LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS

PACS numbers: 42.55.Wd; 42.62.Cf; 89.30.aj
DOI: 10.1070/QE2015v045n06ABEH015516

Propagation of intense laser radiation through a diffusion flame of burning oil

S.V. Gvozdev, A.F. Glova, V.Yu. Dubrovskii, S.T. Durmanov, A.G. Krasyukov, A.Yu. Lysikov, G.V. Smirnov, V.M. Pleshkov

Abstract. **We report the results of measuring the absorption coefficient of radiation from a cw ytterbium fibre single-mode laser with the power up to 1.5 kW by a diffusion flame of oil, burning in the atmosphere air at normal pressure on a free surface. For the constant length (30 mm) and width (30 mm) of the flame and the distance 10 mm between the laser beam axis and the oil surface the dependence of the absorption coefficient, averaged over the flame length, on the mean radiation intensity (varied from 4.5×10^3 to 1.2×10^6 W cm^{-2}) entering the flame is obtained. The qualitative explanation of nonmonotonic behaviour of the absorption coefficient versus the intensity is presented.**

Keywords: *laser, flame, radiation intensity, mean absorption coefficient.*

1. Introduction

The dismounting of metallic constructions, obstructing the head of openly fountaining oil or gas wells, is an important problem, since it allows the reduction of the raw stock losses and facilitates the normalisation of ecological situation in the accident area. The distant cutting of the constructions by laser radiation [1] is the up-to-date and safe method of conducting the emergency and reconstructive works. The efficiency of this method has been successfully demonstrated starting from 2011 by the elimination of the aftereffects of real accidents at gas wells using a MLTK-20 mobile laser technological system [2]. The basis of the system is presented by three high-power ytterbium fibre cw lasers. The success of the laser radiation application for these goals is largely dependent on the efficient and lossless delivery of radiation to the operation site. Obviously, in the case of the radiation beam propagating through the flame, the beam is attenuated, depending on the composition of the burning hydrocarbons and the length of the burning zone [3]. The conditions for radiation transmission through the flame of burning natural gas, even in the presence of sand and water admixtures, are relatively favourable [2]. However, these conditions may change in the case of the radiation passing through a different flame, e.g., the flame of gas condensate or the flame of burning oil.

The goal of the present paper is to study experimentally the dependence of the attenuation of high-power radiation from an ytterbium fibre cw laser on the radiation intensity in the course of radiation propagation through a diffusion flame of burning oil.

S.V. Gvozdev, V.Yu. Dubrovskii, S.T. Durmanov, A.G. Krasyukov, A.Yu. Lysikov, G.V. Smirnov, V.M. Pleshkov State Research Center of the Russian Federation 'Troitsk Institute for Innovation & Fusion Research', ul. Pushkovykh, vladenie 12, 142190 Moscow, Troitsk, Russia; e-mail: gsv@triniti.ru, lysikov@triniti.ru;
A.F. Glova State Research Center of the Russian Federation 'Troitsk Institute for Innovation & Fusion Research', ul. Pushkovykh, vladenie 12, 142190 Moscow, Troitsk, Russia; National Research Nuclear University 'MEPhI', Kashirskoye sh. 31, 115409 Moscow, Russia; e-mail: afglova@triniti.ru

Received 9 April 2014; revision received 16 September 2014
Kvantovaya Elektronika **45** (6) 582–584 (2015)
Translated by V.L. Derbov

2. Experimental setup and measurement techniques

The flame was initiated in a 50 mm × 50 mm metallic cuvette of depth 5 mm by the ignition of the oil vapours filling the cuvette under normal conditions. The flame was stabilised by the side walls of the cuvette and the exhaust ventilation fan located above the cuvette. The radiation source was a cw single-mode ytterbium fibre laser with a radiation wavelength 1.07 μm and a maximal power 1.5 kW. The laser beam was oriented along one of the sides of the cuvette, centred with respect to the perpendicular side and propagating in the yellow part of the flame, the separation between the beam axis and the oil surface being equal to h = 10 mm. The length of the flame along the beam trace was $l \approx 30$ mm. The diameter of the beam waist d_0 located in the central part of the flame in the direction of the beam propagation amounted to 1 or 0.4 mm, depending on the focal length of the lens used. For the caustic length, equal to 140 and 22 cm for the above values of d_0, respectively, the diameter of the beam at the distance l was only slightly different from d_0. The refraction broadening of the beam and the bending of its axis with respect to its position in the absence of the flame could be neglected, which was confirmed by the observations of the beam spot at a distant screen. The input intensity $I_{\rm in}$ of the radiation entering the flame was varied by changing the power and d_0, and the limits of its values, averaged over the radial coordinate, were $4.5 \times 10^3 - 1.7 \times 10^5$ W cm^{-2} for d_0 = 1 mm, and $5.6 \times 10^5 - 1.2 \times 10^6$ W cm^{-2} for d_0 = 0.4 mm. Note that the choice of the above spatial position of the beam in the flame was made based on the preliminary measurements, performed with different values of h. According to these measurements, for the intensity $I_{\rm in} \sim 10^4$ W cm^{-2}, typical for distant cutting of metals, the most unfavourable conditions for the radiation propagation through the maximally absorbing flame correspond to $h \approx 10$ mm. In this case the value of the absorption coefficient is almost independent of the displacement of the beam in the horizontal direction within 15 mm.

The power of the radiation output from the flame can be presented in the form $P_{out} = P_{in}\exp[-(\alpha + \mu)l]$, where α, μ are the radiation absorption and scattering coefficients averaged over the length l, respectively; and P_{in} is the input power at the flame entrance. Based on the results of measuring the fraction of the radiation power, scattered by the similarly-looking flame of the aircraft kerosene [3], we assumed that $\mu \ll \alpha$ and used as a criterion of attenuation the following expression for the mean absorption coefficient, containing all measured quantities: $\alpha = (-1/l)\ln(P_{out}/P_{in})$.

The propagation of radiation through the flame is accompanied by the glowing of the beam trace, and the glow intensity grows with increasing incident radiation intensity. This correlation may be due to a change in the temperature of solid particles, contained in the flame and heated by the laser radiation. In the present paper the temperature measurements were carried out in the central part of the beam trace, selected by means of a diaphragm.

3. Results of the measurements and discussion

The measurements of the flame temperature under the conditions of laser beam propagation have shown that in the range of intensities $3.5 \times 10^4 - 10^5$ W cm^{-2} the temperature linearly grows from 2000 to 3000 K. With a further increase in intensity, the temperature rise becomes slower, and at the value of $I_{in} = 1.2 \times 10^6$ W cm^{-2}, which was maximal in the present experiments, the temperature becomes equal to 3400 K. Note that in the experiments of Ref. [4], where the carbon particles in vacuum were exposed to the CO_2 laser radiation with the intensity $2-3 \times 10^5$ W cm^{-2}, the temperature of the particles achieved 4500 K.

The results of measuring the coefficient α are presented in Fig.1 versus the intensity I_{in}. The measurement error amounts to 20%. The dependence has the following specific features. First, when the intensity of the incident radiation varies within $4.5 \times 10^3 - 10^5$ W cm^{-2}, the absorption coefficient passes its maximum, in which it attains the values 0.12–0.13 cm^{-1} at $I_{in} \approx 10^4 - 4 \times 10^4$ W cm^{-2}. Second, when the intensity increases from 10^5 to 1.2×10^6 W cm^{-2}, the value of α is practically stabilised at a very low level of $5 \times 10^{-3} - 10^{-2}$ cm^{-1}. One can say that for these intensities the clearing of the flame in the channel of light propagation occurs.

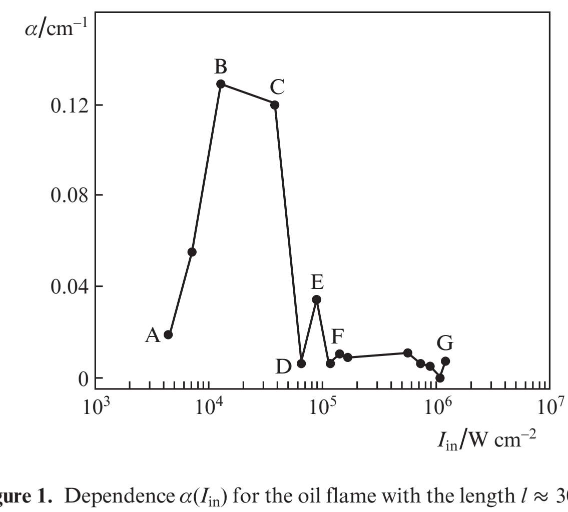

Figure 1. Dependence $\alpha(I_{in})$ for the oil flame with the length $l \approx 30$ mm and the separation between the beam axis and the surface of the oil 10 mm.

For qualitative interpretation of the data presented in Fig. 1 let us restrict ourselves to considering the influence of solid carbon particles, always present in the hydrocarbon flame in the form of soot [5], on the radiation transmission. At the trace region AB, as the radiation intensity increases, the temperature also increases and the heating power losses of laser radiation grow, leading to the growth of the absorption coefficient. Due to relatively low temperature of the flame the evaporation of particles in the laser radiation field does not occur. However, with a rise of temperature, the rate of particle burning dramatically increases. Therefore, the region BC can be considered as the region of dynamic equilibrium between burning of the particles and their convection supply to the interaction zone. It seems that under these conditions the absorption coefficient should not depend on the further intensity increase and is expected to stay at the level, corresponding to the region BC. However, the experiment shows that the increase in the intensity in the region CD leads to a strong, by more than an order of magnitude, decrease in the absorption coefficient in comparison with the region BC. The reason why α is small and independent of I_{in} in the region FG can be the following. In this region the radiation intensity is so high, that the absorbing particles are getting burned already in the peripheral zone of the beam. As a result, the major central part of the beam appears to be free of particles and propagates in the flame, where the power losses are small due to the weak absorption of the laser radiation with the wavelength 1.07 μm by gaseous burning products. As to the region CDEF, it is a transition region between the ones of strong and weak absorption, and here the behaviour of the absorption coefficient can decline from a monotonic decrease (the point E), but this fact does not essentially contribute to the general character of the dependence $\alpha(I_{in})$.

Similar measurements were carried out using radiation of a multimode ytterbium fibre laser. The measurements were performed for the flame of oil and aircraft kerosene TS-1 at the same height $h = 10$ mm, the maximal intensity I_{in}, not exceeding 3.5×10^5 W cm^{-2} and $d_0 = 0.9$ mm. The dependence $\alpha(I_{in})$ has the same features as the one presented in Fig. 1, and the absolute values of the absorption coefficient for the fixed values of I_{in} for the oil flame were virtually the same for the single-mode and multimode lasers. This may evidence in favour of the conclusion that the main role in the clearing of the light propagation channel is played by the intensity of radiation, rather than by the focusing spot size d_0 and the radiation quality.

It is necessary to emphasise that the presented interpretation of the dependence $\alpha(I_{in})$ is qualitative and does not allow for the particle size change in the process of burning, as well as the gas dynamical flows in the flame, related to the heating of the medium in the beam. More rigorous quantitative explanation of the obtained results requires further experimental studies.

4. Conclusions

The results of the measurements presented in this paper show that the mean coefficient of absorption of radiation, generated by a cw ytterbium fibre laser, by the diffusion flame of burning oil varies nonmonotonically depending on the incident radiation intensity, and for the intensity greater than 10^5 W cm^{-2}

becomes stabilised at the low level of $5 \times 10^{-3} - 10^{-2}$ cm^{-1}. The obtained results should be taken into account in the development and application of new-generation mobile laser technological systems, providing the radiation intensity $\sim 10^5$ W cm^{-2} in the active zone and aimed at distant cutting of metallic constructions of gas-condensate and oil wells, fountaining as a result of an accident.

References

1. Blokhin O.A., Vostrikov V.G., Gavrilyuk V.D., et al. *Khim. Neftegaz. Mashinostr*., No. 5, 52 (2001).
2. Durmanov S., Krasukov A., Smirnov G., Cherkovets V. *Tech. Progr. 6-th Int. Symp. on High-Power Fiber Lasers and their Applications* (St. Petersburg, Russia, 2012).
3. Gvozdev S.V., Glova A.F., Dubrovskii V.Yu., et al. *Kvantovaya Elektron*., **42**, 350 (2012) [*Quantum Electron*., **42**, 350 (2012)].
4. Andrukhova T.V., Bukatyi V.I. *Izv. Altayskogo Gos. Univer*., No. 1, (23), 99 (2002).
5. Lee Ch.B., Lee W., Oh K.Ch., Shin H.D., Yoon J.-K. *Fiz. Goreniya Vzryva*, **42**, 74 (2006) [*Combust., Explos., Shock Waves*, **42** (6), 688 (2006)].