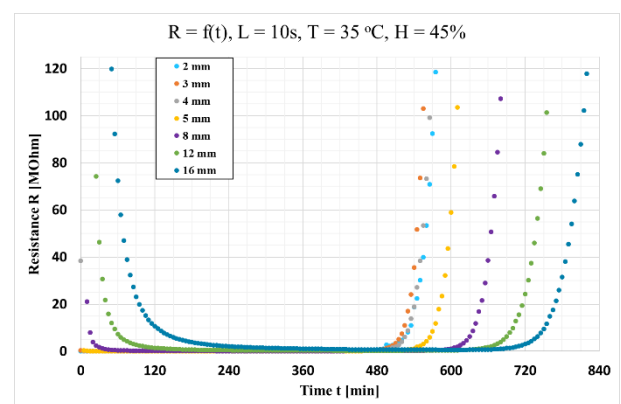

Fig. 11. Process of moisture migration in the surface layer of the sand mould, L = 10s, T = 35 °C, H = 45%
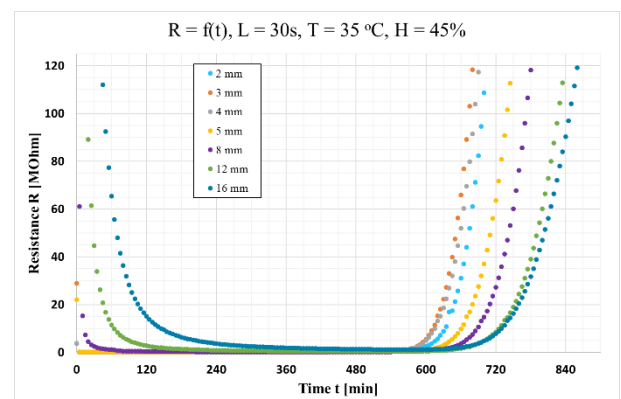

Fig. 12. Moisture migration in the surface layer of the sand mould, L = 30s, T = 35 °C, H = 45%

Investigations of migration processes performed in a room were subjected to uneven conditions, since a temperature as well as air humidity could be changing during measurements. In order to stabilise conditions the core was placed in the climatic chamber. Limiters, which allowed scrapping the coating excess at its deposition, were applied on the core. In such a way the formed coating layers were of the same thickness, regardless of the coating viscosity. A temperature in the climatic chamber was higher than in the room and equaled 35 °C. The air humidity was 45%. The

coarse of the humidity migration process in the sand mould surface layer, for the core covered with the coating of an apparent viscosity 10s, is shown in figure 11. The process course is similar to the one obtained for the core being in the room. The main difference constitutes much shorter time of the process. The third phase of the process, it means desorption, starts about after 480 minutes of a measurement and lasts relatively short (approximately 340 minutes). For the depth of 2 mm, water was removed from the sand after 570 minutes of a measurement while for the depth of 16 mm after 820 minutes. In case of measurements performed in the room (Figs 6 and 10) even after 500 minutes of desorption, water was not fully removed from the sand, especially in measuring points at depth: 8 mm, 12mm, 16mm.

When the coating of the viscosity 30s was deposited on the core (Fig. 12), the humidity migration process course was similar to the one when the viscosity was equal 10s (Fig. 11). The humidity sorption into intergranular spaces lasts the same time regardless of the coating viscosity. External conditions are not essential in this phase of the process. However, the desorption process in case of the coating of apparent viscosity of 30s, starts after 570 minutes of the process, it means later than for the coating of viscosity of 10s (480 minutes). However, the humidity desorption process in case of the coating of viscosity of 30s is shorter, since it lasts only about 300 minutes. For the coating of viscosity of 10s, the humidity desorption process lasts about 330 minutes. This difference probably results from a larger water amount contained in the coating of a lower viscosity.

3. Summary and conclusions

- As a result of depositing the protective coatings on surfaces of cores / moulds, water (diluent of coatings) penetrates intergranular spaces of moulding sands to a significant depth (above 15mm).
- A penetration process is continuous but not the uniform one. It occurs faster in near surface layers. It is observed there right after the deposition of the protective coating, while in deeper layers the process starts with a certain delay and proceeds much slower.
- During drying the near surface layers are drying as the first ones, while the humidity removal from deeper layers lasts much longer.
- Drying of coatings deposited on cores / moulds does not mean a total removal of water from surface layers of moulding sands and this situation can be causing formations of gaseous origin defects on castings.

Acknowledgments

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