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Transient coupled model on efficiency prediction of laser power beaming for aerostat

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HIGHLIGHTS

- Concept of Laser power beaming is firstly demonstrated for an aerostat.
- An empirical model is developed on the atmospheric attenuation of Laser.
- The coupled transient electrical-thermal-mechanical model is established.

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ABSTRACT

The concept of Laser power beaming is firstly demonstrated for remote power supply. Then, an empirical model is developed on the atmospheric attenuation of Laser and numerical examples presented for typical situations. Later on, a transient coupled model is established to analyze the thermo-mechanical effects on light-electricity conversion in the photovoltaic cell. Finally, the overall energy efficiency is discussed for such system of Laser power beaming.

1. Introduction

The concept of Laser power beaming is thought to be very promising in power supply for the situations that is difficult to access by ordinary means, of which the overall performance of the system is determined by the multi-physical nature of the process [1–4]. At the same time, many aerostats are proposed for the monitoring of the (earth) surface ecology and environment, natural disasters and even social accidents, which is always accompanied with the short of both communication and power supply. Long-term service in air of such station requires reliable power supply, for which the wireless charging via Laser power beaming is obviously a tempting option.

The brief sketch of Laser power beaming for an aerostat is shown in Fig. 1, in which φ is the zenith angle and d the altitude of the gondola hung below the aerostat. The gondola is covered with Photovoltaic (PV) cells, which are utilized to receive Laser irradiation and transform the light energy into electric energy. The main design variables for the system include the stay altitude of the aerostat, the zenith angle, Laser wavelength, Laser power as well as band gap of the semiconductors adopted in the Photovoltaic cells.

There is always an ultimate pursuit of maximizing the efficiency of such technique of remote wireless power transfer, in particular in the conditions short of power supply. As we know, the final efficiency of Laser power beaming is largely dominated by the attenuation of the laser beam through atmosphere and loss upon light-electricity conversion within the photovoltaic cells irradiated by Laser [5,6]. It has been further demonstrated that the actual energy conversion efficiency is determined by the coupled electrical-thermal-mechanical mechanism according to the previous work of Wu et al [1], in which a steady state model was established to obtain the equilibrium point between electrical conversion and heat dissipation. The fundamental model is developed in the present article and applied to predict the overall efficiency of the laser power beaming designed to supply power for a remote aerostat, in particular the transient coupled model established to describe the dynamic conversion process among optical, electrical, thermal and mechanical energy.

2. Atmospheric attenuation

The atmospheric attenuation of Laser intensity could be modeled by Lambert-Beer law as

$$\frac{\mathrm{I(d)}}{\mathrm{I_0}} = \exp(-\sec(\varphi)\int_0^d \mu(r,\lambda)dr) \tag{1}$$

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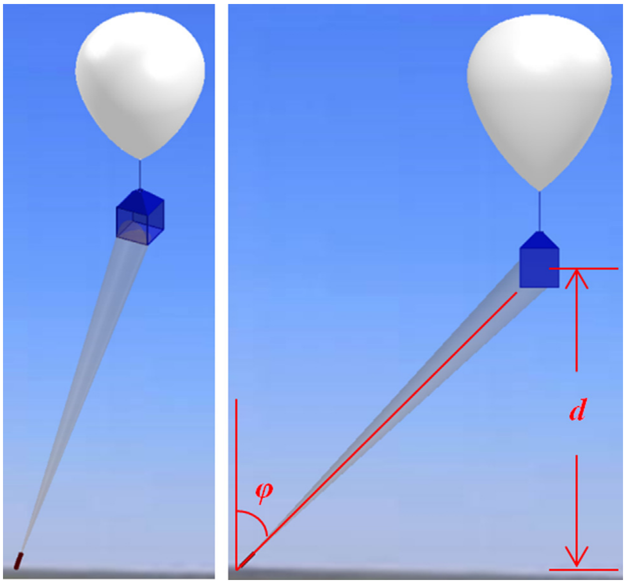

Fig. 1. Sketch of Laser Power Beaming for aerostat.

Wherein, **I(d)** is the transmitted intensity of Laser beam through distance d and I_0 the initial intensity at the Laser source. The term $\mu(r, \lambda)$ [km^{-1}] is the coefficient of atmospheric attenuation of Laser with wavelength λ [nm] at the altitude r [km], for which the empirical formula by Kruse et al [7] is modified and adopted herein as

$$\mu(\mathrm{r}, \lambda) = (\frac{\rho(\mathrm{r})}{\rho_0})(\frac{3.912}{\mathrm{V}_b})(\frac{550}{\lambda})^{\chi} \tag{2}$$

with $\rho(r)$ being the atmospheric density at altitude r, ρ_0 the atmospheric density at sea level and V_b the atmospheric visibility of unit [km]. The index χ is about 1.3 for the cases of average visibility $V_b = 30$ km.

It is noteworthy that the formula (2) should be applied to only the cases of clear day without strong wind as the probable influences of the complex meteorological conditions on it have been ignored for realization, which probably involves rain, snow, hail and atmospheric turbulence. Of course, this could be improved by taking into account these factors based on more experimental data.

Therefore, the atmospheric attenuation of Lasers could be computed by referring to ***1976 American Standard Atmospheric Model*** for the density. Typical results from parametric analysis are shown in Fig. 2. It is revealed that the atmospheric attenuation would be very slight at high altitude, as the transmittance would approach some stationary magnitude in the range of altitude over 20 km.

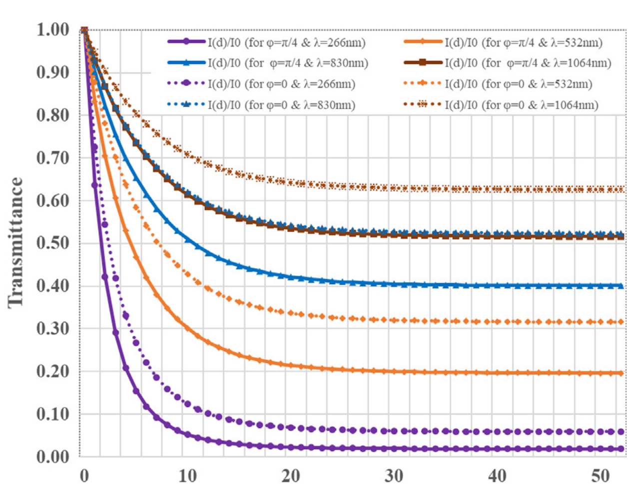

Fig. 2. Transmittance of Laser through atmosphere.

The wavelength dependence of the transmittance is clearly interpreted in these results as the Laser with longer wavelength would penetrate deeper into the atmosphere. Moreover, it is verified that the zenith angle would obviously change the transmittance of Laser.

3. Thermo-mechanical effects

The energy balance equation that involves the coupled electrical-thermal-mechanical effects on PV cell was derived by referring to the work by Wu [1] and considering the transient thermal responses of the photovoltaic cell as following.

$$\frac{dT}{dt} = C_1T^4 + C_2T + C_3 \tag{3}$$

With the coefficients

$$C_1 = -\frac{\varepsilon S_B}{C_h} \tag{4}$$

$$C_2 = \frac{P_l\left(\eta_0\beta_1 + \beta_2\frac{E\alpha}{1-\nu}\right) - h_c}{C_h} \tag{5}$$

$$C_3 = \frac{P_l(1-\eta_0) + \varepsilon S_B {T_0}^4}{C_h} - C_2T_0 \tag{6}$$

Here, T is temperature and t is time. The definition and typical value of the other parameters are listed in Table 1 with the unit areal energy density $U = 1\ kW/m^2$.

Results for typical working conditions are shown in Figs. 3 and 4. It is shown that cell temperature would approach to some steady level for certain absorbed Laser energy density, for which the time till steady could be of 100–600 s in the current situations. At the same time, the cell temperature would increase while the real-time power efficiency would decrease when raise the absorbed Laser energy density.

Considering simultaneously the transmittance of Laser through the atmosphere and the real-time light-electricity conversion efficiency, the mostly optimized overall efficiency could arrive at as following:

$$\frac{\mathrm{I(d)}}{\mathrm{I}_0} \times \frac{\eta}{\eta_0} \times \eta_0 = 0.62 \times 0.93 \times 0.9 \approx 0.51 \tag{7}$$

It should be the theoretical prediction on the case with the parameter combination of laser wavelength 1064 nm and PV cell material bandgap 1.16 eV. It is noteworthy that there is always energy loss during the absorption of Laser by the real cell surface. Of course, it could be further improved by applying the surface texture techniques to the PV cells.

4. Conclusions

The atmospheric attenuation of the Laser is determined by both the

Table 1
Parameters [1].

Symbols	Definition	Value
ε	*Surface emissivity coefficient*	0.8
S_B	*Stefan-Boltzmann constant*	5.67e−8 [$W \cdot m^{-2} \cdot K^{-4}$]
C_h	*Effective heat capacity per unit area*	1750 [$J\ K^{-1}\ m^{-2}$]
η_0	*Light-electricity conversion efficiency for reference status*	0.9
β_1	*Temperature coefficient*	2e−3 [K^{-1}]
β_2	*Stress coefficient*	1e−10 [Pa^{-1}]
E	*Young's elastic modulus*	4.5e10 [Pa]
α	*Thermal expansion coefficient*	5e−6 [K^{-1}]
ν	*Poisson's ratio*	0.3
h_c	*Convective heat exchange coefficient*	20 [$W\ m^{-2}\ K^{-1}$]
P_l	*Absorbed laser power flux*	Ux(1, 5, 10)

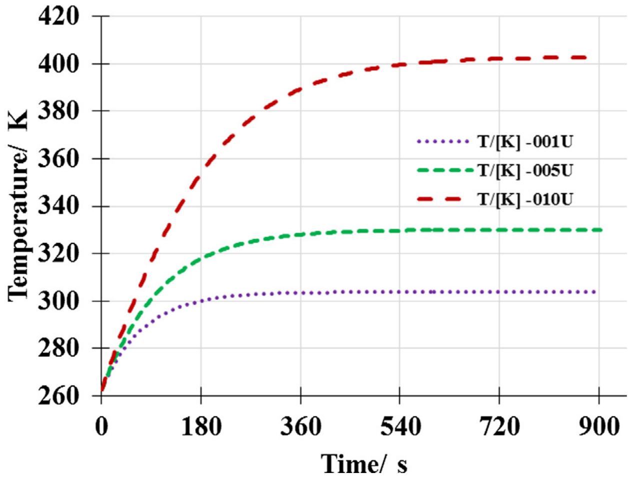

Fig. 3. Cell temperature history.

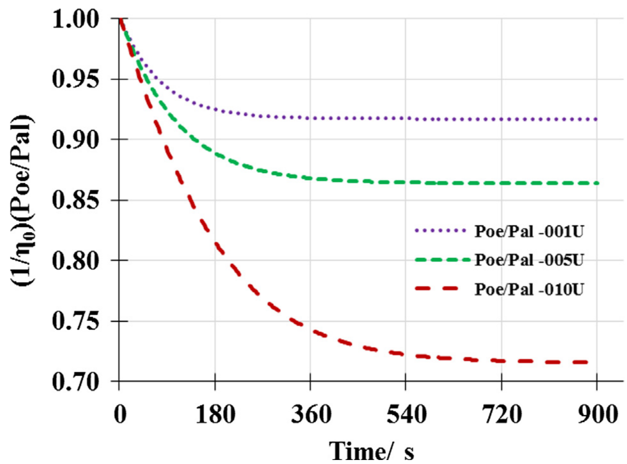

Fig. 4. Real-time power efficiency.

Laser wavelength and the zenith angle for any given weather and altitude conditions. The real-time energy efficiency during light-electricity conversion is approximately inverse-correlated to the absorbed Laser energy density due to thermo-mechanical effects on the PV cell performance. The maximum overall energy efficiency of 51% could be maintained for the laser power transmission and conversion in the present application case of supporting an aerostat.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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