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THE EFFECT OF THE WIND SPEED ON THE THERMAL BLOOMING OF A LASER BEAM PROPAGATING IN THE RAIN

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Abstract

In this paper, we investigate the effect of the wind speed on the thermal blooming of a laser beam propagating in the rain. In view of simulations, we obtain the contour distribution of the laser beam and calculate the change in air density by changing the wind speed for different rain rates. We find that with increase in the rain rate, the effect of the wind speed on the thermal blooming enhances.

Keywords: laser beam, wind speed, air density, thermal blooming.

1. Introduction

In recent decades, the study of a laser beam propagating in air has become a hotspot [1–4]. When the laser beam propagates in air, it will experience many linear and nonlinear effects. Thermal blooming is one of the most important effects. The thermal blooming is not only related to the initial powers of the laser beam, but also related to the wind. The effect of the wind directions on the thermal blooming has been studied by Le Wang et al. [5]. They found that the down-wind direction will weaken the thermal blooming, and the up-wind direction will strengthen the thermal blooming. The effect of the wind speed on the thermal blooming has been studied in [6, 7]. These studies are based on air as the transmission medium. When the laser beam propagates in the rain, what is the effect of the wind on the thermal blooming? In this work, we study the effect of the wind speed on the thermal blooming of a laser beam propagating in the rain.

This paper is organized as follows.

In Sec. 2, we adopt the method elaborated in [8] for calculating the scatter and absorb of raindrops. We present the results of numerical simulations in Sec. 3 and give the summary in Sec. 4.

2. Model and Theory

2.1. The Effective Permittivity of the Rain

When the laser propagates in the rain, the medium is a mixture of raindrops and air. The effective permittivity ε_{eff} of the rain at high frequencies can be calculated by [9, 10]

$$\varepsilon_{\text{eff}} = \varepsilon_a(1 + \chi_e), \tag{1}$$

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where χ_e is the polarization rate of the raindrops. At high frequencies, it can be written as

$$\chi_e = \int_{r_{\min}}^{r_{\max}} \frac{N(r)\sum_{j=1,2,3} g_j(r)}{3\varepsilon_a - N(r)\sum_{j=1,2,3} L_j g_j(r)} dr, \tag{2}$$

$$N(r) = 8000\exp(-8.2R^{-0.21}r)\ , \tag{3}$$

where ε_a is the permittivity of air. We choose the raindrop spectrum $N(r)$ as the Marshall–Palmer spectrum [11] in units $\mathrm{m}^{-3}\cdot\mathrm{mm}^{-1}$. Also, here, R is the rain rate in units mm/h, r is the radius of the raindrop in units mm, L_j denotes the depolarization factor for the spherical raindrop ($r \leq 1$ mm) [12], and $g_j(r)$ is the polarization rate of the raindrop at high frequencies [8, 13].

2.2. The Scalar Wave Equation in the Rain

The equation of the laser-beam propagation in the rain medium can be written as follows [14]:

$$\nabla^2 E - \mu_0\varepsilon_{\text{eff}}\frac{\partial^2 E}{\partial t^2} = 0\ , \tag{4}$$

$$E(x,y,z,t) = \varphi(x,y,z)\exp(i\omega t - ikz)\ , \tag{5}$$

where E is a slowly varying electrical field, $\nabla^2 = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2}$, μ_0 is the magnetic permeability, $k = 2\pi n_0/\lambda$ is the the wavenumber, $\omega = kc/n_0$, with n_0 being the refractive index for the undisturbed atmosphere, and λ is the initial laser wavelength. Substituting Eq. (5) into Eq. (4), we obtain the parabolic equation of of the laser-beam propagation in the rain; it reads

$$2ik\frac{\partial\varphi}{\partial z} = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\varphi + k^2\left[\frac{n_a^2}{n_0^2}(1+\chi_e) - 1\right]\varphi\ . \tag{6}$$

Before solving this equation, we also need to calculate the air refractive index n_a, which is determined by the air density change $\Delta\rho$ as follow [14]:

$$\frac{n_a^2}{n_0^2} - 1 \approx 2(n_0 - 1)\frac{\Delta\rho}{\rho_0}\ , \tag{7}$$

where ρ_0 is the density for the undisturbed air.

2.3. The Hydrodynamic Equation

We assume that the wind direction is perpendicular to the direction of the laser-beam propagation; then the steady-state hydrodynamic equation for the change in the air density reads [15]

$$v\frac{\partial\Delta\rho}{\partial x} = -\frac{(\gamma - 1)}{c_s^2}\alpha I\ , \tag{8}$$

where v is the wind speed, c_s is the sound speed, γ is a specific heat ratio, α is the absorption coefficient of the air, and I is the laser intensity.

3. Numerical Simulations

We solve numerically the model equations (6)–(8) with the initial electric-field-intensity amplitude

$$\varphi(x, y, z)|_{z=0} = \varphi_0 \exp\left[-(x^2 + y^2)/(2a^2)\right], \tag{9}$$

where a is the initial beam radius, and $\varphi_0 = \sqrt{P/\pi a^2}$, with P being the initial power. The parameters are given in Table 1.

Table 1. The Parameters of the Model.

P, W	λ, μm	a, m	γ	z, km	c_s, m/s
10^5	10.6	0.1	1.4	3	339.5597

In Fig. 1, we show the contour distributions of the laser beam for different wind speeds v and rain rates R. One can see that the effect of thermal blooming decreases with increase in v and R. This is due to the fact that strong wind and rain take away a lot of laser energy, the laser energy absorbed by the air will decrease, and the corresponding air density change $\Delta\rho$ will also decrease, resulting in a decrease in the thermal blooming effect.

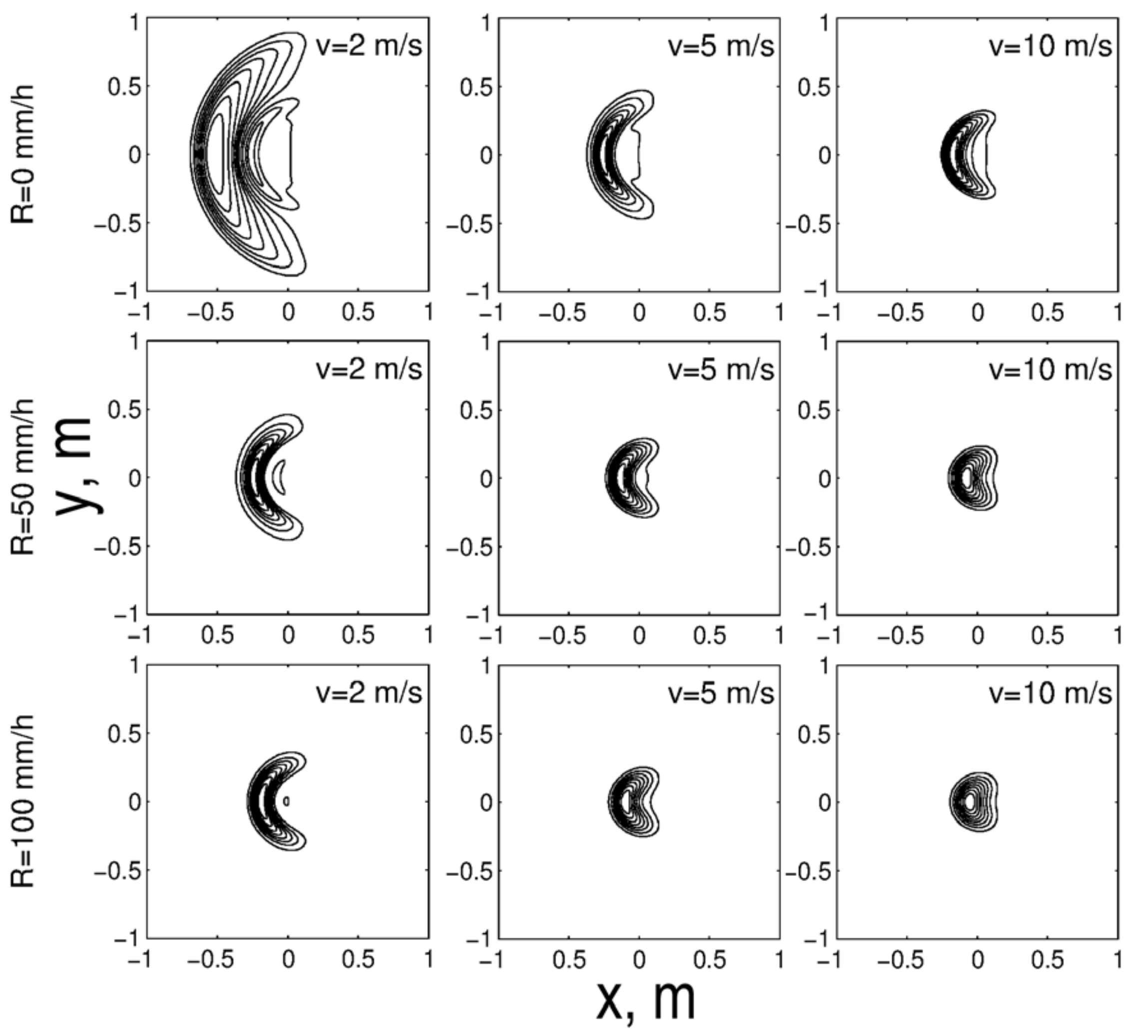

Fig. 1. The contour distributions of the laser beam for different wind speeds v and rain rates R.

In Fig. 2, we show the dependence of the air density change $\Delta\rho$ on the wind speed v for different rain rates. We can see that there is a negative exponential growth of $\Delta\rho$ with respect to v. At $R = 0$ mm/h, $\Delta\rho \sim v^{-0.40}$; at $R = 50$ mm/h, $\Delta\rho \sim v^{-0.45}$, and at $R = 100$ mm/h, $\Delta\rho \sim v^{-0.50}$. From this relation, we learn that, with increase in the rain rate R, the effect of the wind speed v on the thermal blooming enhances.

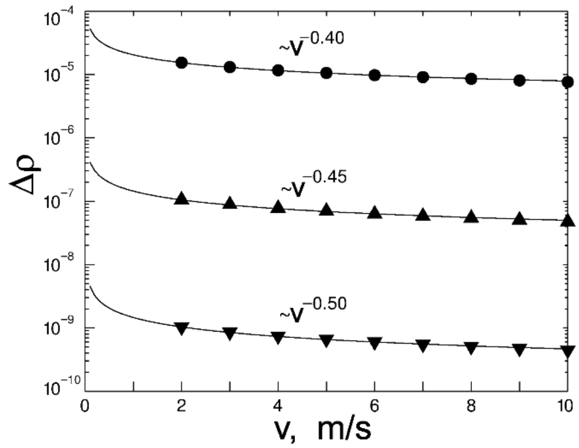

Fig. 2. The dependence of the air density change $\Delta\rho$ on the wind speed v for different rain rates $R = 0$ (●), $R = 50$ mm/h (▲), and $R = 100$ mm/h (▼).

4. Summary

In this paper, we investigated the effect of the wind speed on the thermal blooming of a laser beam propagating in the rain. Numerical simulations performed showed that the rain rate and wind speed play an important role in the thermal blooming, namely, strong wind and rain can decrease the effect of the thermal blooming. On the other hand, we found that there is a negative exponential growth of $\Delta\rho$ versus v, and with increase in the rain rate R the effect of the wind speed v on the thermal blooming enhances.

Acknowledgments

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