Heating of composite solid aerosol particles by laser radiation

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Abstract

The heating of lidar-irradiated multilayered particles is analyzed theoretically and numerically by solution to the heat-conduction equation. The internal intensity and temperature distributions are presented for particles composed of air, quartz and carbon. It is shown that the heating time of such particles substantially depend on particle radius, layer position and thickness. In particular, the decrease of the thickness of surface carbon layer can result in the reduction of the heating time of multilayered particles.

Key words: atmospheric aerosol particles, multilayered particles, heating, laser radiation

1. Introduction

Investigation of laser radiation interaction with solid aerosol particles is one of important practical problems especially in connection with the lidar remote sensing of atmospheric aerosol. Such particles can absorb laser radiation and get warm. Most of theoretical studies on the heating of solid particles by laser radiation are related to homogeneous spheres[1] or core-mantle (two-layered) spheres.[2] But the solid atmospheric particles usually have heterogeneous and composite structure[3] . Examples are particles with trapped air bubbles or composites of mineral aerosols.

In this paper, the heating of composite solid aerosol spherical particles under the action of intense laser radiation is investigated. We simulate such particles assuming that they are three-layered spheres and compare the results with those for two-layered spheres. The particles consist of concentric spherical layers of the two materials: quartz or carbon, each with a specified volume fraction. The innermost layer (core) is assumed to be filled with the air. The volume fraction of the core remains constant in different multilayered particles and occupies one third of the particle volume. Quartz and carbon were chosen because their important role in physics of terrestrial atmosphere. The mathematical formulation of the problem of heating of three-layered particles consists in the solution to the heat-conduction equation in spherical coordinates with corresponding initial and boundary conditions taking into account the nonuniform heat release inside the particles and temperature dependencies of optical and thermophysical properties of particle material.

2. Theory

Let a continuous nonpolarized plane-wave laser beam with irradiance I interacts with a solid three-layered particle of outer radius R_3. The particle absorbs radiation and becomes warmer. The surrounding medium is assumed to be vacuum. The process of heating and the temperature variation inside the three-layered sphere with time t is described by the system of the equations in a spherical coordinate system (r, θ, φ) with the origin at the particle center $(i = 1, 2, 3)$

$$c_i(T_i)\rho_i(T_i)\frac{\partial T_i}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\mathcal{K}_i(T_i)r^2\frac{\partial T_i}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\mathcal{K}_i(T_i)\sin\theta\frac{\partial T_i}{\partial\theta}\right) + \mathcal{Q}_i(r, \theta, T_i, t). \quad (1)$$

Here, index 1 corresponds to the core with radius R_1, index 2 corresponds to the intermediate layer with radius R_2 and index 3 is related to the outer layer. $T_i(r, \theta, t)$ is the local temperature inside the particle, $c_i(T_i)$, $\rho_i(T_i)$ and $\mathcal{K}_i(T_i)$ are the material heat capacity, density, and thermal conductivity, respectively. The internal temperature is independent of the azimuthal angle φ because of the symmetry. The power density of heat sources at a given point inside the particle $\mathcal{Q}_i(T_i)$ is determined by equation

$$\mathcal{Q}_i(T_i) = IB_i\frac{4\pi n_i\chi_i}{\lambda}, \quad (2)$$

where

$$B_i = \frac{|E_r^{(i)}|^2 + |E_\theta^{(i)}|^2}{E_0^2}. \quad (3)$$

In Eqs. (2)-(3), $E_r^{(i)}$ and $E_\theta^{(i)}$ are the components of the electric field inside different layers, E_0 is the electric field of the incident laser beam, $m_i = n_i - i\chi_i$ the complex refractive index of the corresponding material, λ the radiation wavelength. The components of the electric fields at given point in the core can be written as:

$$\begin{cases} E_r^{(1)} = \dfrac{E_0 \cos\varphi}{k_1^2 r^2} \displaystyle\sum_{l=1}^{\infty} l(l+1) \frac{\psi_l(k_1 r)}{\psi_l(k_1 R_1)} \mathcal{C}_l^{(1)} \mathcal{Q}_l(\theta) \sin\theta, \\ \\ E_\theta^{(1)} = \dfrac{E_0 \cos\varphi}{k_1 r} \displaystyle\sum_{l=1}^{\infty} \frac{\psi_l(k_1 r)}{\psi_l(k_1 R_1)} \left[\mathcal{C}_l^{(1)} \mathcal{D}_l(k_1 r) S_l(\theta) + i \mathcal{B}_l^{(1)} \mathcal{Q}_l(\theta) \right]. \end{cases} \tag{4}$$

The expressions for components of the electric fields inside second and third layer have the similar form

$$\begin{cases} E_r^{(2),(3)} = \dfrac{E_0 \cos\varphi}{k_{2,3}^2 r^2} \displaystyle\sum_{l=1}^{\infty} l(l+1) \left[\frac{\psi_l(k_{2,3} r)}{\psi_l(k_{2,3} R_{2,3})} \mathcal{C}_l^{(2),(3)} + \frac{\zeta_l(k_{2,3} r)}{\zeta_l(k_{2,3} R_{2,3})} \tilde{\mathcal{C}}_l^{(2),(3)} \right] \mathcal{Q}_l(\theta) \sin\theta, \\ \\ E_\theta^{(2),(3)} = \dfrac{E_0 \cos\varphi}{k_{2,3} r} \displaystyle\sum_{l=1}^{\infty} \left\{ \left[\frac{\psi_l(k_{2,3} r)}{\psi_l(k_{2,3} R_{2,3})} \mathcal{C}_l^{(2),(3)} \mathcal{D}_l(k_{2,3} r) + \frac{\zeta_l(k_{2,3} r)}{\zeta_l(k_{2,3} R_{2,3})} \tilde{\mathcal{C}}_l^{(2),(3)} \mathcal{G}_l(k_{2,3} r) \right] S_l(\theta) \right. \\ \\ \qquad\qquad \left. + i \left[\dfrac{\psi_l(k_{2,3} r)}{\psi_l(k_{2,3} R_{2,3})} \mathcal{B}_l^{(2),(3)} + \dfrac{\zeta_l(k_{2,3} r)}{\zeta_l(k_{2,3} R_{2,3})} \tilde{\mathcal{B}}_l^{(2),(3)} \right] \mathcal{Q}_l(\theta) \right\}. \end{cases} \tag{5}$$

In Eqs. (4)-(5), $k_i = 2\pi m_i/\lambda$ is wave number in the corresponding layer, $\psi_l(z)$ Riccati-Bessel function, $\zeta_l(z)$ Riccati-Hankel function, $\mathcal{D}_i(z) = \psi_l'(z)/\psi_l(z)$ and $\mathcal{G}_l(z) = \zeta_l'(z)/\zeta_l(z)$ are logarithmic derivatives of the corresponding functions. The angular functions $\mathcal{Q}_l(\theta)$ and $S_l(\theta)$ are defined with the aid of the Legendre polynomials $P_l(\cos\theta)$ and their derivatives. The coefficients $\mathcal{B}_l^i$, $\mathcal{C}_l^i$ and $\tilde{\mathcal{B}}_l^i$, $\tilde{\mathcal{C}}_l^i$ in Eqs. (4)-(5) are ($m_s = 1.0 - i0.0$ is the refractive index of the surrounding medium, $k = 2\pi/\lambda$ is the wave number in vacuum)

$$
\begin{cases}
\mathcal{B}_l^{(1)} = i^l \dfrac{2l+1}{l(l+1)}\, m_{1s}\, \dfrac{1}{\psi_l(k_2R_2)\zeta_l(k_2R_1)}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_1}, \\[2ex]
\mathcal{C}_l^{(1)} = i^l \dfrac{2l+1}{l(l+1)}\, \dfrac{1}{\psi_l(k_2R_2)\zeta_l(k_2R_1)}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_2}, \\[2ex]
\mathcal{B}_l^{(2)} = -i^{l-1} \dfrac{2l+1}{l(l+1)}\, m_{2s}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{A_2}{\Delta_1}, \\[2ex]
\tilde{\mathcal{B}}_l^{(2)} = i^{l-1} \dfrac{2l+1}{l(l+1)}\, m_{2s}\, \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{A_1}{\Delta_1}, \\[2ex]
\mathcal{C}_l^{(2)} = -i^{l-1} \dfrac{2l+1}{l(l+1)}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{\tilde{A}_2}{\Delta_2}, \\[2ex]
\tilde{\mathcal{C}}_l^{(2)} = i^{l-1} \dfrac{2l+1}{l(l+1)}\, \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{1}{\psi_l(k_3R_3)\zeta_l(k_3R_2)}\, \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{\tilde{A}_1}{\Delta_2}, \\[2ex]
\mathcal{B}_l^{(3)} = i^l \dfrac{2l+1}{l(l+1)}\, m_{3s}\, \left[\dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)}\, A_1H_2 - A_2L_2\right] \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_1}, \\[2ex]
\tilde{\mathcal{B}}_l^{(3)} = i^l \dfrac{2l+1}{l(l+1)}\, m_{3s}\, \dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \left[A_2H_1 - \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)} A_1L_1\right] \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_1}, \\[2ex]
\mathcal{C}_l^{(3)} = i^l \dfrac{2l+1}{l(l+1)}\, m_{3s}\, \left[\dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)}\, \tilde{A}_1\tilde{H}_2 - \tilde{A}_2\tilde{L}_2\right] \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_2}, \\[2ex]
\tilde{\mathcal{C}}_l^{(3)} = i^l \dfrac{2l+1}{l(l+1)}\, m_{3s}\, \dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \left[\tilde{A}_2\tilde{H}_1 - \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)}\, \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)} \tilde{A}_1\tilde{L}_1\right] \dfrac{1}{\zeta_l(kR_3)}\, \dfrac{1}{\Delta_2},
\end{cases}
\tag{6}
$$

where

$$
\begin{cases}
\Delta_1 = A_1 \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)} \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)} \left[\dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \dfrac{\zeta_l(k_3R_3)}{\zeta_l(k_3R_2)} F_2L_1 - F_1H_2 \right] \\[2ex]
\qquad + A_2 \left[F_1L_2 - \dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \dfrac{\zeta_l(k_3R_3)}{\zeta_l(k_3R_2)} F_2H_1 \right], \\[2ex]
\Delta_2 = \tilde{A}_1 \dfrac{\psi_l(k_2R_1)}{\psi_l(k_2R_2)} \dfrac{\zeta_l(k_2R_2)}{\zeta_l(k_2R_1)} \left[\dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \dfrac{\zeta_l(k_3R_3)}{\zeta_l(k_3R_2)} \tilde{F}_2\tilde{L}_1 - \tilde{F}_1\tilde{H}_2 \right] \\[2ex]
\qquad + \tilde{A}_2 \left[\tilde{F}_1\tilde{L}_2 - \dfrac{\psi_l(k_3R_2)}{\psi_l(k_3R_3)} \dfrac{\zeta_l(k_3R_3)}{\zeta_l(k_3R_2)} \tilde{F}_2\tilde{H}_1 \right]
\end{cases}
\tag{7}
$$

and

$$
\begin{cases}
A_1 = \mathcal{D}_l(k_2R_1) - m_{12}\mathcal{D}_l(k_1R_1), \\
A_2 = \mathcal{G}_l(k_2R_1) - m_{12}\mathcal{D}_l(k_1R_1), \\
L_1 = \mathcal{D}_l(k_3R_2) - m_{23}\mathcal{G}_l(k_2R_2), \\
L_2 = \mathcal{G}_l(k_3R_2) - m_{23}\mathcal{D}_l(k_2R_2), \\
H_1 = \mathcal{D}_l(k_3R_2) - m_{23}\mathcal{D}_l(k_2R_2), \\
H_2 = \mathcal{G}_l(k_3R_2) - m_{23}\mathcal{G}_l(k_2R_2), \\
F_1 = \mathcal{G}_l(kR_3) - m_{3s}\mathcal{D}_l(k_3R_3), \\
F_2 = \mathcal{G}_l(kR_3) - m_{3s}\mathcal{G}_l(k_3R_3).
\end{cases}
\tag{8}
$$

The expressions for $\tilde{A}_1$, $\tilde{A}_2$, ..., $\tilde{F}_2$ can be obtained from the corresponding expressions for A_1, A_2, ..., F_2 (see Eq. (8)) by the replacement of m_{ij} for m_{ji}, where $m_{ij} = m_i/m_j$.

At the center, interfaces and on the surface of the particle the following conditions must be satisfied:

$$
\begin{cases}
|T_1(0,\theta,t)| < \infty, \qquad 0 \le \theta \le \pi, \qquad t > 0, \\
T_1(R_1,\theta,t) = T_2(R_1,\theta,t), \qquad T_2(R_2,\theta,t) = T_3(R_2,\theta,t), \\
\mathcal{K}_1(T_1)\dfrac{\partial T_1(R_1,\theta,t)}{\partial r} = \mathcal{K}_2(T_2)\dfrac{\partial T_2(R_1,\theta,t)}{\partial r}, \quad \mathcal{K}_2(T_2)\dfrac{\partial T_2(R_2,\theta,t)}{\partial r} = \mathcal{K}_3(T_3)\dfrac{\partial T_3(R_2,\theta,t)}{\partial r}, \\
-\mathcal{K}_3(T_3)\dfrac{\partial T_3(R_3,\theta,t)}{\partial r} = \sigma\varepsilon_\lambda T^4, \\
\left.\dfrac{\partial T_i(R_i,\theta,t)}{\partial \theta}\right|_{\theta=0} = \left.\dfrac{\partial T_i(R_i,\theta,t)}{\partial \theta}\right|_{\theta=\pi} = 0 \qquad i = 1,2,3,
\end{cases}
\tag{9}
$$

where σ is the Stefan-Boltzmann constant and ε_λ is the spectral coefficient of blackness.

The solution of system (1) with the conditions (9) is possible only numerically. For this purpose, the local one-dimensional iterative scheme was created. The iteration cycle is continued up to the achievement of the required accuracy. The temperature dependencies of thermophysical properties of quartz and carbon were taken into account in the calculations. Using the approximate formulas obtained from the data presented in Refs. 4 – 6, the values of thermal conductivity $\mathcal{K}(T)$, heat capacity $c(T)$, and density $\rho(T)$ were corrected at any time according to the temperature of every mesh point.

3. Numerical results

A computer code to solve the coupled set of equations discussed above have been developed. Numerical results are presented for the cases of three-layered non-rotating spheres of air-quartz-carbon and air-carbon-quartz irradiated by lidar beam of wavelength λ=1.06 μm with laser fluxes 10^6W/cm^2 assuming the initial temperature T_0 =210 K. At this wavelength the refractive indices of $m_{\rm quartz} = 1.5 - 0.0077i$ and $m_{\rm carbon} = 2.8 - 0.533i$.

The intensity distribution inside multilayered particles has a substantially inhomogeneous character. The maximum is located near the particle surface in the illuminated or shadow hemisphere in dependence of the particle structure and size. In the case of two-layered particle consisting of the hole and quartz shell (Fig. 1), the region of the maximum intensity lies in the shadow hemisphere near the particle surface that is the result of the focusing of laser radiation by the quartz shell.

If the outer layer is carbonaceous, the intensity distribution is essentially changed (see Fig. 2). The maximum intensity occurs within the thin layer on the particle surface located in the illuminated hemisphere of the particle. The secondary maximum lies in the shadow hemisphere. It vanishes with increasing the particle radius.

If the carbon is in the intermediate layer of the three-layered particle, the intensity distribution (see Fig. 3) resembles those in Fig. 1 but its maximum value is one-fifth only as the intensity in Fig. 1. The enhanced intensity is concentrated in the thin, rather small in magnitude, layer in the illuminated hemisphere for particle of given size (Fig. 3). With increasing the particle size this layer grows and becomes dominating. For larger particles, the energy evolves in the thin shell on the particle surface in the shadow hemisphere, the values of intensity in the remainder part of the particle are very small..

Figures 4,5 show the internal temperature distribution of multilayered particles. In the case of air-quartz particle (Fig. 4), the primary and secondary temperature peaks appear at the places of maxima of internal intensity. The presence of carbon layer independent of its position (as an example, for the air-quartz-carbon particle, see Fig. 5) leads to the smoothing temperature distribution. At the same time, there exists a small difference between the temperature distributions inside different (air-quartz-carbon or air-carbon-quartz) three-layered particles. The core region in air-carbon-quartz particle seems to look smaller and the temperature distributions are more smoother than in air-quartz-carbon particle (Fig. 5) although in both cases the core volume fraction is the same.

It is interesting to compare the radii dependencies of heating time for multilayered particles. They have rather complex character. As follows from Fig. 6 where the results for air-quartz-carbon particles are shown, the heating time grows with particle radius. It reaches a maximum which value depends on the thickness of carbon layer and then decreases. For comparison in the case of two-layered (air-carbon) particles (curve 1 in Fig. 6) the heating time is maximal for $R_3 \approx 20\,\mu$m. When the outer carbon volume fraction inside the air-quartz-carbon particle is reduced, the position of maximum heating time shifts to the region of larger radii and decreases. When the volume occupied by the carbon shell is the one-fifth part of the particle volume, the heating time is maximal for $R_3 \approx 28\ \mu m$ and falls approximately 40 percent.

The value of the heating time is the greatest in the case of the two-layered particles. It decreases when the carbon layer becomes thinner. This behaviour can be explained by the fact that in the case of thick carbonaceous shells the radiation does not penetrate inside the particle. As a result, the particle surface only is heated and the process of the heat-conductivity slows down. Note that when the carbon volume fraction becomes smaller $\sim$20 % the dependence $t(R_3)$ begins to oscillate that reflects the strongly oscillating behaviour of the internal intensity.

Figure 7 shows the size dependence of the heating time of air-quartz and air-carbon-quartz particles. If $R_3 \leq 35\,\mu$m, the heating time of the core-mantle spheres is smaller than that of three-layered particles but the situation reverses if $R_3 > 35\,\mu$m. This is connected with the behaviour of the maximum internal intensity in three-layered particles when the particle radius and the thermophysical properties of the components change.

Comparing the heating of air-quartz-carbon and air-carbon-quartz particles (Fig. 8), we can conclude that it is much more difficult to warm the particles with the outer carbon layer. For example, the heating time of the air-quartz-carbon particles is 10–15 times larger than for air-carbon-quartz particles if $R_3 < 20\,\mu$m. When increasing the particle radii these differences become smaller. For $R_3 \simeq 50\ \mu m$, for example, the heating time of air-quartz-carbon is approximately twofold higher than the heating time of the air-carbon-quartz particle.

Conclusion

Complex structure of aerosol particles has substantially influence on the internal intensity distributions and, as a result, on their heating time and possible destruction. Firstly, the reduction of strongly absorbed outer carbon layer on the multilayered particle surface leads to the decrease of the heating time. Secondly, the heating time of the particles with outer quartz layer is always lower than in the case of the outer carbon shell. In the size particle region $R_3 < 20\ \mu m$ the heating time of the air-quartz-carbon spheres is more than ten times higher than in the case of air-carbon-quartz particles. In the interval $R_3 \geq 30\ \mu m$ these differences become smaller and consist 2–7 times.

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FIGURES

Fig. 1. Irradiance distribution inside the two-layered air-quartz sphere, $V_{\rm air}/V_3 = 1/3$, $V_{\rm quartz}/V_3 = 2/3$, $R_3 = 5\,\mu$m, $\lambda = 1.06\,\mu$m. The arrow shows the direction of the propagation of incident lidar beam.

Fig. 2. Irradiance distribution inside the three-layered air-quartz-carbon sphere, $V_{\rm air}/V_3 = V_{\rm quartz}/V_3 = V_{\rm carbon}/V_3 = 1/3$, $R_3 = 5\,\mu$m, $\lambda = 1.06\,\mu$m. The arrow shows the propagation direction of incident lidar beam.

Fig. 3. The same as in Fig. 2 but for air-carbon-quartz sphere.

Fig. 4. Temperature distribution inside the two-layered air-quartz sphere, $V_{\rm air}/V_3 = 1/3$, $V_{\rm quartz}/V_3 = 2/3$, $R_3 = 5\,\mu$m, $\lambda = 1.06\,\mu$m. The irradiance of lidar radiation is 10^6 W/cm^2. The arrow shows the propagation direction of the incident lidar beam.

Fig. 5. Temperature distribution inside the three-layered air-quartz-carbon sphere, $V_{\rm air}/V_3 = V_{\rm quartz}/V_3 = V_{\rm carbon}/V_3 = 1/3$, $R_3 = 5\,\mu$m, $\lambda = 1.06\,\mu$m. The irradiance of lidar radiation is $10^{\,6}$ W/cm^2.

Fig. 6. The heating time of the air-quartz-carbon spheres from $T = 210$ K to $T = 400$ K as a function of the outer particle radius, $V_{\rm air}/V_3 = 1/3$. The effect of variation of carbon fraction is illustrated. 1 – $V_{\rm carbon}/V_3 = 2/3$, $V_{\rm quartz}/V_3 = 0$; 2 – $V_{\rm carbon}/V_3 = 1/3$, $V_{\rm quartz}/V_3 = 1/3$; 3 – $V_{\rm carbon}/V_3 = 0.25$, $V_{\rm quartz}/V_3 = 0.42$; 4 – $V_{\rm carbon}/V_3 = 0.20$, $V_{\rm quartz}/V_3 = 0.47$; 5 – $V_{\rm carbon}/V_3 = 0.15$, $V_{\rm quartz}/V_3 = 0.52$; The irradiance of lidar radiation with $\lambda = 1.06\,\mu$m is 10^6 W/cm^2.

Fig. 7. The heating time of the air-quartz-carbon spheres from $T = 210$ K to $T = 400$ K as a function of the outer particle radius, $V_{\rm air}/V_3 = 1/3$. The effect of variation of carbon fraction is illustrated. 1 – $V_{\rm carbon}/V_3 = 2/3$, $V_{\rm quartz}/V_3 = 0$; 2 – $V_{\rm carbon}/V_3 = 1/3$, $V_{\rm quartz}/V_3 = 1/3$; 3 – $V_{\rm carbon}/V_3 = 0.25$, $V_{\rm quartz}/V_3 = 0.42$; 4 – $V_{\rm carbon}/V_3 = 0.20$, $V_{\rm quartz}/V_3 = 0.47$; 5 – $V_{\rm carbon}/V_3 = 0.15$, $V_{\rm quartz}/V_3 = 0.52$; The irradiance of lidar radiation with $\lambda = 1.06\,\mu$m is 10^6 W/cm^2.

Fig. 8. The heating time of the air-quartz-carbon spheres from $T = 210$ K to $T = 400$ K as a function of the outer particle radius, $V_{\rm air}/V_3 = 1/3$. The effect of variation of carbon fraction is illustrated. 1 – $V_{\rm carbon}/V_3 = 2/3$, $V_{\rm quartz}/V_3 = 0$; 2 – $V_{\rm carbon}/V_3 = 1/3$, $V_{\rm quartz}/V_3 = 1/3$; 3 – $V_{\rm carbon}/V_3 = 0.25$, $V_{\rm quartz}/V_3 = 0.42$; 4 – $V_{\rm carbon}/V_3 = 0.20$, $V_{\rm quartz}/V_3 = 0.47$; 5 – $V_{\rm carbon}/V_3 = 0.15$, $V_{\rm quartz}/V_3 = 0.52$; The irradiance of lidar radiation with $\lambda = 1.06\,\mu$m is 10^6 W/cm^2.