In-volume heating using high-power laser diodes

Valentin S. Denisenkov*[a,b], Vadim V. Kiyko[a,b], Gleb V. Vdovin[b,c]
[a]Prokhorov General Physics Institute, 38 Vavilova Street, Moscow, Russian Federation 119991;
[b]National Research University of Information Technologies, Mechanics and Optics, 49 Kronverksky Ave., St. Petersburg, Russian Federation 197101; [c]Delft University of Technology, Stevinweg 1, Delft, Netherlands 2628 CN

ABSTRACT

High-power lasers are useful instruments suitable for applications in various fields; the most common industrial applications include cutting and welding. We propose a new application of high-power laser diodes as in-bulk heating source for food industry. Current heating processes use surface heating with different approaches to make the heat distribution more uniform and the process more efficient. High-power lasers can in theory provide in-bulk heating which can sufficiently increase the uniformity of heat distribution thus making the process more efficient. We chose two media (vegetable fat and glucose) for feasibility experiments. First, we checked if the media have necessary absorption coefficients on the wavelengths of commercially available laser diodes (940-980 nm). This was done using spectrophotometer at 700-1100 nm which provided the dependences of transmission from the wavelength. The results indicate that vegetable fat has noticeable transmission dip around 925 nm and glucose has sufficient dip at 990 nm. Then, after the feasibility check, we did numerical simulation of the heat distribution in bulk using finite elements method. Based on the results, optimal laser wavelength and illuminator configuration were selected. Finally, we carried out several pilot experiments with high-power diodes heating the chosen media.

Keywords: high-power laser diodes, in-volume heating, high-power lasers application

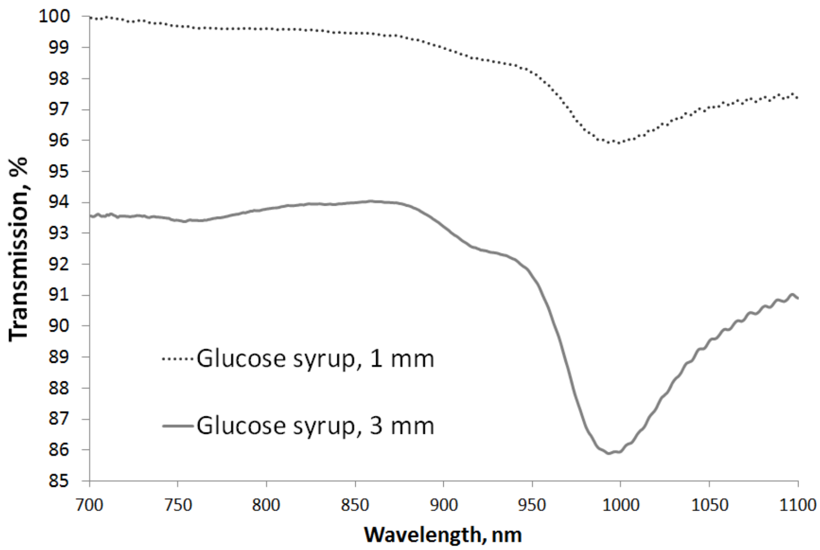
1. INTRODUCTION

Modern food industry makes use of a lot of advanced technologies. However, heating of various substances is mostly carried out by transferring thermal energy from hot surfaces heated by steam. In such processes, it is necessary to transfer the heat from the hot surface and distribute it in the volume, or make the heated substance in the thin films in order to increase the contact area with the hot surface. There are other means of heating, like well-known microwave technology (see [1], for example), or infrared heating [2]. UV light [3] and ultrasonic [4] are also common in food processing but in the case of food heating mostly as auxiliary technologies. In this article we suggest a new way of heating foodstuffs – near IR laser heating. This method has a number of advantages for food industry. It is clean, non-contact and compact, it has short response times, and IR laser radiation can be easily focused or diffused to desirable extent to achieve desirable temperature distribution in the heated medium. Two substances common in food industry – vegetable fat and glucose syrup were investigated in respect of possibility of heating with commercially available near IR laser diode.

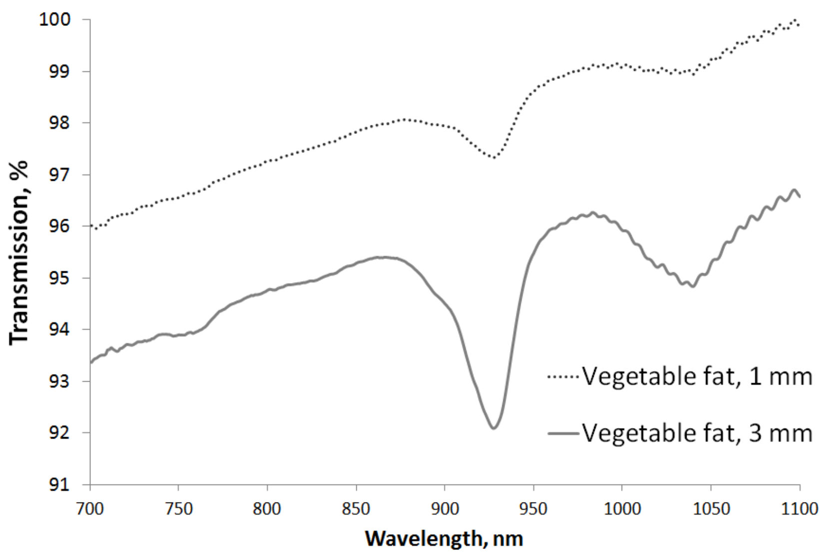
2. EXPERIMENTS

In our study we investigated the possibility of laser heating for two substances: glucose syrup and vegetable fat. In order to determine the absorption of the substances in 940-980 nm range, transmission spectra were measured on Shimadzu UV-3600 spectrophotometer working in 700-1100 nm range with 1 nm step. The spectra were measured for two different thicknesses (1 mm and 3 mm) for both substances. Obtained transmission data was used for calculation of the absorption coefficients for both substances at wavelengths 940-980 nm. Calculated absorption coefficients were included in numerical simulation of laser heating.

High-Power Diode Laser Technology and Applications XIII, edited by Mark S. Zediker,
Proc. of SPIE Vol. 9348, 934812 · © 2015 SPIE · CCC code: 0277-786X/15/$18
doi: 10.1117/12.2079792



(a)



(b)

Figure 1. Transmission spectra for (a) 1 mm and 3 mm of glucose syrup and (b) 1 mm and 3 mm of vegetable fat.

Experimental investigation of laser heating for the two substances was carried out using laser diode. Before the laser-heating experiments, the spectrum and power of laser diode radiation were measured. The obtained laser spectrum is shown in Fig. 2. It can be seen that the laser radiation spectrum has the peak at 962 nm (for temperature 25°C), and FWHM of the spectrum was equal to 2,6 nm. The laser diode used in our study allowed for shifting of the position of the peak with heating/cooling of the diode. The temperature shift coefficient was equal to 0.3 nm/°C. The power provided by the laser diode was also measured using Ophir Nova II power meter. The laser diode power was equal to 10.35 W with 30 A current flowing through the diode.

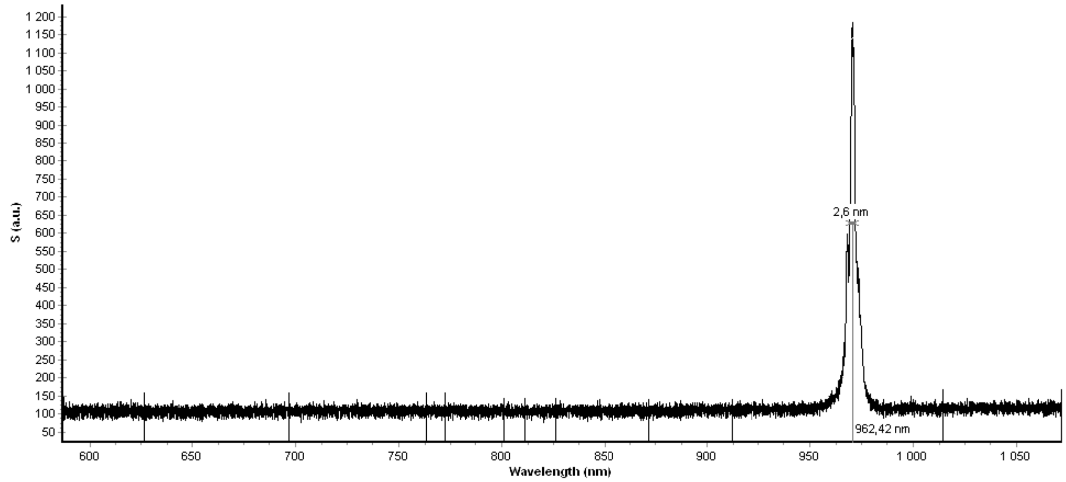


Figure 2.Radiation spectrum of laser diode used in experiments.

The substances were heated in quartz cell having 22 mm thickness. The cell was positioned at the metal support with a layer of thermo-isolating material between the cell and the metal. Laser diode was mounted close to the cell so all the radiation went into the heated substance. Laser-heating of the substances was carried out in two configurations: 1) no back-wall reflector, the case of single propagation through the medium; 2) with back-wall reflector, double propagation through the medium.

Temperature of the heated substance was measured using Cr-Al thermocouple with the accuracy of 0.1°C. The measurement was carried out by dipping the thermocouple into the substances.

3. NUMERICAL SIMULATION

Numerical simulation of laser heating was carried out based on 1D heat equation. The absorption coefficients calculated from the transmission spectra for laser wavelength (962 nm) were used in numerical simulation. The results of laser-heating simulation were compared to the simulation of the same substance in metal container heated by a gas heater.

In the simulation, the considered substance (glucose syrup) was presented by a parallelepiped with 1 cm² cross section and 2.4 cm length. Three cases were simulated:

a) wall of the parallelepiped (1 cm²) is heated by the heat flow of typical gas heater (50 kW/m²); on the opposite wall the heat is blown away by air flow with heat transfer coefficient 5 W/(m² · K) and with temperature of 20°C

b) the parallelepiped is heated from the same side as in a) by a laser having the same power as the gas heater; the heat is blown away from both walls (the one with the laser source and the opposite one) by air flow with heat transfer coefficient 5 W/(m²·K) and with temperature of 20°C

c) is analogous to b), but the back wall is a reflector in this case which means that the radiation is propagating through the heated medium twice

The simulation was based on 1D heat equation in numerical form. The following explicit scheme was used:

$$\rho c \frac{T(x_m, t^{n+1}) - T(x_m, t^n)}{dt} = \lambda \frac{T(x_{m-1}, t^n) - 2T(x_m, t^n) + T(x_{m+1}, t^n)}{(dx)^2} + Q(x_m) \quad (1)$$

where $m = 1 \div 25$ – number of spatial steps, $n = 1 \div 201$ – number of temporal steps, $x = 0 \div 1$ – normalized sample length, $t = 0 \div t_{max}$ – simulated time interval, ρ = 1.5 g/cm^3 – density, c = 1.2 kJ/(kg·K) – heat capacity, λ = 350 W/(m·K) –thermal conductivity, $Q(x)$ – internal heat generation function for the medium.

Boundary condition for the equation (1) were imposed as follows:

a) $Q(x)$ = 0 –no internal heat generation in the medium;

left wall (heat flow from gas heater): $-\lambda\frac{T(x_2)-T(x_1)}{dx} = q$, gas heater flow q = 50 kW/m²;

right wall (heat pickup by air): $-\lambda\frac{T(x_{24})-T(x_{25})}{dx} = \alpha(T(x_{25}) - T_{air})$, heat transfer coefficient α = 5 W/m², air temperature T_{air} = 20°C;

b) $Q(x) = W_0 e^{-ax}$ W/m³ - in-volume heating by laser source, where $W_0 = 2.078 \cdot 10^6$ W/m³ - heat energy absorbed in 1mm layer of the medium closest to the laser source, $a = 42.4$ – absorption coefficient calculated from the transmission spectrum of glucose syrup;

left wall (heat pickup by air): $-\lambda\frac{T(x_2)-T(x_1)}{dx} = \alpha(T(x_1) - T_{air})$;

right wall (heat pickup by air): $-\lambda\frac{T(x_{24})-T(x_{25})}{dx} = \alpha(T(x_{25}) - T_{air})$;

c) boundary conditions are the same as in b), but internal heat generation function is the sum of two functions (first propagation of the radiation through the medium, and propagation of the reflected radiation): $Q(x) = W_0 e^{-ax} + W_1 e^{-ax}$, where $W_0 = 2.078 \cdot 10^6$ W/m³ - heat energy absorbed in 1 mm layer of the medium closest to the laser source, $W_1 = 0.689 \cdot 10^6$ W/m³ - heat energy absorbed in 1 mm layer of the medium farthest from the laser source, $a = 42.4$ – absorption coefficient calculated from the transmission spectrum of glucose syrup;

The initial condition for all the cases was the same:

$T(x, t = 0) = 20$

4. RESULTS

The obtained transmission spectra (Fig. 1) show that glucose syrup has almost flat spectrum at 700-900 nm but there is considerable absorption at 950-1050 nm. The transmission spectrum of vegetable fat has linearly increases with wavelength with minima at 930 and 1040 nm. These results indicate the possibility of laser heating for both substances.

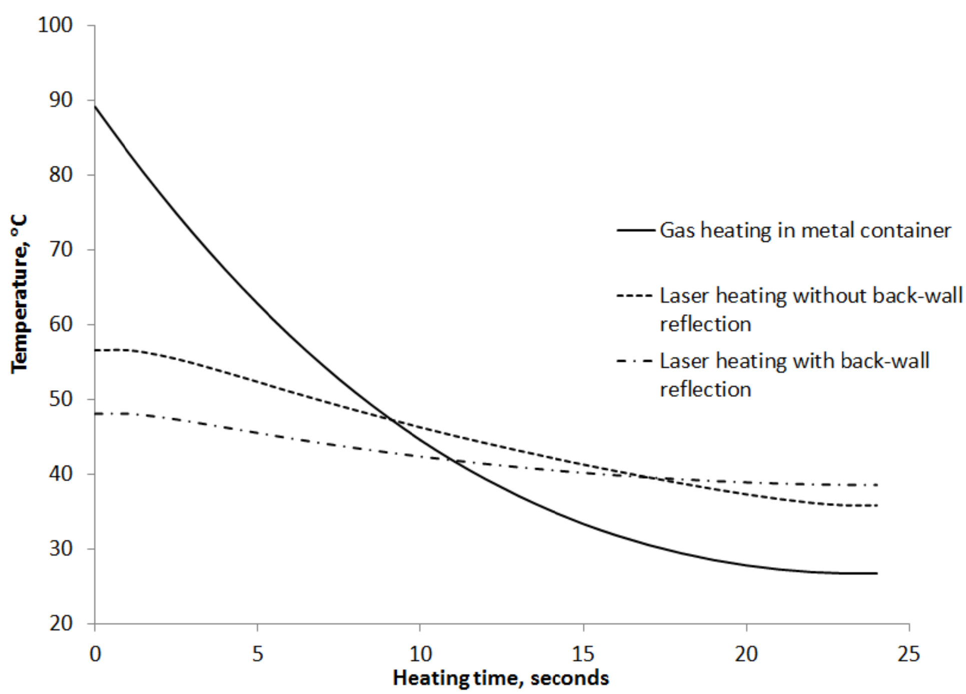


Figure 3. Simulated temperature distribution with average temperature of 45°C for heating in metal container with gas heater, laser heating with and without back-wall reflector.

The transmission spectra were used for calculation of absorption coefficients which then were used in numerical simulation. For all the cases described in section 3, the modeling was done until the average temperature of the medium became equal to 45°C. Temperature distributions for the simulated cases are shown in Fig. 3.

The obtained distributions show that for laser heating the medium is heated more uniformly. Root mean square deviation of temperature is equal to 19°C for gas heating in metal container, 7°C for laser heating with no back-wall reflector (single propagation) and 3.3°C, i.e. laser heating with single propagation is 2.5 times more uniform and laser heating with double propagation is 5.8 times more uniform than heating by gas heater.

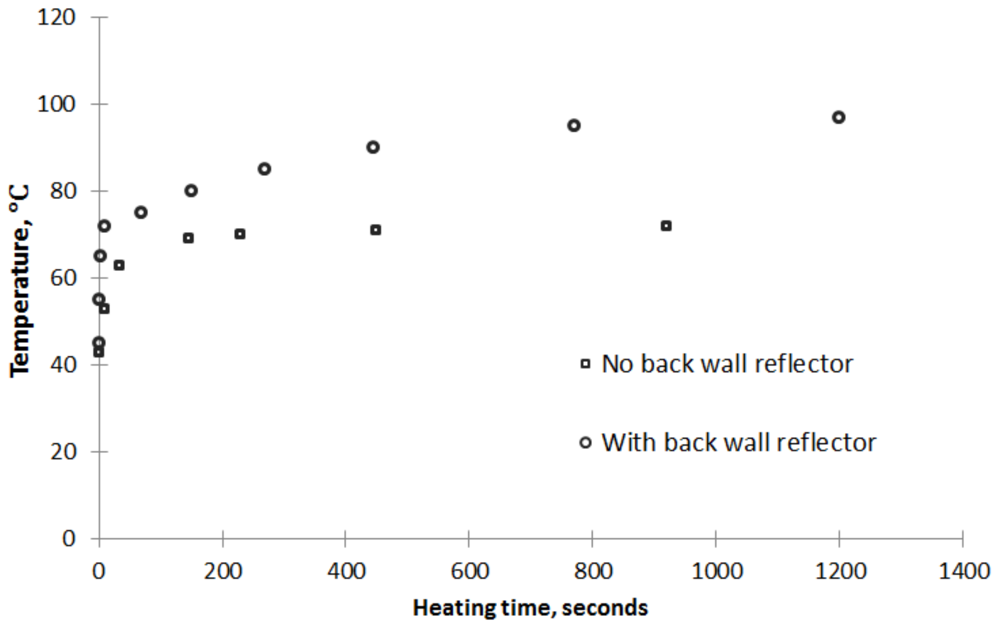


Figure 4. Results of experiments with laser heating of vegetable fat with and without reflection from back wall.

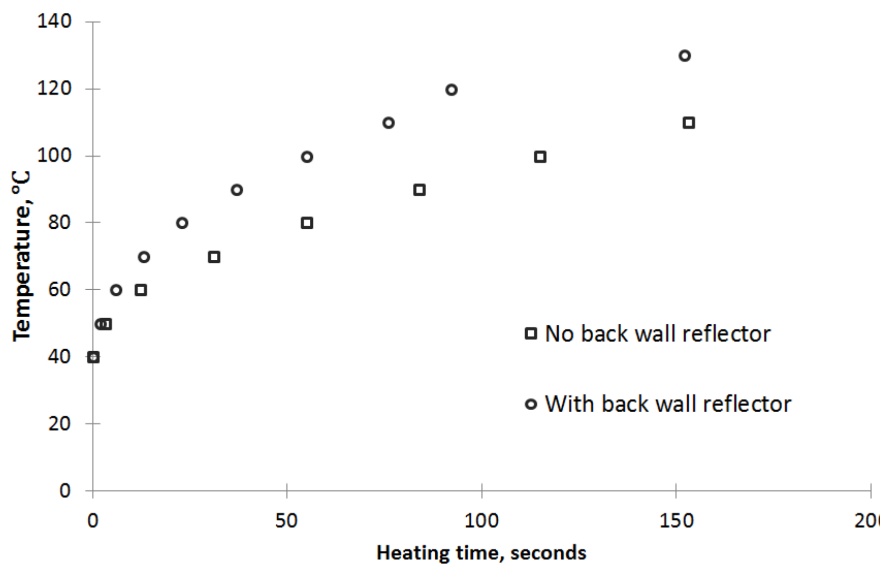


Figure 5. Experimental dependencies of glucose syrup temperature from time of laser heating (with and without reflection from back wall).

After transmission spectra measurements and numerical modeling, the experiments with the substances heated by the laser were conducted. Obtained heating curves for vegetable fat acquired with and without back-wall reflector are shown in Fig. 4.

It can be seen that in the first few seconds the temperature rises rapidly and after that significantly slows down. Also the heating slows down earlier and temperatures achieved are lower when there is no reflector at the back wall of the cell. Abrupt slowdown of the heating can be explained by considerable amount of thermal energy flowing out through the walls of the quartz cell at higher temperatures. At relatively small temperatures, the amount of energy absorbed by the medium exceeds the loss of heat through walls and surface of the medium. But as the temperature rises, heat loss also rises whereas the absorbed energy remains the same. This also explains why the achieved temperatures are higher and the heating slows down later when there is a reflector at the back wall of the cell. Laser radiation passes through the medium twice when there is a reflector, so there is 1.6 times more absorbed energy.

Fig. 5 shows the dependencies obtained for laser heating of glucose syrup. It can be seen from the Fig. 5 that the glucose syrup is heated slower than vegetable fat, but temperatures achieved are higher. Considering that heat capacity for glucose syrup (1.2 kJ/(kg·K)) is less than for vegetable fat (1.8 kJ/(kg·K)), such difference in heating rate can be explained by difference in mass of the samples. Equal volumes of the two substances were used in experiments, but the density of vegetable fat (0.9 g/cm^3) is less than the density of glucose syrup (1.5 g/cm^3), so the amount of energy necessary to heat 1 cm^3 is 1.13 times more for glucose syrup than for vegetable fat. Also, the transmission spectra show that absorption coefficient of 962 nm radiation for vegetable fat is 2.2 times smaller than for glucose syrup. This difference in absorption can explain lower temperatures achieved in heating of vegetable fat, since the amount of energy absorbed per second is smaller, it cannot exceed heat loss through the walls and surface of the medium.

5. CONCLUSIONS

The results obtained in our study show the possibility for application of near IR laser heating in food industry. Two common substances – glucose syrup and vegetable fat were investigated by means of numerical simulation and experimental study. The experimental dependencies show that both substances can be heated with near IR laser radiation. The results also indicate the possibility of changing the amounts of the energy absorbed in the heated medium by changing of distribution of radiation inside the medium. Reducing the rate of energy losses can also be an area for further studies.

REFERENCES

[1] Decareau, R. V., [Microwaves in the Food Processing Industry], Academic Press Inc., Orlando, (1985).

[2] Richardson, P., [Thermal technologies in food processing], CRC Press, New York, 208-228 (2001).

[3] Guerrero-Beltran, J. A., Barbosa-Canovas, G. V., “Advantages and Limitations on Processing Foods by UV Light,” Food Sci. and Tech. Int. 10, 137-147 (2004).

[4] Knorr, D., Zenker, M., Heinz, V., Lee, D. U., “Applications and potential of ultrasonics in food processing,” Trends in Food Sci. and Tech. 15(5), 261-266 (2004).