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Kinetics of Penetration and Drying of Protective Coatings into the sand Mold under Conditions of Variable Porosity of the Mold

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Abstract

This paper presents a study of moisture migration in the surface layer of molding compound during the application and drying of the protective coating. The purpose of the ongoing research is to understand the mechanism of migration, that is, the penetration and drying of moisture from the protective coating applied to the mold or core. Hence, the introduction describes the transport of moisture in porous materials, as well as the process of moisture exchange between the environment and porous materials. In addition, the effects of poor drying of the protective coating applied to the core or mold are presented. In the experiment, a new test rig was used to measure the resistance of the porous medium. The change in resistance of the molding compound occurs due to moisture migration. Test cores were made of molding compound with phenol-formaldehyde resin. To measure the resistance continuously in the mass, electrodes were placed at a depth of 1, 2, 3, 4, 5, 8, 12, 16 and 20 mm. A zirconium alcohol coating was used in the tests. The coating thinner is isopropyl alcohol. The “conventional” viscosity of the coating was determined using a 4mm mesh Ford cup and was 20s. During the study, the course and kinetics of the diluent migration process from the protective coating applied to the core into the top layer of the molding sand were determined, and the effect of the grain size of the sand matrix on the process was determined. Fractionated grain matrix with average grain sizes of 0.20 and 0.63 mm was used to prepare cores. The experiments were conducted under constant climatic conditions. The air temperature was T = 35^{o}C, and the humidity was H = 35%. The research shows that the size of pores has a significant impact on the process of moisture sorption and desorption from porous material. For moulding sand with a grain size of Z=0.20 mm, the drying time is more than four times shorter than for sand with a grain size of Z=0.63 mm.

Key words: Core, Sand mold, Porous medium, Moisture migration, Protective coatings, Resistance measurement

1. Introduction

A molding or core mass is a porous material and has the ability to exchange moisture with its surroundings. The intensity with which moisture is absorbed from the environment or given back to the environment by porous materials depends on several factors. The rate of the process is affected by the relative humidity of the environment, the temperature of the material and the porosity of the material [1,2]. The exchange of moisture between the surroundings and the porous medium is sorption and can occur by the accumulation of moisture on the surface of the material, i.e.

adsorption, or the penetration and dissolution of moisture into the material, i.e. absorption [3-5,30].

Because porous material has a disordered structure, the flow of moisture in such materials varies and proceeds non-uniformly over the full range of material moisture content. The mechanism of moisture movement means that several stages can be distinguished in the sorption process [4,31]. In the first stage, water moves through the movement of water vapor in the vapor-air mixture and surface diffusion. Water transport is caused by the total pressure gradient. At this stage there is low ambient moisture content and water adsorbs on the surface of the porous material [6,7]. In the second stage, there is an increase in moisture in the material, this causes the formation of clusters of liquid called "liquid islands". The pores and capillaries of the medium fill up which reduces the cross-sectional area of the channels. Liquid is transported by evaporation of water on the sides of the "liquid islands" and by condensation [4,7]. The next stage is a further enlargement of the "liquid islands" by the increase of moisture in the porous material. In the transport of liquids, the role of moist air convection and water vapor diffusion becomes decreasingly important and the role of the condensation-evaporation mechanism increases [4,8,28]. The fourth stage is the merging of liquid clusters into liquid strands. Capillary forces cause the movement of the liquid. In the micro-area of the porous medium, moisture equilibrates by increasing mass flux. The porous material reaches a critical moisture content of W^{kr} [4,7]. The last stage is the cessation of capillary motion, and the liquid moves in convective motion. The porous material becomes saturated with water because of exceeding the critical moisture content [4,8,9,27].

The process of removing water from a porous material is called desorption. Desorption occurs when the partial pressure of water vapor on the surface of the porous material is greater than the partial pressure of water vapor in the drying air. The greater this difference is, the more intense the process. When the pressure values, that is, a state of moisture equilibrium is reached, the desorption process stops [10,11]. Drying of materials can be natural or artificial. In the case of natural drying, water vapor spontaneously passes into the atmosphere from the porous material. Two phases can be distinguished in the mechanism of this process: physical evaporation of moisture and convection-diffusion transport from the interior of the material. The intensity of physical evaporation depends on the difference in vapor pressure and air movement over the surface of the material. And, in turn, the intensity of convection-diffusion transport from the structure of the body, i.e. capillary forces of pores of different size and shape [12,13]. The artificial drying process is different, as it is accelerated by the additional heat supplied to the material. The process has three phases. In the first, the material heats up, the temperature of the dried material increases, and the vapor pressure increases, resulting in an increase in the drying rate. In the second phase there is an equilibrium between heat and mass (water) exchange. Drying is at a constant rate until moisture is completely removed from the surface, that is, the critical point of moisture is reached. In the last stage, the drying rate decreases. Drying occurs inside the material; mass transport does not balance heat exchange which slows down the migration of moisture to the surface [14-17,29].

In the foundry industry, the process of drying coatings is carried out by both natural and artificial drying. The choice of natural drying is often determined by its low cost or the simplicity of the process. For large molds or cores, it is practically the only possible form of drying. Long drying times, dependence on weather conditions or little possibility of controlling and controlling the process speak against this solution [17-20].

Casting production is aimed at obtaining a casting with the right parameters without defects. At the boundary between the liquid metal and the casting mold, physical and chemical reactions occur, which can result in the formation of surface casting defects. To counteract this, a protective coating is applied to the surface of the casting mold to improve the quality of the mold surface, which translates into the quality of the casting surface. The protective coating also strengthens the strength of the mold, limits the metal-mold reaction, and reduces the occurrence of burns, pitting, veining and scorching on the casting surface [21,22]. Coatings are applied by various methods, but the most important thing after applying the coating is to dry it to remove the thinner from the coating. Poor drying of the coating, that is, incomplete evaporation of the thinner, can result in defects on the surface or in the top layer of the casting. Punctures, sluggishness, external blistering or plugs are the most common defects of gaseous origin on the casting surface [22-26].

The drying process of protective coatings used in the foundry industry is little recognized. The phenomena of moisture desorption into the top layer of the mold can be studied by several gravimetric, ultrasonic or resistive methods. Of the methods, the resistive method is the best for imaging changes during the diluent soaking and drying process in the surface layer of the molding compound. The method uses the phenomenon of resistance change of the medium after the introduction of electrolyte (diluent) into it, which allows continuously the phenomenon of moisture migration [22,23,26].

This paper presents a study of the penetration and drying (migration) of the diluent from the protective coating applied to the core made of molding compound and the effect of the grain size of the matrix on this process.

2. Experimental procedures and techniques

Studies of the process of moisture migration from the protective coating into the top layer of the molding compound were carried out using the resistance method. Resistance changes in the porous medium, under the influence of moisture changes, were conducted on a core in which 9 pairs of electrodes were installed. A diagram of the electrode arrangement is shown in Figure 1, while the core with the electrodes arranged is shown in Figure 2. The measuring device was calibrated before the measurements, and the resistance measurement error was +/- 0.1 MOhm.

The cores were made of molding compound on a matrix of quartz sand. As a binder, a phenol-formaldehyde resin was used in the amount of 1.2% which was cured with a hardener in the amount of 0.6%. Since the effect of matrix grain size on the moisture migration process will be determined in the study, the quartz sand was sieved for sieve analysis. With this procedure, a sand matrix with a certain grain size was obtained. The sieve matrix with a mesh size of 0.20 mm and 0.63 mm was selected for the study. For the 0.20mm sieve, the matrix grains range in size from 0.20 to 0.32mm, while for the 0.63mm sieve they range from 0.63 to 0.80mm.

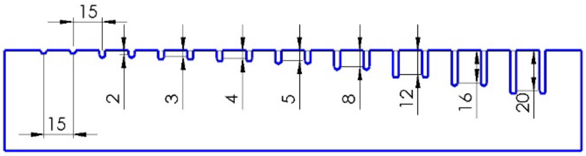

Fig. 1. Schematic of electrode arrangement in the test core

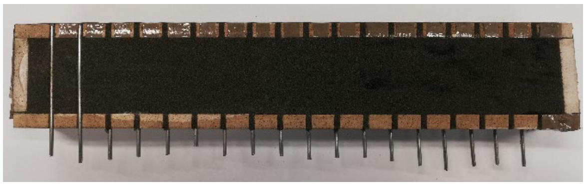

Fig. 2. Test core with electrodes mounted

A protective coating was applied to the prepared core. An alcoholic zirconia coating with kinematic viscosity was used for the tests:

- $\nu = 61 \cdot 10^{-6}\ m^2/s$ (conventional viscosity 20 s);

The coating thinner is isopropyl alcohol. The protective coating on the core was applied by pouring - the thickness of the resulting layer on the core was controlled, uniform and 1mm. The core with the coating applied was placed in a climate chamber. The humidity in the chamber was 35% and the temperature was 35 ^{o}C.

During the study, the course and kinetics of the process of moisture migration in the top layer of the core after the protective coating was applied to it and the effect of the matrix grain size on this process were determined.

3. Results of investigations

First, moisture migration studies were carried out into the top layer of the molding compound core on a matrix with a grain size of Z=0.20mm. Figures 3-6 show the course and kinetics of the process of soaking and drying of the thinner from the alcohol protective coating. The protective coating was applied to the core by pouring. The coating layer thus formed on the core was 1mm. The core was then placed in a climate chamber so that the external conditions of conducting the experiment were stable and uniform during the test. The temperature in the chamber was T=35 oC, and the humidity was H=35%.

Figure 3 is the course of the penetration and drying of the diluent in the top layer of the core. The measurement was carried out continuously at a depth of 1 mm to 20 mm. Initially, the dry core - without a protective coating applied - has a resistance of more than 120 MOhm. As the thinner from the protective coating begins to penetrate the intergranular spaces the resistance of the core begins to decrease. We can divide the process of resistance change in the core into three phases. 1 phase is an intensive decrease in resistance - hydration of the core. 2 phase stabilization of the resistance value - transition stage. 3 phase increase in resistance - drying of the core.

For electrodes placed at a depth of 1-5 mm, the wetting process occurs very quickly. Practically one minute after the coating is applied to the core, the ground resistance at these measuring points is at 1 MOhm, which means that the area has saturated with the diluent. In the case of measuring points placed at a depth of 8 - 20 mm, the wetting process is slower. Only after about 60 minutes at these points the core resistance is at a level below 1 MOhm. Obtaining such a low core resistance at a depth of 20 mm suggests that the diluent has penetrated deeper into the molding compound. The desorption process begins most quickly with an electrode placed at a depth of 1 mm in the mass. Desorption is illustrated on the graph by an increase in resistance. The fastest maximum resistance is reached by measurement at a depth of 1 mm. This electrode is partially placed in the molding compound and partially immersed in the protective coating. Obtaining the maximum resistance after about 120 minutes may indicate that the thinner has been removed from the protective coating, and there is still moisture in the molding compound. For other depths, the moisture removal time is much longer. The fastest moisture is removed from a depth of 20 mm, at about 180 minutes, and the slowest from a depth of 3 mm, at about 230 minutes.

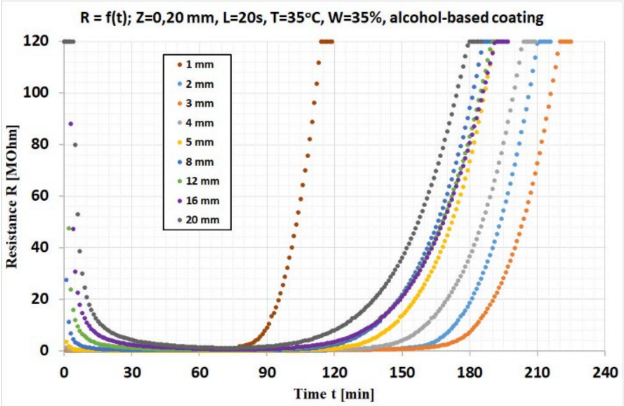

Fig. 3. The course of the process of moisture migration in the surface layer of the sand mold, matrix grain size Z=0.20mm, coating viscosity L=20s, air temperature T=35 ^{o}C, air humidity H=35%

To better illustrate the process of sorption and desorption of the diluent in the core, Figure 4 was made. The figure illustrates the beginning and end of the wetting and drying process depending on the depth of the measurement. In the graph the beginning of the hydration processes up to a depth of 8 mm is practically immediate, that is, immediately after the coating is applied to the core. On the other hand, for greater depths (12,16,20 mm) it is slightly delayed, and with depth the hydration process starts later. This is due to the time required for fluid transport. The end of the humidification process in each mass layer, i.e. reaching the maximum moisture content, is not immediate. The humidification process ends most quickly at a depth of 1mm, after only about 12 minutes. The deeper it gets, the longer the humidification time. At a depth of 8mm, the humidification time is 78 minutes. For the remaining depths, namely 12,16 and 20 mm, the end of the hydration of the mass occurs around 78 minutes of the process. For measurements at a depth of 1 - 8 mm, a transitional phase in the moisture migration process can be observed. The fastest onset of the drying process begins in the near-surface layers, that is, at a depth of 1 mm. The deeper the desorption process begins later. The greatest delay occurs in the layer at a depth of 4 mm. For layers at a depth of 8 - 20 mm, a smooth transition from sorption to desorption (no transition phase) can be observed. This suggests that full hydration has not occurred in these layers. The end of the drying process for the 8 - 20 mm depth occurs after about 190 minutes. On the other hand, for measurements at a depth of 2 - 5 mm, the desorption process takes longer at about 225 minutes (depth of 3 mm). In the case of measurements at a depth of 1 mm, the end of the drying process occurs much faster than at the other measurement points, because after only 120 minutes of the process. This means that the protective coating is already dried when there is still moisture under the surface in the molding compound. Pouring the mold when moisture has not been completely removed from the molding compound can result in surface defects or gas origin in the casting.

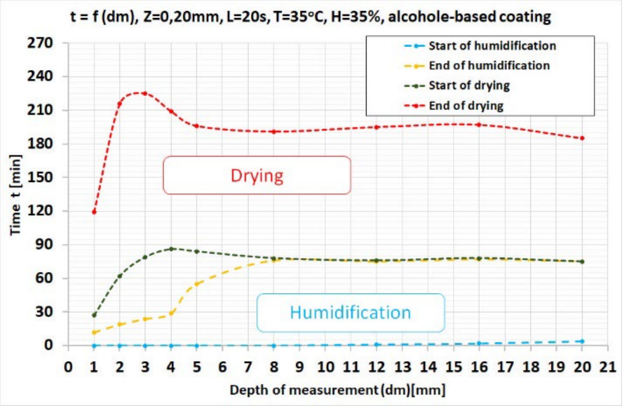

Fig. 4. The course of wetting and drying of the molding compound depending on the depth of measurement. Z=0.20mm, L=20s, T=35^{o}C, H=35%

Figures 5 and 6 show the kinetics of the moisture migration process. By observing the kinetics, we can learn at what rate the process of moisture sorption and desorption occurs. Analyzing Figure 5, for measurements at a depth of 1 - 8, the kinetics of the moisture process have the highest value right at the beginning of the process and decrease with time. The minus next to the value indicates the direction of the process, that is, the penetration of the diluent into the mass. In the case of measuring points at a depth of 12, 16 and 20 mm, the course of changes in kinetics is a little different. In the first phase, the kinetics of the process increase until they reach a maximum and then begin to decrease. At the same time, it can be noted that the deeper the measurement is carried out, the maximum value of kinetics is smaller. When the value of the kinetics of the wetting process decreases to 0, it means that the mass has saturated with moisture, or the wetting process has been stopped, and the drying process begins. In the case of drying process kinetics for all measurement points, it looks similar. The drying kinetics increase slowly until they reach a maximum and then decrease to zero. A value of 0 in this case indicates the end of the drying process. The maximum of the drying kinetics for all points is at a similar level of about 4 MOhm/min but is at the same time several times smaller than the maximum of the wetting kinetics. In addition, the time after which the drying process reaches the maximum is much longer, which means that the course of the drying process is slower than the process of moistening the molding compound. It takes the longest time for the kinetics to reach their maximum for measurements at a depth of 2, 3 and 4 mm. For measurements at a depth of 1 mm, the maximum of kinetics is about 2 times greater than for the other measurement points.

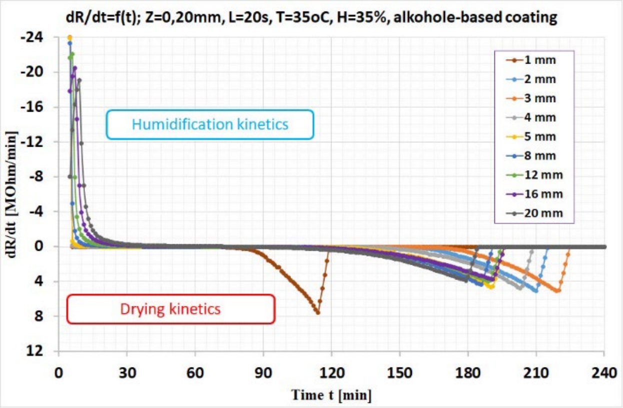

Fig. 5. Kinetics of the moisture migration process in the surface layer of the sand mold, Z=0.20mm, L=20s, T=35^{o}C, H=35%

In turn, Figure 6 illustrates the change in the maximum value of the kinetics of the wetting and drying process of the molding compound depending on the depth of measurement. Analyzing the graph, in the case of the humidification process, the maximum of kinetics decreases with the depth of measurement. And in the range of measurement points at a depth of 5 - 20 mm, the decrease in the maximum of kinetics is close to linear. A similar situation occurs with the kinetics of the drying process. Here, too, a decrease in the value of the maximum of kinetics can be observed with increasing depth of measurement. In the range of measurement points at a depth of 2 to 20 mm, the nature of the changes is close to linear.

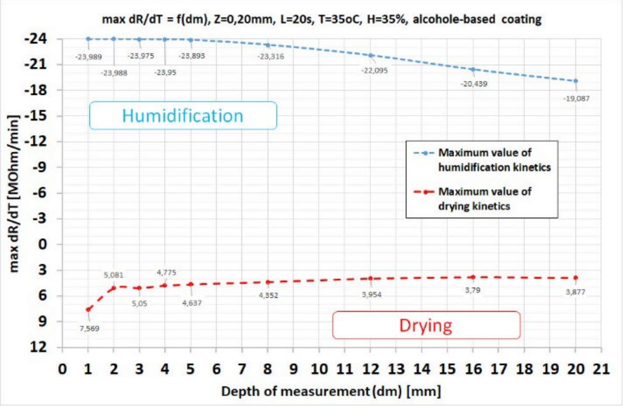

Fig. 6 Maximum value of the kinetics of the process of wetting and drying of the molding compound depending on the depth of measurement. Z=0.20mm, L=20s, T=35^{o}C, H=35%

Another measurement of the process of sorption and desorption of moisture into the top layer of the core was carried out for a mass on a matrix with a uniform grain size of Z = 0.63 mm. The procedure for preparing the core, applying the coating and conducting the measurement was identical to that for the core on a matrix with grain size Z = 0.20 mm. Figures 7 - 10 show the test results.

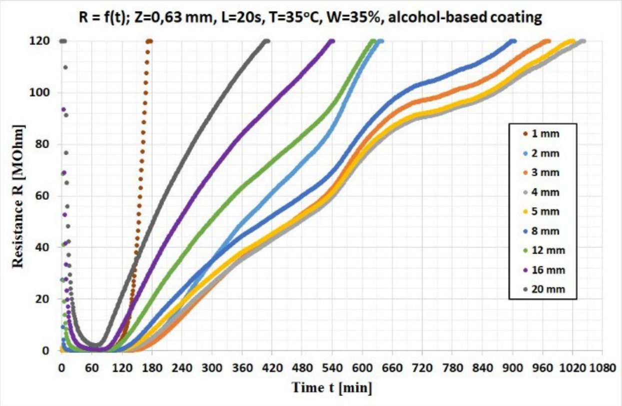

Fig. 7. The course of the process of moisture migration in the surface layer of the sand mold, matrix grain size Z=0.63mm, coating viscosity L=20s, air temperature T=35^{o}C, air humidity H=35%

Figure 7 shows the course of the moisture migration process. As in the previous measurement (Figure 3), in this case the process of moistening the molding compound is very fast. In the case of measurements at a depth of 1 - 5 mm, it occurs practically immediately. Very quickly these layers become saturated with thinner. At the other measurement points of 8, 12, 16, 20 mm, the wetting process takes longer, about 70 - 80 minutes. Particularly noteworthy are the measurements at a depth of 16 and 20 mm. The minimum resistance obtained during the measurements was not lower than 2 MOhm, which means that at these depths the pores have not become saturated with moisture. Hence it can be concluded that with a larger matrix grain size, and thus a larger pore diameter, the penetration of moisture into the molding compound is hindered. The drying process is also different. The drying time of the mass on a matrix with a grain size of Z = 0.63 mm is much longer than that of the mass with a matrix with a grain size of Z = 0.20 mm.

Figure 8, on the other hand, shows the beginning and end of the humidification and drying process depending on the measurement depth. Analysing the graph, the start of the humidification process is practically instantaneous for all measurement points. On the other hand, the time after which the end of the humidification process is determined depends on the measurement depth; the deeper the measurement, the longer the process takes. For measuring points at a depth of 1 - 8 mm, a transition phase in the process can be observed, after which the drying process begins. In contrast, at points 12 - 20 there is a smooth transition from wetting to drying. The time after which the drying process ends is strongly dependent on the depth of measurement. The longest drying process takes place at a depth of 4 mm and is more than 1,000 min. In the 4 - 20 mm depth range, the drying time decreases as the depth increases. In contrast, the drying process is fastest at a depth of 1 mm. The drying process consists of physical evaporation of moisture and convection-diffusion transport from within the material. The intensity of convection-diffusion transport depends on the structure of the material, i.e. the capillary forces of the pores. The size of the pores depends on the size and shape of the matrix grain. Hence, it can be concluded that with larger matrix grains, the capillary forces of the pores are smaller, i.e. the intensity of convection-diffusion transport of moisture will be lower, which translates into longer drying times.

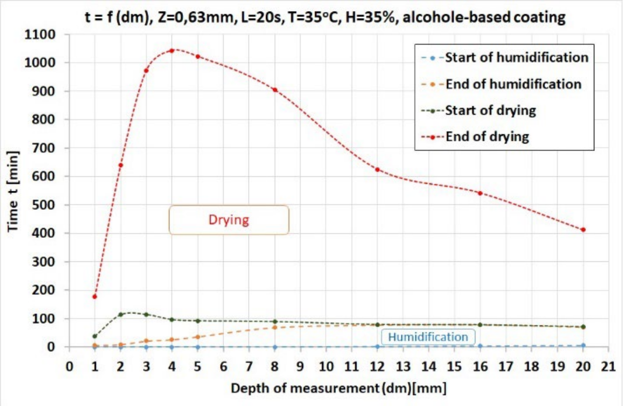

Fig. 8. Course of wetting and drying of moulding sand depending on the depth of measurement. Z=0.63mm, L=20s, T=35^{o}C, H=35%

Figure 9 illustrates the kinetics of the wetting and drying process at the individual measuring points. In the case of the wetting process, for measurement points at a depth of 1 - 8 mm, the kinetics reach a maximum practically at the start of the process and then decreases to zero. On the other hand, for measuring points at a depth of 12 - 20 mm, the kinetics of the process increase until it reaches a maximum and then decreases to 0. In the case of the drying process, the only clear maximum of the kinetics is observed when measuring at a depth of 1 mm. For the other measurement points, the value of the kinetics maximum is very small. To better illustrate the maximum value of the kinetics of the wetting and drying process at the individual measuring points, a graph was made in Figure 10.

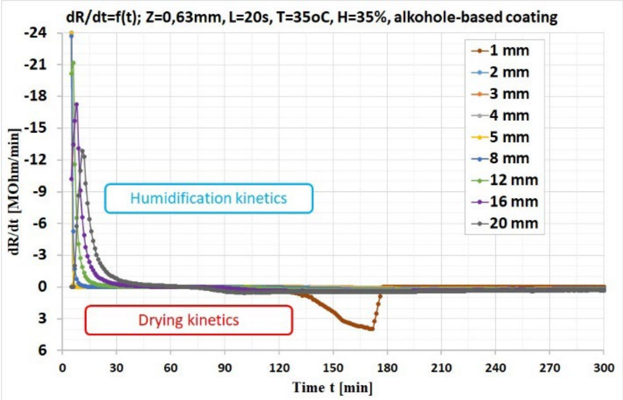

Fig. 9. Kinetics of the moisture migration process in the surface layer of the sand mould, Z=0.63mm, L=20s, T=35^{o}C, H=35%

Analysing Figure 10, it can be seen that in the case of wetting of mass on a matrix with grain size Z = 0.63mm for measurement points at a depth of 1 - 5 mm, the maximum of the kinetics of the penetration process has a similar value of almost 24 MOhm. In contrast, for measurements at a depth of 8 - 20 mm, the maximum of the kinetics of moisture ingress decreases linearly with increasing measurement depth. This means that the deeper one goes, the lower the rate of wetting of the mass, i.e. there is a limiting depth of diluent penetration. In the case of the drying process, for measurement points at a depth of 4 - 20, a linear increase in the maximum of the drying kinetics can be observed as the measurement depth increases. However, these changes are not large. For the measurement at a depth of 4 mm, the maximum of the kinetics is 0.282 MOhm/min and for the measurement at a depth of 20 mm it is 0.554 MOhm/min. The highest drying intensity is at a depth of 1 mm and is 3.971 MOhm/min.

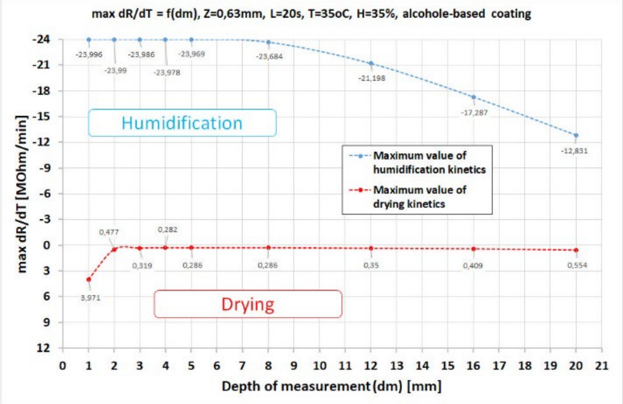

Fig. 10. Maximum value of the kinetics of the wetting and drying process of the moulding compound depending on the measurement depth. Z=0.63mm, L=20s, T=35°C, H=35%

4. Summary and conclusions

- After the protective coating has been applied to the mould or core surface, the thinner starts to penetrate the inter-grain spaces of the moulding sand.
- In the first instance, the thinner very quickly saturated the inter-grain spaces right at the surface, while transport of the thinner into the deeper layers of the sand takes time.
- The thinner can penetrate as deep as 20 mm into the mass.
- The rate at which the diluent penetrates the inter-grain spaces depends on the size of the pores, the size of which is determined by the grain size of the matrix. The maximum value of the penetration kinetics at a depth of 20 mm for a matrix grain size of 0.20 mm is 19.080 MOhm/min and for a matrix grain size of 0.63 mm is 12.831 MOhm/min. That is, it is 1/3 smaller for the larger grain.
- The process of removing moisture from the moulding sand takes longer than the wetting process, especially in the sand layers near the surface - up to 8 mm.
- Drying of the protective coating does not mean complete removal of moisture from the moulding sand, there may still be thinner beneath the surface at a depth of 2 - 4 mm.
- Pore size significantly influences the drying process. The maximum kinetics of the drying process for a mass on a matrix with a grain size of 0.20 mm is many times greater than for a mass on a matrix with a grain size of 0.63 mm. For a Z=0.20mm matrix, the maximum kinetics, depending on the measurement depth, are between 5.081 and 3.817 MOhm/min. In contrast, for a Z=0.63 mm matrix, the maximum kinetics, depending on the measurement depth, is between 0.282 and 0.554 MOhm/min.
- The time after which the diluent was completely removed from the moulding compound for the Z=0.63mm matrix is more than 1000 min, while for the Z=0.20mm matrix it is more than 210 min.
- The longer desorption time of the diluent from the moulding compound is due to the convection-diffusion mechanism of moisture transport from within the porous material. The intensity of this transport depends on the capillary forces present in the pores. The larger the pores, the smaller the capillary forces, i.e. the intensity of transport is lower.
- The use of a moulding compound with a larger matrix grain improves permeability, which is advantageous because it facilitates the discharge of gases from the casting mould. However, the longer drying time of the protective coating, or more precisely of the thinner from moulding sand, must be considered in the technological process.

Acknowledgments

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