Analytical Modeling of the Light-to-Heat Conversion by Nanoparticle Ensemble under Radiation Action

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Abstract-The investigations and the use of nanoparticles (NPs), as photothermal agents in light-to-heat conversion processes in nanoenergy and nanotechnology are fast growing areas of research and applications. Analytical investigation of the light-to-heat conversion by nanoparticle ensemble under radiation action was conducted. The investigation of the influence of NPs parameters (their radii, absorption efficiency factor, density and heat capacity of NP material, concentration), the characteristics of radiation (wavelength, pulse duration, radiation beam radius), the surrounding material (its density, heat capacity, and heat conduction coefficient, characteristic length of radiation extinction) on the efficiency of the light-to-heat conversion is carried out. The possibility of thermal confinement (saving NP and material thermal energy practically without heat exchange with surrounding) has been established for single NP and irradiated volume of medium with NPs for determined time intervals. These results can be used for the description of the light-to-heat conversion processes in experimental investigations in nanoenergy and nanotechnology.

Keywords- Light-to-Heat Conversion; Nanoparticles; Ensemble; Thermal Confinement; Analytical Investigation

I. INTRODUCTION

In recent years the absorption of radiation energy by NPs, light-to-heat conversion, heat dissipation and exchange with a surrounding material (medium), and following thermal and accompanied phenomena have become increasingly important topics in nanotechnology [1-24]. Many reasons exist for this interest, including the applications of the light-to-heat conversion in nanoenergy [1-12], in photothermal laser nanomedicine [13-16] and catalysis [17, 18], in laser processing of NPs (laser induced transformation of NP size, shape and structure) [19-24], etc. These advances in nanotechnology are based on the efficiency of light-to-heat conversion, thermal effects and the processes induced by the laser–NP interaction [1-12]. Many different radiation sources were used in experimental investigations [1-24], including different lasers, sources of intensive optical radiation, solar radiation.

Theoretical investigation of the light-to-heat conversion under action of radiation on NPs [1-12] is predominantly based on the description of the processes with single NP. The light-to-heat conversion with NP ensemble practically did not investigate and only a few general equations were formulated and the estimations were made.

It is important to describe theoretically the temporal and the spatial-temporal behavior of the NPs and medium (material) temperatures during the processes of light-to-heat conversion. Computer and analytical modeling are widely used for the description of different processes and can be applied for these purposes. But analytical modeling has a few advantages in comparison with computer one because its results much simpler and convenient and can be used for description of different experiments.

In this paper the analytical model of the description of light-to-heat conversion by nanoparticle ensemble, placed in medium, under radiation (laser) action has been developed. Analytical description of heating of NP ensemble under action of pulsed optical (laser) radiation and its cooling after the termination of radiation action is conducted. The dependences of NP temperature on time during the processes of NP heating and cooling, heat exchange of heated NP with environment are investigated. The temperature dependences of optical and thermo-physical parameters of NPs and surrounding medium are taken into account under modeling. The heat localization within the NP and medium (material) volumes (thermal confinements) during some time intervals without heat exchange with surrounding ambience is investigated.

II. MODEL

It was considered heterogeneous two-component system containing an ensemble of NPs in surrounding solid or liquid medium. Let medium contains an ensemble of spherical NPs with the characteristic radiuses of r_0, which absorb and scatter the radiation energy. For simplicity, the NPs are assumed to be monodispersed ones. It was investigated ordering system of NPs on the base of cell's approximation with regular placement of NPs in the center of each computational cell with radius r_c [25]. Such model presents real heterogeneous medium loaded by NPs with rather good accuracy.

Simplified geometrical picture of coordinate systems is presented in Fig. 1. It were introduced two coordinate systems – the first one is the system of the cylindrical coordinates R, Z, the second one is the spherical coordinate systems with radius r and with the origin fixed at the centre of each NPs and cells. The Z axis is directed along the direction of radiation (laser) beam propagation. Radiation beam with wavelength λ has the intensity I_0 constant over its cross section or Gaussian distribution of the radiation intensity I over the beam cross section:

$$I(Z=0,R,t) = \begin{cases} I_0(t), R \le R_B \\ 0, R \ge R_B \end{cases} \text{(a)}, \; I(Z=0,R,t) = I_0(t)\exp\left(-\frac{R^2}{R_B^{\,2}}\right) \text{(b)} \tag{1}$$

where t – time, $Z = 0$ is the coordinate of the irradiated surface, I_0 is the intensity of laser radiation at the irradiated surface and R_B is the radius of the irradiated spot at the surface (radius of the laser beam) for (1a), I_0 is the maximum intensity on the beam axis and R_b is the characteristic beam radius for Gaussian distribution (1b).
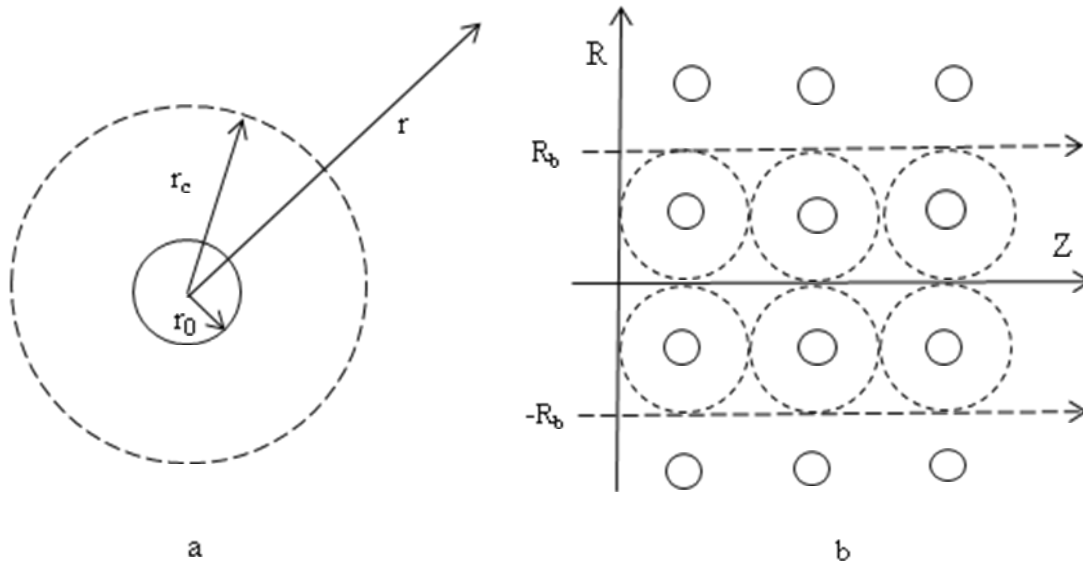

Fig. 1 Schematic presentation of spherical coordinate system for single NP (a), where r radius with the origin fixed at the centre of NP, r_0 - radius of NP, r_C - radius of cell; and for NP ensemble (b) - cylindrical coordinates R, Z, where R_b radius of radiation beam, small solid circles present NPs, dashed circles present the boundaries of cells, Z axes is directed along the direction of radiation propagation and presented by dashed arrows

One – dimensional Beer law can be used for description of radiation transfer inside two-component system with NPs

$$I(Z,R,t) = I(Z=0,R,t)\exp\left(-\alpha_{ext} Z\right) \tag{2}$$

where $\acute\alpha_{ext}$ -coefficient of extinction (absorption and scattering) of radiation by medium loaded with NPs, $\acute\alpha_{ext} = \acute\alpha_{abs1} + \acute\alpha_{sca1} + \acute\alpha_{abs0} + \acute\alpha_{sca0}$, $\acute\alpha_{abs1}$, $\acute\alpha_{sca1}$ - the coefficients of absorption and scattering by pure surrounding medium, $\acute\alpha_{abs0} = N_0 S_S K_{abs}$, $\acute\alpha_{sca0} = N_0 S_S K_{sca}$ – the coefficients of radiation absorption and scattering by NPs, K_{abs}, K_{sca} - the efficiency factors for radiation absorption and scattering accordingly by a NP with radius r_0 [26], $S_S = \pi r_0^2$ - surface square of transversal section of NP sphere, N_0 – concentration of NPs in medium. Thermal processes are described by system of heat conduction equations for each component of our system [25, 27]

$$c_i \rho_i \frac{\partial T_i}{\partial t} = \nabla\left(k_i \nabla T_i\right) + q_i \tag{3}$$

where i - index denotes of the i-component of two-component system including NPs ($i=0$) and surrounding medium ($i=1$) parameters, T_i is the temperature, c_i, ρ_i, k_i are heat capacity, density and thermal conductivity respectively, q_i is the power density of heat sources.

The thermal processes of radiation-NP interaction include the absorption of radiation energy by single NP and its heating, heat transfer into medium and NP cooling after the termination of action are based on the heat conduction equation for spherical geometry following from Eq. (3) [27]:

$$c_i \rho_i \frac{\partial T_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 k_i \frac{\partial T_i}{\partial r}\right) + q_i \tag{4}$$

where the NP parameters are determined for $r \leq r_0$ ($i = 0$) and the surrounding medium parameters are determined for $r > r_0$ ($i = 1$), for $r \leq r_0$ $q_0 = I_0 K_{abs} \pi r_0^2 / V_0$, $q_1 = 0$ for $r > r_0$, $V_0 = 4/3\pi r_0^3$ is the volume of NP.

Fig. 1 presents the schematic picture of the spherical coordinate system with radius r for single NP, and the cylindrical system with coordinates R, Z, where R is directed along the radius of radiation beam, Z axes is directed along the direction of radiation propagation. The condition of "ideal" heat contact was used between NP surface and ambient medium [1, 28].

The heat transfer Eq. (3) for cylindrical geometry for all volume of medium under consideration [27]

$$c_1 \rho_1 \frac{\partial T_1}{\partial t} = \frac{1}{R} \frac{\partial}{\partial R} \left(R k_1 \frac{\partial T_1}{\partial R} \right) + \frac{\partial}{\partial Z} \left(k_1 \frac{\partial T_1}{\partial Z} \right) + q_1 \tag{5}$$

in (5) $q_1 = \alpha_{abs1} I_0 + N_0 S_0 J_C$ - density of thermal energy generation due to absorption of laser energy by medium and heat transfer from NPs, $k_1 = k_{1\infty} \left(\frac{T_1}{T_\infty} \right)^a$ – the coefficient of thermal conductivity of medium [26], $k_{1\infty} = k_1(T=T_\infty)$, $a = const$, ($a \approx 0.5$ for water [26]), T_∞ - the initial temperature of NP and medium, $S_0 = 4\pi r_0^2$ – surface square of NP sphere, J_C – heat flux from NP surface by conductive heat transfer. The initial and boundary conditions for Eqs. (4)-(5) are:

$$\frac{\partial T_0}{\partial r}\Big|_0 = 0 \ , \quad k_0 \frac{\partial T_0}{\partial r}\Big|_{r_0} = k_1 \frac{\partial T_1}{\partial r}\Big|_{r_0} \ , \quad T_i(r,t=0) = T_\infty \tag{a}$$

$$\frac{\partial T}{\partial R}\Big|_{R=0} = 0 \ , \qquad T_1(Z,R,t=0) = T_\infty \qquad \text{(b)} \tag{6}$$

where conditions (6a) are used for Eqs. (4) and (6b) for (5). The system of Eqs. (2), (4), (5) involves radiation transfer equation – Beer's law (2), Eqs. of NP heat balance (4,5) for spherical NPs and two-dimensional heat transfer equation for whole volume under consideration. The use of Eq. (5) means that the particles are assumed to be point-like heat sources with identical temperature in a physically infinitesimal volume. The volume $N_0 V_0$ occupied by the NPs and the volume $N_0 V_{or}$ occupied by heat aureoles around them with characteristic radius $r_{0r} \sim 5 \, r_0$ are much smaller than the volume of the surrounding medium in 1 cm^{-3} of system. It means that next conditions should be fulfilled: $N_0 V_0 = N_0 \, 4/3 \, \pi \, r_0^3 << 1$, $N_0 V_{or} = N_0$ $4/3 \, \pi \, r_{or}^3 << 1$. For example, for $r_0 = 25$ nm, $N_0 = 1 \times 10^{11}$ cm^{-3}, $N_0 V_0 = 6,5 \times 10^{-6}$ cm^{-3} $<< 1$ cm^{-3} and volume $N_0 V_{or} = 8 \times 10^{-4}$ cm^{-3} $<< 1$ cm^{-3} and the conditions of the use of NPs as point-like sources are fulfilled.

The study of the integral energy parameters is of special interest, that characterizes the interaction of radiation with a NP - its absorption, heating, heat transfer from the onset of irradiation $t = 0$ to the time instant considered t: the quantities of radiation energy Q_{abs}, Q_{sca}, absorbed and scattered by an NP, the quantity of heat removed from an NP by heat conduction Q_C and also the NP thermal energy E_{0T}:

$$Q_{abs} = \pi r_0^2 \int_0^t I_0(t) K_{abs} \, dt, \quad Q_C = 4 \pi r_0^2 \int_0^t J_c \, dt, \quad Q_{sca} = \pi r_0^2 \int_0^t I_0(t) K_{sca} \, dt, \quad E_{0T} = \rho_0 c_0 V_0 T_0 \tag{7}$$

The energy conservation laws for an NP and medium in 1 cm^{-3} are fulfilled for different time instants during the radiation action and after its end:

$$E_{0T} = E_{0T\infty} + Q_{abs} - Q_C \tag{8}$$

$$E_{1T} = E_{1T\infty} + N_0 Q_C - Q_{1C}$$

$E_{0T\infty} = \rho_0 c_0 V_0 T_\infty$, $E_{1T\infty} = \rho_1 c_1 T_\infty$ and $E_{0T} = \rho_0 c_0 V_0 T_0$, $E_{1T} = \rho_1 c_1 T_1$ are the initial and current thermal energies of a NP and medium, Q_{1C}-thermal energy transferred from heated volume of medium to ambience.

The correlation between the heat energies contained in NP and transferred to medium at a current moment and in the course of time is very essential for the initiation and the realization of different thermal physical-chemical processes inside a NP and in surrounding medium. Next parameters are used for the description of the processes of light-to-heat conversion

$$P_1 = \frac{Q_{abs}}{Q_{sca}}, \quad P_2 = \frac{Q_C}{Q_{abs}}, \quad P_3 = \frac{Q_{abs} - Q_C}{Q_{abs}} \tag{9}$$

The parameter P_1 describes the correlation between absorption and scattering of radiation by NP. The parameter P_1 is determined by optical characteristics of a NP and had been investigated for the metallic NPs in [29]. The parameter P_2

determines the correlation between heat loss energy by NP and absorbed energy by NP and P_3 determines the correlation between NP thermal energy and absorbed energy during the heat exchange with medium.

The processes of light-to-heat conversion under action of radiation pulses with pulse duration t_P on NP ensemble are described by next characteristic times, connected with the thermal processes inside and around single NPs and inside the volume irradiated by radiation beam:

$$\tau_{0T} \sim \frac{r_0^2}{4\chi_0}, \ \tau_{1T} \sim \frac{r_0^2}{4\chi_1}, \ \tau_{TN} \sim \frac{N_0^{-2/3}}{16\chi_1}, \ \tau_{TR} \sim \frac{R_b^2}{4\chi_1}, \ \tau_{TZ} \sim \frac{Z_{ext}^2}{4\chi_1} \tag{10}$$

χ_0, χ_1 – the thermal diffusivities of NP material (metal) and medium respectively, L – the characteristic length of radiation extinction by medium with NPs [26, 29]. The distance of r_1 between the centers of neighboring NPs is equal to $r_1 \approx 1/N_0^{1/3}$ and the cell radius r_c is to equal $r_c = r_1/2 = 1/2N_0^{1/3}$ (see Fig. 2). The characteristic time of the overlapping of temperature fields from neighboring NPs is equal to $\tau_{TN} \sim \dfrac{r_c^2}{4\chi_1} = \dfrac{N_0^{-2/3}}{16\chi_1}$ (see (10)). The characteristic length of radiation extinction is equal to

$Z_{ext} \sim 1/\acute{\alpha}_{ext}$, $\acute{\alpha}_{ext}$ – the coefficient of extinction of radiation by heterogeneous system.
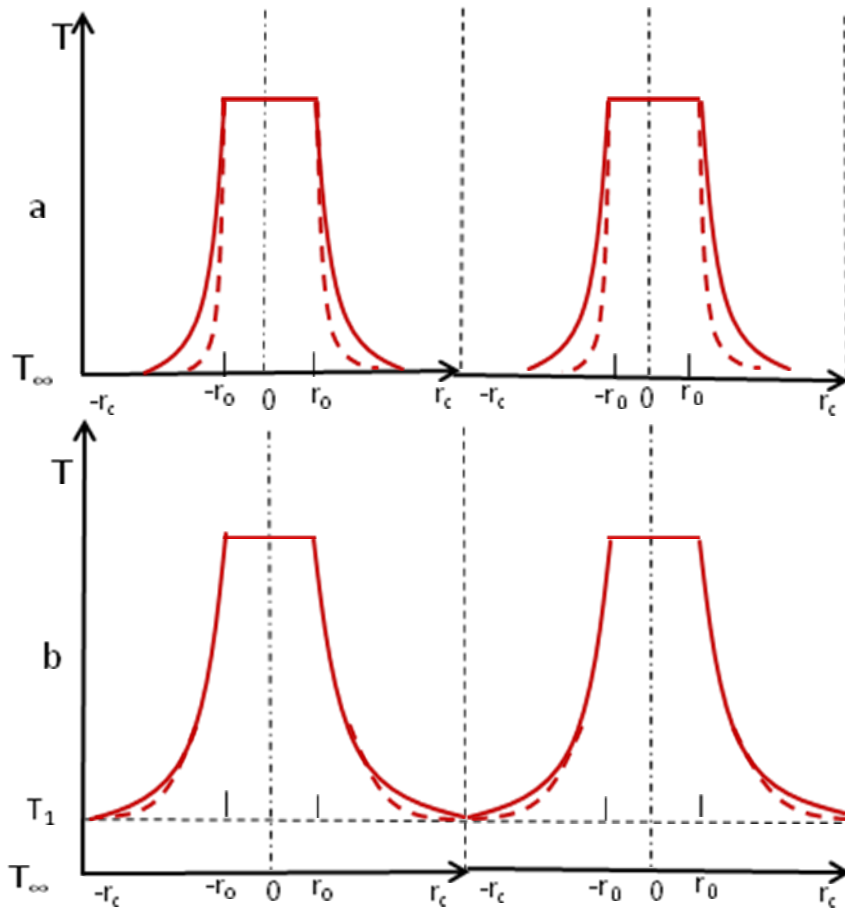

Fig. 2 Qualitative presentation of the dependences of temperature T on r inside the two neighboring cells for analytical quasi-stationary (solid lines) and numerical non-stationary (dashed lines) distributions for some time instants and for the cases of $T_1 = T_\infty$ (a) and $T_1 > T_\infty$ (b). Vertical dashed lines denote the boundaries of spherical cells ($-r_C$, r_C), vertical dashed-dotted lines denote the centers of NPs and cells, horizontal dashed line denotes the level of medium temperature (b), scale marks ($-r_0$, r_0) denote of the radii of NPs

The use of the assumptions of non-interacting of temperature fields (thermal aureoles) from neighboring NPs and the presentation of NPs as point like heat sources is fulfilled because of non-stationary distributions $T_1(r)$ in comparison with quasi-stationary distributions of $T_1(r)$ (see Fig. 2).

The characteristic times τ_{0T}, τ_{1T} describe the heat transfer and formation of quasi-stationary temperature distributions inside and around single spherical NP accordingly [1], τ_{TN} – the characteristic time of the formation of quasi-stationary temperature distribution in medium, when overlapping of temperature fields between neighboring spherical NPs has been realized. The parameters τ_{TR}, τ_{TZ} are the characteristic times, describing development of quasi-stationary heat transfer from heated volume inside radiation beam into adjacent ambience along R and Z coordinates.

Estimations of these characteristic times give the next values for gold spherical NP with $r_0 = 25$ nm in water - $\tau_{0T} \sim 1.2 \times 10^{-12}$ s and $\tau_{IT} \sim 1 \times 10^{-9}$ s accordingly. For heterogeneous system with concentrations $N_0 = 1 \times 10^9$, 1×10^{12} cm^{-3} τ_{TN} is equal to $\tau_{TN} \sim 4.4 \times 10^{-5}$, 4.4×10^{-7} s. Experimental works [1-24] used laser beam with characteristic beam radius $R_b \sim 0.1$ cm, radiation beam from optical sources with $R_b \sim 1.0$ cm and more. The characteristic times for heat removal beyond beams with radius $R_b \sim 0.1$, 1.0 cm are equal $\tau_{TR} \sim 1.6$, 1.6×10^2 s.

The optical parameters of the NP ensemble can be estimated with monodispersed system of gold NPs with $r_0 = 25$ nm and surrounding medium (water). The radiation wavelength 532 nm was used (plasmonic interval of wavelength for gold NPs), which allows to achieve maximal values of absorption and extinction NP properties [26, 29]. Characteristic length Z_{ext} of the radiation extinction by heterogeneous medium is determined by the equation

$$Z_{ext} = \frac{1}{\alpha_{ext0} + \alpha_{ext1}} = \frac{1}{N_0 \pi r_0^2 K_{ext} + \alpha_{ext1}}$$

where $\acute{\alpha}_{ext0}$, $\acute{\alpha}_{ext1}$ – accordingly coefficients of extinction of radiation by NPs and medium solely, K_{ext} is the efficiency factor of the radiation extinction by single NP. The value of $\acute{\alpha}_{ext1}$ is equal to $\acute{\alpha}_{ext1} = 4 \times 10^{-3}$ cm^{-3} (water) [30] and characteristic length of radiation extinction by pure water $Z_{ext} = 1/\acute{\alpha}_{ext1} = 2.5 \times 10^2$ cm and water practically does not extinct the radiation, especially for the optical length smaller or much smaller than 10^2 cm. For NP ensemble $\acute{\alpha}_{ext0} = \pi N_0 r_0^2 K_{ext}$, $K_{ext} = 4.0$ and for $N_0 = 10^9$ cm^{-3} $\acute{\alpha}_{ext0}$ is equal to $\acute{\alpha}_{ext0} = 7.8 \times 10^{-2}$ cm^{-1} and $Z_{ext0} = 1.27 \times 10^1$ cm and the value of Z_{ext0} decreases with increasing of N_0. For $N_0 \geq 10^8$ cm^{-3} NP ensemble predominantly influences on radiation extinction in comparison with pure water and determines optical properties of heterogeneous medium. Approximation of optically thin medium can be used for characteristic lengths smaller than 10 cm that satisfies usual laboratory conditions. The characteristic time for heat removal beyond volume with characteristic length $Z_{ext} \sim 10$ cm is equal to $\tau_{TZ} \sim 1.6 \times 10^3$ s.

Approximate values of the presented characteristic times satisfy next inequalities $\tau_R \sim \tau_Z >> \tau_{TN} >> \tau_{IT} >> \tau_{0T}$. The values of radiation action duration t_P can change in wide interval from very short pulses with $t_P \sim 10^{-9} - 10^{-12}$ till CW action and a few characteristic time intervals were separated for the realization of different thermal processes taking into account mentioned inequalities.

Here, four characteristic cases of the radiation interaction with pulse duration t_P with NPs ensemble in medium can be distinguished: a) the radiation pulse duration t_P is bigger than characteristic time τ_{0T} and it is smaller than characteristic time τ_{IT}; b) the radiation pulse duration t_P is bigger than characteristic times τ_{T0}, τ_{T1} and simultaneously t_P is smaller than τ_{TN}, τ_{TR}, τ_{TZ}; c) the radiation pulse duration t_P is bigger than characteristic times τ_{TN}, τ_{0T}, τ_{IT} and simultaneously t_P is smaller than τ_{TR}, τ_{TZ}; d) the radiation pulse duration t_P is bigger than characteristic times τ_{TR}, τ_{TZ}, τ_{TN}, τ_{0T}, τ_{IT}:

$$\tau_{IT} > t_P > \tau_{0T} \text{ (a)}; \quad \tau_{TR}, \tau_{TZ}, \tau_{TN} > t_P > \tau_{0T}, \tau_{IT} \text{ (b)}$$

$$\tau_{TR}, \tau_{TZ} > t_P > \tau_{TN}, \tau_{0T}, \tau_{IT} \text{ (c)}; \quad t_P > \tau_{TR}, \tau_{TZ}, \tau_{TN}, \tau_{0T}, \tau_{IT} \text{ (d)}$$

(11)

The characteristic times (10) are situated in very different time intervals that allow to divide and to investigate thermal processes severely one after another. The time intervals were estimated for the realization of the conditions (11 a-d) for gold NP with radius $r_0 = 25$ nm placed in water: a) $1 \times 10^{-9} > t_P > 1 \times 10^{-12}$ s, b) $4.4 \times 10^{-5} > t_P > 1 \times 10^{-9}$ s, c) 1.6 s $> t_P > 4 \times 10^{-5}$ s, for $N_0 = 1 \times 10^9$ cm^{-3}, d) $t_P > 1.6$ s.

The formation of quasi-stationary (usually uniform) temperature distribution inside an NP volume is realized very soon during time τ_{0T} in comparison with the formation of quasi-stationary temperature distribution out the NP volume in the near medium because of $\tau_{T0} << \tau_{T1}$ (see Fig. 2 (11a)). When $\tau_{IT} > t_P > \tau_{0T}$ the radiation energy absorbed by the NPs does not practically succeed in transfer to the surrounding medium and irradiated NPs are heated up severely during laser action.

The fulfillment of condition (11b) means that under laser irradiation and heating of NP quasi-stationary temperature distributions (thermal aureoles) have been formed around single NPs without formation of temperature distributions between NPs. This case will be described quasi-stationary solutions of the Eq. (4) under condition $T = T_\infty$ (6a). The fulfillment of condition (11c) means, that temperature distributions (fields) between NPs, placed in irradiated volume, have been formed without initiation of heat exchange of this volume with outer medium, placed out of radiation beam volume. This case will be described by Eq. (5). The fulfillment of condition (11d) means, that temperature field has been formed inside and around radiation beam volume and heat exchange with outer medium placed out of laser beam volume has been developed. This case will be described by Eqs. (4), (5). The pressure in the medium is uniform and constant.

The NP cooling process can be realized in the time intervals that can interrupt the time conditions (11-13). The cooling process of NPs after the termination of radiation action is carried out under overlapping of thermal aureoles from neighboring NPs and the formation of general distribution of $T_1(R, Z, t)$ and the following heat exchange with the ambience out of heated volume by radiation beam. This assumption is confirmed by the computer calculation results and also the non-equality.

The description and investigation of the processes light-to-heat conversion can be divided into four steps, when we can apply different assumptions to simplify the system of equations and to get analytical solutions.

III. ANALYTICAL MODELING

The approximation of optically thin medium is used that means equal values of radiation intensity in all points of the medium under radiation action. This assumption doesn't allow investigating the radiation transfer through medium (Eq. (2)).

Analytical model of the thermal processes of radiation-NP interaction is based on two main assumptions– the first one is the use of uniform temperature inside NP volume during heating and cooling of NP for $t_P \geq \tau_{0T}$ (11a). The equation with uniform temperature T_0 over NP volume, that describes the heating and cooling of an NP, has the form [1]:

$$\rho_0 \, c_0 V_0 \, \frac{dT_0}{dt} = I_0(t)K_{abs} \, S_s - J_C \, S_0, \qquad T_0(t=0) = T_\infty \tag{12}$$

The second assumption is the use of the quasi-stationary heat exchange of NP with medium (quasi-stationary dependence of T on r for $r > r_0$), that is described by Eq. (4) with $\frac{\partial T}{\partial t} \approx 0$ for $t_{P > \tau_{0T}}$ (11a):

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 k_i \frac{dT}{dr}\right) = 0, \tag{13}$$

A. Heating of NP Ensemble as Single NP Heat Sources

The consideration of the heating of NP ensemble as single NP heat sources is based on the fulfillment of the conditions $\tau_{IT > t_P > \tau_{0T}}$ (11a) and $\tau_{TR}, \tau_{TZ}, \tau_{TN} > t_P > \tau_{T0}, \tau_{TI}$ (11b) without the formation of the temperature field in medium.

The quasi-stationary temperature distribution around of NP and heat flux J_C due to the heat conduction from a NP in the quasi-stationary approximation is described by analytical solutions of Eq. (13) with boundary condition

$$T(r \to \infty, t) = T_\infty = \text{const}$$

$$r \geq r_0 \, a \neq -1: \; T(r) = T_\infty \left[1 + \frac{r_0}{r}\left(\left(\frac{T_0}{T_\infty}\right)^{a+1} - 1\right)\right]^{\frac{1}{a+1}}, \; J_C = \frac{k_\infty T_\infty}{(a+1)\,r_0}\left[\left(\frac{T_0}{T_\infty}\right)^{a+1} - 1\right] \tag{14}$$

The solution of Eq. (13) for $a = -1$ is presented in [1]. It has been noted that $T_0 = T_0(t)$, see (12) and $T(r)=T(r,t)$, $J_C=J_C(t)$ in (14). The constant value of the coefficient of heat conduction is used $k_1 = k_\infty$, $a=0$ in the following consideration for simplicity.

Fig. 2a presents the qualitative dependences of the temperature T on r inside the two neighboring cells for analytical quasi-stationary (solid lines) distribution accordingly Eq. (14), and numerical non-stationary (dashed lines) distribution for some time instant $t < t_P < 10^{-5}$-10^{-6} s and for the case of $T_1=T_\infty$. It means the heating of NP ensemble as single NP heat sources, conditions (11 a, b) and without significant heating of the medium in general). Temperature is uniform over NP volumes (see (12)) and non-stationary distributions of $T(r)$ around NPs differ significantly in comparison with quasi-stationary distributions (14).

The dependence of spherical NP temperature T_0 on t during laser pulse action with duration t_P under constant radiation intensity $I_0 = \text{const}$ is obtained from (12, 14):

$$T_0 = T_\infty + \frac{I_0 K_{abs} r_0}{4 k_\infty}\left[1 - \exp(-\frac{t}{\tau_0})\right] \tau_0 = c_0 \rho_0 r_0^2 / 3 k_\infty \tag{15}$$

τ_0 - characteristic time of NP heat exchange. Characteristic time τ_0 for gold NP in water and for $r_0 = 5$ - 100 nm is equal τ_0 ~3.2×10^{-11} - 1.28×10^{-8} s.

B. Thermal Confinement of Single NP

The characteristic time τ_0 determines the temporal dependences of T_0 (15). The pulse duration t_P should be smaller than the characteristic time τ_0 to provide efficient heating of NP without heat loss. The fulfillment of thermal confinement of NP means achievement of maximal value of NP temperature $T_{max} = T_0(t_P)$ and saving own heat energy practically without heat exchange with ambience during "short" pulse action with $t_P < \tau_0$. In this case by the expansion of "exp" from (15) can be obtained the following solution for $0 < t \leq t_P$ and T_0 increases proportionally to time t:

$$0 < t \leq t_P < \tau_0 \; T_0 \approx T_\infty + \frac{3 I_0 K_{abs} t}{4 \rho_0 c_0 r_0}, \tag{16}$$

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In the opposite case ("long" radiation pulses) the condition of NP thermal confinement is interrupted for $t_P > \tau_0$ and the heat loss from NP by heat conduction has to be taken into account during the period of time $0 \le t \le t_P$. The case $t_P > \tau_0$ and for CW irradiation can be used for intensive heat exchange of NP with medium. In this case from (15)

$$t_P > \tau_0 \quad T_0 \approx T_\infty + \frac{I_0 K_{abs} r_0}{4 k_\infty} \qquad (17)$$

But for "long" pulse action time interval $0 < t < \tau_0 < t_P$ can be separated and during this time interval the condition of thermal confinement will be also fulfilled.

The high peak temperature exists only for the short period of time at $t \sim t_P$ as an NP rapidly cools after the ending of pulse. The cooling of an NP after laser action can be described by expressions, which can be derived from (12) under $I_0 = 0$, $T_0(t=t_p) = T_{0M}$ and $t > t_P$:

$$T_0 = T_\infty + (T_{0M} - T_\infty) \exp\left(-(t - t_p)/\tau_0\right) \qquad (18)$$

T_{0M} - maximal value of NP temperature at the end of laser pulse $t=t_P$.

This expression describes the cooling of NPs with constant value of the surrounding temperature T_∞= const. This situation is realized, when thermal energy of heated NP ensemble is much smaller than thermal energy of the medium with temperature T_∞. But in the case of high thermal energy of heated NP ensemble the cooling of NP ensemble will be accompanied by overlapping of thermal aureoles from neighboring NP, the heating of surrounding medium because of the heat exchange with NPs and its temperature will be increased.

Energy Q_C can be analytically calculated using Eq. (7) and expressions for J_C (14), T_0 (t) (15) for period of time $[0, t_P]$:

$$Q_C(t) = Q_{abs}(t) \left[1 + \frac{\tau_0}{t}\left(\exp\left(-\frac{t}{\tau_0}\right) - 1 \right) \right] \qquad (19)$$

Q_C ($t=0$) = 0, and using the Eq. (20) for $t > t_p$ and taking into account $T_{0M} = T(t=t_p)$

$$Q_C(t) = Q_{abs}(t_P) \left[1 + \frac{\tau_0}{t_P}\exp\left(-\frac{t}{\tau_0}\right)\left(1 - \exp\left(\frac{t_P}{\tau_0}\right)\right) \right] \qquad (20)$$

The values of $Q_C(t_P)$ from Eqs. (19) and (20) are equal each to other for $t = t_P$, and for $t \to \infty$ $Q_C(t) = Q_{abs}(t_P)$.

Under condition $t_p > \tau_0$ $Q_C \approx Q_{abs}\left(1 - \dfrac{\tau_0}{t_p}\right)$ for $0 < t \le t_P$ and $t_p \gg \tau_0$ $Q_C \approx Q_{abs}$.

The parameters P_2, P_3 (9) are determined by analytical expressions for Q_C (t) (19, 20) and have the forms:

$$P_2 = 1 + \frac{\tau_0}{t}\left(\exp\left(-\frac{t}{\tau_0}\right) - 1 \right) \quad P_3 = \frac{\tau_0}{t}\left(1 - \exp\left(-\frac{t}{\tau_0}\right)\right) \quad 0 < t \le t_P$$

$$P_2 = 1 + \frac{\tau_0}{t_P}\exp\left(-\frac{t}{\tau_0}\right)\left(1 - \exp\left(\frac{t_P}{\tau_0}\right)\right) \quad P_3 = \frac{\tau_0}{t_P}\exp\left(-\frac{t}{\tau_0}\right)\left(\exp\left(\frac{t_P}{\tau_0}\right) - 1\right) \quad t \ge t_P \qquad (21)$$

The accuracy and the regions of the applicability of analytical model have been estimated and established based on the comparisons and definite coincidences of the analytical results with the computer results, which validate developed analytical model. Computer simulation confirms the possibility to use analytical model for the description of the temporal dependence of NP temperature T_0 for $t_P \ge 10^{-7}$ s including CW irradiation, for NP heating during time interval $1 \times 10^{-12} < t_P \le 1 \times 10^{-11}$ s and outward distributions $T(r)$ for $t_P \ge 10^{-7}$ s and for CW irradiation with satisfactory accuracy.

Fig. 3 presents the temporal dependences of NP temperature T_0 and parameters P_2, P_3 on t for different NP radii $r_0 = 5, 25, 100$ nm, $I_n = I_0 K_{abs} = 1 \times 10^2, 1.6 \times 10^2, 1.65 \times 10^3$ W/cm^2, $t_P \approx 1 \times 10^{-9}$ s determined on the base of the analytical dependences (15, 18, 21). Immediately after commencement of irradiation the NP heating and its heat exchange with the surrounding medium (water) start. The temporal dependences of T_0 on t have the significant features for different values of r_0.

For $r_0 = 5$ nm the NP heating up to maximal temperature T_{max} is realized very rapidly after that the absorption of energy is compensated by heat losses because of the heat conduction. The temperature T_0 achieves the value of $\sim T_{max}$ to the time instant $t \sim 0.1 t_P$.

For $r_0 = 25$, 100 nm the temperature T_0 achieves the value of T_{max} exactly to time instant $t = t_P$ at the end of pulse action. After the radiation pulse is turned off, an NP gives up energy to medium for time interval about τ_0. Its temperature T_0 moves down and becomes equal initial temperature T_∞. The values of τ_0 for $r_0 = 5$, 25, 100 nm are equal to $\tau_0 = 3.45 \times 10^{-11}$, 8.6×10^{-10}, 1.38×10^{-8} s respectively.

The cooling is carried out with the characteristic times τ_0 (see Fig. 3). It means that $\tau_0 \sim r_0^2$ and period of cooling increases with r_0. The cooling of NP with $r_0 = 5$ nm is realized very quickly, and the cooling of NP with $r_0 = 100$ nm is realized rather slowly.

Analytical dependences of the parameters P_2, P_3 on t for Au NPs with the radius $r_0 = 5$, 25, 100 nm, $t_P \approx 1 \times 10^{-9}$ s were presented in Fig. 3b, c. It is interesting to note different time intervals in what sharp increasing of the values of P_2 and decreasing of P_3 is realized. Some points of curve are seen at the time instant $t_P \approx 1 \times 10^{-9}$ s, when the radiation action is turned off.
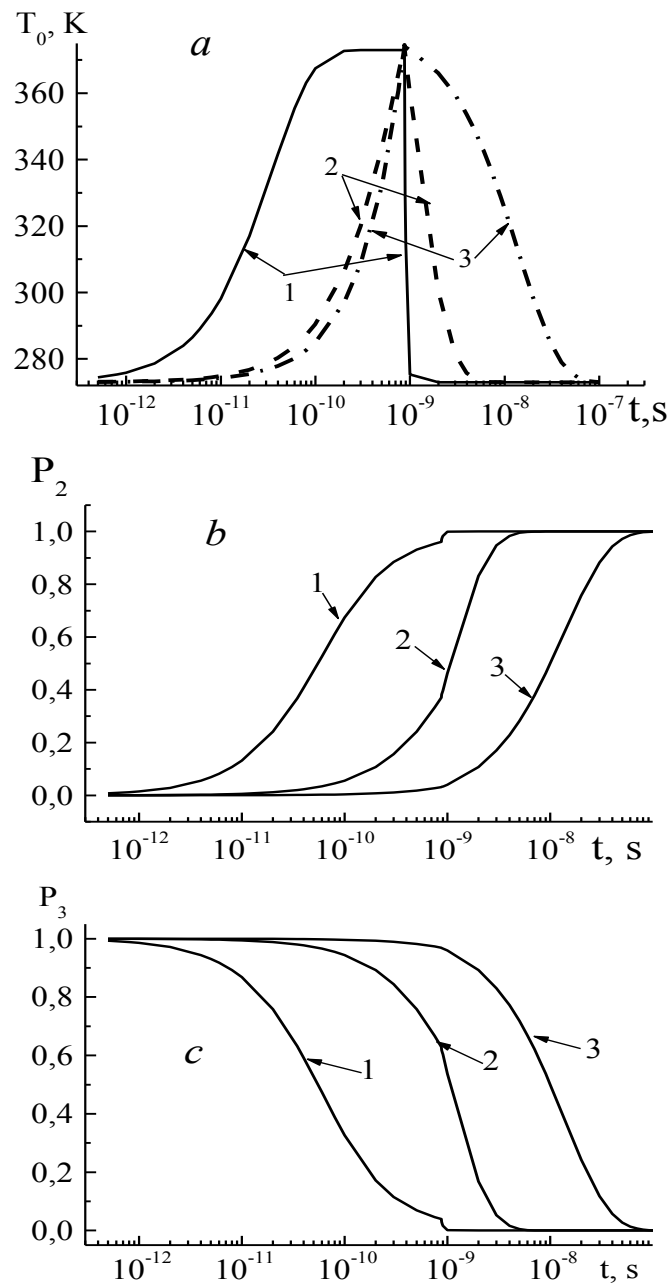

Fig. 3 The dependences of NP temperature T_0 (a) for $r_0 = 5$ (solid,1), 25 (dashed, 2), 100 (dashed-dotted, 3) and parameters P_2 (b), P_3 (c) on t for $r_0 = 5$ (1), 25 (2), 100 (3) nm, $I_n = 1 \times 10^2$ (1), 1.6×10^2 (2), 1.65×10^3 (3) W/cm², $t_P \approx 1 \times 10^{-9}$ s

C. Heating of Medium by Heat Exchange with Irradiated NP Ensemble

Thermal energy of surrounding water at initial temperature $T_\infty = 273$ K is equal to $E_{IT\infty} \approx 1.14 \cdot 10^3$ J/cm^3 and it is much bigger than thermal energy $E_{0T\infty} \approx 4.2 \times 10^{-2}$ J/cm^3 of NP ensemble of gold NPs with $r_0 = 25$ nm with high NP concentration $N_0 = 10^{12}$ cm^{-3}. It means that the heating of this NP ensemble till maximal temperature $T_{0M} = 373$ K by "short" radiation pulse action and following cooling cannot heat the surrounding water to noticeable value of temperature and medium heating is negligible under single action of short radiation pulse with $t_P < 10^{-6}$ s. On the other hand, for the remarkable heating of medium the train of short pulses, single pulse with "long" pulse duration or CW irradiation can be used, when developed heat exchange of heated NPs with medium during "long" period of time will lead to significant heating of the medium.

The consideration of medium heating by heat exchange with irradiated NP ensemble by "long" radiation action is based on the fulfillment of the condition (11c) $\tau_{TR}, \tau_{TZ} > t_P > \tau_{TN}, \tau_{0T}, \tau_{1T}$.

The solution of the Eq. (13) with the boundary condition $T(r \to \infty, t) = T_1(t)$, taking into account the heating of medium in general with temperature $T_1(t)$ has the form

$$r \geq r_0 \; a \neq -1: \; T(r) = T_1 \left[1 + \frac{r_0}{r} \left(\left(\frac{T_0}{T_1} \right)^{a+1} - 1 \right) \right]^{\frac{1}{a+1}}, \; J_C = \frac{k_\infty T_1^{a+1}}{(a+1) \, T_\infty^a \, r_0} \left[\left(\frac{T_0}{T_1} \right)^{a+1} - 1 \right] \tag{22}$$

Consider the heating of irradiated NPs and medium under heat exchange between them. The system of equations which describes these processes has the next form from (12) and (5) without taking into account heat conduction inside and outside the heated volume of heterogeneous medium for $a = 0$:

$$c_0 \rho_0 V_0 \frac{dT_0}{dt} = I_0 K_{abs} \pi r_0^2 - 4\pi r_0 k_\infty (T_0 - T_1)$$

$$c_1 \rho_1 \frac{dT_1}{dt} = N_0 4\pi r_0 k_\infty (T_0 - T_1) \tag{23}$$

with the initial condition:

$$T_0(t=0) = T_\infty, \; T_1(t=0) = T_\infty \tag{24}$$

It is the two-temperature model for the NP and medium temperatures. It is a little bit analogous one to the two-temperature model for electron and lattice temperatures under action of short pulses on metals or metallic NPs [31].

Fig. 2b presents the qualitative dependences of temperature T on r inside the two neighboring cells for analytical quasi-stationary (solid lines) distribution accordingly Eq. (22), and numerical non-stationary (dashed lines) distribution for some time instant $t_P > t > 10^{-5}$ s and for the case of $T_1 > T_\infty$ (heating of medium by heat exchange with irradiated NP ensemble, conditions (11 c) and increasing of medium temperature T_1). Temperature is uniform over NP volumes (see (23)) and non-stationary distributions of $T(r)$ around NPs are close to quasi-stationary distributions, because $t_P > \tau_{1T}$.

The solutions of this system of equations have the next forms:

$$T_0 = T_\infty + \frac{I_0 K_{abs} \pi r_0^2 t N_0}{c\rho} + \frac{I_0 K_{abs} r_0 (c_1 \rho_1)^2}{4 k_\infty (c\rho)^2} \left[1 - \exp\left\{ -\frac{t}{\tau_{01}} \right\} \right]$$

$$T_1 = T_\infty + \frac{I_0 K_{abs} \pi r_0^2 t N_0}{c\rho} - \frac{I_0 K_{abs} r_0 c_1 \rho_1 N_0 c_0 \rho_0 V_0}{4 k_\infty (c\rho)^2} \left[1 - \exp\left\{ -\frac{t}{\tau_{01}} \right\} \right] \; \tau_{01} = \frac{c_0 \rho_0 c_1 \rho_1 r_0^2}{3 k_\infty c\rho} \tag{25}$$

$c\rho = c_1 \rho_1 + 4\pi r_0^3 c_0 \rho_0 N_0 / 3$ - heat capacity of heterogeneous system for 1g, $I_0 K_{abs} \pi r_0^2 t N_0 = Q_{abs}(t) N_0$. The

characteristic time $\tau_{01} = \dfrac{c_0 \rho_0 c_1 \rho_1 r_0^2}{3 k_\infty c\rho} = \tau_0 \dfrac{c_1 \rho_1}{c\rho}$ determines the dependences of temperatures T_0 and T_1 on time t. The value

of τ_{01} will be equal τ_0, when $N_0 = 0$.

D. Thermal Confinement for Irradiated Volume of System

If the condition $t / \tau_{01} \ll 1$ is obeyed and the loss of heat from a NP by heat conduction during the time t can be ignored, we find from expression (25) that expansion of the exponential function gives the values of T_0 on t and T_1:

$$T_0 \approx T_\infty + \frac{3I_0 t \, K_{abs}}{4\rho_0 c_0 r_0} \, , \, T_1 \approx T_\infty, \, T_0 - T_1 \approx \frac{3I_0 t \, K_{abs}}{4\rho_0 c_0 r_0} \tag{26}$$

For "short" radiation pulses the heat exchange the NPs with surrounding can be practically ignored and T_0 is proportional t and medium temperature $T_1 \approx T_\infty$. The expression for T_0 is equal Eq. (16) for single NP. If the condition $t / \tau_{01} >> 1$ is obeyed for "long" radiation action and the loss of NP heat determines the values of temperatures:

$$T_0 \approx T_\infty + \frac{I_0 K_{abs} \pi r_0^2 t N_0}{c\rho} + \frac{I_0 K_{abs} r_0 (c_1 \rho_1)^2}{4k_\infty (c\rho)^2}$$

$$T_1 \approx T_\infty + \frac{I_0 K_{abs} \pi r_0^2 t N_0}{c\rho} - \frac{I_0 K_{abs} r_0 c_1 \rho_1 N_0 c_0 \rho_0 V_0}{4k_\infty (c\rho)^2} \tag{27}$$

In this case temperatures T0 and T increase in time t and will have no stationary maximal values because there is no heat exchange of heated volume of medium with surrounding ambience. Stationary overheating of NPs in comparison with medium T0 -T1 is constant during the radiation action:

$$T_0 - T_1 = \frac{I_0 K_{abs} r_0 c_1 \rho_1}{4k_\infty c\rho}$$

The analysis of the influence of thermal properties of the NPs in surrounding medium on τ_{01} allows to make next conclusions. The estimation of characteristic time $\tau_{01} = \tau_0 \dfrac{c_1 \rho_1}{c\rho}$ for gold NP with radius $r_0 = 25$ nm placed in water gives next values: $\tau_{01} = \dfrac{\tau_0}{1 + N_0 V_0 c_0 \rho_0 / c_1 \rho_1} = \dfrac{\tau_0}{1 + N_0 9.3 x 10^{-18}}$ and up to extremely high values of NP concentrations $N_0 > 10^{16}$ cm^{-3} the influence of NP ensemble on τ_{01} is negligible and $\tau_{01} \approx \tau_0$. Cooling of NP after the pulse action will be determined by expressions:

$$T_0 = T_{0M} - (T_{0M} - T_{1M})\frac{c_1 \rho_1}{c\rho}\left[1 - \exp\left(-\frac{(t - t_P)}{\tau_{01}}\right)\right]$$

$$T_1 = T_{1M} + (T_{0M} - T_{1M})\frac{N_0 c_0 \rho_0 V_0}{c\rho}\left[1 - \exp\left(-\frac{(t - t_P)}{\tau_{01}}\right)\right] \tag{28}$$

T_{0M} and T_{1M} are the values of NP and medium temperatures at $t = t_P$, for $t \to \infty$ stationary values of NP and medium temperatures will be equal to each other

$$T_{0S} = T_{1S} = \frac{T_{0M} N_0 c_0 \rho_0 V_0 + T_{1M} c_1 \rho_1}{c\rho}$$

or from Eqs. (8), (9)

$$T_{0S} = T_{1S} = T_\infty + \frac{Q_{abs} N_0}{N_0 c_0 \rho_0 V_0 + c_1 \rho_1}$$

Energy Q_C can be analytically calculated using Eq. (27) and expressions for J_C (22), T (10) taking into account $T_{max} = T(t = t_p)$, $t_{max} = t_p$ for the period of time $[0, t_p]$:

$$Q_C(t) = Q_{abs}(t) \frac{c_1 \rho_1}{c\rho}\left[1 + \frac{\tau_{01}}{t}\left(\exp\left(-\frac{t}{\tau_{01}}\right) - 1\right)\right] \tag{29}$$

$Q_C(t = 0) = 0$, and for $t > t_p$

$$Q_C(t) = Q_{abs}(t_P)\ \frac{c_1\rho_1}{c\rho}\left[1+\frac{\tau_{01}}{t_P}\exp\left(-\frac{t}{\tau_{01}}\right)\left(1-\exp\left(\frac{t_P}{\tau_{01}}\right)\right)\right] \qquad (30)$$

for $t= t_P$ values of $Q_C(t_P)$ from Eqs. (29), (30) are equal to each other, for $t\to\infty$ $Q_C(t) = Q_{abs}(t_P)\ \dfrac{c_1\rho_1}{c\rho}$.

The parameters P_2, P_3 for heat exchange between NPs and medium are presented from (9, 29, 30)

$$P_1= \frac{c_1\rho_1}{c\rho}\left[1+\frac{\tau_{01}}{t}\left(\exp\left(-\frac{t}{\tau_{01}}\right)-1\right)\right],$$

$$P_2= 1- \frac{c_1\rho_1}{c\rho}\left[1+\frac{\tau_{01}}{t}\left(\exp\left(-\frac{t}{\tau_{01}}\right)-1\right)\right],$$

$$\qquad (31)$$

$$P_1= \frac{c_1\rho_1}{c\rho}\left[1+\frac{\tau_{01}}{t_P}\exp\left(-\frac{t}{\tau_{01}}\right)\left(1-\exp\left(\frac{t_P}{\tau_{01}}\right)\right)\right],$$

$$P_2= 1- \frac{c_1\rho_1}{c\rho}\left[1+\frac{\tau_{01}}{t_P}\exp\left(-\frac{t}{\tau_{01}}\right)\left(1-\exp\left(\frac{t_P}{\tau_{01}}\right)\right)\right].$$

Fig. 4 presents the dependences of NP T_0 and medium T_1 temperatures on t/t_P for $t_P= 1\times10^{-6}$, 1×10^{-3}, 1 s for $r_0 = 25$ nm. Fig. 4 shows the temporal dependences of the temperatures T_0 of gold NP and T_1 of surrounding water for different pulse durations of radiation determined on the base of the analytical dependences (25, 28).
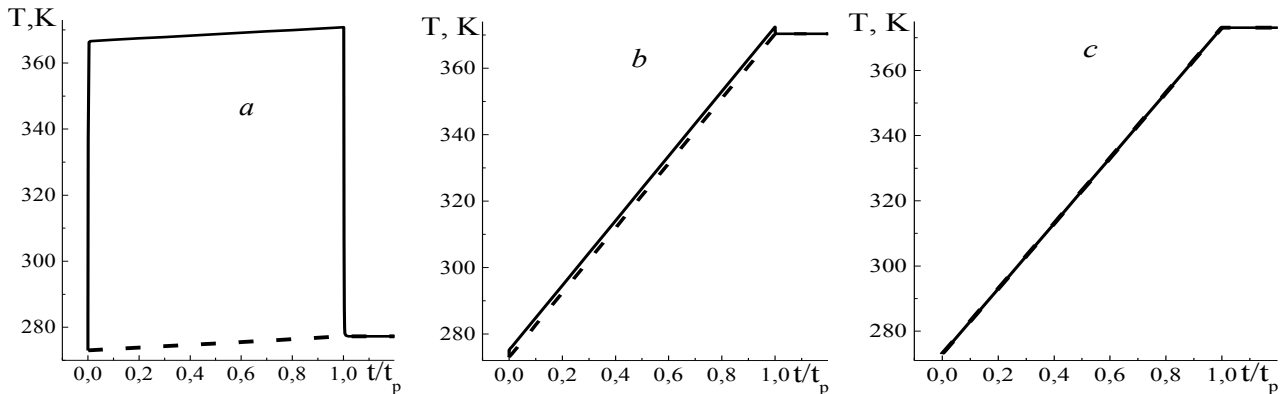

Fig. 4 The dependences of NP T_0 (solid) and medium T_1 (dashed) temperatures on t/t_P for $t_P= 1\times10^{-6}$, 1×10^{-3}(b), 1(c) s for $r_0 = 25$ nm, $I_n = 9\times10^5$ (a), 2.07×10^4 (b), 2.13×10^1 (c) W/cm^2

The temporal dependences of T_0 on t have significant features for different values of t_P. For $t_P = 1\times10^{-6}$ s the temperature T_0 achieves the value of $0.9T_{max}$ up to time instant $t \sim 1\times10^{-2}$ t_P and after that the heat release in NPs is completely compensated by heat exchange with surrounding medium. During the rest part of t_p T_0 slowly achieves T_{max}. The temperature of T_1 slowly increases as a result of the energetic heat exchange with NP ensemble. Stationary overheating of the NP ensemble in comparison with medium is constant during radiation action. The NPs give up thermal energy to medium for the time interval about 1×10^{-8} s after the termination of the pulse with $t_P = 1\times10^{-6}$ s and their temperature T_0 moves down and equals to some stationary temperature $T_{0S} = T_{1S}$.

The heating of the NPs and their intensive heat exchange with the surrounding water start immediately after irradiation commencement for $t_P = 1\times10^{-3}$, 1 s (and CW irradiation), see Fig. 4b, c. The temperatures T_0 and T_1 achieve own maximal values to the end of radiation action $t = t_P$. In these cases the energy release in NPs and heat exchange leads to rapid increase of the temperatures T_0 and T_1 in time and with small difference between them, $T_0 - T_1$ is equal for $t_P = 1\times10^{-3}$, 1 s $T_0 - T_1 = 2$, 0.5 K respectively. The temperatures have equal stationary temperature $T_{0S} = T_{1S}$ after the end of radiation action, for $t_P = 1\times10^{-3}$, 1 s $T_{0S} = T_{1S} \approx 373$ K.

E. Heat Exchange of Heated Volume of System with an Ambience

The consideration of this case is based on the fulfillment of the condition (11d) $t_P > \tau_R, \tau_Z, \tau_{TN}, \tau_{0T}, \tau_{1T}$ with the formation of the temperature field in medium and heat exchange of heated volume of system with ambience. The stationary solution, when energy release in NPs and medium in irradiated volume of system is compensated by heat exchange with surrounding: $\dfrac{dT_0}{dt} = 0$ $\dfrac{dT_1}{dt} = 0$ and temperatures have stationary values T_{0s} and T_{1s} and NP overheating in comparison with medium is equal to

$$T_{0S} - T_{1S} = \frac{I_0 K_{abs} r_0}{4 k_\infty}$$

For the general description of the light-to-heat conversion processes in this case the system of Eqs. (2-5, 7, 9) have numerically be solved with boundary and initial conditions (6).

IV. CONCLUSIONS

The problem of the light-to-thermal energy (heat) conversion under optical (laser) radiation heating of NP ensemble is important for different applications in nanoenergy, laser nanomedicine, laser processing of NPs, etc. It is important to theoretically describe the temporal and spatial-temporal behavior of the NPs and surrounding medium temperature and the parameters of the light-to-heat conversion for these applications. The analytical modeling has a few advantages in comparison with computer one because its results much simpler and convenient and can be used for the description of different experiments.

The analytical investigation of the light-to-heat conversion by NP ensemble in medium under radiation action was conducted in this article. The system of Eqs. (2)-(5) was formulated and the analytical model was developed for the description of the thermal processes of the light-to-heat conversion by NP ensemble in medium under radiation (laser) action including heating and cooling stages. Developed analytical model demonstrates the advantages and novelty in comparison with previous analytical approaches because of the possibility to describe entirely the processes of NPs and medium heating and cooling for light-to-heat conversion.

The characteristic cases of the radiation interaction with pulse duration t_P with NP ensemble in medium were distinguished and four characteristic time intervals were separated for realization of different thermal processes: a) $\tau_{1T} > t_P > \tau_{0T}$; b) $\tau_{TR}, \tau_{TZ}, \tau_{TN} > t_P > \tau_{0T}, \tau_{1T}$; c) $\tau_{TR}, \tau_{TZ} > t_P > \tau_{TN}, \tau_{0T}, \tau_{1T}$; (d) $t_P > \tau_{TR}, \tau_{TZ}, \tau_{TN}, \tau_{0T}, \tau_{1T}$. The estimations of these time intervals for the realization of the conditions (a-d) for gold NP with radius $r_0 = 25$ nm, placed in water are equal to: a) $1 \times 10^{-12} > t_P > 1 \times 10^{-9}$ s, b) $4.4 \times 10^{-5} > t_P > 1 \times 10^{-9}$ s, for $N_0 = 10^9$ cm^{-3}, c) 1.6 s $> t_P > 4 \times 10^{-5}$ s, d) $t_P > 1.6$ s (see (10)).

In the cases a), b) the heating of NP ensemble is considered as single NP heat sources without formation of the temperature field in medium. The case c) describes the heating of medium by heat exchange with irradiated NP ensemble and with the formation of the general temperature field in medium. The case d) describes the heat exchange of irradiated and heated volume of system (NPs and medium) with ambience and the formation of the temperature field out of irradiated volume of system. The radiation action of "long" pulses (cases c, d) allows effective heating of the surrounding medium.

The analytical descriptions of NP ensemble heating under action of pulsed optical (laser) radiation and its cooling after the termination of radiation action are conducted. Analytical solutions for temporal dependences of the NP T_0 and medium T_1 temperatures, parameters Q_C, P_2, P_3 on t (15-28) during the processes of NP heating and cooling for the cases of a, b, c were received and investigated. The investigations of the influence of NPs parameters (their radii, absorption efficiency factor, density and heat capacity of NP material, concentration), characteristics of radiation (wavelength, pulse duration, radiation beam radius), the medium (its density, heat capacity, and heat conduction coefficient, characteristic length of radiation extinction) on the efficiency of the light-to-heat conversion are conducted. The temporal dependences of the thermo-optical parameters P_2, P_3 characterize the heating efficiency of NPs and the redistribution of the absorbed energy between NPs and their environment. Estimations of characteristic values of times, NP concentrations, optical properties of heterogeneous systems are carried out.

The possibility of thermal confinement (saving own thermal energy practically without heat exchange with surrounding) has been established for single NP (case a) and for the irradiated volume of medium with NPs (case c) for determined time intervals. The fulfillment of thermal confinement means achievement of maximal value of NP and medium temperatures and the heat localization within the NP and irradiated medium volume during selected time intervals without heat exchange with ambience.

Developed analytical model gives quantitatively (in determined time intervals) and qualitatively correct description of the dynamics of heating and cooling of NP ensemble and surrounding medium, and this model is quite suitable for the modeling of

the thermal processes of the radiation-NP ensemble interaction. These results are important for the description of the light-to-heat conversion processes in experimental investigations in nanoenergy and nanotechnology.

REFERENCES

[1] V. K. Pustovalov, "Theoretical study of heating of spherical nanoparticle in media by short laser pulses," *Chem. Phys.*, vol. 308, pp. 103-108, 2005.

[2] O. Wilson, X. Hu, D. G. Cahill, and P. Braun, "Colloidal metal particles as probes of nanoscale thermal transport in fluids," *Phys. Rev. B*, vol. 66, pp. 224-301, 2002.

[3] A. O. Govorov and H. H. Richardson, "Generating heat with metal nanoparticles," *Nanotoday*, vol. 2, pp. 30-38, 2007.

[4] D. Keith Roper, W. Ahn, and M. Hoepfner, "Microscale heat transfer transduced by surface plasmon resonant gold nanoparticles," *J. Phys. Chem. C*, vol. 111, pp. 3636-3641, 2007.

[5] M. Tribelsky, A. Miroshnichenko, Yu. Kivshar, B. Lukyanchuk, and A. Khokhlov, "Laser pulse heating of spherical metal particles," *Phys. Rev. X*, vol. 1, pp. 021-024, 2011.

[6] N. Zeng and A. Murphy, "Heat generation by optically and thermally interacting aggregates of gold nanoparticles under illumination," *Nanotechnology*, vol. 20, pp. 375-702, 2013.

[7] G. Baffou and R. Quidant, "Thermo-plasmonics: using metallic nanostructures as nano-sources of heat," *Laser Photonics Review*, vol. 7, pp. 171-187, 2913.

[8] V. K. Pustovalov, L. G. Astafyeva, and W. Fritzsche, "Selection of thermo-optical parameters for achievement of their maximal thermal energy under optical irradiation," *Nano Energy*, vol. 2, pp. 1137-1141, 2013.

[9] U. Palanchoke, H. Kutz, R. Noriega, S. Arabi, V. Jovanov, P. Magnus, H. Aftab, A. Salleo, H. Stiebig, and D. Knipp, "Tuning the plasmonic absorption of metal reflectors by zinc oxide nanoparticles," *Nano Energy*, vol. 6, pp. 167-172, 2014.

[10] K. Jiang, D. A. Smith, and A. Pinchuk, "Size dependent photothermal conversion efficiencies of plasmonically heated gold nanoparticles," *J. Phys. Chem. C*, vol. 117, pp. 27073-27080, 2014.

[11] S. Niu, Y. S. Zhou, S. Wang, Y. Liu, L. Lin, Y. Bando, and Z. L. Wang, "Simulation method for optimizing of an integrated triboelectric nanogenerator energy harvesting system," *Nano Energy*, vol. 8, pp. 150-156, 2014.

[12] H. Ma, P. Tian, J. Pello, L. B. Oddershede, and P.M. Bendix, "Heat generation by irradiated complex composite nanostructures," *Nano Lett.*, vol. 14, pp. 612-619, 2014.

[13] X. Huang, P. K. Jain, I. H. El-Sayed, and M. A. El-Sayed, "Plasmonic photothermal therapy (PPTT) using gold nanoparticles," *Lasers Med. Sci.*, vol. 23, pp. 217-221, 2008.

[14] L. Kennedy, L. Bickford, N. Lewinsky, et al., "A new era for cancer treatment," *Small*, vol. 7, pp. 169-176, 2010.

[15] M. A. Philips, M. L. Gran, and N. A. Peppas, "Targeted nanodelivery of drugs," *Nano Today*, vol. 5, pp. 143-158, 2010.

[16] V. K. Pustovalov, A. S. Smetannikov, and V. P. Zharov, "Photothermal and accompanied phenomena of selective nanophotothermolysis with gold nanoparticles and laser pulses," *Las. Phys. Lett.*, vol. 5, pp. 775-792, 2008.

[17] J. R. Adleman, D. A. Boyd, D. G. Goodwin, and D. Psaltis, "Heterogeneous catalysis mediated by plasmon heating," *NanoLett.*, vol. 9, pp. 4417-4420, 2009.

[18] H. Jing, Q. Zhang, N. Large, C. Yu, D. A. Blom, P. Nordlander, and H. Wang, "Tunable plasmonic nanoparticles with catalytically active high-index facets," *Nano Lett.*, vol. 14, pp. 3674-3682, 2014.

[19] H. Muto, K. Miyajima, and F. Mafune, "Mechanism of laser-induced size reduction of gold nanoparticles as studied by laser pulse excitation," *J. Phys. Chem. B*, vol. 112, pp. 5810-5815, 2008.

[20] A. Pyatenko, M. Yamaguchi, and M. Suzuki, "Mechanisms of size reduction of colloidal silver and gold nanoNPs irradiated by Nd:Yag laser," *J. Phys. Chem. B*, vol. 113, pp. 9078-9085, 2009.

[21] S. Hashimoto, D. Werner, and T. Uwada, "Studies on the interaction of pulsed lasers with plasmonic gold nanoparticles toward light manipulation, heat management, and nanofabrication," *J. Photochem. Photobiol. C*, vol. 13, pp. 28-54, 2012.

[22] A. Urban, S. Carretero-Palacios, A. Lutich, T. Lohmüller, J. Feldmann, and F. Jäckel, "Optical trapping and manipulation of plasmonic nanoparticles," *Nanoscale*, vol. 6, pp. 4458-4474, 2014.

[23] M. Honda, Y. Saito, N. I. Smith, K. Fujita, and S. Kawata, "Nanoscale heating of laser irradiated single gold nanoparticles in liquid," *Optics Express*, vol. 19, pp. 12375-12379, 2011.

[24] A. Stalmashonak, G. Seifert, and A. Abdolvand, *Ultra-short pulsed laser engineered metal-glass nanocomposites*, Cham, Heidelberg, New York, Dordrecht, London, Springer, 2013.

[25] R. I. Nigmatulin, *Dynamics of Multiphase Media*, vol. 1, no. 2, New York, Hemisphere, 1990.

[26] C. F. Bohren and D. R. Huffman, *Absorption and Scattering of Light by Small Particles*, New York, Wiley, 1983.

[27] F. Kreith and W. Z. Black, *Basic heat transfer*, New York, Harper and Row, 1980.

[28] R. J. Warzoha and A. S. Fleischer, "Heat flow at nanoparticle interfaces," *Nano Energy*, vol. 6, pp. 137-158, 2014.

[29] V. K. Pustovalov, L. Astafyeva, and W. Fritzsche, "Comparative Analysis of Thermo-Optical Properties of Metallic Nanoparticles for Photonic Applications in Nanotechnology," *Science of Advanced Materials*, vol. 4, pp. 480-488, 2012.

[30] V. E. Zuev, *Propagation of visible and infrared waves in atmosphere*, Moscow, Sov. Radio, 1970 (in Russian).

[31] S. I. Anisimov, B. L. Kapeliovich, and T. L. Perelman, "Electron emission from the surface of metals under action of ultrashort laser pulses," *Sov. Phys. JETP*, vol. 39, pp. 375-380, 1974.