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# The Variation of Radiation Transmittance by the cw 1.07 μm Fiber Laser and Water Aerosol Interaction

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Among the atmospheric effect of laser propagation, the variations of the radiation transmittance by water aerosol evaporation have quantitatively been investigated. When the aerosol was exposed by a 1.07 μm cw fiber laser, the increased amount of the transmittance variation was a maximum of 19.1% and the volume concentration variation of aerosol was observed as an increasing of laser intensity. Also, significant irregularity of refractive index was not found in the heated area during the continuous laser heating.

*Keywords* : Water-aerosol interaction, Evaporation, Heating laser, Radiation transmittance, Volume concentration variation
*OCIS codes* : (010.0010) Atmospheric and oceanic optics; (010.1110) Aerosols; (010.1300) Atmospheric propagation

## I. INTRODUCTION

The laser interaction with water aerosols brings as a result the attenuation of laser energy by scattering and absorption. The absorbed energy consequently raises the temperature of water droplets when the aerosol is exposed by a high power laser. If the temperature increase is significant, the droplets will begin to evaporate. At the same time, the change in the droplet size further alters the radiation transmittance. The interaction of a high power laser with water droplets is an important topic in the study of atmospheric propagation [1-6].

It has been reported by the previous papers that two evaporation extremes of heated aerosol by heating laser are known to occur. For a highly intense beam, it is the explosive vaporization regime, in which droplet deformation and shattering may occur. At the other extreme, droplet interaction with less intense beams falls into what may be termed as the slow evaporation regime, where the droplet evaporation occurs at its surface [7-11].

In this paper the intensity and profile variation of the laser by aerosol evaporation are investigated and subsequent variation in the radiation transmittance is observed to understand the cw laser interaction with water aerosol.

## II. HEATING MECHANISM REVIEW

By assuming spherical symmetry, the laser heating property is represented by the thermal diffusion equation (1),

$$c\rho\frac{\partial T}{\partial t} = \nabla\cdot(K\nabla T) + f \cong \frac{1}{r^2}\frac{\partial}{\partial r}\left(Kr^2\frac{\partial T}{\partial r}\right) + f, \quad (1)$$

where $c$ is the specific heat at constant pressure, $\rho$ is the fluid density, $T$ is the temperature, $K$ is the thermal conductivity, $r$ is the radius, $f = \frac{4\pi Re(n) Im(n)}{\lambda_0} IS$ is the heat production distribution, $Re(n)$ and $Im(n)$ are the real and imaginary parts of the refractive index of water, respectively, $\lambda_0$ is the wavelength of the incident laser, $I$ is the input irradiance, and $S = \frac{|\vec{E}|^2}{|\overrightarrow{E_{inc}}|^2}$ is the normalized source function with the electric field $\vec{E}$ at a given point and the electric field $\overrightarrow{E_{inc}}$ of the incident laser beam.

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It is possible to estimate the critical irradiance $I_{sf}$ which divides the slow and fast heating using the two terms of the right hand side in equation (1). The terms represent the thermal diffusion and heating terms respectively [9]. Using these relations we can deduce the critical irradiance shown in equation (2), where $\Delta T$ is the temperature variation corresponding to the radial variation $\Delta R$. It is shown that $I_{sf}$ depends upon the absorption coefficient and droplet radius variation as,

$$I_{sf} = \frac{K \Delta T \lambda_0}{4\pi S (\Delta R)^2 Re(n) Im(n)}. \quad (2)$$

For the case of the interaction between water droplet of radius $R_0$=6 μm and a 2.08 μm heating laser, the calculated $I_{sf}$ are approximately $10^3$ W/cm$^2$. For 1.07 μm wavelength, the fast heating may occur in laser intensity more than $10^8$ W/cm$^2$. The difference between the two cases is due to the absorptivity according to the wavelength.

## III. EXPERIMENTS AND DISCUSSION

In order to investigate the water aerosol evaporation effect in laser propagation, first it is necessary to identify the particle size and volume concentration, the volume of aerosol particles per unit volume, of water aerosol in the test chamber. A schematic of the experimental setup to measure particle size and volume concentration of water aerosol is shown in Fig. 1. The chamber which is 34 mm width and 100 mm length is located within the particle sizer (System 2600 LC, Malvern Instruments). The particle sizer measures size and obscuration, the portion of aerosol area obscured, of aerosol generated by an aerosol generator (DRW-2000). At the same time, the transmittance was measured by the silicon detector (PD300, Ophir) and 543.5 nm wavelength cw green laser (dia. 0.8 mm, Melles Griot) is used as a probing laser.

The measured average particle size was 6 μm and particle volume concentration was obtained from the measured obscuration and particle size. The relationship between particle volume concentration and measured obscuration is shown in Fig. 2. The measured transmittance as a function of the particle volume concentration and its polynomial fitting is shown in Fig. 3. From those results, it is possible to estimate the variation of volume concentration in each test.

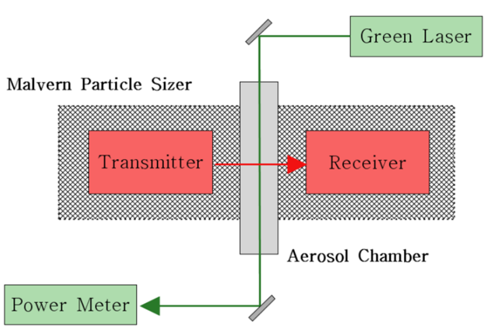


FIG. 1. Particle size and volume concentration measurement setup.

In order to investigate the water aerosol effect by high-energy laser heating, another experimental setup was constructed as shown in Fig. 4. As a heating laser, a 1.07 μm wavelength single-mode cw fiber laser (IPG Photonics Inc) with a power of 1 kW and beam diameter of 5.85 cm was used. Maximum intensity of the heating laser is 7.5 × $10^3$ W/cm$^2$ (This is the value of the middle area of the beam profile.). It is too low a value to investigate the effect of fast heating. Despite slight differences between these experimental conditions and prerequisites for calculation, it is of course considered that this experiment can be regarded as a slow heating regime. The 543.5 nm wavelength cw green laser is used as a probing laser to measure the variation in the transmittance of aerosol.

Because the probing laser has the same path as the heating laser in the chamber and its diameter is smaller than that of the heating laser beam, it will pass through the center of heated path exposed by the heating laser. The dichroic beam splitters (HR at 1.07 μm, AR at 543.5 nm, incident

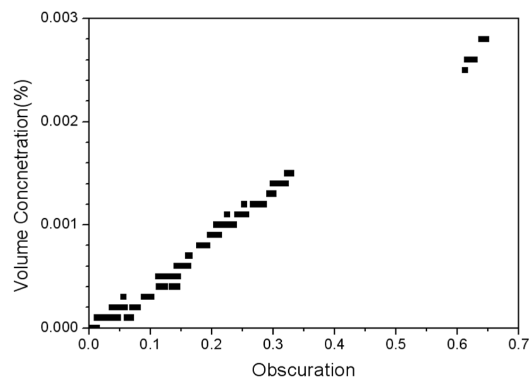


FIG. 2. Relationship between volume concentration and obscuration.

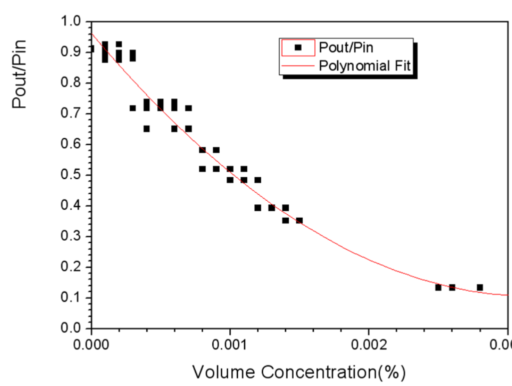


FIG. 3. Measured transmittance as a function of the particle volume concentration.

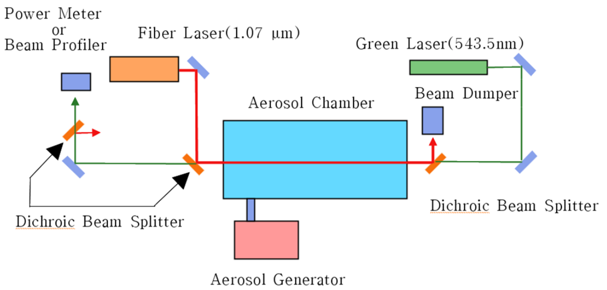


FIG. 4. Transmittance variation measurement setup by the heating laser.

angle 45°) are used to separate two beams and minimize the power which enters the power meter directly from the heating laser. The power disturbance due to the retro-reflection or scattering of the heating laser over the path is measured in the vacant chamber and the result is shown in Fig. 5 (a). It is estimated that the disturbance is as small as about 0.6% of measured power, so we make sure that the direct backward power from the heating laser is not large enough to affect the results. The power variation with heating laser intensity 1.5 kW/cm$^2$, 3.0 kW/cm$^2$, 4.5 kW/cm$^2$, 6.0 kW/cm$^2$ and 7.5 kW/cm$^2$ are shown in Fig. 5(b)~(f) respectively. While the heating laser irradiates a path through

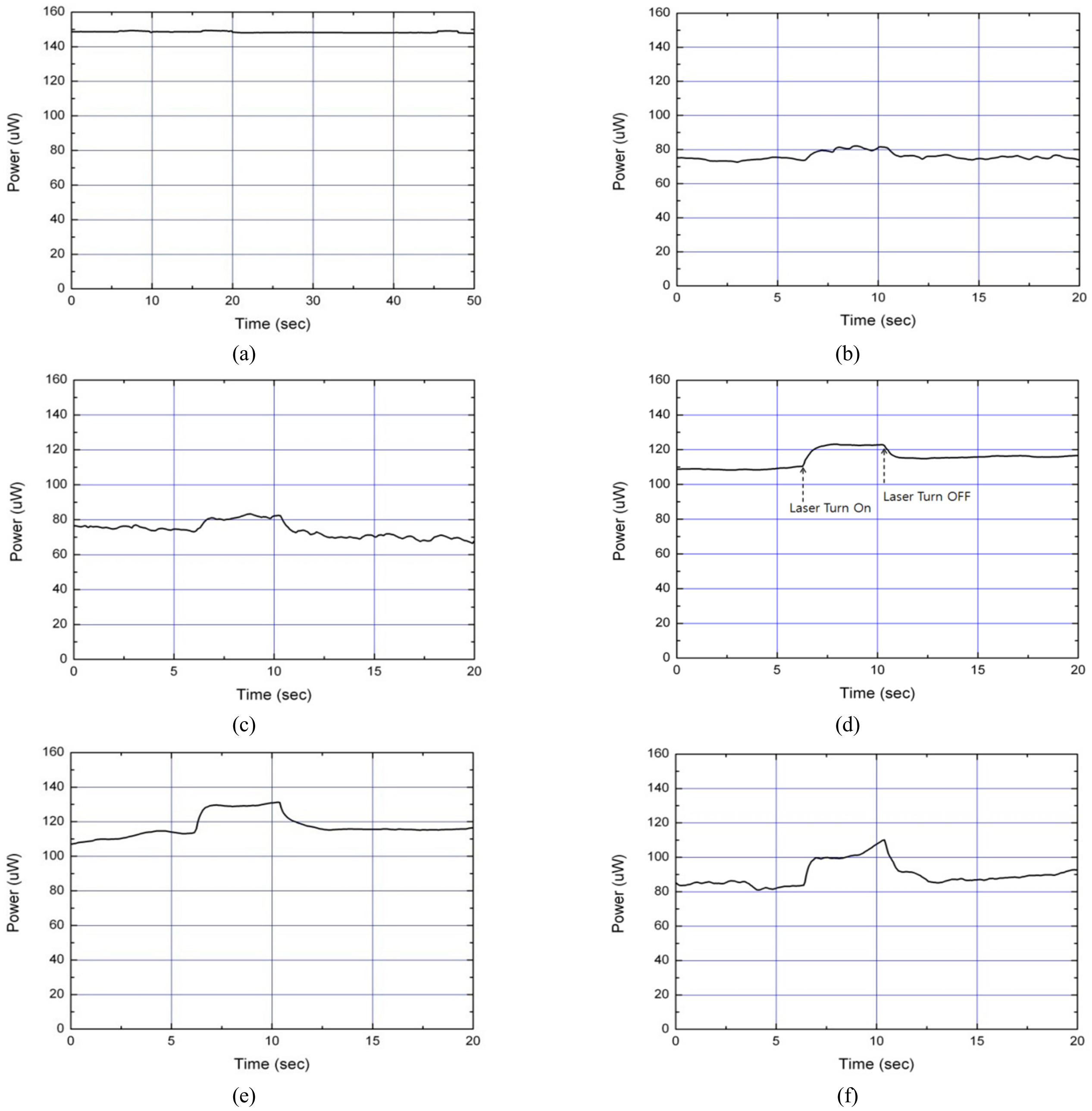


FIG. 5. Power variation of aerosol by the heating laser. (a) No aerosol, 6.0 kW/cm$^2$ heating laser intensity, (b)~(f) 1.5 kW/cm$^2$, 3.0 kW/cm$^2$, 4.5 kW/cm$^2$, 6.0 kW/cm$^2$ and 7.5 kW/cm$^2$ heating laser respectively.

the aerosol chamber, the measured power of the probing beam is significantly increased in proportion to the heating laser intensity.

Aside from the above, it is observed that there are time delays of the power response about 0.5 seconds at most whenever the heating laser turns on and off as shown in Fig. 5. The time delays are much longer than the time that is needed to evaporate the aerosol by laser heating [7-9]. So, it is believed that the time delay is due to the presence of aerosol movement in the chamber. The power difference between before and after laser heating is thought to be as a result of the aerosol evaporation by laser heating. When the high energy laser propagated through the chamber, aerosol exposed by the heating laser begins to be heated and evaporated in a short time. As a result, its density on the optical path is decreased and aerosol uniformity in the cell is altered. After turning off the heating laser, the density may not be recovered to its initial value as quickly. Therefore the power level after laser heating showed a tendency to increase as in Fig. 5(d), (e) and (f).

The logarithmic scale of radiation transmittance with the heating laser intensity is shown in Fig. 6. From the transmittance variation in Fig. 5 and the relation of radiation transmittance with the particle volume concentration in Fig. 3, the volume concentration variation with the heating laser intensity is obtained. The logarithmic scale of volume concentration variation with the heating laser intensity is shown in Fig. 7. It shows that the volume concentration decreases rapidly by water aerosol evaporation depending on the heating laser intensity.

The intensity profiles of probing laser when there is no aerosol, no heating and when heated by the 1 kW laser are shown in Fig. 8(a), (b), and (c) respectively. Though there is a slight peak intensity and beam diameter variation, the intensity profiles do not show any noteworthy distorted distribution. This shows that any considerate irregularity of refractive index in heating area does not occur during the laser heating.

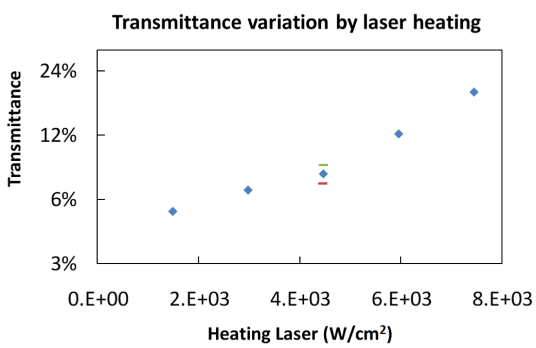


FIG. 6. Radiation transmittance as a function of the heating laser intensity.

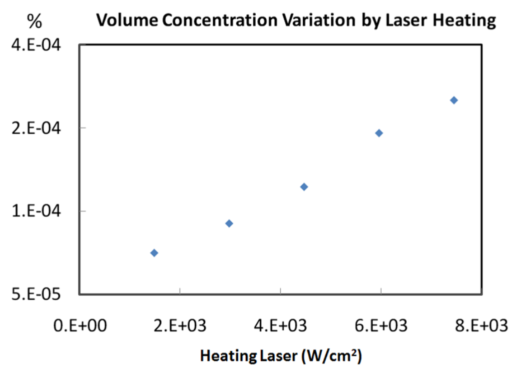


FIG. 7. Volume concentration reduction as a function of the heating laser intensity.

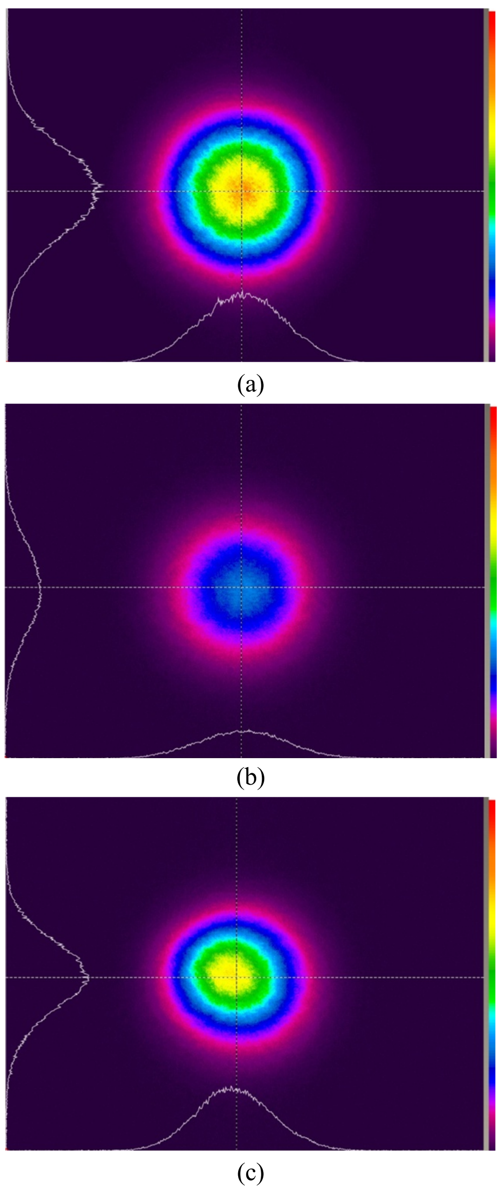


FIG. 8. Transmitted probing laser intensity profile by the laser heating using profiler (SP503U Spiricon). (a) when there is no aerosol , (b) no heat, (c) heated by the 1 kW laser.

## IV. CONCLUSION

We observed the variation in the radiation transmittance generated by a cw laser interaction with water aerosol using a probing laser. The transmittance is significantly increased and the volume concentration of aerosol logarithmically increased with the intensity of the heating laser. Also, when the measured intensity profiles were investigated, there was no change in the relative refractive index at the heated area. Based on the results, when a high energy laser is propagated through the atmosphere with aerosol, we concluded that the energy will be able to be much more completely delivered than as predicted by a calculated value which does not consider the self-induced aerosol evaporation.

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