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## Influence of Selected Factors on Penetration and Drying Kinetics of Protective Coatings into Sand Mould Surface Layer

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### Abstract

This paper presents the results of measuring moisture migration in the surface layer of a sand mould during the soaking and drying processes of protective coatings. In the introduction, the process of moisture exchange between the surroundings and the moulding sand is briefly introduced, and the flow of moisture in porous materials is presented. Since the aim of the research is to understand the mechanism of the penetration and drying processes of a protective coating that is applied to a core or mould, the purpose of protective coatings and the consequences of poor drying are presented. During the research, a novel test rig was used to measure the resistance of a porous medium due to moisture migration. An alcohol-based zirconia coating with a conventional viscosity of 20 s was used for the tests. The viscosity of the coating was determined by using a Ford cup with a mesh clearance of 4 mm. The cores for the tests were made from a phenol-formaldehyde resin moulding compound. The average grain size of the sand matrix was  $d_L = 0.25$  mm. During the core preparation, pairs of electrodes were placed in the mass at depths of 1, 2, 3, 4, 5, 8, 12, 16, and 20 mm. The resistance was measured continuously. During the tests, the moisture-migration process in the top layer of the core was determined after the protective coating was applied to it. The tests were conducted in a climatic chamber with air temperatures of  $T = 25^\circ$  and  $35^\circ\text{C}$  and humidity levels of  $H = 39$  and  $80\%$ .

**Keywords:** Core, Sand form, Porous medium, Moisture migration, Protective coatings, Resistance measurement

### 1. Introduction

Due to the shape and size of the matrix grains and the way they are combined, a moulding compound can be regarded to be a porous material; hence, moulding sand has the ability to exchange moisture with its surroundings. The rate at which the moisture exchange will occur depends on the relative humidity of the surroundings, the ambient temperature, the material temperature, and the porosity of the material [1,2].

The exchange of moisture of a material with its surroundings (i.e. sorption) can take place in two ways: when water vapour molecules accumulate on the surfaces of the pores, then this is adsorption; when water vapour enters the volume of the solid and dissolves in it, then this is absorption [3–5].

A porous material has a disordered structure; hence, the movement of moisture in such a material is a complex phenomenon that takes place non-uniformly over the full moisture range. Depending on the mechanism of the moisture movement, several stages of moisture sorption into a porous material can be distinguished [4]. In the first stage, a pressure gradient induces



water transport through surface diffusion and vapour movement [6,7]. In the second stage, liquid transport occurs by the condensation and evaporation of water [4,7]. Stage 3 is an increase in the importance of the condensation-evaporation mechanism, and in Stage 4, the porous material reaches a critical moisture content, and the moisture moves by capillary forces [4,8]. In the fifth stage, the liquid saturates the porous material, the capillary movement ceases, and the flow is only in a convective movement [4,8,9].

The opposite phenomenon to the moisture-ingress process is the desorption process, which is the process of removing moisture from a porous material. This process occurs when the partial pressure of the water vapour on the surface of the material is greater than the partial pressure of the water vapour in the air. The greater the difference between these pressures, the faster the process occurs. As soon as these are equalised, the desorption process stops [10,11].

The drying process can be natural or artificial. In the case of natural drying, the mechanism of water transport takes place in the stage of the physical evaporation of the moisture from the surface of the material and in the stage of the convection-diffusion transport of the moisture from the interior of the material [12,13].

On the other hand, the process can be divided into three stages in the case of artificial drying: a warm-up period, a period of a constant drying rate, and a period of a decreasing drying rate [14–17].

The natural drying process is still used because of the low cost and simplicity of the process. Sometimes it is the only possible way to remove moisture – especially for large mould or core sizes. The disadvantages of the natural drying process are the long drying times and the low controllability and controllability of the process (which depends on weather conditions) [17–20].

The mechanism of the moisture sorption and desorption in porous material is described in more detail in the article [22].

When making castings, the aim is to obtain a product with the desired properties without casting defects. In the case of surface defects, a protective coating is applied to the surface to prevent the reactions of any physical and chemical agents between the liquid metal and the casting mould. The protective coating improves the surface quality of the mould, increases its strength, reduces the metal-mould reaction, and improves the quality of the casting surface layer. The use of coatings reduces the occurrence of scorching, scabs, veins, and pitting on the casting surface [21]. Protective coatings are applied by various methods – most commonly by dipping or pouring, but also by spraying or painting. Each method has its own application limitations [23]. The coating must be dried after its application in order to remove the thinner. Small cores are usually dried in tunnel ovens; in contrast, large moulds and cores typically undergo natural drying. A poorly dried coating can result in defects in a casting – especially on the surface or in the top layer of the casting. The most common defects of a gaseous origin include external blistering, punctures, sluggishness, or plugs [21–25].

In the case of the foundry industry, there is a lack of comprehensive information on the course of moisture sorption and desorption in the top layer of a core or moulding sand. The course of the drying process can be studied using gravimetric, ultrasonic, or resistive methods; however, only the resistive method (which uses the phenomenon of the resistance change of the medium after introducing an electrolyte into it) allows us to observe the processes

of the sorption and desorption of the moisture in the surface layer of a sand mould [23,25]. This paper presents a novel stand for measuring changes in the resistance of a porous medium as a result of moisture migration. An attempt was also made to determine the course of the moisture soaking and drying from the applied protective coating to the core and the influence of external conditions (air humidity) on this process.

## 2. Own investigations

### 2.1. Aim and investigation methodology

The study of resistance changes in a porous medium under the influence of moisture migration was conducted on a core in which nine pairs of electrodes were placed. The electrodes were placed at distances of 1, 2, 3, 4, 5, 8, 12, 16, and 20 mm from the surface of the core. The distance between the electrodes was fixed at 15 mm. Figure 1 shows a diagram of the electrode placement in the core, and Figure 2 shows the core with the electrodes installed. The mass for making the cores consisted of a “Szczakowa” sand matrix and a phenol-formaldehyde binder in the following proportions:

- matrix – 100 parts – sand BK50 –  $d_L = 0.25$  mm, main fraction  $F_g = 80.9\%$  (0.2/0.16/0.32);
- binder – 1.2% (relative to quantity of matrix);
- hardener – 50% (relative to amount of binder).

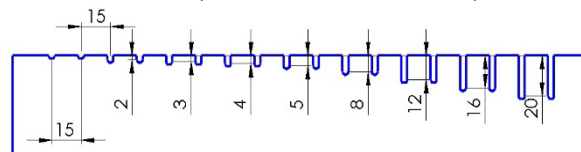


Fig. 1. Schematic of electrode arrangement in test core

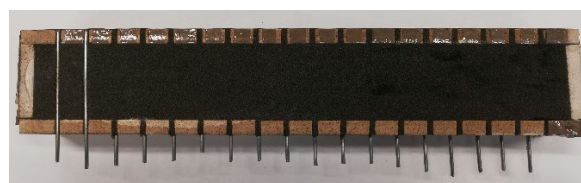


Fig. 2. Test core with formed electrodes

A protective coating was applied to the prepared core. The alcoholic zirconia coating had the following kinematic viscosity:  $\nu = 61 \cdot 10^{-6} \text{ m}^2/\text{s}$  (20 s).

The protective coating was applied to the core by pouring – the thickness of the resulting layer on the core was controlled, uniform, and 1 mm thick. The core with the applied coating was placed in a climate chamber; the humidity levels in the chamber were 39 and 80%. During the tests, the course and kinetics of the moisture-migration process in the top layer of the core after coating and the influence of the air humidity on this process were determined.

## 2.2. Results of investigations

Figures 3–6 show the course and kinetics of the process of the penetration and drying of the diluent from the protective alcohol coating into the top layer of the moulding compound. The test was conducted in a climatic chamber in which the humidity was  $H = 39\%$  and the temperature was  $T = 35^\circ\text{C}$ . The coating had a conventional viscosity of 20 s and was applied to the core by pouring. The thickness of the resulting coating layer on the core was 1 mm. The graph in Figure 3 shows the process of the moisture migration into and out of the core (as was recorded at all of the measurement points). The resistance of the moulding compound changed during the process. The dry core had a resistance of more than 120 MOhm. As soon as moisture appeared in the respective moulding compound layer, the recorded resistance started to decrease. In the first phase, the moisture from the coating penetrated the top layer of the moulding compound very quickly. In the case of the electrodes that were placed at the depths of 1, 2, 3, 4, and 5 mm, a very low resistance of less than 1 MOhm was recorded – practically at the moment that the coating was applied. This meant the very rapid penetration of the moisture into the ground layer. For the electrodes that were placed at the depths of 8 and 12 mm, the penetration process was slower. In contrast, the change in the resistance of the mass did not start until around 25 minutes into the experiment for the electrodes that were placed at the depth of 16 mm; this meant that it was only after about 25 minutes that the diluent had reached this depth. For this depth, the minimum resistance of the mass was about 24 MOhm, which meant that the mass was not saturated with the diluent. For the electrodes that were placed at the depth of 20 mm from the surface, no change in resistance could be observed; this suggested that the diluent had not reached this depth. For the electrodes that were placed at the depths of between 1 and 8 mm, a transitional phase can be observed on the graph. In this phase, the moisture content of the mass did not change. In contrast, the transitional phase was absent for the electrodes that were placed at the depths of 12 and 16 mm.

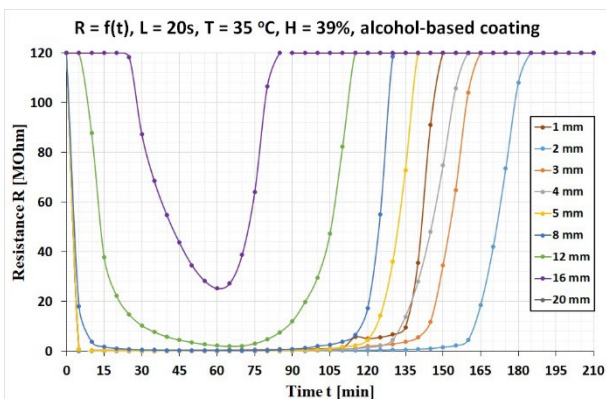


Fig. 3. Course of moisture-migration process in surface layer of sand mould (coating viscosity  $L = 20\text{s}$ , air temperature  $T = 35^\circ\text{C}$ , air humidity  $H = 39\%$ )

Once the moisture sorption process is complete, the desorption phase begins. During the desorption process, moisture is removed from the mass, resulting in an increase in resistance. By analysing the graph in Figure 3, it can be seen that the fastest moisture is

removed from the mass layer at the depth of 16 mm, and the slowest from the mass at the depth of 2 mm.

To better illustrate the start and end of the moisture sorption and desorption processes in the moulding sand, the graph that is shown in Figure 4 was made. This shows the starts and ends of the wetting processes as well as the starts and ends of the drying processes for the different depths of the placements of the measuring electrodes.

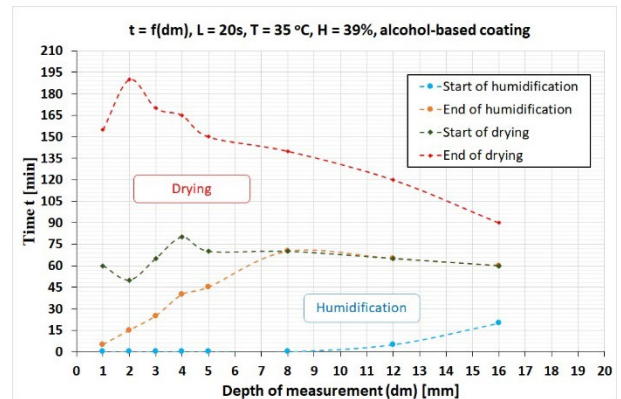


Fig. 4. Course of wetting and drying of moulding sand depending on depth of measurement ( $L = 20\text{s}$ ,  $T = 35^\circ\text{C}$ ,  $H = 39\%$ )

Up to the depth of 8 mm, the wetting process of the moulding sand practically began when the protective coating was applied to the core; however, this was delayed for the depths of 12 and 16 mm. The deeper it got, the later the wetting process started; this was related to the time that was required for the transport of the diluent. On the other hand, the end of the wetting process (i.e. reaching the maximum moisture in a given layer of the mass) was not immediate. The earliest moisture maximum was reached at the depth of 1 mm, and the latest was at the depth of 8 mm. When measured at the depths of 12 and 16 mm, the end of the wetting occurred earlier than the end of the wetting at the depth of 8 mm; this was due to the fact that, at the depths of 12 and 16 mm, the maximum wetting of the moulding sand did not occur, and the drying process started at the same time as the end of the wetting. For the measurements at the depths of 1 through 5 mm, a transitional phase could be observed. The fastest moisture-desorption process from the moulding sand started closest to the core surface (i.e. at the depths of 1–2 mm). This process started later for the deeper layers. In turn, the end of the drying process (i.e. the complete removal of the diluent from the mass) was inversely proportional to the distance from the core surface. The deeper the layer, the earlier that the end of the drying process occurred. The moisture in the deeper layers of the mass needed to be removed by the mass layers that were closer to the surface; hence, it could be concluded that the rate of the moisture transport through the individual mass layers was at a similar level. The only exception was the mass layer near the surface; at the measuring point at the depth of 1 mm, the end of the drying process occurred faster than it did at the depths of 2–4 mm. This meant that the protective coating was practically dried out and there was still moisture below the surface in the moulding compound to the depth of 4 mm. Flooding the mould with liquid metal at this point could result in defects of a gaseous origin in a casting (or surface defects).



Figures 5 and 6 show the kinetics of the wetting and drying processes of the moulding compound diluent. The kinetics of the process shows at what rate the process takes place (whether wetting or drying). During the course of the moisture-migration process, the process rate is not constant. By analysing the graph in Figure 5, it can be seen that, for the measurements that were carried out at the depths of 1–8 mm, the wetting kinetics had the highest value at the beginning of the process. A minus next to the kinetics value indicates that it was a wetting process. As time passed, the value of the kinetics (i.e. the rate at which the humidification process occurred) decreased. When the value of the kinetics was 0 and this value persisted over time, this meant that the mass had become saturated with moisture at the measuring point. In the case of the measurements at the depths of 12 and 16 mm, the wetting kinetics first increased until it reached a maximum value and then decreased to 0. The maximum value of the kinetics at these measuring points was smaller than at the other measuring points. The changes in the maximum value of the humidification kinetics as a function of the measurement depth are shown in Figure 6. In the case of the mass humidification, the maximum value of the kinetics was increasingly smaller with increasing depths within the measurement depth range of 5–16 mm; the nature of the changes was close to linear. This means that, the deeper one goes, the slower the moisture penetration process occurs; also, there is a certain limiting depth to which the moisture from the protective coating will penetrate. Hence, no resistance changes could be observed at the depth of 20 mm in the case of the alcohol coating.

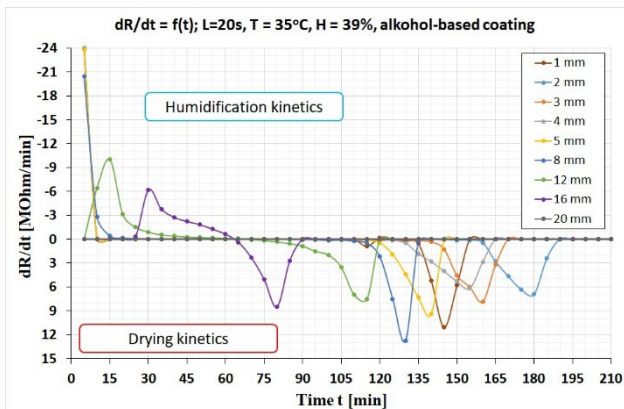


Fig. 5. Kinetics of moisture-migration process in surface layer of sand mould ( $L = 20s$ ,  $T = 35^{\circ}C$ ,  $H = 39\%$ )

On the other hand, the course of the kinetics changes was similar for all of the measuring points when the changes in the kinetics of the drying process were analysed (Figure 5). In the first phase, there was an increase in the kinetics until a maximum value was reached; then, there was a decrease to a value of 0. Zero meant that the drying process at the given depth had ended (i.e. the moisture had been removed). In the case of the measurements at the depths of 12 and 16 mm, the change in the kinetics from the wetting process to the drying process occurred continuously without stopping at 0; that is, there was no transition phase at these measurement points (as could be observed at the other measurement points). The maximum value of the drying kinetics at the individual measuring points varied (Figure 6) – oscillating between 6–12 MOhm/min. The drying process was most intensive

right at the surface – measuring the points at the 1 and 8 mm depths. In contrast, the slowest process occurred at the depths of 2–4 mm.

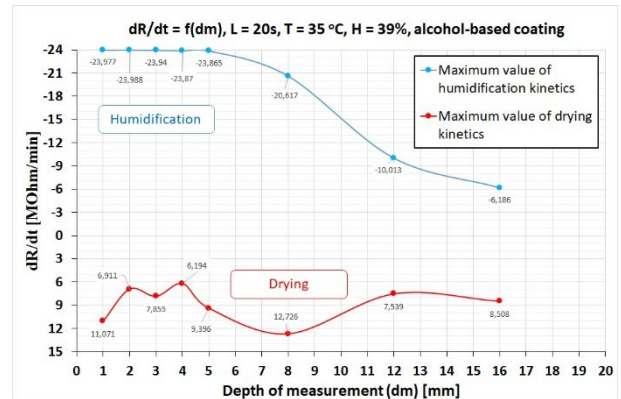


Fig. 6. Maximum value of kinetics of wetting and drying processes of moulding compound depending on measurement depth ( $L = 20s$ ,  $T = 35^{\circ}C$ ,  $H = 39\%$ )

A second measurement of the moisture-migration process into the top layers of the moulding compound was carried out under altered conditions; the air humidity was increased to 80% in the climate chamber. During the measurement, the air temperature in the chamber was 25°C. An alcohol coating with a conventional viscosity of 20 s was applied to the core by pouring (as in the first measurement). The thickness of the resulting protective coating on the core was controlled and was 1 mm. Figures 7–10 show the course and kinetics of the moisture-migration process in the top layer of the moulding compound.

Increasing the air humidity in the climate chamber to  $H = 80\%$  significantly affected the course of the moisture migration in the surface layer of the moulding sand (Figure 7). The humidification process followed a similar pattern. In this measurement, the moisture also penetrated very quickly into the sand layers to the depths of up to 5 mm. In contrast, the process was slower and did not reach maximum wetting for the measurements at the depths of 8, 12, and 16 mm. The minimum resistance that was reached at these points was greater than 0. The first difference for this measurement was due to the fact that the diluent penetrated the mass to the depth of 20 mm. The graph that shows the start and end of the wetting process looks similar (Figure 8). For the measurements that were carried out at the depths of 1–8 mm, the wetting process practically started when the coating was applied to the core. For the measurements at the depths of 12–20 mm, however, delays in the starts of the humidification could be observed; these were greater the deeper that the measurements were carried out. The end of the humidification also depended on the depth of the measurement; the deeper the soil, the longer the humidification time took for a given layer. Only at the depth of 20 mm was the humidification time of the mass layer shorter than for the depth of 16 mm. The air humidity at  $H = 80\%$  in the chamber did not affect the humidification of the mass layers at the depths of 1–8 mm. The end time of the humidification of these layers was similar to the first measurement (when the humidity in the chamber was  $H = 39\%$ ); however, there were differences for the mass layers at the depths of 12–20 mm. When the air humidity was  $H = 39\%$  at the depths of 12–16 mm, the humidification process ended earlier

than at the depth of 8 mm (Figure 4). However, the humidification process took longer at the depths of 12–20 mm than it did at the depth of 8 mm for the air humidity of  $H = 80\%$ . This meant that the low air humidity above the protective coating accelerated the drying process in the deeper layers of the moulding compound. The moulding compound was humidified less.

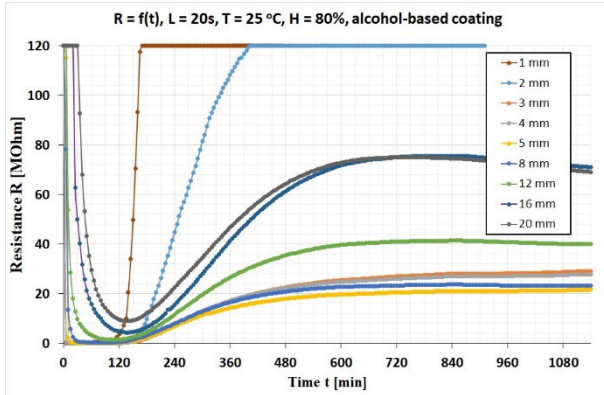


Fig. 7. Moisture-migration process in surface layer of sand mould (coating viscosity  $L = 20s$ , air temperature  $T = 25^\circ C$ , air humidity  $H = 80\%$ )

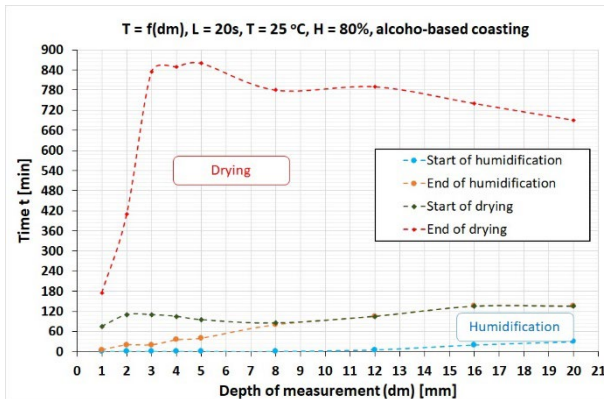


Fig. 8. Course of wetting and drying of moulding sand depending on depth of measurement ( $L = 20s$ ,  $T = 25^\circ C$ ,  $H = 80\%$ )

In the case of the drying process (Figure 7) for the air humidity of  $H = 80\%$ , the course was different to that for the air humidity of  $H = 39\%$ . For the measurements at the depths of 1 and 2 mm, the moisture was completely removed from the moulding compound; however, the diluent was not completely removed for the other measurement points (the depths of 3–20 mm). The maximum resistance that was reached during the measurement was 75 MOhm (for 16 and 20 mm), 35 MOhm (for 12 mm), and about 25 MOhm (for the others). For the moisture to be completely removed, the resistance that was measured at a given point needed to be above 120 MOhm. Figure 8 shows the beginning and end of the drying process; the air humidity of  $H = 80\%$  significantly affected the moisture-removal process from the moulding compound, and it increased the time for the moisture removal from the sand layers at the 1 and 2 mm depths. For the depth of 2 mm, the drying process lengthened by more than two-fold as compared to the measurement at the air humidity of  $H = 39\%$ . For the other measurement points,

the drying process was even longer. For the measurements at the depths of 3–5 mm, it was about 800 minutes; this was several times longer than for the measurements that were carried out at the air humidity of  $H = 39\%$ . At the same time, the end of the drying process that is marked in Figure 8 for the measurements at 3–20 mm does not indicate the complete removal of the moisture from the mass but only the inhibition of the process. The application of a protective coating on the core or mould and the subsequent drying of this coating under high air-humidity conditions may result in the insufficient removal of moisture from the moulding sand.

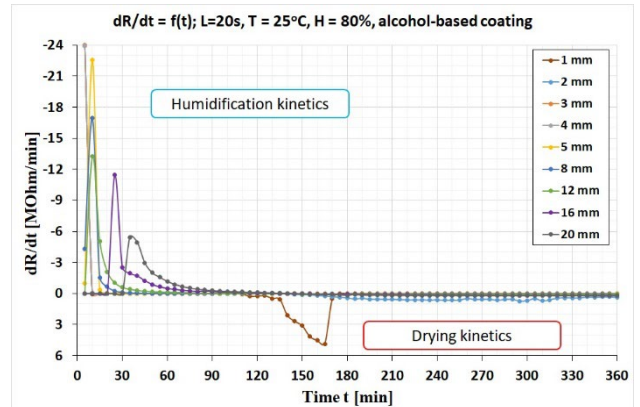


Fig. 9. Kinetics of moisture-migration process in surface layer of sand mould ( $L = 20s$ ,  $T = 25^\circ C$ ,  $H = 80\%$ )

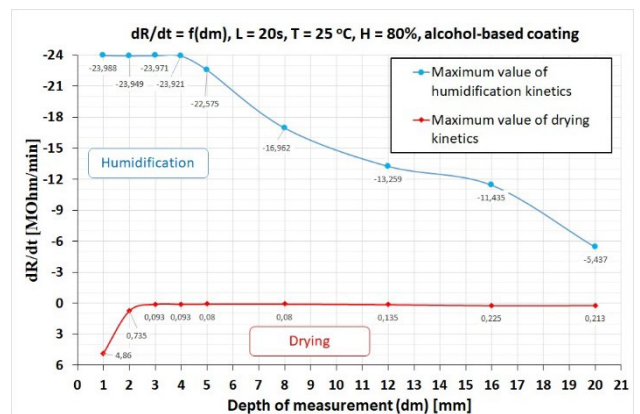


Fig. 10. Maximum value of kinetics of wetting and drying process of moulding compound depending on measurement depth ( $L = 20s$ ,  $T = 25^\circ C$ ,  $H = 80\%$ )

The kinetics of the moisture-migration process in the top layer of the sand mould that is shown in Figures 9 and 10 for the air humidity of  $H = 80\%$  in the chamber was similar to the measurements for the air humidity of  $H = 39\%$ . For the humidification process, the highest value of the kinetics was for the measurements at the depths of 1–4 mm. For the depths of 5–20 mm, the deeper the measurement, the smaller was the value of the kinetics. This change was close to a linear relationship (Figure 10). From this, it could be concluded that the diluent would penetrate the moulding compound to depths of 24–25 mm. This also meant that the rate at which the wetting occurred was dependent on the distance from the moisture source (i.e. the protective coating). In

the case of the drying process, the kinetics of the process were significantly different; the only clear maximum of the kinetics occurred for the measurement at the depth of 1 mm (Figure 9). At this point, the drying-process kinetics was the highest; however, this was nearly three-times lower than the drying-process kinetics for the air humidity of  $H = 39\%$  (Figure 6). This meant that the drying process was slower under high air humidity conditions. When measured at the depth of 2 mm, the maximum of the process kinetics is more difficult to read from the graph, while it is not determinable for the other measurement points (Figure 9). The maximum values of the drying kinetics for the measurements at the depths of 3–20 mm were very small, ranging from 0.08 to 0.21 MOhm/min (Figure 10). The smallest value could be found for the measurements at the depths of 5 and 8 mm. Such a small value of the drying kinetics indicated the very slow removal of the moisture from the moulding compound.

### 3. Summary and conclusions

- After the protective coating has been applied to a mould or core surface, the thinner starts to penetrate the inter-grain spaces of the moulding sand.
- In the first instance, the thinner saturates the inter-grain spaces at the surface very quickly, while it takes time for the thinner to transport into the deeper layers of the sand.
- The thinner can penetrate as deep as 20 mm into the sand.
- The process of removing moisture from a moulding compound takes longer than the wetting process – especially in the compound layers near the surface (up to depths of 8 mm).
- The drying of the protective coating does not mean the complete removal of moisture from the moulding compound; there may still be thinner under the surface at depths of 2–4 mm.
- Low atmospheric humidity above the protective coating promotes shorter migration times (wetting and drying) of moisture into the sand layer and limits the depth of the thinner's penetration.
- High air humidity increases the penetration depth of the thinner into the moulding compound and increases the moisture-migration time. In particular, the process of removing moisture from the sand takes several-times longer than in the case of low air humidity.
- With high air humidity, the diluent is removed from the sand below the surface of the shell up to a depths of 2 mm; deeper down, the drying process is inhibited, and moisture remains in the sand (this can cause casting defects).

### Acknowledgments

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