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Materials

An experimental study of temperature and moisture content of wet porous materials under short-pulsed laser heating

Renxi Jin[1,2) and Xiulan Huai[2)

1) Nuclear Power Teaching Unit, Naval Submarine Academy, Shandong 266071, China
2) Institute of Engineering Thermophysics, Chinese Academy of Science, Beijing 100080, China
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Abstract: The measurements of temperature and moisture content of a wet porous material were accomplished on the micro-seconds scale. The temperature wave was observed when the wet porous material was heated by short-pulsed laser with high power. It firstly revealed that the moisture content of wet porous material rapidly rises twice in one laser irradiation. The influences of laser parameters, the thickness and initial moisture content of the wet porous material on its temperature and moisture content were investigated.

Key words: porous material; transient measurement; temperature; moisture content; short-pulsed laser

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1 Introduction

Porous materials are ubiquitous. Soil, rock, sand, cement and concrete are all significantly porous, and almost all biomaterials are porous. Porous materials can be subdivided by whether they are hygroscopic or non-hygroscopic or by dimensions. The porous materials whose pore radiuses are of order $0.5\times10^{-9}\text{m}<r<10^{-7}$ m are called micro-capillaries, and the porous materials whose pore radiuses are greater than 10^{-7} m are called macro-capillaries. The porosity of porous materials varies between 0 and 1 due to their different inner structures.

The temperature and moisture content of a wet porous material play an important role in the exploration of geothermal energy, thermally enhanced oil recovery, protection and utilization of underground water resource, precaution of coal self-burning, safe operation of nuclear fuel, safe underground nuclear waste disposal, foundry, heat pipe, food storage and high-efficient drying [1-3]. It has a broad applied background, and it is also the growing point of cross and brink sciences. The temperature and moisture content of a wet porous material are very complicated, and there are many difficulties in its development in theory and experiment [4-6]. With the progress of science and technology, the high-efficient drying such as impinging stream drying, impinging jet drying and pulsed laser drying is coming into use [7]. Its feature is short time lasting, high intensity and complicated process, which induces more difficulties in theoretical and experimental analyses. Compared to normal drying, the wet porous material under high-intensity and transient heating has different characteristics. Investigations on this field have an important academic significance, and it plays important roles in high-tech fields such as high- efficient drying.

In this paper, the temperature and moisture content of the wet porous material under short-pulsed laser heating with high intensity were investigated *via* platinum resistor and pulsed electric conductance method with high-sampling rate. The measurements of temperature and moisture content of the wet porous was accomplished on the microsecond scale, to find the new phenomena of heat and mass transfer in the wet porous material, and it laid the theoretical and experimental foundation on subsequent investigations.

2 Experimental

The schematic diagram of the experimental apparatus is shown in **figure 1.** The wet porous material specimen was heated by short-pulsed laser with high intensity. The temperature and moisture content of the specimen were measured by their measuring units at

Corresponding author: Xiulan Huai, **E-mail:** hxl@mail.etp.ac.cn

the specimen bottom. The voltage variations induced by the change of specimen temperature or moisture content were transiently outputted to digital storage oscilloscope with high-sampling rate and were recorded by computer. The laser parameters can be adjusted and controlled by computer.

Temperature was measured by platinum resistor. The temperature measuring unit was a tiny platinum thread with 0.2 mm in width and 1 urn in thickness. The tiny platinum thread was sputtered under vacuum condition on the upper surface of the quartz cylinder substrate with a diameter of 2 mm. It maintains in high temperature (about 600°C) about 1 h twice to stabilize its temperature-resistance characteristic. Such a tiny temperature measuring unit adopted here was to achieve temperature response time short enough. The response time is less than 1 μs in this paper. The variation of electricity resistance resulting from the change of temperature was measured by electricity balancing bridge and recorded by high sampling-rate digital oscilloscope. The temperature can be calculated according to the temperature-resistance feature of the platinum thread. The temperature is calculated by

$$T = T_0 + \frac{1}{\alpha}\ln\left(\frac{U_0 R_2 (R_3 + R_4) - U_1 R_2 R_4}{R_{P_t 0}\left(U_0 (R_3 + R_4) - U_1 R_3\right)}\right),$$

where T_0 is the initial temperature of the platinum thread, α is the temperature-resistance coefficient of the platinum thread, U_0 is the voltage difference of diagonals, U_1 is the voltage supplied by power, $R_{P_t 0}$ is the initial resistance of the platinum thread, R_2, R_3, R_4 are the resistances of bridge circuit, R_4 can be adjusted and $R_2 = R_3$, $R_4 = R_{P_t 0}$.

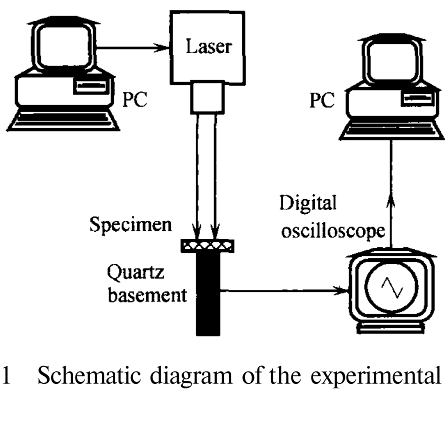

Figure 1 Schematic diagram of the experimental apparatus.

It has great difficulty in measuring the moisture content of a wet porous material due to the complicity of its interior structure and heat mass transfer. It is more difficult in measuring the moisture content when the wet porous material is heated by short-pulsed laser on microsecond scale. The major difficulty is that the temperature response time of the measuring unit is not small enough. The moisture content of a wet porous material was measured by the pulsed electric conductance method in this paper. The schematic diagram of moisture content measurement is shown in figure 2. With regard to the non-metal framework of the wet porous material, the resistance of the wet porous material changes with its moisture content. Therefore, the moisture content of the wet porous material can be obtained by measuring its resistance. Two tiny metal threads with 0.3 mm of space served as the moisture measuring poles. Because of the too large electrical resistivity of porous material, such short space between the two measuring poles adopted is to reduce the resistance of wet porous material. It can improve the sensitivity of moisture the content measurement, and make it possible to measure local moisture content. The response time of moisture is less than 1 μs. The resistance of the wet porous material is not linear with its moisture content, so the moisture content measured by resistance should be calibrated. The aim of this paper was to accomplish the transient measurement of temperature and moisture content on microsecond scale and reveal their evolution laws under short-pulsed laser heating with high intensity. The concrete temperature and moisture content was not the objective in this paper, so the arduous calibrations have not been done. The RC high-frequency filter electric circuit was designed to eliminate the influence of air capacitance. Consequently, it improved the ratio of signal to noise.

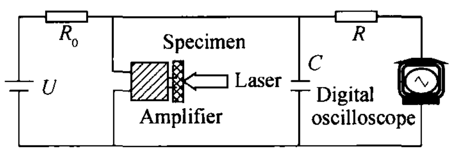

Figure 2 Schematic diagram for moisture measurement.

The Nd^{3+}:YAG laser generator is programmable. The laser wavelength is 1.06 μm, and its power density, pulse duration and facula diameter of laser beam can be adjusted within ranges of 10-10000 MW/m^2, 1-30 μs and 1-10 mm, respectively. The sampling rate of DL2700 digital storage oscilloscope is 500 MS/s. Experiments were carried out under atmospheric pressure at room temperature maintained at 27°C.

3 Results and discussion

3.1 Temperature

The wet porous material specimen is fresh radish. The area of cross section is 2 mm×2 mm. The thicknesses of 5 mm, 2 mm, 1 mm were chosen respectively to investigate the influence of specimen thickness *(d)* on temperature. It is shown in figure 3. It (including the subsequent figures 4 **and** 5) is the display image of transient temperature measurement of digital storage oscilloscope.

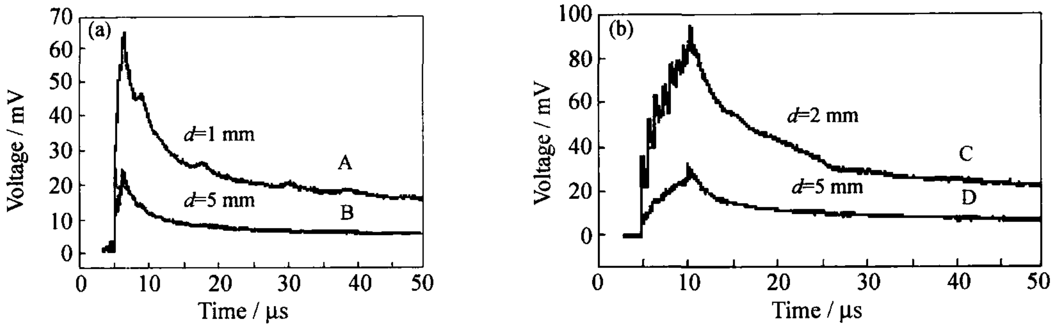

Figure 3 Influence of specimen thickness on temperature of the wet porous material: (a) $t_p=2\ \mu s$; (b) $t_p=7\ \mu s$ (t_p is large laser pulse duration).

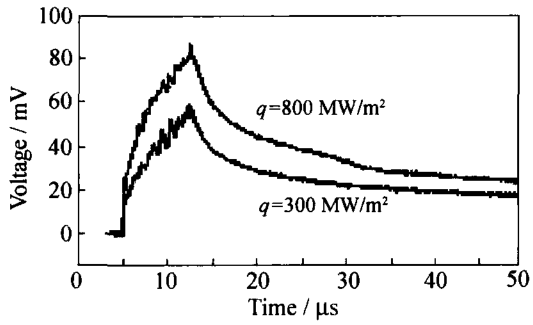

Figure 4 Influence of laser heat flux on temperature.

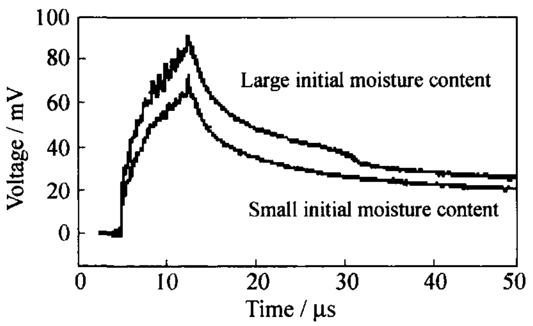

Figure 5 Influence of moisture content on temperature.

As shown in figure 3, with the decrease of specimen thickness, the temperature at the specimen bottom increases and the temperature wave appears more apparently. When the specimen thickness is small enough (1 mm, 2 mm), the temperature wave only appears after the laser heating in the short laser pulse duration (2 μs) situation, and the frequency of temperature wave is relatively low, as shown the curve A in figure 3(a). However, in the case of large laser pulse duration (7 μs), the temperature wave appears only during the laser heating, and the frequency of temperature wave is relatively high, as shown the curve C in figure 3(b). Keeping the other experimental parameters fixed, the laser heat flux is changed between 300 MW/m^2 and 2500 MW/m^2 in order to investigate the influence of the laser heat flux *(q)* on temperature. It shows that with the increase of the laser heat flux, the temperature at the specimen bottom rises with a larger amplitude, however the fluctuation amplitude of temperature wave decreases, as shown in figure 4. Keeping the other parameters fixed, the initial moisture content *(s)* of the specimen is changed to study the influence of initial moisture content on temperature. The result shows the temperature rises higher at a larger initial moisture content and the temperature wave appears more apparently, as shown in figure 5.

The classical Fourier heat conduction equation implies that the thermal disturbance propagates at an infinite speed in medium. It is quite right in the quasistatic situation with long-time disturbance and small amplitude. The thermal relaxation time of the wet porous material reaches from several milliseconds to several tens of seconds [8]. When the wet porous material is heated by laser on microsecond scale, the time of thermal disturbance is near to or much less than its thermal relaxation time. In this case, the heat quasistatic balance can not hold water any more, and the classical Fourier heat conduction equation is not right. The well known Cattane-Vernotter equation is applied to express the non-Fourier heat conduction. The heat transfer in the wet porous material caused by convection mass transfer can be neglected on microsecond scale. According to the conversation of energy, the equation of the variation in temperature of the wet porous material is [9]

$$(\rho c)_{\text{eff}}\frac{\partial T}{\partial t}+h_{\text{vap}}\dot{m}=\lambda_{\text{eff}}\nabla^2 T-\tau_q(\rho c)_{\text{eff}}\frac{\partial^2 T}{\partial t^2},$$

where ρ is the density, c is the specific heat capacity, T is the temperature, t is the time, h_{vap} is the latent heat of evaporation, m is the evaporation rate, λ is the thermal conductivity, τ_q is the thermal relaxation time of the wet porous material. The subscript of "eff" denotes the effective value of the wet porous material calculated by the volume averaging method. Mathematically, the above equation is a wavy one. When the thermal relaxation time is large, temperature fluctuation appears apparently. The temperature measurement shows that the temperature wave appears actually when the wet porous material is heated by short-pulsed laser in this paper. The non-Fourier heat conduction should be taken into account in this situation.

It is noted that not all the lasers heat the top surface of the wet porous material specimen. Some lasers penetrate into the specimen, and the laser energy is absorbed by the wet porous material alone the penetration. When the specimen is thin, not all the laser energies are absorbed alone the penetration, and the residual laser makes the liquid at the specimen bottom evaporate into water vapor. On the one hand, the consumer of the latent heat of evaporation at the specimen bottom lowers the temperature. On the other hand, the continuing input of laser energy during the laser pulse keeps on increasing the temperature of the specimen. As a result, the two opposite factors cause the temperature fluctuate to some extent.

3.2 Moisture content

The specimen of the wet porous material is fresh radish. The area of cross section is 2 mmx2 mm. The thickness is 1 mm. Such a thickness chosen is because a larger thickness makes the measuring signal weak and insensitive. Keeping the other experimental parameters fixed, only the laser pulse duration was changed. The adopted laser pulse duration was 4, 10, and 20 μs. It is noted that the moisture content evolves with a same tendency except for the concrete value. In the experiment, the phenomenon that is different from normal drying is discovered. Heated by short-pulsed laser with high intensity, the specimen bottom does not dry efficiently. On the contrary, its moisture content increases rapidly and intensely two times. To the knowledge of authors, there are no other literatures have reported similar results. Keeping the laser pulse duration fixed, the laser heat flux was changed to investigate the heat flux influence on moisture content. According to the measuring principle of moisture content, the electrical resistance of the specimen and the voltage between two measuring poles decrease with the increase of moisture content. It means the moisture content and the voltage evolve with an opposite tendency. Take the laser pulse duration of 20 μs, the heat fluxes of 500 MW/m^2 and 1700 MW/m^2 for an example to illustrate the moisture evolution of the wet porous material heated by short-pulsed laser. The measuring result is shown in **figure 6.** When the laser heat flux is 500 MW/m^2, the moisture content at the specimen bottom rises rapidly within 15 μs during the laser heating, then it decreases slightly about 20 μs. Afterwards, the moisture content rises rapidly once more, and the increasing amplitude is slightly smaller than the first time. Since then, the moisture content decreases slightly again. The whole evolution is the curve A shown in figure 6. When the laser heat flux is 1700 MW/m^2, the moisture content at the specimen bottom rises rapidly within 5 μs during the laser heating, then it decreases slightly about 30 μs. Afterwards, the moisture content rises very speedily once more, and the increasing amplitude is larger than those during the laser heating period. Since then, the moisture content decreases slightly again. The whole evolution is the curve B in figure 6. With the increase of the laser heat flux, it is evident that the first increase of moisture content experiences a shorter period with a larger amplitude, and it takes a longer time to decrease slightly the moisture content. Since then, the second increase of moisture content is larger than those during the laser heating period.

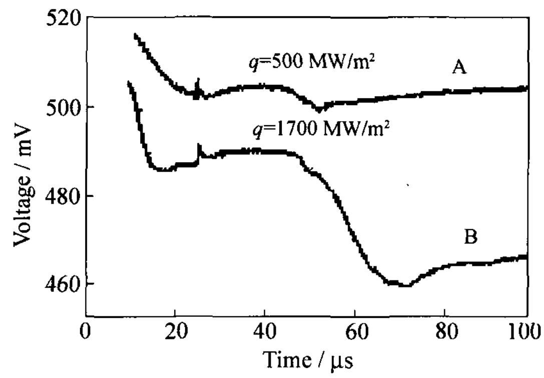

Figure 6 Moisture increase at one laser irradiation.

The moisture transport in the wet porous material is driven by the moisture content gradient, temperature gradient, pressure gradient and so on. When the wet porous material is heated by short-pulsed laser with high intensity on microsecond scale, the large pressure gradient resulting from rapid evaporation induces the fast movement of moisture. The moisture transport induced by the gradients of temperature and moisture content is a kind of slow movement, and it can be negligible during the short-pulsed laser heating. According to the mass conversation, the equation of liquid content of the wet porous material is given by [10]

$$\frac{\partial}{\partial t}(\rho_l \varepsilon_l) = \frac{\rho_l K K_{rl}}{\mu_l}\left(\nabla^2 P_g - \nabla^2 P_c\right) - \dot{m},$$

where ρ_l is the liquid density, ε_l is the volume fraction of liquid, K is the intrinsic permeability, K_{rl} is the relative permeability, μ_l is the dynamic viscosity of liquid, P_g is the vapor gas pressure, P_c is the capillary pressure.

In this experiment, the short-pulsed laser with high intensity irradiates on the top of the wet porous specimen. The large pressure gradient due to rapid evaporation on the top surface of the specimen pushes the moisture move to the bottom, so that the moisture content at the bottom of the wet specimen rises rapidly. When the laser energy is large enough, a number of liquid inner the wet porous material evaporates into water vapor besides that fast evaporation of the liquid at the top surface of the specimen takes place. It results in that the liquid content at the bottom of the specimen does not increase longer and becomes the period of slight decrease in moisture content in figure 6. When the laser heating is over, the temperature of the specimen falls, and the water vapor inner the specimen condenses into liquid water. As a result, it increases the bottom moisture content, and the second increase of liquid content appears. Comparing the curves A and B in figure 6, it can be shown that the larger the laser energy is, the larger the pressure gradient due to rapid evaporation; the more liquid is pushed to the bottom of the specimen; the more liquid inner the wet porous material evaporates; the earlier the moisture begins to slightly decrease; the larger the second increase of moisture content due to water vapor condensation. The fast movement of the moisture due to rapid evaporation has been ever reported by M.H. Shi [11]. He heated a wet porous material by electron beam with high intensity and discovered the displacement flow.

4 Conclusion

The temperature and moisture content of the wet porous material under short-pulsed laser heating with high intensity has been investigated on microsecond scale. The temperature wave due to non-Fourier heat conduction and rapid evaporation of moisture was observed. It firstly reveals the moisture content rapidly rises two times in one laser irradiation, as is different from normal drying, and it relates to the large pressure gradient resulting from rapid evaporation during the laser heating and the condensation of water vapor after the laser irradiation.

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