PROPAGATION OF CO2-LASER RADIATION IN A TURBULENT CLOUD MEDIUM
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Résumé.- Les résultats de l'étude du processus ayant lieu dans le faisceau du CO\textsubscript{2}-laser à fonctionnement continu dans un milieu nuageux turbulent, le régime régulier de l'évaporation des gouttes sont présentés. Les résultats théoriques sont comparés aux données expérimentales obtenues dans une chambre de volume 3200 m\textsuperscript{3}, dans laquelle on a créé une turbulence artificielle d'une manière mécanique \(10^3 \text{ wt}\). On examine le rôle de la diffusion turbulente des gouttes s'évaporant dans la formation des profils de température et de transparence dans la région de la propagation du faisceau. On analyse les pulsations de la température, du contenu en eau et de la permittivité diélectrique qui prennent naissance dans la zone d'interaction dues à la hétérogénéité du milieu, ainsi que leur influence sur les fluctuations de l'intensité du rayonnement passé à travers le milieu. On a déterminé de certaines régularités de la propagation du rayonnement, du CO\textsubscript{2}-laser dans l'atmosphère à l'indice de réfraction hétérogène.

Abstract.- Given are the results of studying CO\textsubscript{2}-laser continuous beam self-action in a turbulent cloud medium at regular evaporation of droplet. Theoretical results are compared with the data of model experiments carried out in an aerosol chamber 3200 m\textsuperscript{3} in volume with artificial mechanical turbulence using a source of radiation with a power of up to \(10^3 \text{ wt}\). The role of conductive heat extraction and turbulent diffusion of evaporating droplets in the formation of temperature and transmittancy profiles in the area of laser beam propagation is considered. Pulses of temperature, liquid water content and dielectric constant which occur in the interaction zone due to turbulent mixing are analysed as well as their effect on the intensity fluctuations of the radiation passed through the medium. Some features of self-action are investigated in the presence of CO\textsubscript{2}- laser radiation fluctuations, for example, those due to the atmospheric inhomogeneities of refractive index.

Up to the present numerous works (see for example, / 1,2/ and references there) have been carried out on studying CO\textsubscript{2}-laser radiation propagation in water aerosol resulting in cloud medium clearing (hole-boring). The authors of these works assume that cloud medium and laser radiation parameters do not fluctuate. However, in a turbulent cloud medium wind velocity \(V\) and its other parameters are random functions, and the process of clearing such medium has some peculiarities. In particular, in the turbulent cloud medium being cleared additional fluctuations of its parameters and those of laser radiation (besides the existing ones before their perturbation) as well as changed are the medium mean characteristics / 3-7/. In the present paper given are theoretical and experimental results on thermal self-action of continuous CO\textsubscript{2}-laser radiation in a turbulent cloud medium.

A set of equations describing laser radiation and aerosol interaction at an assumed liquid water content approximation involves equations for laser radiation field \(E\), cloud medium temperature \(T\) and liquid water content \(W\):

\[
\begin{align*}
\frac{\partial E}{\partial t} + \nabla \cdot (E \mathbf{V}) &= 2 \frac{ik}{
abla^2} E + \Delta E + 1kC_l WE + k^2 (\frac{\partial}{\partial \mathbf{r}})_{p} (T - T_0) E = 0 ,
\end{align*}
\]

\[
\frac{\partial T}{\partial t} + \nabla \cdot (\mathbf{V} T) - \chi_2 \Delta T = \lambda \mathbf{W}(\mathbf{r},t)I(\mathbf{r},t) ,
\]

\[
\frac{\partial W}{\partial t} + \nabla \cdot (\mathbf{V} W) + \mu \mathbf{W}(\mathbf{r},t) = 0 ,
\]

with the initial and boundary conditions:

\[
E(\mathbf{r},t)|_{z=0} = E_0(\mathbf{r},t) ; \quad T(\mathbf{r},t)|_{t=0} = T_{0} ,
\]

\[
W(\mathbf{r},t)|_{t=0} = W_0 \quad \text{and} \quad W(\mathbf{r},t)|_{r=\infty} = W_\infty = \text{const} .
\]

Here \(T_0, W_0\) - temperature and liquid water content of undisturbed cloud medium, \(k=2 \pi / \Lambda\) - the wave number, \(\mathbf{V} = (\mathbf{\beta},z)\) - the coordinate along laser radiation propagation direction, \(\mathbf{\beta} = (x,y)\), \(t\) - time, \(I|E|^2\) - radiation intensity, \(\frac{\partial}{\partial \mathbf{r}}\) - temperature gradient of the dielectric constant \(\varepsilon\), \(A = \frac{(1-\beta_p)^2 C_p}{\lambda}\), \(M = \beta_T C_a / L\), \(\beta_T\) - coefficient of realization of the radiation energy absorbed by droplets / 1/, \(C_p\) - heat capacity per air volume unit, \(L\) - water specific evaporation heat, \(C_a, C_\perp\) - numerical coefficients correspondingly equal to 75x10\textsuperscript{2} cm\textsuperscript{2}/g.
1.5\times 10^3 \text{ cm}^2/\text{g} \text{ for radiation at } \lambda = 10.6 \text{ m.}

\( \chi_T \) – molecular temperature conductivity.

A solution of (1)-(3) is considerably dependent on boundary conditions imposed and medium motion character. In case when boundary conditions and wind velocity are regular, the values of \( W, T, E \) in a cleared medium are regular as well. In a turbulent medium wind velocity and radiation intensity at cloud medium boundary are random values, therefore under clearing fluctuations of \( W, T, E \) arise in it.

1. Consider first a situation when the single source of random inhomogeneities are fluctuations of \( V \). In this case \( \vec{V} = \vec{V}_0 + \vec{V}' \), where \( \vec{V}_0, \vec{V}' \) mean and pulsed components of wind velocity. Fluctuation characteristics of \( \vec{V}' \) are assumed to be given.

The solution of the equation system (1) – (3) for generally realized atmospheric conditions \( \delta^2 = \frac{V_0^2}{V'^2} \ll 1 \) gives the following expressions for the additional fluctuation dispersions of \( W, T \) and \( E \):

\[
\begin{align*}
G^2_W & = \frac{W_0^2}{V_0^2} \times V'_j^2 \times p^2_j \quad (x), \\
G^2_T & = (\frac{\delta T}{\delta W})^2 G^2_W \quad (x), \\
G^2_E & = G^2_R + G^2_I,
\end{align*}
\]

(4)

where \( G^2_R, G^2_I \) – fluctuation dispersions of real and imaginary parts of \( E \),

\[
F_j = \theta_j e^{-\Theta}, \quad \Theta_x = \Theta = \frac{\mu}{V_0} x
\]

\[
\int_{-\infty}^{\infty} dx_1 \mathcal{I}(x^1, y, z)
\]

thermal action function determining cloud medium clearing extent (for example, \( W = W_0 e^{-\Theta} \), and the more \( \Theta \), the higher is the clearing extent), \( \Theta_y = \int_{-\infty}^{\infty} \frac{\partial \Theta(x^1, y, z)}{\partial y} \).

Here and later on repeated indices indicate summing-up, the line above means averaging. When obtaining (4) and (5) it is accepted that \( \vec{V}_0 \) is directed along the \( x \)-axis, fluctuations of \( V \) are homogeneous and isotropic.

From (4), (5) it follows that space distributions of \( G^2_W, G^2_T, G^2_E \) are determined by the functions \( F_j(\Theta) \), and at \( \Theta > 1 \) they decrease exponentially with increasing \( \Theta \). In Fig.1 given are typical distributions (calculated with (4)) of \( G^2_T = F_j - \) normalized dispersion of \( T \) fluctuations (similar to \( W, E \) along the coordinate \( \varphi = x/a_0 \) at \( \mathcal{C} = C_1 W_0 = 5 \) \( \mathcal{C} \) – the optical thickness of a undisturbed medium, \( a_0 - \) \( \text{CO}_2 \)-laser beam radius) and \( \Theta_0(0) = \Theta_0|_{x=0} = 5 \).

The calculations made have shown that the fluctuation maximum of \( T, E \) is reached at \( \Theta = 1 \), where the cloud medium clearing extent is not high. The maximum value of \( T, E \) fluctuations induced at clearing for cloud typical liquid water contents may exceed turbulent pulsations of \( T, E \) in the cloudless atmosphere. But in the clearance zone there can be specified a region the properties of which relative to the pulsations of \( T, E \) are close to those of the cloudless atmosphere. For the radiation intensity \( I_0 \), decreasing from the laser beam center to its periphery, this region adjoins the \( x \)-axis at the beam downwind side. From (4), (5) it follows also that the fluctuations of \( T, W, E \) are inhomogeneous and non-isotropic despite homogeneity and isotropy of the
The installation is described in detail in [5]. The parameters of CO$_2$-laser beam in the experiment are the following: $P_0 = 700$ w, $a_0 = 3.5$ cm. The solid curve in Fig.2 presents the calculated results (2) in case of $V' = 0$. The results obtained demonstrate the blurring of mean temperature profile due to conductive heat extraction. The experimental results [5] have shown as well that the mean extent of clearing of the turbulent aerosol medium depends on the flow turbulence intensity and the CO$_2$-laser structure. At radiation intensity uniform distribution the clearing extent of the turbulent medium on the laser beam axis were smaller than those in case of the medium with $V' = 0$. The experimental data on measurements of the turbulent medium optical thickness decrease under clearing process are in rather a good agreement with the calculated curves if the formula [2] for cloud medium regular motion includes a correction for the droplet diffusion:

$$\theta(x) = B(x) \frac{P_0}{2a_0V_0(1+\Gamma)}$$

where $B(x)$ - the value depending on medium temperature, aerosol microstructure, laser beam profile, $\Gamma = 2D/a_0V_0$ - the ratio of conductive and convective terms of drop transformation equation within a beam, $D$ - turbulent diffusion coefficient. If $\Gamma > 1$, the prevailing mechanism of the cleared zone blurring is turbulent diffusion, if $\Gamma < 1$ - wind.

The pulsations of $V$ induced within the cleared turbulent cloud medium in their turn result in radiation parameter flu-
Let us calculate now intensity fluctuation dispersion $\mathcal{g}_x^2$ of a narrow ($a_{op} \ll a_0$, $a_{op}$ - probing beam radius) probing radiation beam propagating along the $z$-axis in the cleared medium. The fluctuations of $\xi$ are given in the form of (5) in view of the imaginary part variations of $\xi$ for the probing beam radiation:

$$\mathcal{g}_{p\xi}^2 = \mathcal{g}_x^2 \frac{k_p^2}{k_p^2} \mathcal{g}_x^2 \mathcal{I},$$

where $k_p$ - probing beam radiation wave number, $\mathcal{I}$ - function relating the cleared medium extinction coefficients for the probing ($\alpha_p$) and CO$_2$-laser ($\alpha$) radiations, depending as well on the aerosol microstructure. For the radiation wavelength $\lambda_p = 0.63\,\mu\text{m}$ in the cleared water aerosol the form of $\mathcal{I}$ has the form of $1/2$:

$$\mathcal{I} = \mathcal{I}_0 e^{\theta / 2} / 2, \quad \mathcal{I}_0 = 3\sqrt{\alpha + 1}(\alpha + 2) / 2 \, C_2 \rho_b R_{o2} (\alpha + 3),$$

where $\alpha$, $R_{o2}$ - gamma distribution parameters, $\rho_b$ - water density.

The solution of (1) for a probing beam found with the use of the method of smooth perturbation gives an expression for $\mathcal{g}_x^2$:

$$\mathcal{g}_x^2 = \mathcal{g}_x^2 + \mathcal{g}_x^2 + \mathcal{g}_x^2,$$

$$\mathcal{g}_x^2 = \mathcal{g}_x^2 + \mathcal{g}_x^2,$$

$$\mathcal{g}_x^2 = \mathcal{g}_x^2 + \mathcal{g}_x^2,$$

$$\mathcal{g}_x^2 = \mathcal{g}_x^2 + \mathcal{g}_x^2,$$

where $\beta_1 = (\frac{\partial \xi}{\partial T})_{pA_{o}}/a_{op}$, $\beta_2 = C_0 a_{op} / k_p v_o$ - radius-vector of the probing beam.

The first summand (6) is determined by radiation scattering on temperature inhomogeneities of $\xi$, the second one is connected with the extinction coefficients fluctuations of the cleared medium, the third one is the result of the two mechanisms correlation. It should be noted that the third summand $\mathcal{g}_x^2$ is negative ($\mathcal{I}_1 > 0$) and partially compensates for the contribution $\mathcal{g}_x^1$ and $\mathcal{g}_x^2$. The extent of compensation increases when the beam advances into the clearance zone. The value of $\mathcal{g}_x^2$ in this zone quickly decreases with increasing $\theta$.

The agreement of the experimental data (4)-(6) is demonstrated in Fig. 3. In this figure given are the dependencies of $\mathcal{g}_x^2$ and $\mathcal{g}_x^2$ in the cleared...
ared turbulent medium on its initial optical thickness $\tau_{po}$. The cloud medium and CO$_2$-laser beam parameters in the experiment have been: $V_0 = 7$ cm/s, $\delta = 0.2$, the path length $z = 4$ m, $I_o(0) = 50$ w/cm$^2$, $2a_0 = 4.5$ cm.

\[ \sigma_{o}^2 = 10^3 \]

\[ G_x^2 \]

\[ G_T^2 \]

\[ 0.3 \]

\[ 7.5 \]

\[ 0.2 \]

\[ 5.0 \]

\[ 0.1 \]

\[ 2.5 \]

\[ 0 \]

\[ 0.5 \]

\[ 1.0 \]

\[ \tau_{po} \]

Fig. 3. Dependence of dispersions for both temperature fluctuations $G_x^2$ and intensity level $G_T^2$ on the cloud medium optical thickness $\tau$ (for $G_x^2$: 1 - calculations, $G_T^2$: 2 - calculations, $G_T^2$: 0 - experiment).

One can see that at these parameters the values of $G_x^2$ and $G_T^2$ increase with increasing $\tau_{po}$. However, as the calculations show at further growing $\tau_{po}$ the value of $G_x^2$ tends to a constant level and $G_T^2$ decreases.

2. Consider the other mechanism of initiation of additional fluctuations of the cleared cloud medium and radiation parameters connected with the incident radiation pulsations $\gamma$. CO$_2$-laser radiation parameter fluctuations at boundary of penetration into the cloud can take place both due to pulsations in a radiation source, and at radiation propagation through the turbulized atmosphere subcloud layer.

Mathematically it means that in (1)-(3) the radiation intensity $I_o$ (or $E$) at the boundary $z=0$ is a given random function. In this case the solution (1)-(3) (without defraction and refraction effects) is as follows:

\[ w(x,t) = w_0[1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau}] - 1, \]  

(10)

\[ \Delta T = T - T_0 = \Delta W / \mu \left[ 1 - (1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau}) \right], \]  

(11)

\[ I(x,t) = I_0(\rho,t)(1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau})^{-1} \]

(12)

where $I_0(\rho,t) = I_0(\rho,t)$ - fluctuating function of thermal action.

In the range of small fluctuations of $\tilde{\theta}_0 (G_{\theta}^2 < 1)$ from (10)-(12) for mean values of $\tilde{w}$, $\Delta T$ and transmittance $\tilde{\Pi} = I/I_0$ one finds

\[ \tilde{w} = w_0/[1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau}] - 1, \]

(13)

\[ \Delta T = \Delta w_0 / \mu \left[ 1 - (1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau}) \right], \]

(14)

where $G_{\theta}^2$ - fluctuation dispersion of $\tilde{\theta}_0$, $\Pi_1 = [1 + (e^{\tilde{\theta}_0 - 1}) e^{-\tau}]^{-1}$ - cloud medium transparency at its clearing by radiation when $\tilde{\theta}_0 = \tilde{\theta}_0$.

In (13)-(15) the first terms correspond to the values of $T, w, \Pi$ at medium clearing by radiation with regular profiles of $I_o(\tilde{\theta}_o = \tilde{\theta}_0)$, the second ones determine variations of $T, w, \Pi$ connected with fluctuating $I_o$. The analysis carried out indicates that the second summands (13)-(15) change the sign at $\tilde{\theta}_0 = \rho(x (e^{\tau} - 1)$ for $w, \Delta T$ and $\Pi_1 = 0.5$ for $\Pi$. This causes profile smoothing of $T, w, \Pi$ as compa-
In conclusion it should be noted that the problems considered do not comprise all the aspects of clearing a turbulent cloud medium. In particular, of certain interest is to study the effect of large-scale \((l > 2a_o)\) pulsations of wind velocity on water aerosol clearing. A numerical analysis through model incorporating large-scale pulsations of \(\bar{V}\) has shown that the presence of such pulsations result in an increase of cloud medium mean transmittance \(\Pi_p\) at the beam upwind side and in a decrease of \(\Pi_p\) at the downwind side as compared to the cloud medium regular motion. In this case the range of maximum variations of \(\Pi_p\) is close to the beam upwind edge at increasing \(I_o, \delta\) and decreasing \(a_o\). The large-scale pulsations of \(\bar{V}\) cause considerable fluctuations of the clearance zone boundaries. \(\delta\) is the clearance zone boundaries. \(\delta\) is defined as a surface of equal and high transmittance level. In this case the fluctuation dispersion of the clearance zone maximum height \(h_{max}\) has the form:

\[
G^2_T = \frac{h_{max}}{V^2} \int dz B_V(z),
\]

where \(B_V(z)\) is the fluctuation correlation function of \(V\).
References


