

Control of hydrogen leaks from storage tanks and fuel supply systems to mining transport infrastructure facilities[☆]

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ABSTRACT

In the mining industry, the work system relies on equipment that consumes large amounts of energy. In mining operations, diesel equipment is widely used due to its flexibility, load capacity and adaptability to various terrain conditions. However, it has high diesel consumption and high greenhouse gas emissions, mainly carbon monoxide. Using hydrogen as a fuel not only offers the opportunity to decarbonize transportation and the mining industry, but also significantly reduces local air pollution. The list of possible objects for using the proposed hydrogen technology includes: diesel power plants, high-voltage diesel distillation stations, mining excavators, drilling rigs, diesel-powered loading and hauling vehicles and others. The use of hydrogen as a fuel to drive engines of power plants and transport facilities in the mining industry requires the development of equipment to control the leakage of hydrogen from storage elements and fuel supply to the engines. The solution to the problem of monitoring hydrogen leaks from fuel tanks of mining vehicles and power equipment that ensures the operation of mining enterprises using Raman lidar is considered. It is shown that at a laser radiation wavelength of 532 nm it is possible to obtain the minimum time for measuring the hydrogen concentration in the air with a Raman lidar at a given sensing distance. It was found that lidar sensing from geostationary orbit at a laser radiation wavelength of 532 nm also provides the minimum measurement time for a given concentration of the hydrogen molecules under study.

1. Introduction

The mining industry consumes large amounts of energy in the course of its core activities, including exploration, extraction, transportation and processing. Fuel consumption is the main source of transportation costs in open-pit and underground mining. According to the International Council on Mining and Metals (ICMM), fuel costs can account for up to 32% of total energy consumption in mines. This means that for a large mining enterprise, the cost of diesel fuel can become a significant factor in the overall profitability of the company [1,2].

One of the problems associated with fossil fuel engines is the emissions of gases, including carbon oxides, hydrocarbons, particulate matter (soot) and nitrogen oxides, which directly affect the environment

[1–5].

Thus, the heavy consumption of diesel fuel is motivating the search for renewable energy alternatives that are consistent with reducing the environmental impact of using petroleum-derived fuels. Among the renewable energy opportunities, «Green Hydrogen» is hydrogen produced using renewable energy sources such as solar, wind or hydropower, and then stored, transported and used in fuel cells or internal combustion engines [6].

Hydrogen is considered the best candidate as an additive to diesel fuel, since it is a renewable source that meets the required characteristics of engines, for example, diesel-powered loading and delivery vehicles: PD-2D, PD-5A; PD-2G, improves productivity and also reduces carbon dioxide emissions. Adding hydrogen to diesel fuel in compression

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ignition engines increases the engine’s fuel efficiency and significantly reduces emissions of carbon dioxide (CO₂), nitrogen oxides (NO_x) and particulate matter. Additionally, the addition of hydrogen also improved engine performance by increasing power and torque. This is caused by the higher flame propagation speed of hydrogen compared to diesel fuel [7].

Using hydrogen in vehicles is safe and in many ways safer than gasoline and diesel. This is because hydrogen is 14 times lighter than air and therefore dissipates quickly if it leaks, thereby reducing the risk of fire (unlike gasoline and diesel). The most promising application of hydrogen is electric transport using fuel cells. In this case, the efficiency of hydrogen use is approximately two to three times higher than that of vehicles with an internal combustion engine using conventional fuel. In addition, transport using hydrogen has zero emissions of harmful substances, so the only emission is water vapor [8–10].

The International Energy Agency recently announced that clean hydrogen is currently experiencing «unprecedented political and business momentum». Numerous countries, including the world’s largest economies, have hydrogen energy policies and projects. In 2017, a group of the world’s leading energy, transport and industrial companies created the Hydrogen Council to bring together political and private stakeholders to promote hydrogen as a «key element of the energy transition» [11–13].

Hydrogen is now emerging as a viable means of decarbonizing hard-to-cut sectors such as road transport, where electrification alone may not be enough to achieve ambitious climate targets that will culminate in net-zero greenhouse gas emissions by mid-century [11–13].

The first experiments in the use of hydrogen in the energy sector date back to the beginning of the 19th century [14]. Some researchers of this issue believe that the first hydrogen engine appeared before the gasoline engine. Interest in hydrogen in the 19-th century and beyond was not only driven by energy, there are also other industrial applications, including mining.

In the mining industry, the use of hydrogen is possible to operate the engines of BELAZ 75710 series mining dump trucks.

The main advantage of alternative fuels is the reduced content of toxic components in engine exhaust gases compared to diesel fuel used in the mining industry. Of the possible alternative fuels, hydrogen is the most preferable, since its combustion produces environmentally friendly water vapor [15].

Currently, the following methods for producing hydrogen are used: methane conversion with water vapor; carbon gasification with water vapor; thermal decomposition of methane; electrolysis of water [14].

A. Meyer Stanley proposed using a fuel cell to produce pure hydrogen [16]. At the XXVI conference “Laser Information Technologies – 2018”, the authors of the article proposed introducing laser radiation into the reaction zone to increase the efficiency of the fuel cell [17].

When using hydrogen as fuel when operating mining dump trucks, they use hydrogen filling stations (HAFS), which is unsafe [15,18].

The use of hydrogen as a fuel to drive the engines of mining dump trucks, loading and delivery vehicles PD-2D, PD-5A; PD-2G and other mining equipment require the development of equipment to control its leakage from storage tanks and fuel supply systems to engines.

NOMENCLATURE

Abbreviations table	
ICMM	International Council on mining and Metals
RSS	Raman scattering
ADRYa-315 and ADRya-400	Diesel power plants
UBG-S-30 «Berkut»	Drilling rigs
cm ³	unit of volume in the CGS system, cubic centimeter
mJ	unit of measurement of work, energy and heat, 0,001J
kHz	unit of frequency of periodic processes (for example, oscillations), Hz, kHz = 1000Hz

(continued on next column)

(continued)

Nm	Nanometer, nm
Ns	Nanosecond, ns
letters of the latin alphabet	
F	Pulse repetition rate
n ₀	Number of photons
τ ₀	Laser radiation duration
ν ₀	Gaussian with a maximum at frequency
G ₀	Half-width
G _a	Half-width
G(z)	Geometric function of the lidar
n(ν, z)	Number of photons
N(z)	Concentration of hydrogen molecules
(ν ₀ – G ₀) to (ν _R – G _R)	Photon counting mode as an integral in the interval
dσ/Dω	Differential cross section for Raman scattering of light by hydrogen molecules
T	Time of measurement or signal accumulation
0 < G(z) < 1; N(z)	Concentration of hydrogen molecules
Z	Sensing distance
S ₀	Area of the telescope receiving aperture
Φ(ν)	Distribution function of laser radiation photons in the lasing line
α(ν ₀ , r) and α(ν _R , r)	Attenuation coefficients at the frequencies of laser radiation and Raman scattering of light by hydrogen molecules
A(ν)	Hardware function or spectral transmittance of the lidar receiving system
ν _R	Frequency
K _L	Lidar constant
ξ(ν _R)	Relative spectral sensitivity of the photodetector at frequency ν _R of Raman radiation
Nd-YAG	Laser with wavelengths of 355 and 532

2. Laser diagnostic methods for hydrogen leaks

In the air environment of mining enterprises, the concentration of hydrogen molecules is approximately equal to 1.345·10¹³ cm^{–3}, which poses a big problem for measuring their concentrations [19].

Currently, gas chromatography or spectrophotometry is used to measure hydrogen concentration in the atmosphere [19]. The disadvantage of the methods is their low performance, which complicates their use in open-pit mining of mineral deposits.

The methods for laser monitoring of hydrogen molecules in the atmosphere are based on the following optical phenomena: Rayleigh scattering, Raman scattering, Mie scattering on particles, fluorescence and absorption.

From the literature [19] it follows that the Mie scattering cross section can be so large that even a small number of molecules can produce a scattered radiation signal that completely overlaps the Rayleigh or Raman scattering signals. This property is used to detect low concentrations of hydrogen molecules.

The proposed monitoring system used the optical design of a Raman lidar [19], which is shown in Fig. 1.

Radiation from the third and second harmonics of an Nd-YAG laser with wavelengths of 355 and 532, a semiconductor laser with a wavelength of 405 nm, and two gas lasers with wavelengths of 377 and 510 nm with a pulse duration of 10 ns and pulse energies up to 1 mJ at a pulse repetition rate f up to 100 kHz [18,23,24].

The radiation from laser 8, as shown in Fig. 1, was directed along the axis of the receiving telescope perpendicular to the Earth’s surface. Raman radiation from hydrogen molecules in the backward direction was collected by a Newtonian telescope and focused by lens 9 on photodetector 3, the voltage from which U_l was recorded by a data acquisition board. Part of the laser radiation was directed by plate 5 to photodiode 7 to control the energy of the laser pulse.

We will characterize the lidar laser by the number of photons n₀ in a laser pulse of duration τ₀ sent into the atmosphere, and we will consider the laser generation line to be Gaussian with a maximum at frequency ν₀ and half-width G₀. Then the number of photons n(ν, z) of radiation from Raman scattering of light by hydrogen molecules with a

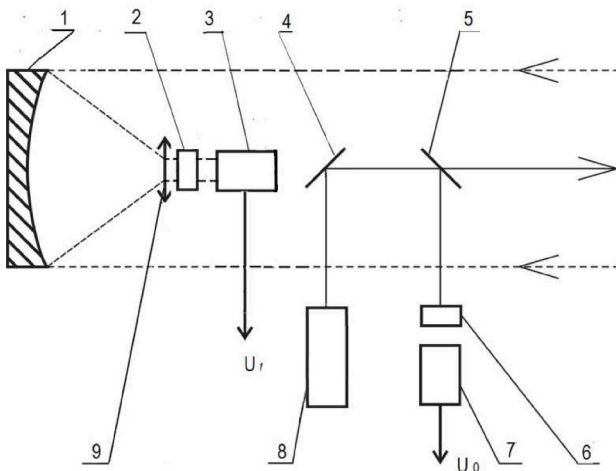


Fig. 1. RSS lidar: 1, 4 – mirror, 2, 6 – filters, 3 – photo receiver, 5 – glass plate, 7 – photodiode, 8 – laser, 9 – lens.

concentration $N(z)$ at the lidar photodetector can be obtained from the lidar equation in the backward direction in the photon counting mode in the form of an integral in the range from $(\nu_0 - G_0)$ to $(\nu_R - G_R)$ [20]:

$$n(\nu, z) = n_0 c \tau_1 G(z) f t S_0 N(z) \left(\frac{d\sigma}{d\Omega} \right) \int_{\nu_0 - G_0}^{\nu_R - G_R} T_0(\nu_0, z) \cdot T(\nu_R, z) \cdot \Phi(\nu) A(\nu) d\nu \Big/ 2z^2 \quad (1)$$

where $n(\nu, z)$ is the number of photons recorded by the lidar photodetector at the Raman frequency ν_R from the sensing distance z ; n_0 is the number of photons at frequency ν_0 of laser radiation; S_0 is the area of the telescope receiving aperture; $G(z)$ – geometric function of the lidar, which lies within the limits $0 < G(z) < 1$; $N(z)$ – concentration of hydrogen molecules; t – time of measurement or signal accumulation; $(d\sigma/d\Omega)$ – differential cross section for Raman scattering of light by hydrogen molecules.

Two factors in (1) – atmospheric transmission – are equal, respectively:

$$T_0(\nu_0, z) = \exp \left[- \int_0^z \alpha(\nu_0, r) dr \right] \text{ и } T(\nu_R, z) = \exp \left[- \int_0^z \alpha(\nu_R, r) dr \right],$$

where $\alpha(\nu_0, r)$ and $\alpha(\nu_R, r)$ are the attenuation coefficients at the frequencies of laser radiation and Raman scattering of light by hydrogen molecules.

Let $\Phi(\nu)$ be the distribution function of laser radiation photons in the lasing line, in our case, Gaussian. In addition, we will assume that the hardware function or spectral transmittance of the lidar receiving system $A(\nu)$ also has a Gaussian shape and is tuned exactly to the frequency ν_R of the Raman scattering band of hydrogen molecules with a half-width G_R , which is greater than G_0 , K_I – lidar constant at frequency ν_0 of laser radiation, measured experimentally in, and $\xi(\nu_R)$ is the relative spectral sensitivity of the photodetector at frequency ν_R of Raman radiation.

Then we rewrite equation (1) in the form:

$$n(\nu, z) = \frac{B}{z^2} N(z) t I(\nu, z). \quad (2)$$

In expression (2), the constant B is equal to:

$$B = \frac{c \tau_1}{2} S_0 f, \quad (3)$$

and some function $I(\nu, z)$, using the error integral [15], can be represented as:

$$I(\nu, z) = G(z) n_0 \left(\frac{d\sigma}{d\Omega} \right) \cdot 0.34 K_I \xi(\nu) T_0(\nu_0, z) \cdot T(\nu_R, z), \quad (4)$$

provided that $\Phi(\nu) = 1$, when the half-width of the generation line is much less than the half-width of the lidar instrumental function. We also believe that the differential cross section of Raman scattering of light can be considered constant within the frequency integration interval, as well as the attenuation coefficients at the frequencies of laser radiation and Raman scattering of light by hydrogen molecules [20].

$$t = \frac{n(\nu, z) z^2}{B I(\nu, z) N(z)} \quad (5)$$

Next, we will consider single Raman scattering (RSS) and a homogeneous atmosphere [18,21].

3. Results and discussion

The results of solving the problem of estimating the time of measuring the concentration of hydrogen molecules depending on the distance of sensing by a Raman lidar using the lidar equation (1) are

shown in Figs. 2 and 3.

Using the third and second harmonics of an Nd-YAG laser with wavelengths of 355 and 532, a semiconductor laser with a wavelength of 405 nm and two gas lasers with wavelengths of 377 and 510 nm with pulse durations of 10 ns and pulse energies up to 1 mJ at repetition rates pulses f up to 100 kHz, we solve the problem of monitoring hydrogen leaks from a mining dump truck [21,22].

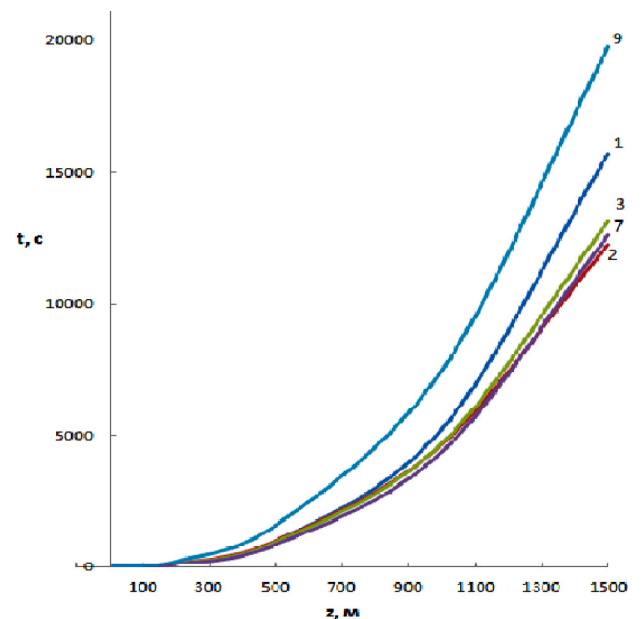


Fig. 2. Dependence of measurement time t , s, on ranging distance z , m, for wavelengths 355 (1), 532 (2), 405 (3), 377 (7) and 510 (9) nm.

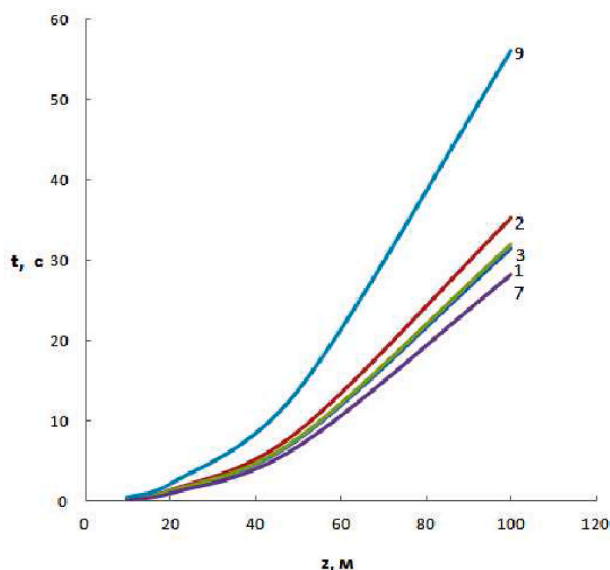


Fig. 3. Dependence of measurement time t , s, on ranging distance z , m, for wavelengths 355 (1), 532 (2), 405 (3), 377 (7) and 510 (9) nm and the same experimental condition.

The lidar equation (1) was solved under the assumption that the concentration of hydrogen molecules is $N(z) = 10^{13} \text{ cm}^{-3}$ and 200 photons will be recorded during the measurement time t .

The results of solving equation (1), presented in Fig. 2 show that at a laser wavelength of 532 nm it is possible to obtain the minimum time for measuring the hydrogen concentration in the air of mining enterprises using a Raman lidar.

When operating mining vehicles, for example, BELAZ 75710 series mining dump trucks, and power equipment - diesel power plants ADrya-315 and ADrya-400 when converting their engines to hydrogen fuel, it is of interest to probe hydrogen molecules in the air of the working area at distances of up to 100 m. For To achieve this, we will reduce the range of probing distances to 100 m and construct a graph in the form shown in Fig. 3, with the same laser wavelengths.

Analysis of Fig. 3 shows that lidar sensing by an unmanned aerial vehicle from a height of up to 100 m at a wavelength of 532 nm gives a minimum measurement time of 25 s for the concentration of hydrogen molecules of 10^{13} cm^{-3} in the atmosphere.

The use of hydrogen technology at mining enterprises will increase the level of scientific and technological development of both this industry and the entire country as a whole. This is indicated in the list of initiatives for the socio-economic development of the Russian Federation until 2030, approved by Government Order No. 2816-r dated October 6, 2021, where paragraphs 27 and 37 of Section V. Technological breakthrough note the need for the development of hydrogen energy and transport [23,24].

4. Conclusion

In the mining industry, the work system relies on equipment that consumes large amounts of energy. In mining operations, diesel equipment is widely used due to its flexibility, load capacity and adaptability to various terrain conditions. However, it has high diesel consumption and high greenhouse gas emissions, mainly carbon monoxide. Using hydrogen as a fuel not only offers the opportunity to decarbonize transportation and the mining industry, but also significantly reduces local air pollution. The list of possible objects for using the proposed

hydrogen technology includes: diesel power plants ADrya-315 and ADrya-400, providing energy to a small camp and drilling rigs; high-voltage diesel distillation stations, quarry excavators, UBG-S-30 «Berkut» drilling rigs, diesel-driven loading and delivery vehicles (PD-2D, PD-5A, PD-2G and others [25].

The use of hydrogen as a fuel to drive engines in power plants and transportation facilities in the mining industry requires the development of equipment to control hydrogen leakage from storage tanks and fuel supply systems to engines. Lasers are beginning to take leading positions in remote sensing of the air and production of hydrogen. It is shown that at a wavelength of 532 nm it is possible to obtain the minimum time for measuring the hydrogen concentration in the atmosphere with a Raman lidar at a given sensing distance. Lidar sensing from geostationary orbit at a wavelength of 532 nm also provides the minimum measurement time for a given concentration of the hydrogen molecules being studied.

The use of hydrogen technology at mining enterprises is facilitated by the order of the Government of the Russian Federation dated October 6, 2021 No. 2816-r, where in Section V. Technological breakthrough the need for the development of hydrogen energy and transport is noted.

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