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Experimental investigation of bioheat transfer characteristics induced by pulsed-laser irradiation

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Abstract: An experimental study of bioheat transfer characteristics induced by pulsed-laser irradiation was presented. The heat transfer characteristics of bio-materials, and the influences of pulse duration, power density, species of bio-materials, thickness and initial moisture content of bio-materials on heat transfer were studied in details. The experimental results indicate that the penetration and absorption of laser in bio-materials are considerable, the heat transfer inside the bio-materials should include the effects of volumetric absorption, pulse duration, power density, bio-materials thickness, and material species have a significant influence on the temperature variation.

Key words: pulsed-laser; bio-materials; heat transfer characteristic; temperature measurement

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1 Introduction

Laser technology is being widely applied in many areas, such as biological and medical engineering, including laser surgery, laser mend and local heat treatment, laser diagnoses and sickness cures. More and more advantages of laser medical application are shown recently, and surprising effects have been found in this area [1-3]. Pulse laser is also used to clean contaminated surface of expensive and minute objects, to melt and joint materials, and to dry the porous materials *etc* [4,5]. All of these applications are relative with thermal effects of laser irradiation materials. No matter what applications of laser, some fundamental problems are still faced, including physical nature of interaction between laser and materials, adaptability and thermal reaction of normal and metastasis tissues toward laser, laser parameters selection for various cure, tissue variation, and the control of temperature and energy *etc*. The solutions to all these problems are very helpful to ensure optimum medical results, and protect around health tissue from injuring.

Furthermore, the absorption peak value is different for various structures and components, which contrarily affect the absorption depth [6]. When laser beam penetrates through the materials, scatter makes the cross section increase and power density decrease; as a result penetrating rate is affected. It is necessary to determine interaction law between laser and materials by both quality and quantity, to understand the mechanisms of light and thermal action as well as thermal physical process of materials, in order to provide reliable foundation for practical application of laser.

2 Experimental setup and measure principle

2.1 Experimental setup

Figure 1 is the schematic diagram of the experimental system. Heating source is a microsecond pulsed-laser (NdYAG), its wavelength is 1.06 μm, and its power density, pulse duration and spot diameter can be adjusted within the ranges of 1.0-1.4×10^4MW/m^2, 1-30 μs and 1-10 mm respectively. A platinum resistor (about 2 μm thick), which was put on the upper surface of a 1.6 mm diameter quartz glass cylinder under vacuum condition, was used as the temperature sensor. Silver thread was applied to

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connect the platinum resistor and the instrument for temperature measurement. The response time to the temperature variation was less than 1 μs [7-9]. In the experiments, bio-material was put on the upper surface of platinum resistor. The diameter of laser spot is larger than that of bio-material which was closely contacted with the platinum resistor, to ensure the heat transfer only take place in the longitudinal direction. Other facilities included a DL2700digital oscilloscope (sampling rate is 500 MS/s) and a computer.

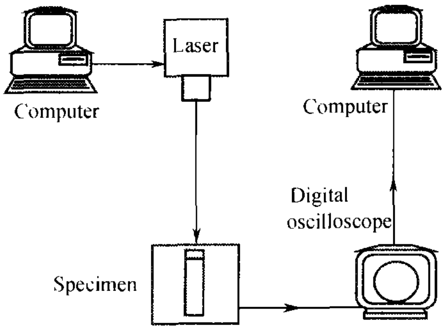

Figure 1 Schematic diagram of experimental set-up.

2.2 Measure principle

When laser beam irradiates on the surface of sample (bio-materials), the laser acts on the sample and transfers its energy to every layer of sample gradually. Heat absorbed by sample is propagated step by step, leading the temperature change of lower surface of the sample. At the same time, these changes will result in the changes of platinum resistance. The resistance signal is transferred from the sensor to the signal converter, then converted into voltage signal, and finally sent to the oscilloscope (sampling rate is 500 MS/s) which is used to record the signal.

2.3 Experimental process analysis

The interaction between laser and object is very complicated when laser beam irradiates on the object, and the laser heating is traditionally treated as non-source heat conduction with second type of boundary condition, that is, the interaction between laser beam and object only takes place on the surface. However, in fact, the absorption of laser energy by the object does not only take place on the surface of the object, especially for the bio-materials, which is also testified by this experiments. In the process of laser irradiation, a part of laser energy is reflected, and the rest enters into the object interior. Laser energy attenuates gradually because of the absorption and dispersion on its way. Dispersion makes the effect area of laser beam extend many times after laser entering into the heterogeneous object and the absorbed energy is transferred into thermal energy to make the object temperature rise. It is proved that bio-materials absorption to laser energy is volumetric absorption in certain space range [10,11].

In this study, bio-materials (mutton, potato and carrot) from 1.2 mm to 5 mm thickness were used as materials, a piece of bio-materials was laid closely on the upper surface of temperature sensor. When the laser beam irradiates on the surface of bio-materials, a part of energy is reflected, the rest enters into bio-materials which is absorbed and scattered along its path. The energy attenuates according to certain law, and the remained energy will reach the upper surface of the sensor. Then a part of energy is reflected into the bio-materials from the upper surface of the sensor and then absorbed again. As a result, laser energy is reflected many times and absorbed finally. Tested temperature is the temperature of sensor surface, which roughly reflects the temperature of the lower surface of bio-materials.

Due to the difference of thickness and initial moisture content of bio-materials, the measured temperature induced by single pulsed-laser irradiation was various, and besides, the influence of laser irradiation parameters (pulse duration, power density) also played an important role in the change of measured temperature.

3 Result and discussion

Figure 2 shows the temperature variation of lower surface of the mutton. It can be seen that temperature rises rapidly and reaches its maximum within the duration of laser pulse, then drops sharply at the end of laser irradiation, and levels off afterwards. The trend of temperature variation is almost the same for various conditions. If the interaction between laser and bio-materials only takes place on the surface, the lower surface could not feel so strong temperature variation in such a short time for bio-materials with low thermal diffusion coefficient. This shows that the penetration depth of pulse laser into bio-materials is considerable, and the heat transfer inside the bio-materials should include the effect of volumetric absorption. It can also be seen that pulse duration has an important influence on the temperature variation, and namely, temperature increases with the increasing of pulse duration at the same thickness and power density. The longer the pulse duration, the longer the laser heating time, and the larger the total energy, the higher the temperature of bio-materials. Figure 2(b) shows the close observation of the temperature variation during the early stages of the process shown in figure 2(a), focusing on the laser heating and subsequent cooling after the laser pulse run over. The temperature curves reveal sudden decline (fluctuation characteristics) in the rising rate during laser heating, which can be attributed to the evaporation of water inside the bio-materials and the reflection of top surface of sensor to the coming laser beam as well, and therefore reduce the laser energy input to the platinum film.

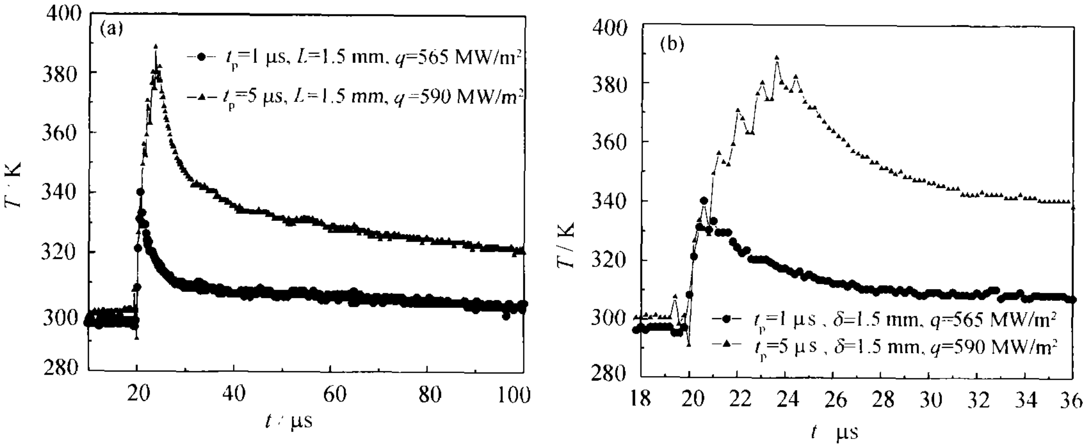

Figure 2 Temperature variation at various pulse duration t_p(mutton), (a) whole measuring process; (b) the early stages of the process given in (a).

Figure 3 presents the temperature variation of mutton at various power densities. The temperature increases with the increasing of power density. The higher the power density, the more energy can be absorbed by the sensor and the larger the maximum temperature become. Figure 3(b) shows the further observation of the temperature variation during the early stages of the process displayed in figure 3(a). The temperature curves reveal similar fluctuation characteristics during laser heating.

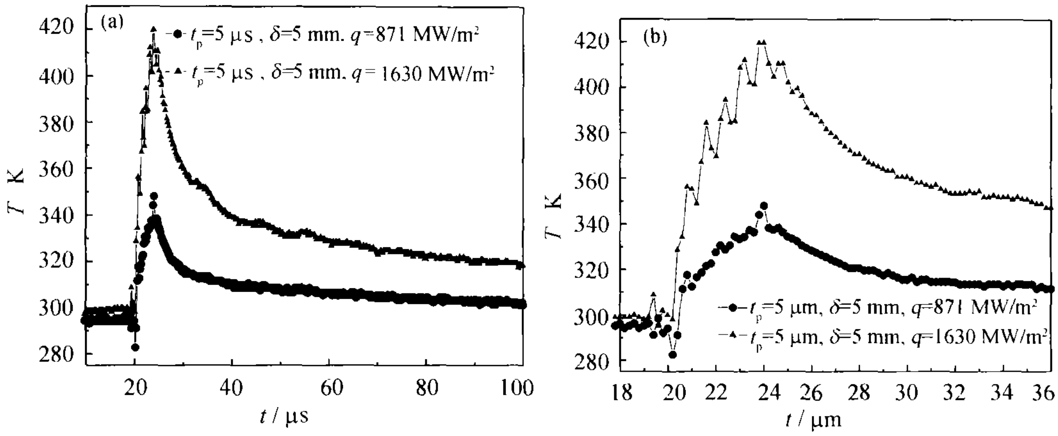

Figure 3 temperature variation for various power density q (mutton), (a) whole measuring process; (b) the early stages of the process given in (a) procedure.

In order to observe the temperature variation at various layers inside the mutton, the measurements for different thickness of bio-materials were carried out. **Figure 4** shows the variation of temperature with various thicknesses. The temperature decreases with the increasing of the thickness, *i.e.* the further from the heating distance, the faster the energy attenuation, the weaker the temperature signal and the smaller its variation range.

In addition, in order to investigate the influence of material species on the heat transfer characteristics, potato and carrot were used as the materials, and the related experiments were carried out too. **Figures 5** and **6** show the measuring results of potato. It can be seen from the figures that temperature variation is similar to that of mutton, pulse duration, power density and thickness have significant influence on the temperature variation. **Figure 7** also shows an abnormal phenomenon, *i.e.* after the laser pulse is over, the temperature drops down quickly to the value that is lower than that before the laser is triggered. The phenomenon is defined as the rapid transient over-vaporization, which is because the temperature of potato with high moisture content go up sharply when the laser irradiate the potato, large amounts of water evaporate quickly, as a result, the temperature drops down quickly. The experiments indicate that rapid transient over-vaporization is closely related with many factors, such as pulse duration and power density of laser, and initial moisture content and thickness of materials. The main reason is probably related with the heating quantity, evaporation quantity and thermal capacity of materials. When heating quantity of laser and evaporation quantity of materials are large, thermal capacity of materials is small, the temperature decrease caused by vaporization is large, after the laser pulse is over, the temperature probably drops down to the point which is less than that of former laser heating. However, when heating quantity of laser and vaporization quantity of materials are small, thermal capacity of materials is large, rapid transient over-vaporization will not occur. The phenomena on rapid transient over-vaporization need to be further investigated theoretically and experimentally.

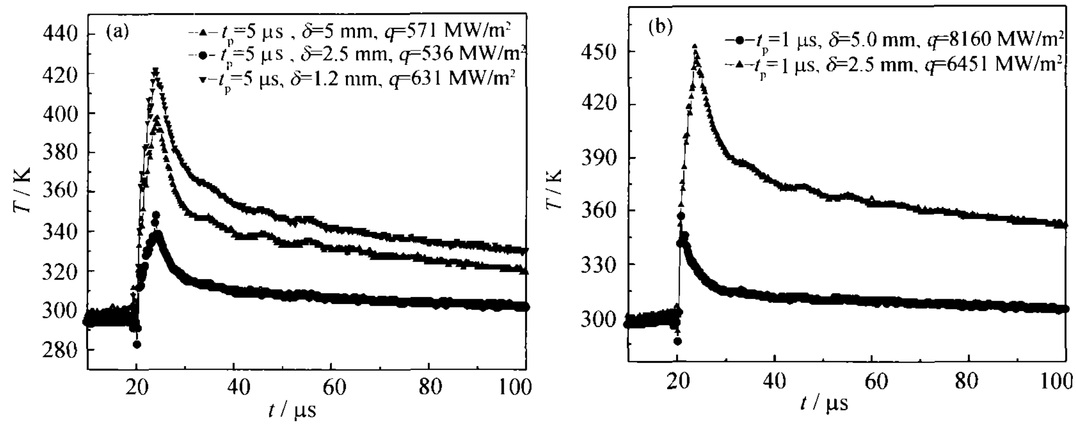

Figure 4 Temperature variation for various thicknesses δ of mutton, (a) t_p=5 μs (b) t_p=1 μs.

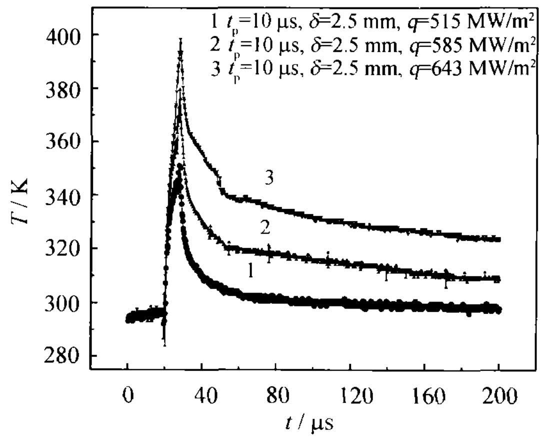

Figure 5 Temperature variation for various power density (potato).

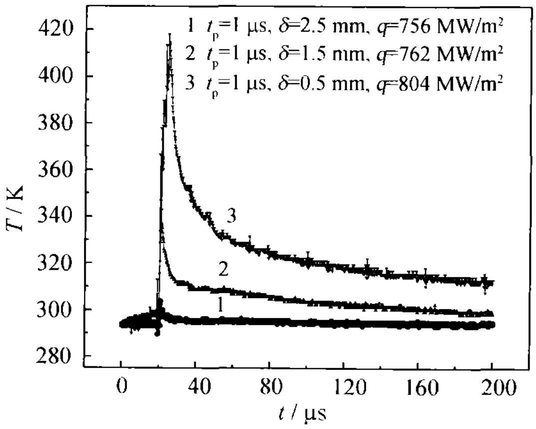

Figure 6 Temperature variation for various thickness of potato.

Figure 8 shows the temperature variation for fresh potato (initial moisture content was about 365% dry basis) and carrot (initial moisture content was about 701% dry basis). The temperature of carrot is lower than that of potato. One reason is that the absorption ratios of potato and carrot to laser beam are different and radiation flame is only visible on the surface of carrot in the experiment; the other reason is that the initial moisture content of carrot is higher and need more quantity of heat to evaporate water inside it.

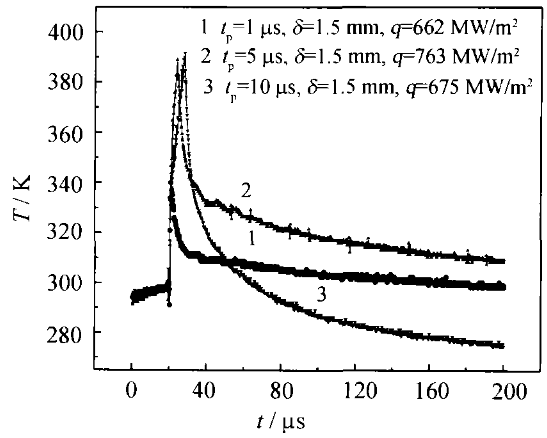

Figure 7 Temperature variation at various pulse duration (potato).

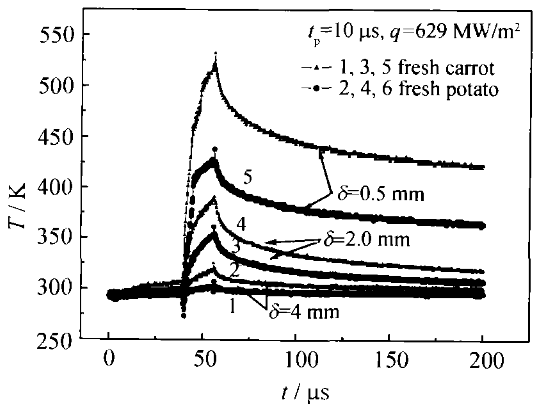

Figure 8 The influence of materials species on temperature variation (potato, carrot).

Although here the accuracy of temperature measurement needs to be improved, valuable investigation and information should be provided to further explore the heat transfer characteristics of laser on bio-materials.

4 Conclusion

Experiments of Bioheat transfer characteristics induced by pulsed-laser irradiation were carried out. The dynamic temperature variations of bio-materials were determined with a temperature measuring system of platinum resistor. The heat transfer characteristics of bio-materials, and the influences of various factors on heat transfer performance were studied in details. Following results were obtained:

(1) The penetration and absorption of laser in bio-materials is considerable, heat transfer inside the bio-materials should include the effect of volumetric absorption and can not be treated as heat conduction without source.

(2) Pulse duration, power density, bio-material thickness and material species have an significant influence on the temperature variation. The temperature increases with the increasing of pulse duration and power density, and decreases with the increasing of bio-material thickness.

(3) The abnormal phenomenon, *i.e.* when the laser pulse is over, the temperature drops down to the value that is lower than that the former laser is triggered. The phenomenon is explained as the rapid transient over-vaporization and need to be further investigated.

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