DYNAMICS OF THERMAL AND MOISTENING FRONTS IN POROUS MATERIAL UNDER CAPILLARY MOISTENING

by

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Infrared thermography and gamma-ray method were used to experimentally study motion of thermal and moistening fronts in a porous material under capillary moistening. It is shown that at capillary moistening propagation of the moistening front may be accompanied by the thermal front due to sorption processes. On the basis of obtained experimental data the relation between propagation of two fronts has been established.

Key words: *heat transfer, porous materials, thermal effect, moisture, infrared thermography*

Introduction

At moistening of porous materials there are physical processes accompanied by variation of surface temperature, namely evaporation, a process proceeding with heat absorption, and vapor condensation and sorption occurring with heat release. The analysis shows that these processes develop depending on the characteristics of porous-structure of the material, its humidity, and temperature. For instance, under certain conditions moistening of dry porous material may result in significant increase of its temperature. This thermal effect results from possible water-vapor sorption in dry porous material subjected to moistening that goes along with heat release. Normally, heat release at physical sorption is insignificant; however, in some microporous materials used in industry and, in particular, power industry, the thermal effect can be quite pronounced [1, 2].

Porous media are widely used in many processes and apparatuses: in drying and moistening of materials [3, 4], in thermal insulation of building structures [7, 8], in heat and mass exchangers [5, 6], heat pumps [9, 10], heat pipes [11], *etc*. Thus, investigation into sorption processes and related thermal effects in porous media is of much scientific interest, besides, the data gained in such studies have many applications. For modeling of the phenomena there is a need in simple yet efficient calculation models for heat- and mass-transfer processes whose verification in turn requires a reliable experimental database. That is why experimental studies of heat- and mass-transfer processes proceeding in porous materials under moistening are rather topical now.

In experimental studies of heat- and mass-transfer processes in porous materials wide opportunities are offered by contactless methods. Such methods allow for non-destructive measurements and exclude inaccuracies caused by material structure disturbances. For ivnestigation

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of mass transfer processes in porous materials such contactless methods, as nuclear magnetic resonance technique [12-14], neutron radiography [15, 16], and gamma-ray method [17] are widely used.

The most promising contactless method for studying thermal characteristics of materials is infrared (IR) thermography method [18, 19]. In spite of the large number of works employing this method, there are several research areas where it has been used insufficiently actively. In addition, this applies to the study of combined heat- and mass-transfer processes in porous materials. In particular, this method may become an efficient tool for studying specific features of heat generation processes in porous materials conditioned by sorption, and, besides, for investigation of thermal-front dynamics in porous media with phase transitions.

Experimental methods

The experiments investigating thermal processes that accompany capillary moistening of porous material were performed in the stand which diagram is shown in fig. 1. The experimental stand included a reservoir with distilled water where samples of porous material sized 10(a) × 100(b) × 100(h) mm were placed. The samples soaked with water were in advance dried until reaching their fixed mass. The side surfaces of the samples were made impermeable to moisture with the use of a thin heat-conducting film. The experiments were conducted at fixed temperature and fixed humidity of ambient air (t_{air} = 24 °C, φ = 30%). Initial temperatures of the sample and water were identical, t = 22 °C.

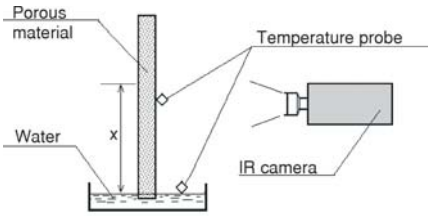

Figure 1. Experimental arrangement used to examine the thermal processes proceeding in the porous material under capillary moistening

The heat-transfer processes were examined using the contactless IR thermography method. Gained information about temperature distribution over the sample surface at different times enables application of this method to studying non-stationary thermal processes. The distribution of surface temperature was measured with a NEC TH 7102WV IR camera operating in the LWIR spectral region (8-14 μm). At 30 °C the temperature sensitivity of the instrument was 0.03 °C. The camera allowed registering temperature distribution at 60 Hz frame rate.

The experimental procedure used to examine the heat-transfer processes during capillary moistening of the sample was as follows. The lower surface of the sample was brought in contact with the water surface while the upper surface contacted the ambient air. So, the moisture transfer process proceeded in upward direction. It was considered that the experiment started when the lower surface of the sample was brought in contact with the water surface. In the course of the experiment, the IR camera was used to register thermograms on one of the side surfaces of the sample at 5 second intervals. For more accurate calibration of the measured thermograms the surface temperatures at several points on the sample surface were measured with thermocouples. In the course of the experiment the water and air temperatures, as well as air humidity were continuously monitored.

The moisture-transfer processes in the porous material under capillary moistening were examined using the contactless gamma-ray method [17]. The essence of the method is to determine moisture distribution in the material on the attenuation of gamma beam intensity. The inaccuracy in determination of relative mass moisture content of the material with this method was $\Delta W_m = (12\ W_m + 1)\cdot 10^{-3}$.

The experiments aimed at examination of moisture-transfer processes at capillary moistening were carried out similarly to the ones studying heat-transfer processes (fig. 1). Here, instead of IR camera a gamma densimeter was used to determine moisture profiles in the material. A more detailed description of the experiments employing gamma densimeter and the used experimental and data-processing procedure may be found in [17].

Experimental results and discussion

Structure of porous material

In our experiments, the porous material was steam-cured foam concrete with 600 kg/m^3 density and 80% total porosity. The main structure-forming component in the concrete is tobermorite containing a small amount of hydrosilicate and hydroaluminate additives [20]. The rate and pattern of heat- and mass-transfer processes in porous materials is largely defined by the porous structure of the samples; therefore, to analyze the transfer characteristics of the foam concrete, we examined the porous structure of our samples.

The distribution of coarse pores with radius $r > 10^{-4}$ m was examined by optical microscopy, whereas the distribution of fine pores with radius $r < 10^{-4}$ m, by the mercury porometry method [21]. The differential size distribution of pores is shown in fig. 2.

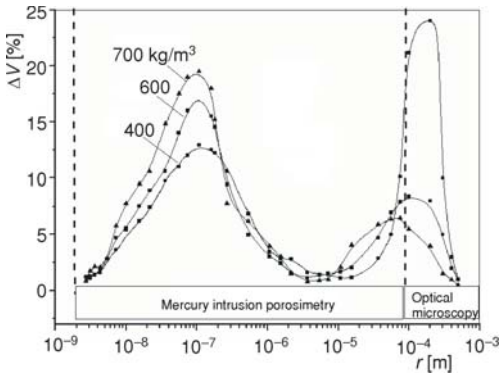

Figure 2. Differential size distribution of pores in the foam concrete

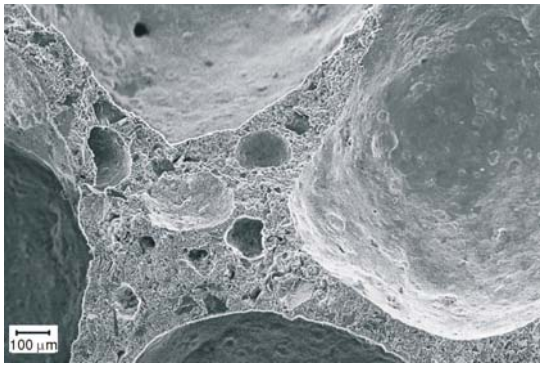

Figure 3. Photomicrograph of a concrete sample taken at 200× magnification

The porous structure of the foam concrete had a bimodal size distribution into large voids ($r \approx 10^{-4}$ m) and micropores ($r \approx 10^{-7}$ m), the latter pores being contained in the walls of the large voids [22]. The porosity of the concrete samples was assumed interrelated since the inter-void walls were pierced with micropores. This is fairly illustrated by the photomicrograph of the foam concrete shown in fig. 3.

Thermal effects

A typical thermogram taken from the side surface of the sample is shown in fig. 4; there the temperature field was obtained one minute after the experiment started. At that time, in the lower part of the sample a cool region with temperature reduced to 20.5 °C was observed. At the height of 5 mm from the lower surface the temperature showed an abrupt increase to 34 °C over the entire side surface and, then, with increasing co-ordinate x the temperature gradually

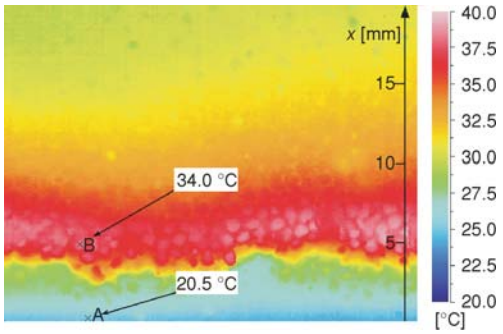

Figure 4. Thermogram taken from the side surface of the sample one minute after the beginning of moistening
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decreased to the initial value. Thus, despite isothermal experimental conditions the temperature distribution during capillary moistening became non-uniform over the height of the sample.

The obtained thermograms were used to determine the temperature distribution over the height of the sample at different times from the beginning of the moistening procedure (fig. 5).

As it follows from the measuring data, during the capillary moistening of dry porous material the temperature profile varied over the height of the sample in the course of time. Consider the temperature profile obtained one minute after the beginning of moistening. From the data shown in fig. 5 it may be inferred that, in the course of time in the bottom part of the sample temperature decreased to a certain extent compared with initial value. This may be explained by evaporation process taking place in particular region of the sample and resulting in the sample cooling. At the height of 8 mm, an abrupt increase of temperature to 34 °C was observed, since in that region there was an intense sorption moistening of the material, accompanied by heat release. Further over the height of the sample the surface temperature showed gradual reduction to a value close to the ambient temperature.

From the temperature profiles in fig. 5 it is seen that in time the maximum temperature in the sample decreased, and the cross-section at which this temperature was observed shifted upwards in the sample. For instance, three minutes after the beginning of capillary moistening

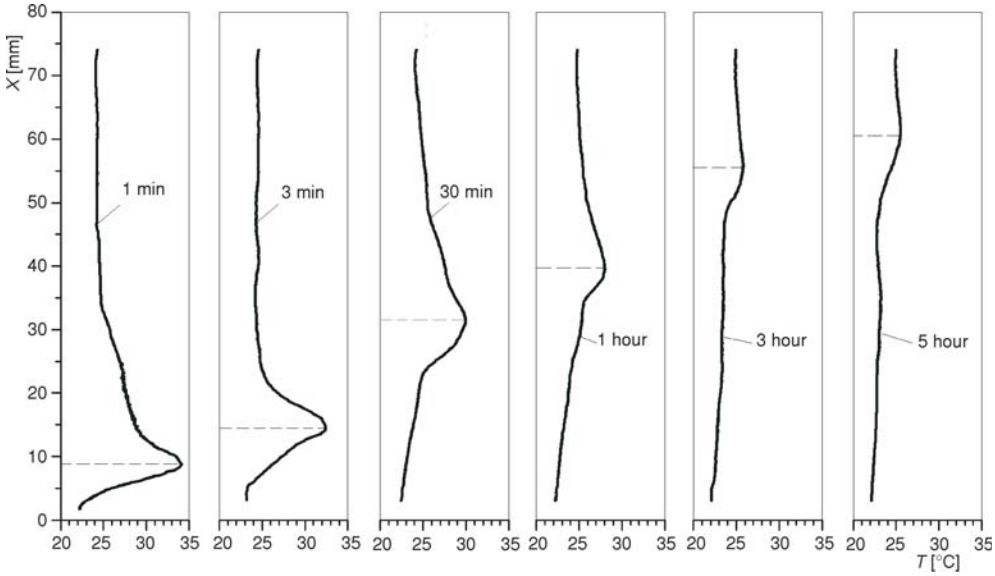

Figure 5. Temperature distribution over the height of the sample at different times after the beginning of moistening

the maximum temperature over the height of the sample was 33 °C; this temperature was observed at the distance of 15 mm from the lower side of the sample. In three hours the maximum temperature equaled 25.5 °C and was observed at the distance of 55 mm from the lower surface of the sample.

Thus, during sample moistening the water ascended upwards in the material pore system. At that, ahead of the liquid-moisture front evaporated water vapor moved. This vapor was sorbed by pore walls resulting in heat release. Hence, ahead of the moving moistening front a thermal front propagated. The formation of a thermal front due to sorption processes in porous materials was earlier noted in [21, 22]. However, until now this phenomenon was not observed during capillary moistening of such materials.

To clarify the mechanism of thermal effect observed in the experiment we performed several additional experiments at different water and sample temperatures ranging from 20 to 30 °C. In all those experiments similar thermal effects were observed.

In addition, experiments were repeatedly performed with the same samples of the porous material that were preliminarily dried and, then, used again for capillary moistening. During drying all the moisture having penetrated into the material during the previous experiment freely left the sample. Thus, the water molecules in the material were in a free state, and they were not chemically bound to the material. Hence, in the experiments on capillary moistening we observed a thermal effect caused by physical (and not chemical) sorption.

The thermal effect is clearly manifested in the graphs illustrating the variation of temperature in time at different heights in the sample (fig. 6).

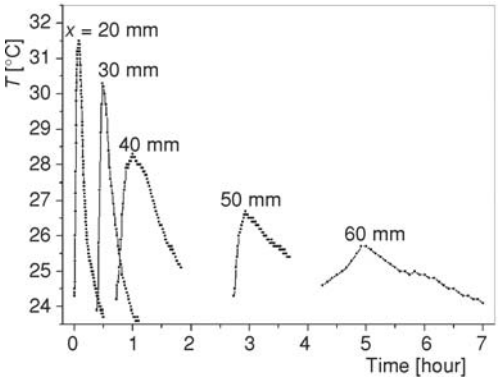

Figure 6. Variation of temperature in time at various heights in the sample

The experimental data show that the temperature at the cross-section located at a height of 20 mm from the lower surface of the sample started sharply increasing already in several seconds after the experiment started; and approximately 400 seconds later the temperature reached its highest value, t = 31.5 °C. Then, the temperature at this cross-section decreased to the initial value of t_{air} = 24 °C. Most likely, the reduction of the maximal temperature observed as the front propagated upwards in the sample was due to redistribution of heat and related heat losses occurring in the sample, as well as due to the gradually decreasing intensity of sorption processes.

Previously in [23] for the porous material used in the present study a sorption diagram presenting the dependence of mass moisture content on the relative humidity of ambient air at temperature 20 °C was obtained. Figure 7 shows a fragment of the sorption isotherm. In the isotherm, one can identify an initial area where the moister content of the material rap-

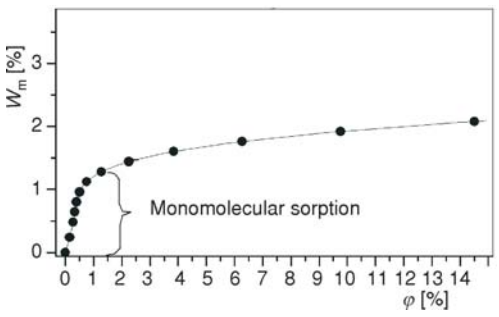

Figure 7. Sorption isotherm for foam concrete with 600 kg/m^3 density

idly grows in value from 0 to 1-1.5% that is typical for monomolecular sorption regime. According to [24, 25] at monomolecular sorption the absorption of moisture is accompanied by the most intense heat release inside the material. As further moistening proceeds, a stage of polymolecular sorption begins; during this stage the rate of heat release significantly diminishes. Thus, in the porous material under study the most intense heat release due to sorption processes should be expected in the region where 1.5% moisture content is reached.

Moistening-front propagation

Moisture profiles over the height of the sample under capillary moistening at different times obtained by the gamma-ray method are shown in fig. 8. The data show that one hour after the beginning of the material moistening the moisture content at the height of 40 mm was about 1.5%. Hence, according to the sorption isotherm (fig. 7), at this cross-section and at that time the most intense release of heat due to monomolecular sorption processes may be expected. This is proved by the data on temperature distribution shown in fig. 5; according to these data one hour after the beginning of moistening the maximum temperature was observed at a height of 40 mm. In a similar way, for the times of three and five hours after the beginning of the moistening procedure cross-sections with W_m = 1.5 % were found coincident with the cross-sections at which the maximum temperature was observed.

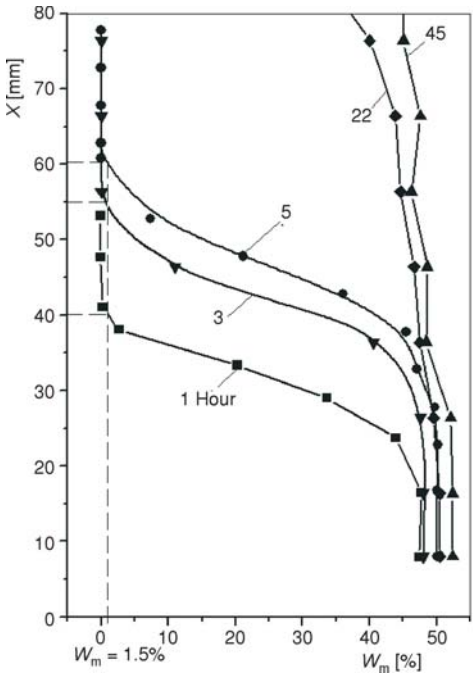

Figure 8. Moisture profiles over the height of the sample under capillary moistening at different times

More detailed data on the variation of moisture content in time at several cross-sections in the bottom part of the sample are shown in fig. 9. It is seen that in 380 seconds after the beginning of moistening at the cross-section x = 20 mm the moisture content reached a value W_m = 1.5 %. Indeed, according to the data of fig. 6 at that time the maximum temperature was observed at the indicated cross-section.

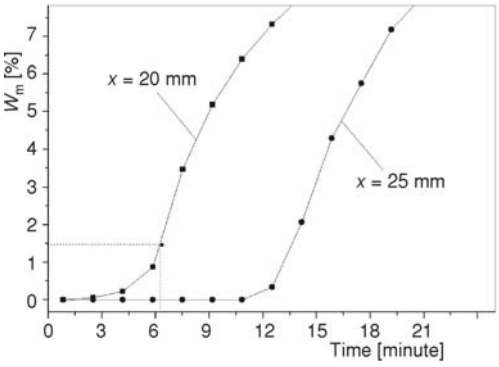

Figure 9. Variation of moisture content in time at different cross-sections in the material subject to capillary moistening

The experimental data on the position of the temperature maximum and the co-ordinate where the moisture content was W_m =1.5% over the height of the sample at different times are shown in fig. 10. These data characterize the propagation velocity of the thermal and moistening fronts in the material under capillary moistening. It is seen that the co-ordinate of tempera-

ture maximum was fairly well coincident with the position of the moistening front at $W_m = 1.5$ %. This finding conclusively proves that the experimentally revealed thermal effect resulted from heat release due to sorption processes. Besides, from fig. 10 it may be inferred that the propagation velocity of the thermal front showed considerable changes as the front moved upwards in the sample. The magnitude of this velocity is determined by the sloping angle of the line tangent to the curve generalizing the experimental points in fig. 10. As it can be deduced from the figure, the thermal-front propagation velocity was maximal at initial times, when the front propagated in the lower part of the sample and then, as the front ascended higher, its propagation velocity exhibited a substantial reduction.

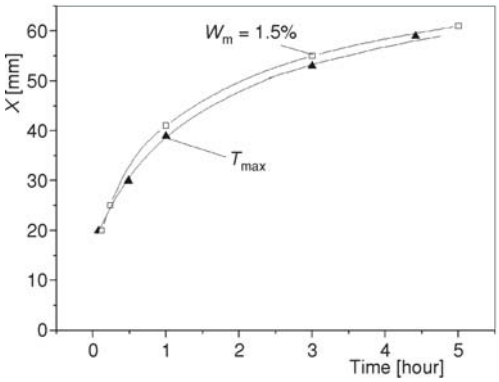

Figure 10. Variations of the position of the cross-sections where the maximum temperature and moisture content W_m = 1.5% were detected

Conclusions

The performed investigation showed that the IR thermography and gamma-ray methods used in the present study offer a high potential in experimental studying thermal and diffusion processes proceeding in porous media. They have rather high sensitivity and allow quick investigation into the processes of interest.

The experimental study has resulted in the data on temperature and moisture content variation in time in the porous material under capillary moistening. The obtained data prove that propagation of the moistening front in the sample is accompanied by propagation of the thermal front due to sorption processes.

Based on practical coincidence of the positions of the moistening and thermal fronts we have concluded that the found thermal effects are bound with sorption processes. It is shown that the propagation velocity of the thermal and moistening fronts significantly decreased over the sample height along with their propagation from the water surface.

Acknowledgments

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Nomenclature

r – pore radius, [m]
T – temperature, [°C]
t – time
W_m – relative moisture content of the material, [%]
ΔV – volumetric fraction of pores in the material, [%]
x – spatial co-ordinate, [m]
φ – relative humidity of air, [%]

Subscripts

m – mass

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