BIOMEDICAL MEASUREMENTS AND DEVICES

METHOD FOR MONITORING THE FILL LEVEL OF AN INHALER RESERVOIR

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Abstract. This paper proposes an optical method for monitoring the fill level of an inhaler reservoir, based on the phenomenon of total internal reflection within a light guide. A detector design has been developed that enables the detection of the presence of working fluid (glycerine, propylene glycol, or their mixture) in various orientations of the inhaler. A theoretical analysis of the operational boundary conditions has been conducted, including calculations of light losses in the light guide depending on its material and surrounding medium. Additionally, a method for determining the critically low level of working fluid in the inhaler reservoir has been developed. The functionality of the proposed method has been experimentally validated. This approach can be applied in biomedical devices to enhance the safety and comfort of inhalation therapy.

Keywords: Inhaler, liquid fill monitoring, optical sensor, light guide, liquid detector

1. Introduction

Nowadays, various types of inhalers (nebulizers) are widely used in respiratory therapy to deliver active substances to the mucous membranes. These include ultrasonic, compressor, evaporative, and other types of devices.

In evaporative inhalers, the working fluid containing dissolved active substances is stored in a dedicated reservoir. At the bottom of this reservoir lies a cavity with a heating element, filled with a porous material—commonly referred to as a wick. The primary material used for the wick is organic cotton, which effectively absorbs liquid and ensures uniform delivery to the heating element. Other materials such as bamboo or cellulose may also be used, although they are less common than cotton. During operation, the working fluid enters the evaporation chamber and saturates the wick, where it is vaporized by the heating element. The resulting vapor exits the inhaler through a central channel in the reservoir.

For inhalers that generate aerosol mechanically (e.g., compressor or ultrasonic types), monitoring the fill level of the inhalation fluid is not critical, as the absence of liquid typically signals the end of the session. In contrast, evaporative inhalers pose a risk of wick overheating when the fluid is depleted, potentially releasing harmful or unpleasant byproducts into the respiratory tract. Therefore, detecting the presence of liquid is a vital functional requirement for such devices.

Numerous methods exist for monitoring liquid levels in containers, including mechanical (float sensors) [6], capacitive [7], ultrasonic [8], resistive [9], hydrostatic (pressure-based), optical, and others [10]. However, the operating conditions of inhalers—such as portability and temperature fluctuations—impose constraints on the choice of method. Additionally, miniaturization remains a significant challenge.

This paper focuses on the development of an optical method for monitoring the fill level of the working fluid in an inhaler reservoir.

2. Problem statement.

The evaporative inhaler is a compact, portable device (Fig. 1). Since it is not feasible to protect a mobile device from mechanical shocks or to ensure a fixed orientation during operation, the monitoring method must be insensitive to such factors. Additionally, due to the use of polymeric materials in the construction of the inhaler body and reservoir, the method must also be immune to electromagnetic interference.

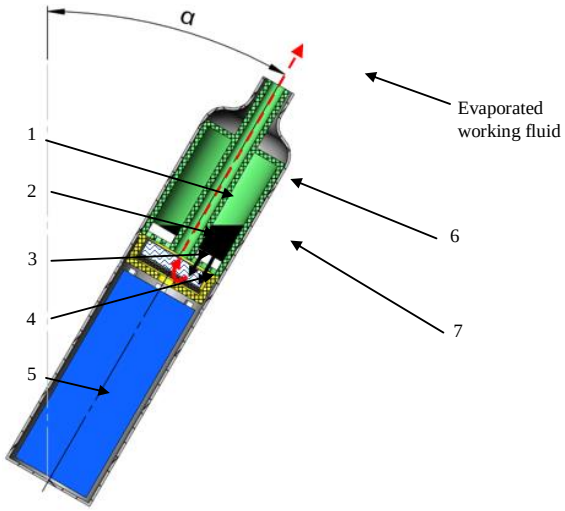


Fig. 1. Schematic diagram of the inhaler: 1 – Reservoir, 2 – Liquid detector, 3 – Wick, 4 – Heating element, 5 – Battery, 6 – Vapor outlet channel, 7 – Working fluid

During inhalation, the inhaler may be positioned at an angle α ranging from 0 to 90 degrees (Fig. 1). This condition is essential for setting operational boundary parameters in further analysis.

Therefore, to ensure safe use of the inhaler, continuous monitoring of the reservoir fill level is required, along with automatic deactivation of the heating element when the fluid level drops to a critical threshold.

The method for detecting the presence of liquid in the reservoir must be capable of operating across the full range of device orientations, even when only a small amount of fluid remains.

3. Method for monitoring the fill level of the inhaler reservoir.

Optical methods for monitoring liquid levels are based on changes in the direction, intensity, or other parameters of a light beam. These methods are classified into reflective and fiber-optic types. Reflective methods operate on the principle of an optical rangefinder [5] and are unsuitable for solving the given task, as the liquid's surface may be positioned at various angles relative to the reservoir's axis during operation, preventing accurate level determination. Fiber-optic monitoring methods are classified into those with continuous or discrete output signals (while remaining analog). Discrete methods can be implemented using grooves on the optical fiber [11], or air gaps within the fiber core [12] that is immersed in liquid. Essentially, this method is a direct analogue of a ruler placed inside a reservoir, where the grooves or air gaps serve as the ruler's divisions. These methods are also unsuitable for solving the given task due to the limitations described above. Fiber-optic methods with continuous output signals may be based on interference in multimode fiber [13], where the interference effect causes a change in the output signal depending on the length of the fiber segment immersed in the liquid, or on the disruption of total internal reflection at the surface of an uncoated optical fiber upon contact with the liquid. The method based on the disruption of total internal reflection is implemented by intertwining two multimode optical fibers, one of which carries the energy signal (light is transmitted through it), while the other carries the information signal. The information signal is generated as a result of mutual light penetration between the fibers, which occurs only along the segment of the fiber pair immersed in the liquid, due to light scattering outward upon contact with the liquid [14]. This method can also be implemented by shaping the cladding of a single-mode optical fiber into a D-shaped form, which leads to localized light losses along the immersed segment and attenuation of the output signal [15]. Another implementation of the method based on the disruption of total internal reflection in a lightguide is an optical prism that alters the direction of light beams in a dry state but ceases to function when wetted [5]. Sensors based on this method are used to detect maximum or minimum liquid levels in static containers, rather than mobile ones such as the inhaler reservoir.

Taking operational requirements into account, a combined optical method has been developed in which the sensitive element is a waveguide, but the operating principle is analogous to that of a prism. To implement this method, an optical detector is proposed, with a conceptual design shown in Fig. 2.

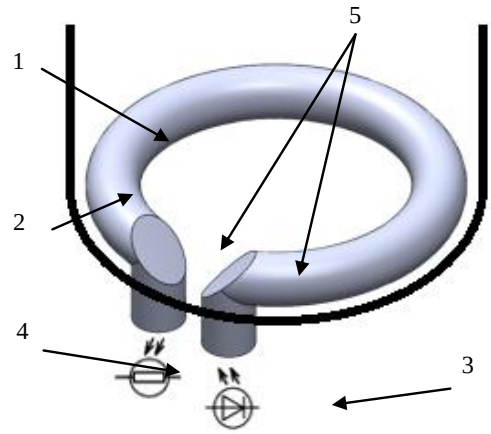


Fig. 2. Detector Design: 1 – waveguide, 2 - reservoir, 3 – light source (LED), 4 – photodetector, 5 – reflective facets.

The method is based on the phenomenon of total internal reflection of light within the lightguide and its disruption upon contact with the working fluid. As long as the reservoir is filled and the lightguide is immersed in the liquid, light is scattered at the bend of the toroidal lightguide and does not reach the detector. In the absence of liquid, light beams pass through the waveguide, allowing the detector to receive a signal that indicates the reservoir has been emptied.

Glycerin, propylene glycol, or their mixture are used as the working fluid in the inhaler. The physical properties of these liquids under normal conditions are presented in Table 1 [1].

Table 1. Physical Properties of Inhaler Liquids.

Working Fluids	Density, g/cm^3	Refractive index, n^D
Glycerin	1.261	1.4735
Propylene glycol	1.036	1.4323

Common materials for waveguides include polycarbonate and plexiglass. Their optical and mechanical properties are presented in Table 2.

It should be noted that no droplets should remain on the lightguide after the liquid in the reservoir is depleted, as residual fluid may form a film on the lightguide surface and promote light scattering, resulting in a false signal indicating that the reservoir is full. Table 2 shows that lightguide materials exhibit moderate oleophilic properties, as their contact angles fall within the range of 0–90°. On one hand, such values indicate the wettability characteristics; on the other hand, the greater the contact angle, the lower the adhesion work, which is the ability of droplets to remain on the surface [4]. Additionally, the lightguide surface is convex, and the liquid level decreases gradually, which discourages droplet formation. Therefore, considering these factors, the formation of a film or droplets on the lightguide surface is not expected.

Table 2. Optical and Mechanical Properties of Lightguide Materials.

Lightguide Material	Refractive index, n^D	* Critical angle, n_2-air, Θ_{cr}^{air}, (°)	*Critical angle, n_2-glycerin, Θ_{cr}^{gl}, (°)	* Critical angle, n_2- propylene glycol, Θ_{cr}^{pg}, (°)	**Wetting angle, glycerin, Θ_{gl}^{w}, (°)	**Wetting angle, propylene glycol, Θ_{pg}^{w}, (°)
Polycarbonate (PC)	1.59	39.0	67.9	64.3	59.0	59.0
Polymethyl methacrylate (Plexiglass) (PMMA)	1.49	42.2	81.5	74.0	63.8	63.3

* The critical angles Θ_{cr}^{air}, Θ_{cr}^{gl} та Θ_{cr}^{pg} were calculated using Snell's law.
** The contact angles for the material pairs were calculated using Young's law [3].

4. Operational boundary conditions.

Depending on the reservoir's fill level and the operating orientation of the inhaler, the following boundary conditions can be identified:

4.1. The reservoir is full, and the inhaler is in a vertical position (α = 0o, Fig. 3)

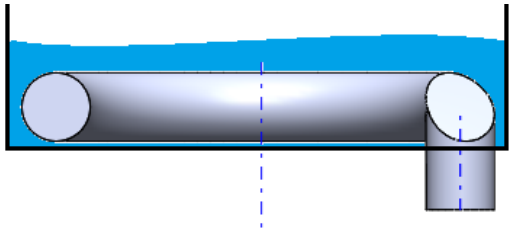


Fig. 3. Full reservoir.

Full or significant immersion of the detector in the working fluid disrupts total internal reflection in the lightguide, causing light rays to scatter and resulting in a minimal output signal.

4.2. The reservoir is empty, and the inhaler is in a vertical position (α = 0o, Fig. 4)

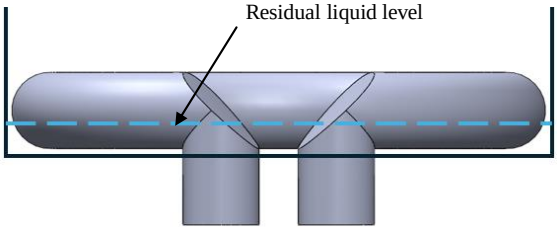


Fig. 4. Empty reservoir, vertical position of the inhaler.

Since the inhaler reservoir is a cylinder with a height significantly greater than its diameter (Fig. 1), the critical volume of residual liquid at the detector's sensitivity threshold is larger when the inhaler is positioned horizontally (α=90°, Fig.1). In other words, the area of the lightguide surface immersed in the liquid is smaller when the inhaler is positioned horizontally rather than vertically, assuming the same volume of residual liquid. Therefore, in the vertical position, the operating conditions are less critical compared to the horizontal orientation and do not require further consideration.

4.3. The reservoir is empty, the inhaler is in a horizontal position (α = 90°, Fig. 5), with the lightguide outputs facing upward (worst-case scenario).

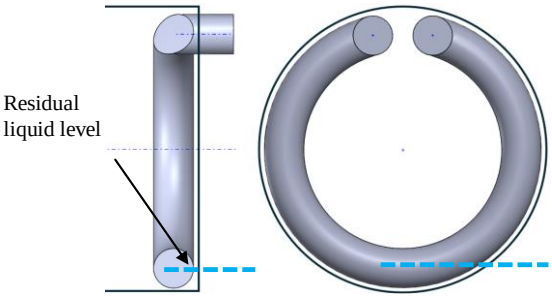


Fig. 5. Empty reservoir, horizontal position of the inhaler.

The residual liquid level must be sufficient to ensure that the immersed section of the lightguide causes adequate scattering of light rays.

5. Determination of lightguide losses when immersed in air and liquid.

To enable quantitative evaluation, we define the structural parameters of the detector as follows: the radius of the lightguide, denoted by a = 0.75 mm, and the torus radius, denoted by R = 8 mm (Fig.6).

To verify the optimality of the lightguide radius and its compliance with the critical curvature radius (i.e., whether it meets the specified design parameters), we determine the numerical aperture [2]:

$$NA = \sqrt{n_1^2 - n_2^2}; \quad (1)$$

n_1, n_2 – the refractive indices of the lightguide and the external medium, respectively.

The numerical apertures for the proposed material combinations are presented in Table 3.

Table 3. Numerical aperture for material combinations.

$n_1 \setminus n_2$	Air	Glycerin	Propylene glycol
Polycarbonate (PC)	1.24	0.597	0.69
Plexiglass (PMMA)	1.10	0.22	0.41

Critical bend radius of the optical fiber:

$$R_c = \frac{a}{NA^2}; \quad (2)$$

a – lightguide radius, NA – numerical aperture.

The critical bend radius of the lightguide in air and working fluids is presented in Table 4.

Table 4. Critical bend radius of the lightguide, Rc (mm).

$n_1 \setminus n_2$	Air	Glycerin	Propylene glycol
Polycarbonate (PC)	0.49	2.1	1.6
Plexiglass (PMMA)	0.61	15.3	4.4

In the material combination “plexiglass–glycerin,” the critical bend radius already exceeds the design-defined threshold, which clearly indicates a violation of total internal reflection within the lightguide made of this material. For this combination, one should expect the maximum difference in optical signal between the filled and empty reservoir.

To account for the rapid increase in losses as the torus curvature radius approaches the critical radius, a verification step is introduced in the proposed method, in accordance with the loss calculation procedure [2]:

$$\frac{R}{R_c} > 8n_2^2; \quad (3)$$

R – structural curvature radius of the lightguide, R_c – critical bend radius, n_2 – refractive index of the surrounding medium.

The results of verifying Condition 3 within the inhaler’s structural constraints and for the proposed material combinations are presented in Table 5, where “+” indicates the condition is satisfied, and “–” indicates it is not.

Table 5. Results of Condition 3 verification

$n_1 \setminus n_2$	Air	Glycerin	Propylene glycol
Polycarbonate (PC)	+	-	-
Plexiglass (PMMA)	+	-	-

Thus, the optical fiber does not function as a lightguide when immersed in working fluids of any type, and therefore transmits a significantly attenuated signal.

Losses in the lightguide operating in air are determined using the expression for macrobending losses in optical fiber [2]:

$$\alpha_R = 10lg\left\{(n_1^2 - n_2^2)/\left(n_1^2 - \left(\frac{\rho+1}{\rho-1}\right)^2 n_2^2\right)\right\}; \quad (4)$$

where ρ is the normalized bend radius.

$$\rho = \frac{R}{2a}; \quad (5)$$

For the lightguide made of polycarbonate, α_R =5.9 дБ, and for polymethyl methacrylate (plexiglass), α_R =11.6 дБ.

6. Geometric method for determining the critical level of residual liquid.

Let us consider a lightguide that is not in contact with liquid (i.e., the case of an empty inhaler reservoir). A beam of rays from the light source strikes the inner wall of the lightguide at an angle exceeding the critical angle, resulting in total internal reflection (see Fig. 6). If the light spot from this beam falls on a section of the lightguide immersed in liquid, the rays will exit the guide and fail to reach the photodetector, leading to a reduction in output signal compared to the “dry” lightguide. The minimum liquid level sufficient to cover this spot defines the critical level of residual liquid.

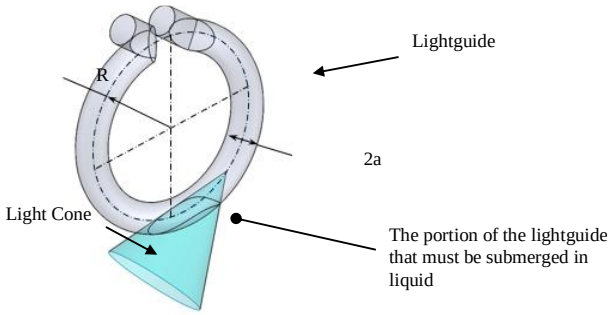


Fig. 6. Beam of light rays in the lightguide.

The proposed method enables determination of the height h of the lightguide segment (see Fig. 7) on which the light beam from the source is incident. The beam consists of rays that strike the wall of the lightguide at an angle equal to or greater than the critical angle Θ_{cr}^{air} for the air medium (Table 2). The liquid must cover this portion of the lightguide in order to disrupt total internal reflection. The ray path is analyzed based on the projection that has the greatest impact on the output signal level.

Thus, the method for determining the residual liquid level consists of the following steps:

1. Verify whether the angle φ is not less than the critical angle:

$$\varphi = sin^{-1}\left(\frac{R-a}{R+a}\right) \geq \theta_{кр}; \quad (6)$$

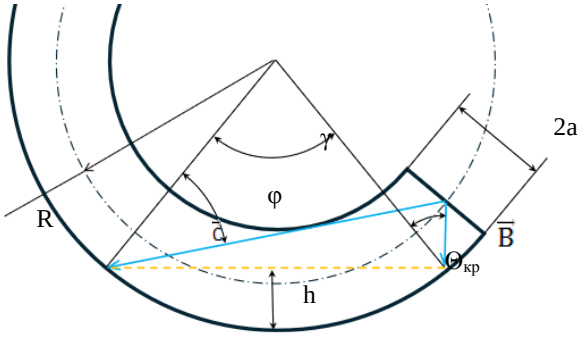


Fig. 7. Ray path diagram: R – structural radius of the central axis of the toroidal lightguide, a – radius of the lightguide, $\vec{B}$, $\vec{C}$ – boundary rays of the light beam, h – height of the segment on which rays $\vec{B}$ and $\vec{C}$, φ – angle of incidence of ray $\vec{C}$, γ – central angle of the segment. The angle of incidence of ray $\vec{C}$ is assumed to be equal to the critical angle $\Theta_{кр}$.

If the condition is not satisfied, the angle φ is set equal to the critical angle $\theta_{кр}$. For the suggested structural dimensions, φ = 56°, , which exceeds θ_{cr}^{air} (see Table 2).

2. The height h of the segment is calculated using the following expression:

$$h = (R + a)\left(1 - \cos\frac{\gamma}{2}\right); \quad (7)$$

where the central angle γ is given by:

$$\gamma = \theta_{кр} + \pi - \sin^{-1}\left(\frac{R+a}{R}\sin\theta_{кр}\right) - \sin^{-1}\left(\frac{R-a}{R}\right) - \varphi; \quad (8)$$

The values of h and the central angle γ are presented in Table 6.

Table 6. Values of angle γ and segment height h.

	γ°	h, mm
Polycarbonate (PC)	54.5	0.97
Plexiglass (PMMA)	53.9	0.95

The calculated height h of the lightguide segment defines the critical level of working fluid in the reservoir and represents the threshold immersion depth at which the inhaler reservoir is still considered filled. Any further drop in the fluid level will reduce the submerged area of the lightguide and increase the number of light rays reaching the photodetector, thereby triggering a signal indicating reservoir depletion.

7. Experimental validation of the method.

The aim of the experiment was to validate the operability of the developed method, specifically: to record changes in the output optical signal level during immersion of the lightguide into the working fluid; to verify the assumption that the primary contribution to the output signal is made by rays propagating in the projection shown in Fig. 7; and to assess the sensitivity of the method.

7.1. Materials and Equipment.

- Optical radiation source – LED.
- Lightguide – polycarbonate rod, diameter 3.0 mm, length 1 m.
- Photodetector – smartphone optical sensor. Sensor model: TCS3701, operating range: 0–60000 lux.
- Virtual laboratory – mobile application Phyphox. The app provides direct access to smartphone sensors, including proximity and ambient light sensors.
- Food-grade glycerin.

7.2. Setup Description.

The experimental setup is shown in Fig. 8a and Fig. 8b.

7.3. Experimental Procedure.

The experiment is conducted under normal conditions. The procedure is as follows:

1) Fill the tray with the working fluid
2) Immerse the bent section of the lightguide, which represents a toroidal liquid detector, into the tray
3) Switch on the light source
4) Launch the virtual laboratory on the smartphone and close the light-shielding cover
5) Lift up the mounting panel with the lightguide until the lightguide appears above the fluid level. This step simulates reservoir depletion, where the detector is no longer in contact with the liquid
6) Re-immerse the lightguide to its previous level. This step ensures repeatability of measurements
7) Stop the virtual laboratory and switch off the light source

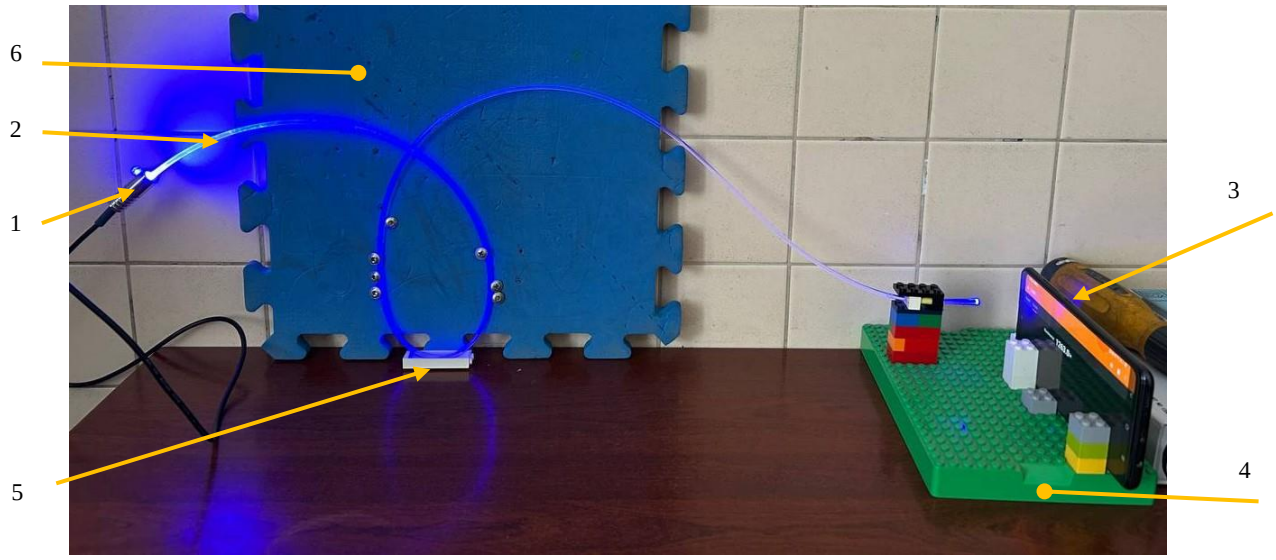
1.1 Data Analysis.

Fig. 9 shows the photodetector illumination intensity graph.

The graph clearly reflects the stages of the experiment: from 0 to approximately 30 seconds, the lightguide is immersed in liquid; from 30 to 85 seconds, the lightguide is “dry,” simulating an empty inhaler reservoir; starting at the 85th second, the lightguide is re-immersed in the fluid tray.

The experimental results confirm the operability of the method and allow for several important conclusions:

- The signal amplitude change between the depleted and filled reservoir states reaches 600 lux (30%), indicating sufficient sensitivity of the method
- The drainage of residual fluid droplets occurs rapidly enough to ensure timely shutdown of the inhaler and protection against overheating.



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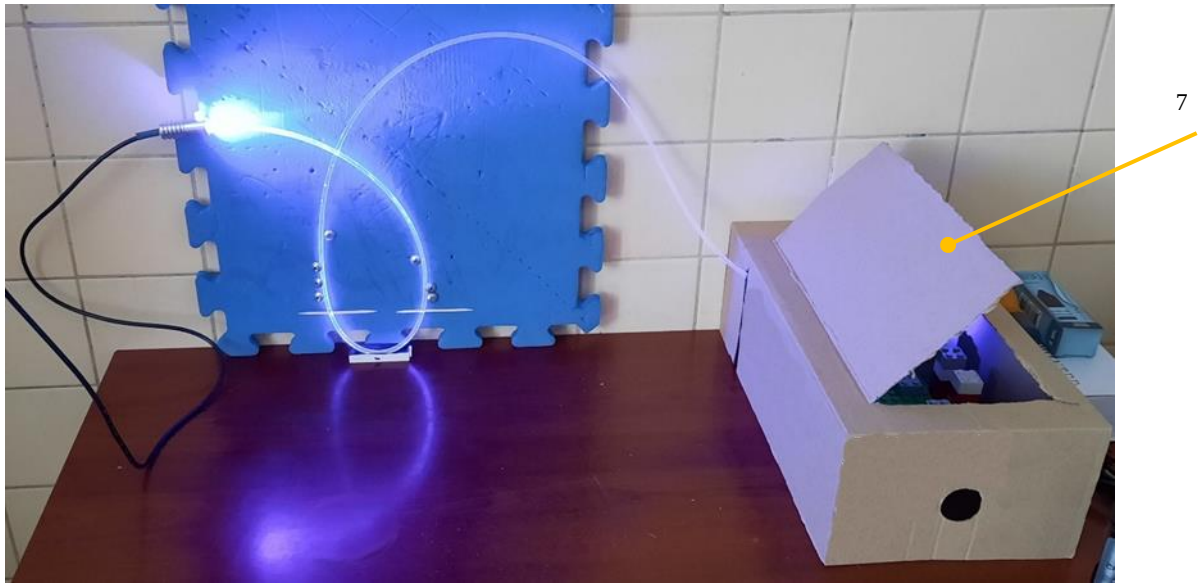

b

Fig. 8. Experimental setup: 1 - light source, 2 – lightguide, 3 – photodetector, 4 – base frame, 5 – tray for working fluid, 6 – lightguide mounting panel, 7 – light shield of the photodetector.

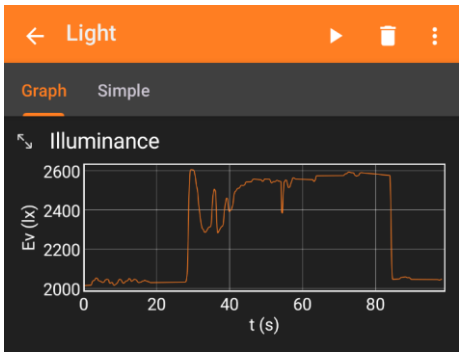

Fig. 9. Output signal graph

8. Conclusion

The liquid detector, implemented as a toroidal lightguide made of polycarbonate or plexiglass, transmits an optical signal when it is either fully or partially not immersed in the working fluid – glycerin or propylene glycol. The resulting optical signal of a specific level serves as an indicator of inhaler reservoir depletion. Equation 7 enables calculation of the minimum residual liquid level under the limiting operating condition described in Section 4.3. Fulfilment of other boundary conditions depends on the reservoir volume and is subject to technical design.

The conducted experiment confirmed the operability of the method. The observed sensitivity supports its practical use.

The upgraded inhaler is an intelligent biomedical device and can be used in respiratory therapy.

Conflict of Interest

The authors declare that there are no financial or other potential conflicts of interest related to this work.

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