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REMOTE LASER BURNING OF LIQUID HYDROCARBONS ON WATER AND ICE SURFACES

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Transmission spectra were measured and absorption coefficients were determined for gas condensate and oil using laser radiation with wavelength 1.07 μm. The dependences of the reflection coefficient on the laser-radiation angle of incidence on the surface of oil, gas condensate, and diesel fuel were obtained. Threshold intensities of laser radiation providing stable ignition and subsequent self-sustaining combustion of hydrocarbons on water and ice surfaces were experimentally determined. Laser afterburning (scanning) of heavy oil fractions remaining on the water surface after self-sustaining combustion was performed for the first time.

Keywords: laser, hydrocarbons, ignition, radiation intensity, self-sustaining combustion, ray scanning.

Recovery, offloading, and transportation of oil and oil products from offshore platforms create the probability of accidental spills, which is especially critical under Arctic conditions because of natural and climatic factors (shifting ice, low temperatures, limited visibility, etc.). The destructive potential of oil-recovery technologies is determined by climatic and anthropogenic factors and is part of a more general question about contemporary ecological anthroposphere interfaces [1]. Oil remains on water and ice surfaces much longer than other hydrocarbons because it evaporates more slowly and is practically not decomposed by bacteria at northern latitudes.

A timely, economical, and reliable method for cleaning water surfaces is combustion of oil spills, for which activators, i.e., combustible compounds with high burning temperatures, are used for reliable ignition of them. The disadvantages of this method are the high consumption of pyrotechnic compounds, significant financial costs, and incomplete combustion of the oil [2].

Laser combustion is a promising method for igniting and removing as much of an oil film as possible from water surfaces. The advantages of the method are:

– low financial costs (determined only by the insignificant energy demand of the laser complex and labor costs for complex operators);

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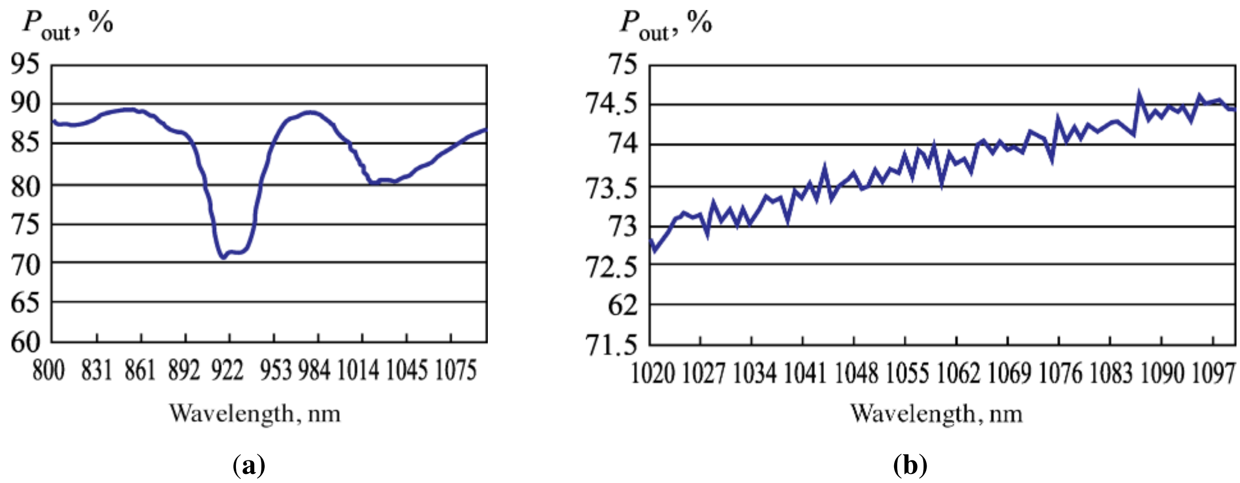

Fig. 1. Transmission spectra of layers of gas condensate of thickness 10 mm (a) and of oil of thickness 11–12 μm (b): P_{out}, radiation power exiting an oil or gas condensate layer expressed in percent of radiation power P_{in} entering the layer.

– timeliness (without preliminary work except for installation of spill boom containment); the starting time of the laser complex operation is determined only by the time needed for the transportation vessel (ship or helicopter) with the equipment to arrive in the affected region;

– remoteness and contact-free (operation outside the hydrocarbon spill zone).

Vaporization, combustion, and splashing of the liquid layer (kerosene, oil) from the water surface by a powerful CO_2 laser in pulsed or continuous modes were experimentally studied in seminal work on the action of laser radiation on an oil film on water surfaces [3, 4]. Use of laser radiation was proposed in a patent for cleaning large water areas from oil pollutants [5]. Later, researchers at SRC Keldysh Center obtained analogous results for ignition of an oil film using a gas-dynamic continuous-wave CO_2 laser (100 kW) as the radiation source [6].

The goal of the present work was to determine the criteria of the laser radiation (wavelength $\lambda = 1.07$ μm) providing stable ignition of various hydrocarbons and their subsequent self-sustaining burning on water and ice surfaces. Interaction of laser radiation of wavelength ~1 μm with oil and other hydrocarbons is inadequately studied and has practical interest.

Experimental Apparatuses and Measurement Methods

Determination of Absorption Coefficients of Laser Radiation for Oil and Gas Condensate. Transmission spectra of oil samples (well No. 321–14, Chayanda oil-gas condensate field) and gas condensate (well No. 3, Kirin field) were measured under laboratory conditions on a UV-3600 spectrophotometer (Shimadzu, Japan).

The transmission spectrum of gas condensate (Fig. 1a) was obtained using a 10-mm cuvette with optical quartz windows for input/output of radiation.

The transmission spectrum of oil was obtained by placing a drop of oil from a calibrated pipette onto a special quartz plate and covering it with another plate (Fig. 1b). The total surface area of the plate was 2 cm^2. The calculated thickness of the oil layer between the plates was 11–12 μm. Evenly colored samples without air bubbles between plates were selected from several that were prepared. Samples were cooled to ~0 ºC before measurements to avoid oil leakage.

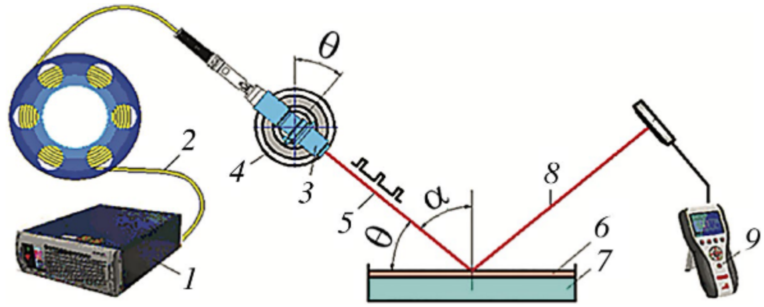

Fig. 2. Diagram of experiment for determining reflection coefficient of laser radiation from surfaces of various hydrocarbons.

Determination of Laser Radiation Reflection Coefficient as a Function of Angle of Incidence of the Beam on the Hydrocarbon Surface. An experiment according to the diagram in Fig. 2 with three types of hydrocarbons, i.e., gas condensate, diesel fuel, and oil, poured onto a water surface was conducted under normal laboratory conditions.

Radiation from an LK-150/1500-QCW-AC fiber Yb-laser *(1)* [7] (Fig. 2) was fed through optical transport fiber *2* onto laser collimator *3* that was installed on a stage with the ability to change the angle at site *4*. Laser beam *5* fell on the surface of the studied hydrocarbon poured onto the water surface in cuvette *7* at an angle θ to the surface (correspondingly, incidence angle $\alpha = 90° - \theta$). Reflected laser beam *8* fell on the optical head of a PE50BB-DIF *9* laser radiation pyroelectric energy meter (Ophir, Ireland) [8]. The laser operated in pulsed mode (constant pulse length $\tau_{pul} = 1$ msec, pulse energy $W = 123$ mJ, pulse repetition rate $f = 1$ Hz). Three successive laser pulses were used at each angle α. Then, the reflected radiation power was determined and the mean power was calculated from the recorded energies.

Determination of Hydrocarbon Ignition Criteria. The diagram for conducting the experiment was analogous to that in Fig. 2 except for the use of an LS-1.5-OM continuous fiber Yb-laser *(1)* [6] with output radiation power up to 1.5 kW and a protective screen instead of radiation energy meter *9*. A variable focusing device for increasing the radiation intensity was used instead of collimator *3* in experiments with diesel fuel and gas condensate. The laser-beam angle of incidence α was set at 79°, which corresponded to a safe distance of 100 m to the ignited hydrocarbon spill at a height of 19 m from the focusing system (characteristic height of an icebreaker deck on which the laser complex might be installed). The experiments were conducted under laboratory conditions at air temperature 12 °C and in open air at temperatures of –15 to –17 °C. The radiation intensity sufficient for stable ignition of the hydrocarbons and their subsequent self-sustaining burning was determined by varying the laser-radiation output power and changing the focusing. The experiments were conducted with hydrocarbons spilled on the surface of water in cuvette *7* and on the surface of ice in the same cuvette.

Laser Afterburning (Scanning) of Heavy Oil Fractions. A surfactant (SA) was added upon completion of self-sustaining combustion of oil in a pan with ice, a water layer on the surface of the ice, and unburnt heavy oil fractions on the water surface. Oil residues and their area decreased by greater than an order of magnitude and; correspondingly, the thickness of the oil residue layer increased because the surface tension of the SA solution was less than that of the oil. This simplified considerably its further burning. The experimental diagram was analogous to that in Fig. 2 except that the stage for rotating the angle at the site was installed on an automatic horizontal shift system. The beam scanning at which intense afterburning of the oil residues was observed was reproduced at 5 mm/sec over ~ 20 min.

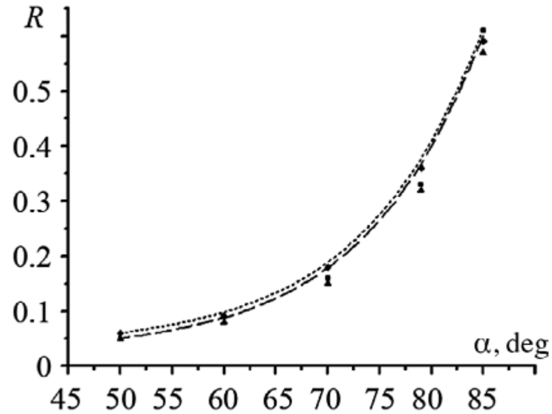

Fig. 3. Dependence of reflection coefficient of laser radiation on angle of incidence of laser beam on surface: oil (■), gas condensate (▲), diesel fuel (♦), oil (calc.) (- - -), and gas condensate (calc) (— — —).

Results and Discussion

The obtained dependences of the reflection coefficient of the laser radiation on beam incidence angle on the hydrocarbon surfaces (Fig. 3) agreed with the calculated reflection coefficients for these same angles of incidence considering random polarization of the laser beam.

The ratio of the amplitudes of the reflected and incident light waves for two types of linear polarization obeyed the expressions:

$$\frac{E_{\perp}}{E_{0\perp}} = -\frac{\sin(\alpha-\psi)}{\sin(\alpha+\psi)}, \qquad \frac{E_{\parallel}}{E_{0\parallel}} = \frac{\tan(\alpha-\psi)}{\tan(\alpha+\psi)}, \tag{1}$$

where $E_{\perp}$ is the amplitude of the reflected *s*-polarized light wave, $E_{0\perp}$, the amplitude of the incident *s*-polarized light wave, $E_{\parallel}$, the amplitude of the reflected *p*-polarized light wave, $E_{0\parallel}$, the amplitude of the incident *p*-polarized light wave, α, the angle of incidence of the light wave; and ψ, the angle of refraction of the light wave.

The angles of incidence and refraction of the light beam were related by:

$$\frac{\sin\alpha}{\sin\psi} = \frac{n_2}{n_1} \Rightarrow \sin\psi = \frac{\sin\alpha}{n_2}, \tag{2}$$

where $n_1 \approx 1$ is the refractive index of dry air, n_2, the refractive index of the hydrocarbon ($n_2 = 1.5$ for oil, $n_2 = 1.4$ for gas condensate).

Because the radiation intensity I and wave amplitude E were related by $I \sim E^2$ and the reflection coefficient was equal to the intensity ratio of the reflected and incident light waves, the expressions for the reflection coefficients of the *s*- and *p*-polarized light waves considering Eq. (1) became:

$$R_{\perp} = \frac{|E_{\perp}|^2}{|E_{0\perp}|^2} = \frac{\sin^2(\alpha-\psi)}{\sin^2(\alpha+\psi)}, \qquad R_{\parallel} = \frac{|E_{\parallel}|^2}{|E_{0\parallel}|^2} = \frac{\tan^2(\alpha-\psi)}{\tan^2(\alpha+\psi)}. \tag{3}$$

Because a laser with random polarization of the radiation was used in the experiments, the reflection coefficient was determined by

$$R = (R_{\perp} + R_{\parallel})/2. \tag{4}$$

The obtained results (Fig. 3) could be useful for developing protective measures for reflected laser radiation during laboratory studies and natural tests of laser complexes.

The power decrease of the laser radiation at the exit from the hydrocarbon layer P_{out} that was due to absorption of radiation was determined by

$$P_{\text{out}} = P_{\text{in}} \exp(-k \cdot l),$$

where P_{in} is the radiation power at the entrance to the layer; k, the hydrocarbon absorption coefficient; and I, thickness of the hydrocarbon layer.

Absorption coefficient $k = (-1/l)\ln(P_{\text{out}}/P_{\text{in}})$ for oil was 0.025 μm^{-1}; for gas condensate, 0.14 cm^{-1}.

Mechanism of Ignition of Hydrocarbons on Water and Ice Surfaces

The interaction zone of the radiation on the surface is elliptical in shape for the action on the hydrocarbon surface of laser radiation with incident angle $\alpha > 0$.

The average intensity (in the radial distribution) in a radiation beam on the hydrocarbon surface I_{sur} at certain laser-radiation parameters corresponded to the conditions for intense vaporization of hydrocarbons. The average radiation intensity at a focal point I_{foc} located 1.5–2.0 cm over the hydrocarbon surface was sufficient to ignite the hydrocarbon vapors. Stable (in the air temperature range from 10 to –30 ºC) ignition of hydrocarbons on the ice surface for time of action τ and subsequent self-sustaining combustion without radiation action at certain radiation-intensity criteria for all types of hydrocarbons were:

– for oil, $I_{\text{sur}} \geq 4 \cdot 10^2$ W/cm^2, $I_{\text{foc}} \geq 2 \cdot 10^3$ W/cm^2, $\tau \approx 5$ sec,

– for diesel fuel, $I_{\text{sur}} \geq 2.3 \cdot 10^3$ W/cm^2, $I_{\text{foc}} \geq 1.2 \cdot 10^4$ W/cm^2, $\tau \approx 840$ sec,

– for gas condensate, $I_{\text{sur}} \geq 3.8 \cdot 10^3$ W/cm^2, $I_{\text{foc}} \geq 2.1 \cdot 10^4$ W/cm^2, $\tau \approx 1200$ sec.

Such substantial differences in the intensities and times of action were explained by the different absorption coefficients for the radiation of the examined hydrocarbons. The greater the absorption coefficient of the radiation was, the less the required intensity and duration of action to ignite the hydrocarbon were.

Wind was another important external factor affecting the duration of ignition of the hydrocarbon. Strong wind from the zone of beam action carried away more vapor, which hindered ignition of the hydrocarbon and required longer ignition times.

A hydrocarbon layer 1.0–1.5 mm thick burned during the self-sustaining combustion. The upper water layer was heated and boiled vigorously as the combustion front gradually approached the surface. This extinguished the flame. Therefore, the percent burning of the hydrocarbon layer was greater for thicker initial layers. For example, 85–90% of an oil layer 10 mm thick was burned.

Heavy oil fractions remained on the water surface after self-sustaining combustion of the oil was complete. Afterburning of these was observed only with the action of laser radiation. Afterburning of oil residues with radiation parameters of beam scan rate 5 mm/s and radiation action time ~ 20 min could decrease the mass of unburnt oil residues by ~ 2.5 times as compared to afterburning of oil without using laser scanning (Fig. 4).

Fig. 4. Afterburning of oil film residues on water surface (ice is visible under the clean water section).

CONCLUSION

The established laser-radiation criteria indicated that a continuous laser at wavelength 1.07 μm and power of several kW could be used for reliable ignition of hydrocarbons on water and ice surfaces. Measurements of the residual oil mass found that the beam-scanning method was highly efficient for heavy oil fractions after self-sustaining oil combustion was complete. The results could be useful for developing and using mobile laser technological complexes for providing radiation intensities of 10^2–10^4 W/cm^2 at distances of 100–120 m from the focusing system.

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