# The temperature field distributions in a Fe target under low power laser irradiation and low heat transfer coefficient conditions: experiments versus simulations

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In this paper, we present a new approach to elaborate a laser-metal thermal interaction model with consideration of solving instead the two temperatures model (TTM): electron and phonon temperatures equations, just one common Fourier equation. Because the power of laser beam is low and the heat transfer coefficients are low we may consider using two temperatures model that: the electron temperature is equal with phonon temperature. In this situation we may use only one heat Fourier equation. Experimental data versus simulations are also presented.

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## 1. Introduction

The two temperature model was discovered by the Russian school of theoretical physics almost 35 years ago. The research was not stopped but appearing a lot of articles in the following years, especially most of the papers were published in *Physical Review*. The solutions of the TTM can get from solving two coupled differential equations. In 1997, Nolte [1, 2] proposed a simplified TTM. In our special situation, in which we have: low power irradiation and low transfer coefficient, the TTM reduces to Fourier model [1, 3].

## 2. The model

Using the integral transform technique we have the solution (using the notations from references [3, 4]):

$$T_e = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\sum_{k=1}^{\infty} I_1(\lambda_i,\mu_j,\xi_k)\cdot I_2(\lambda_i,\mu_j,\xi_k,t)\cdot K_x(\lambda_i,x)\cdot K_Y(\mu_j,y)\cdot K_z(\xi_k,z) \tag{1}$$

If we take into account just the first 10 terms (for *i*, *j*, *k*) we obtain an analytical solution:

$$T_e = \sum_{i=1}^{10}\sum_{j=1}^{10}\sum_{k=1}^{10} I_1(\lambda_i,\mu_j,\xi_k)\cdot I_2(\lambda_i,\mu_j,\xi_k,t)\cdot K_x(\lambda_i,x)\cdot K_Y(\mu_j,y)\cdot K_z(\xi_k,z) \tag{2}$$

Here:

$$I_1(\lambda_i,\mu_j,\xi_k) = \frac{1}{KC_iC_jC_k}\int_0^a\int_0^b\int_0^c P_a(\vec{r},t)\cdot K_x(\lambda_i,x)\cdot K_y(\mu_j,y)\cdot K_z(\xi_k,z). \tag{3}$$

and

$$I_2(\lambda_i,\mu_j,\xi_k,t) = \frac{1}{\lambda_i^2+\mu_j^2+\xi_k^2}\left[1-e^{\gamma_{ijk}^2\cdot t}-\left(1-e^{-\gamma_{ijk}^2(t-t_0)}\right)\cdot H(t-t_0)\right] \tag{4}$$

Where

$$\gamma_{ijk}^2 = \gamma\left(\lambda_i^2+\mu_j^2+\xi_k^2\right) \tag{5}$$

$P_a$ represents the absorbed power. $C_i, C_j, C_k$ are the normalizing constants [4-7]. We have 3 differential equations from traditional theory [4, 5] ($K$ –represents the eigen-functions, $\lambda, \mu, \xi$ the eigen-values):

$$\frac{\partial^2 K_x}{\partial x^2}+\lambda_i^2 K_x = 0\ ; \frac{\partial^2 K_y}{\partial y^2}+\mu_j^2 K_y = 0;$$

$$\frac{\partial^2 K_z}{\partial z^2}+\xi_k^2 K_z = 0 \tag{6}$$

## 3. Experiments versus simulations

We have in general three types of heat transfer by: i) radiation, ii) convection and iii) conduction. In our case the heat lost by conduction is not neglected as the sample is fixed on a plastic support. The heat rate lost by radiation may be written $\sigma\cdot \boldsymbol{E}\cdot(\boldsymbol{T}^4-\boldsymbol{T}_0^4)$, which in linear approximation is given by $4\sigma\cdot\boldsymbol{T}_0^3\cdot\boldsymbol{E}\cdot(\boldsymbol{T}-\boldsymbol{T}_0)\equiv \boldsymbol{h_{rad}}\cdot(\boldsymbol{T}-\boldsymbol{T}_0)$. Here $\boldsymbol{h_{rad}} = 4\cdot\sigma\cdot\boldsymbol{T}_0^3\cdot\boldsymbol{E}$, where $T_0$=298K, $\sigma$ = 5.6x10$^{-8}$ Wm$^{-2}$K$^{-4}$ is the Stephan Boltzmann constant, and $E$ is the thermal emissivity which for polished metallic surfaces can be taken 0.05. We obtain $\boldsymbol{h_{rad}} = 3\cdot10^{-7}\boldsymbol{W\,mm^{-2}K^{-1}}$. The heat rate loss by convection when the sample is in air obeys a power law given by $20\cdot10^{-9}(\boldsymbol{T}-\boldsymbol{T_0})^{5/4}[\boldsymbol{W\,mm^{-2}}]$. This expression can be further linearized:

$$20\cdot10^{-9}(\boldsymbol{T}-\boldsymbol{T_0})^{1/4}(\boldsymbol{T}-\boldsymbol{T_0})[\boldsymbol{W\,mm^{-2}}] = \boldsymbol{h_{conv}}\cdot(\boldsymbol{T}-\boldsymbol{T_0})[\boldsymbol{W\,mm^{-2}}]$$

In consequence we can conclude: $\boldsymbol{h_{conv}} \cong 0.8\cdot10^{-7}\boldsymbol{W\,mm^{-2}K^{-1}}$, where we have considered: $\boldsymbol{T}-\boldsymbol{T_0} = 300\boldsymbol{K}$. The total heat transfer coefficient is: $\boldsymbol{h_{total}} = \boldsymbol{h_{rad}} + \boldsymbol{h_{conv}} \cong 3.8\cdot10^{-7}\boldsymbol{W\,mm^{-2}K^{-1}}$, which corresponds to the sample surrounded by air. For a sample fixed on a plastic support:

$$\boldsymbol{h_{total}} = \boldsymbol{h_{rad}} \cong 3\cdot10^{-7}\boldsymbol{W\,mm^{-2}K^{-1}}.$$

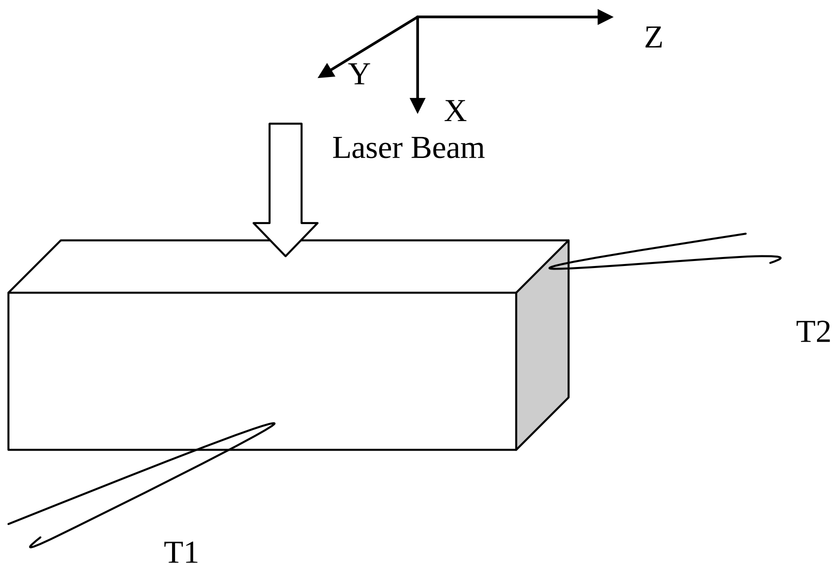


*Fig. 1. The experimental set-up*

*Table 1. The experimental values on faces 1 and 2 of the Fe target under laser irradiation with a laser with fluence of 7 J/cm$^2$*

| | **1** | | **2** | | **3** | | **4** | | **5** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. pulses** | **100** | | **150** | | **200** | | **300** | | **500** | | **pulses** |
| **Fluence** | **6.9** | | **6.9** | | **7** | | **7** | | **7** | | **J/cm$^2$** |
| **TempT1** | 25.3 | 25.6 | 25.5 | 25.8 | 25.5 | 25.8 | 25.7 | 26.5 | 25.8 | 26.8 | **$^0$C** |
| **tempT2** | 25.5 | 25.7 | 25.7 | 26.1 | 25.7 | 26.1 | 25.8 | 26.6 | 25.9 | 27.2 | **$^0$C** |
| **□ T1** | | 0.3 | | 0.3 | | 0.3 | | 0.8 | | 1 | **$^0$C** |
| **□ T2** | | 0.2 | | 0.4 | | 0.4 | | 0.8 | | 1.3 | **$^0$C** |

*Table 2. The experimental values on faces 1 and 2 of the Fe target under laser irradiation with a laser with fluence of 47 J/cm$^2$*

| | **1** | | **2** | | **3** | | **4** | | **5** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **No. pulses** | **100** | | **150** | | **200** | | **300** | | **500** | | **pulses** |
| **Fluence** | **46.7** | | **46.7** | | **47.05** | | **47.05** | | **47.05** | | **J/cm$^2$** |
| **TempT1** | 26.8 | 27.1 | 26.9 | 27.5 | 27.1 | 27.7 | 27.1 | 28.1 | 27.2 | 28.8 | **$^0$C** |
| **tempT2** | 26.8 | 27.3 | 27 | 27.7 | 27.1 | 28 | 27.2 | 28.5 | 27.2 | 29.5 | **$^0$C** |
| **□ T1** | | 0.3 | | 0.6 | | 0.6 | | 1 | | 1.6 | **$^0$C** |
| **□ T2** | | 0.5 | | 0.7 | | 0.9 | | 1.3 | | 2.3 | **$^0$C** |

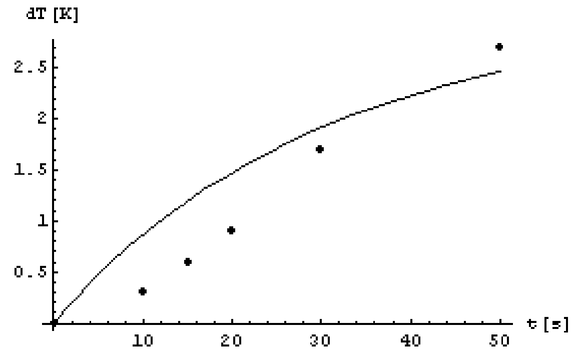


*Fig. 2. The experimental points versus simulated temperature fields (continuous line) for T1 and a fluence of 7 J/cm$^2$*

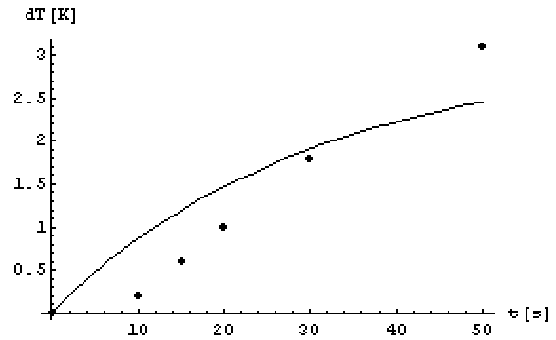


*Fig. 3. The experimental points versus simulated temperature fields (continuous line) for T2 and a fluence of 7 J/cm$^2$.*

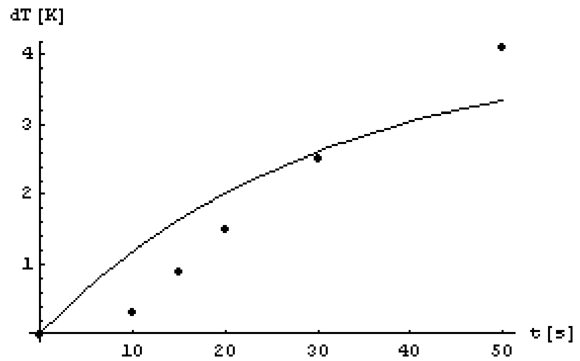


*Fig. 4. The experimental points versus simulated temperature fields (continuous line) for T1 and a fluence of 47 J/cm$^2$*

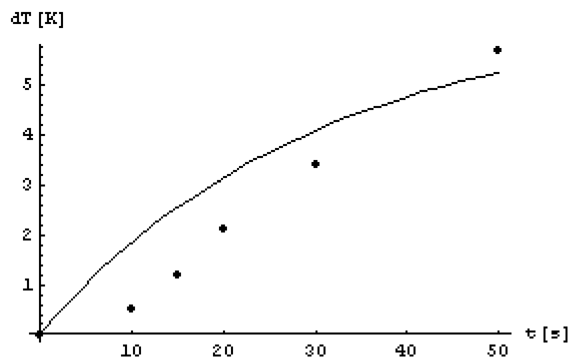


*Fig. 5. The experimental points versus simulated temperature fields (continuous line) for T2 and a fluence of 47 J/cm*

We have a 1cm × 1 cm × 1cm Fe target. Like heating source we have used a Nd:YAG laser working on his third harmonic at 355 nm (Continuum – Surelite II). The laser has a pulse length at FWHM of 5ns, with a repetition frequency of 10 Hz and a beam divergence of 0.6 mrad.

## 4. Conclusions

We have obtained a simple solution for the two model temperature. The solution–can help to know the thermal effect in laser-metal interaction.

Our conclusion regarding the fit between experimental data and theoretical simulations is that we have a good agreement between them. In fact it is the same kind of experiments and simulations like in references [4, 5] with the only difference that now we have photons instead of electrons.

Our simulation is an analytical one, because we take just first 10 values of the indices*: i,j,k*. These, involve an absolute error of about $10^{-2}$ K [8]. Our solution should be taken like a simple one, which give the first information about the thermal field in laser-metal interaction; and can be of great help for all following future experiments.

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