Attenuation of laser radiation by the flame of burning hydrocarbons and efficiency of remote cutting of metals

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Abstract. Mobile laser technological complex MLTC-20 with radiation power 20 kW and radiation wavelength 1.07 μm created in SRC RF TRINITI on the base of a three cw fiber Yb lasers is used successfully at remote cutting of the metalworks at carrying out of the emergency-reduction works on the out of control gas wells. In this work the results of the investigation of the possibility and the efficiency of laser radiation application for remote cutting of metals on the emergency oil wells have been presented. Measurements of the mean absorption coefficient of the radiation of a cw fiber Yb laser under its propagation in a flame of burning oil in dependence on radiation intensity have been carried out. It was shown that at the intensity ~10⁴ W/cm² the absorption coefficient traverses the maximum where its value is equal to ~0.1 cm⁻¹, and at the intensity increasing to the values 10⁵ – 10⁶ W/cm² it stabilizes on a small level ~5·10⁻³ – 10⁻² cm⁻¹. It is established that the maximal velocity and the efficiency of remote cutting of the steel plates with a thickness up to 10 mm by the radiation with the intensity 10⁶ W/cm² exceed these factors at the intensity 10⁴ W/cm². The possibility of the efficient remote cutting of steel plate with a thickness of 60 mm by laser radiation having the power 7.5 kW and the intensity 10⁵ W/cm² has been demonstrated.

1. Introduction
Dissection of the metalworks at the accident on the out of control oil or gas well is the actual problem since it allows the works to perform upon the accident elimination and to replace the damaged equipment. Modern and safety method of the performing of emergency-reduction works in these conditions is remote separating cutting of the constructions by laser radiation [1]. The efficiency of this method at elimination of the consequences of real accidents on the gas wells is demonstrated successfully beginning from 2011 by the mobile laser technological complex MLTC-20 with radiation power of 20 kW [2]. Three cw fiber Yb lasers with radiation wavelength of 1.07 μm serve as the basis of the complex. Lasers are being housed in the same container; in a separate container three-channel lens forming telescope with a systems of guidance and control for the complex operation is housed (see figure 1). The range of the telescope radiation focusing is equal to 20 – 75 m, the cutting process is carried out at the laser radiation intensity on the metal surface I₀ ≈ 10⁴ W/cm². Figure 2a shows the typical view of the accident on gas well and operation of the MLTC-20 complex at the accident: the bright point on the dark background indicates the position of laser beam incidence. The fragment of...
the gas fittings sheared on the accident site by laser beam of the complex MLTC-20 in figure 2b is presented.

![Figure 1. Total view (a) and telescope view (b) of the complex MLTC-20.](image1)

![Figure 2. Operation of the complex MLTC-20 at the accident (a) and the fragment of the gas fittings sheared on the accident site by laser beam (b).](image2)

The success of the laser radiation application for these goals is largely dependent on the efficient and lossless delivery of the 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 are relatively favourable. However, these conditions may change in the case of the radiation passing through another flame, for example, the flame of burning oil.

The goal of the given paper is to study experimentally the dependence of the attenuation of high-power radiation from cw fiber Yb laser on the radiation intensity in the course of radiation propagation through a diffusion flame of burning oil and determination of the efficiency of remote cutting of metals. These studies were performed in lab conditions.

2. Attenuation of laser radiation by the diffusion flame of burning oil

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 stabilized by the side walls of the cuvette. The radiation source was a cw fibre Yb laser with a radiation wavelength 1.07 µm and a maximal power 1.5 kW or 2.7 kW when single-mode or multimode laser was used. The laser beam propagates in the yellow part of the flame, the separation between the beam axis and the oil surface being equal to \( h = 10 \text{ mm} \). The length of the flame along the beam trace was \( l \approx 30 \text{ mm} \). The diameter of the beam waist \( d_0 \) amounted to 1 or 0.4 mm for single-mode laser and to 0.9 mm for multimode laser. The caustic length for both lasers greatly exceeds the flame length therefore the diameter of the beam at the distance \( l \) was only slightly different from \( d_0 \). The input intensity \( I_{\text{in}} \) of the radiation entering the flame was varied by changing the power and \( d_0 \) in the case of single-mode laser.

The value of the radiation absorption coefficient is a main criterion of the power attenuation of laser radiation under its propagation through the flame. Really, the power of the radiation output from the flame can be presented in the form \( P_{\text{out}} = P_{\text{in}} \exp[-(\alpha + \mu)l] \), where \( \alpha, \mu \) 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 aviation kerosene [3], we assumed that \( \mu \ll \alpha \) and for mean absorption coefficient obtain the following expression which was used in experiments for its value determination:

\[
\alpha = \frac{1}{l} \ln\left(\frac{P_{out}}{P_{in}}\right).
\]

The dependence of \( \alpha \) on \( I_{in} \) for single-mode laser in figure 3 is presented. The measurements of the flame temperature under the conditions of laser beam propagation have shown that in the range of intensities \( 3.5 \cdot 10^4 - 10^5 \) 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 maximal value of \( I_{in} = 1.2 \cdot 10^6 \) W/cm\(^2\) the temperature becomes equal to 3400 K.

![Figure 3. Dependence of \( \alpha \) on \( I_{in} \) at propagation of the radiation of single-mode laser in oil flame.](image)

For qualitative interpretation of the data presented in figure 3 let us restrict ourselves to considering the influence of solid carbon particles on the radiation transmission [4]. These particles are always present in the hydrocarbon flame in the form of soot [5]. On the growing branch of the dependence \( \alpha(I_{in}) \), the radiation intensity increases, the temperature also increases and the heating power losses of laser radiation grow, leading to the grows of the absorption coefficient. Due to relatively low temperature of the flame the evaporation of the particles in the laser radiation field does not occur. However, with a rise of temperature, the rate of particle combustion dramatically increases [6]. Therefore, the section in figure 3, corresponding to the band of the intensity change \( \sim 10^4 - 5 \cdot 10^4 \) W/cm\(^2\), can be considered as the region of unstable dynamic equilibrium between combustion of the particles and their convection supply to the interaction zone. At further increase in the intensity, strong, by more than an order of magnitude, decrease in the absorption coefficient takes place, and then its value practically stabilizes at a very low level of \( 5 \cdot 10^{-3} - 10^{-2} \) cm\(^{-1}\). One can say that at \( I_{in} \geq 10^5 \) W/cm\(^2\) the brightening of the channel of the radiation propagation occurs. The reason of this can be the following. At \( I_{in} \geq 10^5 \) W/cm\(^2\) 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 with small power losses due to the weak absorption of the laser radiation with the wavelength 1.07 \( \mu \)m by gaseous burning products.

Similar measurements were carried out using radiation of a multimode laser. Results of the measurements for oil flame and aviation kerosene flame in figure 4 are presented. The dependences \( \alpha(I_{in}) \) have the same features as the one presented in figure 3, and the absolute values of the absorption coefficient for the fixed values of \( I_{in} \) for the oil flame are virtually the same for the single-mode and multimode lasers. This may evidence in favour of the conclusion that the main role in the cleaning 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.
3. Remote cutting of metals by laser radiation

Reduction of the radiation absorption coefficient in oil flame at radiation intensities $I_\alpha \geq 10^5$ W/cm$^2$ can evidence about the basic possibility of the remote cutting of metalworks on the emergency oil well. But the question arises for the cutting efficiency, because due to decreasing of the focal spot size at the intensity increasing and absence of the auxiliary gas jet for melt removal, their removal can be hampered along of the viscosity of the melt.

To answer this question, the comparative experiments were carried out upon remote cutting of the verticality St.3 steel plates with a thickness $H = 3, 4, 6$ and 10 mm by the horizontal beam of a cw fiber Yb laser with the radiation power $P_0 = 2.7$ kW at and two values of the radiation intensity on the metal surface $I_0 = 10^4$ W/cm$^2$ (the size of the focal spot $d_0 = 6$ mm) and $I_0 = 10^6$ W/cm$^2$ ($d_0 = 0.6$ mm). The results of the experiments are shown in figure 5.

In figure 5 $V_{\text{max}}$ is the maximal velocity of the beam moving at which the solid cut still exists, $\beta = V_{\text{max}}H/P_0$ is the cutting efficiency determined as the area of the cut related to the unity of the expended energy [7]. It is seen, that at $I_0 = 10^6$ W/cm$^2$ as maximal velocity as well as the efficiency exceed these factors at $I_0 = 10^4$ W/cm$^2$ for all values of the plate thickness. The reason of this is increase of the role of the vapour recoil momentum at melt removal [8], the influence of which can neglect at removal under action of the gravity force [9,10] at $I_0 \leq 10^4$ W/cm$^2$. 

![Figure 4](image1.png)

**Figure 4.** Dependences of $\alpha$ on $I_\alpha$ at propagation of the radiation of multimode laser in oil flame (1) and aviation kerosene flame (2).

![Figure 5](image2.png)

**Figure 5.** Dependences on $H$ of the maximal velocity $V_{\text{max}}$ (1,2) and cutting efficiency $\beta$ (3,4) at $P_0 = 2.7$ kW and $I_0 = 10^4$ (1,3) and $10^6$ W/cm$^2$ (2,4).
The efficient remote cutting by laser radiation with an increased intensity $\sim 10^5$ W/cm$^2$ is possible also at cutting of the metals of largest thickness typical for cutting of the fittings at the accident. As an example in figure 6 the picture of the frontal cut on the verticality A40G steel plate with a thickness $H = 60$ mm is shown. The cutting process was performed by radiation of cw fibre Yb laser with radiation power $P_0 = 7.5$ kW at $I_0 = 10^5$ W/cm$^2$, $d_0 = 3$ mm and the velocity of the beam moving $V = 0.1$ mm/s. In table 1 the dependences on the velocity of the total irradiation time, the cut depth and the frontal width of the cut are presented.

![Figure 6. View of the frontal cut on the verticality A40G steel plate with a thickness $H = 60$ mm at $P_0 = 7.5$ kW, $I_0 = 10^5$ W/cm$^2$ and $V = 0.1$ mm/s.](image)

| Velocity (mms$^{-1}$) | Time (min) | Depth (mm) | Width (mm) |
|------------------------|------------|------------|------------|
| 0.1                    | 12         | 50         | 10         |
| 0.2                    | 6          | 34         | 10         |
| 0.3                    | 4          | 27         | 10         |
| 0.4                    | 3          | 23         | 10         |

4. Conclusions
The investigations performed in this work have shown that the mean absorption coefficient of the radiation of a cw fiber Yb laser by the diffusion oil flame changes non-monotonic in dependence on the intensity of incident radiation and at the intensity more than $10^5$ W/cm$^2$ stabilizes on a level of $5 \cdot 10^{-3} - 10^{-2}$ cm$^{-1}$. The possibility of the efficient remote cutting of metals by radiation of these lasers with the intensity $\geq 10^5$ W/cm$^2$ has been demonstrated exceeding 1.5 – 2 times the efficiency at cutting by the radiation with the intensity $\leq 10^4$ W/cm$^2$. It became possible due to the change of the main mechanism of the melt removal under action of the gravity force at low intensity on the removal under action of the vapour recoil momentum at higher intensity.

The obtained results should be taken into account in the development and application of new-generation mobile laser technological complexes providing the radiation intensity on the level of $10^5$ W/cm$^2$ in the active zone and aimed at remote cutting of metalworks of gas-condensate and oil wells, spouting as a result of an accident.

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