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Fiber optic sensor design and prototyping for humidity detection in biogas reactors

Biyogaz reaktörlerinde nem tespiti için fiber optik sensör tasarımı ve prototip çalışması

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Fiber Optic Sensor Design and Prototyping for Humidity Detection in Biogas Reactors

Highlights

- ❖ To show the superiority of fiber optic sensors in harsh working conditions.
- ❖ Fast and safe detection of water vapor caused by increased humidity in biogas reactors.
- ❖ Occupational safety is ensured with the remote sensing system.
- ❖ Suitable for measuring different physical parameters in similar environments.

Graphical Abstract

A fiber-optic water vapor and condensation sensor was designed and implemented for biogas reactors. It enabled the detection of water due to water vapor and condensation that will occur with the increase of humidity level.

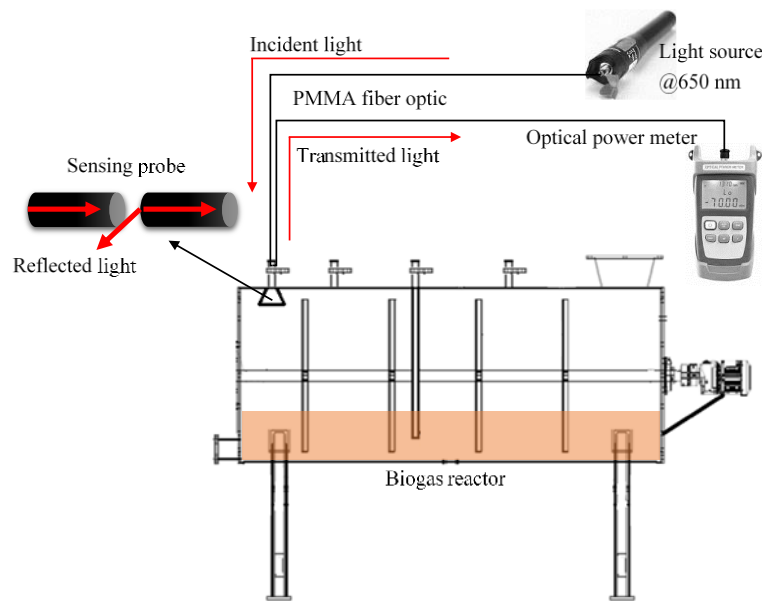


Figure. Experimental setup.

Aim

Quickly and safely detecting humidity in biogas reactors.

Design & Methodology

The fiber input signal is modulated by combining the effects of fiber loss mechanisms, depending on the medium refractive index.

Originality

This study is based on humidity detection with a fiber optic sensor for the first time in biogas reactors.

Findings

In the sensor design, it has been observed that multiple loss mechanisms such as reflection losses and longitudinal alignment losses influence the sensor performance.

Conclusion

With the fiber optic sensor, the refractive index's change due to the water vapor formation in the biogas reactor was successfully detected.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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(This study was presented at FCE'21 conference.)

Araştırma Makalesi / Research Article

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ABSTRACT

In biogas reactors, it is vital to monitor the condensation of water vapor with increasing humidity. The use of fiber optic-based sensors that allow this control to be done online quickly and reliably facilitates the process. In this study, a fiber-optic water vapor and condensation sensor was designed and implemented for biogas reactors. It enables the detection of water due to water vapor and condensation that will increase humidity level based on the combination of fiber reflection losses and longitudinal alignment losses. By creating a very low-cost sensor mechanism that can react quickly and is not affected by environmental variables other than the parameter to be detected, the increasing water vapor and the initial moment of the condensation can be detected with high precision and speed.

Keywords: Fiber optic humidity sensor, biogas reactor, Fresnel reflection loss, plastic optical fiber.

Biyogaz Reaktörlerinde Nem Tespiti İçin Fiber Optik Sensör Tasarımı ve Prototip Çalışması

ÖZ

Biyogaz reaktörlerinde, artan nem ile su buharının yoğunlaşmasının izlenmesi hayati önem taşır. Bu kontrolün çevrimiçi olarak hızlı ve güvenilir bir şekilde yapılmasına izin veren fiber optik tabanlı sensörlerin kullanılması, süreci kolaylaştırır. Buna göre bu çalışmada, biyogaz reaktörleri için fiber optik su buharı ve yoğunlaşma sensörü tasarlanmış ve uygulaması yapılmıştır. Fiber yansıma ve boyuna hizalama kayıplarına bağlı olarak nem seviyesinin artması ile oluşacak su buharı ve yoğunlaşması algılanabilmiştir. Hızlı tepki verebilen ve tespit edilecek parametre dışındaki çevresel değişkenlerden etkilenmeyen çok düşük maliyetli bir sensör mekanizması oluşturularak, artan su buharı ve yoğunlaşmanın başlangıç anı yüksek hassasiyet ve hızla tespit edilebileceği gösterilmiştir.

Anahtar Kelimeler: Fiber optik nem sensörü, biyogaz reaktörü, Fresnel yansıma kaybı, plastik optik fiber.

1. INTRODUCTION

Humidity measurement plays a vital role in improving production conditions and preventing high water vapor and condensation problems. Humidity measurement is required in many applications in all physical or chemical processes such as the food industry, civil engineering, aviation, air conditioning, electronic processing. Therefore, it is essential to develop a fast-reacting low-cost humidity sensor [1]. It is also vital for biogas reactors to perceive and interpret processes such as the degree of humidity, which is an important physical parameter, and the condensation of water vapors due to its increase under appropriate conditions. Compared to conventional electrical-based sensors, fiber optic-based sensors measuring different physical parameters such as humidity and condensation in systems operating under severe physical conditions such as biogas reactors provides advantages in many ways. Other prominent

features of fiber optic sensors include real-time monitoring, fast response, temperature endurance, stability, sensitivity, and remote access.

Furthermore, since light does not carry an electrical charge, it is immune to electromagnetic fields. Thus, they should be used as potential detectors flammable and explosive environments such as biogas reactors. It is easy to transmit the signal over long distances and to be combined with semiconductor materials. Because of these advantages, fiber optic sensors are more reliable and safer in most cases. Fiber optic sensors benefit conventional sensors, such as the use area's width and ability to carry the perceived signal through an electrically insulating medium [2]. Fiber optic sensors offer a completely passive (dielectric) property that is often vital in prospering medicine applications, including patients' electrical isolation, eliminating conductive paths in high-voltage environments, and easing adaptation to existing materials. These devices' light and small dimensions are critical in aviation and provide significant advantages to many products. Contrary to

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what is thought, conventional electrical sensors have units that increase the cost, weight, and size. Fiber optic sensors perform well in severe conditions, including environmental ruggedness, high-temperature operation, and variations that can withstand shock levels and extreme vibration. Perfecting these features are large bandwidth and high sensitivity, easy connection to sensor arrays, and the ability to carry the data obtained. Many fiber optic-based humidity sensors have been developed in the literature. Among these, structures using different film types as sensing elements [3-6], designs based on Fabry-Perot interferometer [7-9], systems based on surface plasmon resonance principle [10], fiber Bragg gratings-based studies [11] can be counted. Although most of the studies measure the humidity in the assemblies created in the laboratory environment, no such sensor mechanism has been found for biogas reactors.

Absolutely oxygen in the fermentor (production tank-digester) should not be found. There must be sufficient nitrogen for the creation and growth of new bacteria in the environment. Acidity in the production tank should be between pH=7.0-7.6. The fermentor temperature should be kept constant at 38°C. No light should enter the production tank, and the environment should be dark. There should be a minimum of 50% and optimum 90% water in the production tank. Therefore, the control and measurement of humidity in the environment are of vital importance. It has been observed that any glare and ignition negligence is more unthinkable, so it is crucial to make these measurements with fiber optic sensors.

In this study, a fiber-optic water vapor and condensation sensor was designed and implemented for biogas reactors. It enabled the detection of water due to water vapor and condensation to occur depending on the humidity level based on the combination of fiber reflection losses and longitudinal alignment losses. By creating a very low-cost sensor mechanism that can react quickly and is not affected by environmental variables other than the parameter to be detected, increased water vapor and the initial moment of condensation were detected with high precision and speed.

2. MATERIAL and METHOD

This chapter focuses on the system theory based on the combination of fiber reflection losses and longitudinal alignment losses. It then proceeds with the creation of the detection zone.

Undesirable fiber optic losses in telecommunications can be converted into sensor mechanisms using them in a controlled manner to create fiber optic sensors. When two fibers are added together from these losses, all the first fiber's power cannot be transferred to the second fiber due to coupling errors. Coupling losses in these connections can occur due to various reasons. These can be said as Fresnel reflection losses and fiber alignment losses. Alignment losses consist of three situations: longitudinal, lateral, and angular misalignment. In Figure

1, part of the power coming from the first fiber can be reflected, and the remaining part can only be guided in the second fiber. With the amount of loss due to reflection, defining the reflection coefficient formed at the fiber-air-fiber interfaces is necessary. This value is given in Equation (1) [12].

$$R = \frac{P_{\text{reflection}}}{P_{\text{incident}}} = \left(\frac{n_1 - n_0}{n_1 + n_0} \right)^2 \quad (1)$$

Where P_{incident} and $P_{\text{reflection}}$ show incident and reflected optical powers, respectively. n_1 and n_0 represent the refractive index values of the fiber core and the external environment, respectively. Accordingly, there is a relationship between the incoming and passing power as follows.

$$P_{\text{transmitted}} = (1 - R) \times P_{\text{incident}} \quad (2)$$

The total reflection loss is given by Equation (3) in L_R dB [13].

$$L_R = -10 \log(1 - R)^2 \quad (3)$$

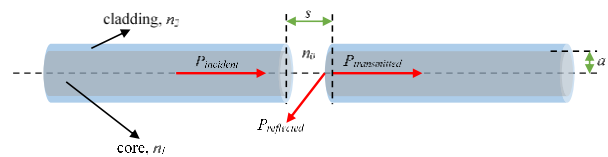


Figure 1. Fresnel reflection and longitudinal misalignment losses.

As in Figure 1, the coupling loss (attenuation) due to longitudinal misalignment in the fiber assembly with a gap of s between them, L_M is calculated from [14],

$$L_M = -10 \log \left(1 - \frac{s \times NA}{3 \times n_0 \times a} \right) \quad (4)$$

where a is the core radius of the fiber, and NA is the numerical aperture value of the fiber, and NA value can be calculated with Equation (5) [15]. In Equation (5), n_2 indicates the refractive index of the fiber cladding.

$$NA = \sqrt{n_1^2 - n_2^2} \quad (5)$$

The total amount of loss is given in dB as follows.

$$L_T = L_R + \\ = -10 \log(1 - R)^2 - 10 \log \left(1 - \frac{s \times NA}{3 \times n_0 \times a} \right) \quad (6)$$

When Equation (6) is simplified,

$$L_T = -10 \log \left[(1 - R)^2 \times \left(1 - \frac{s \times NA}{3 \times n_0 \times t} \right) \right] \quad (7)$$

it is obtained in the form. For example, a typical PMMA plastic optical fiber has a value of $n_f=1.492$, $NA=0.5$, and $a=490 \mu\text{m}$. When a gap length of $s=2 \text{ mm}$ is selected, Fresnel Reflection Loss (L_R), Lateral Misalignment Loss (L_M), and Total Insertion Loss (L_T) values according to the refractive index value of the medium are given in (a), (b), and (c) in Figure 2, respectively.

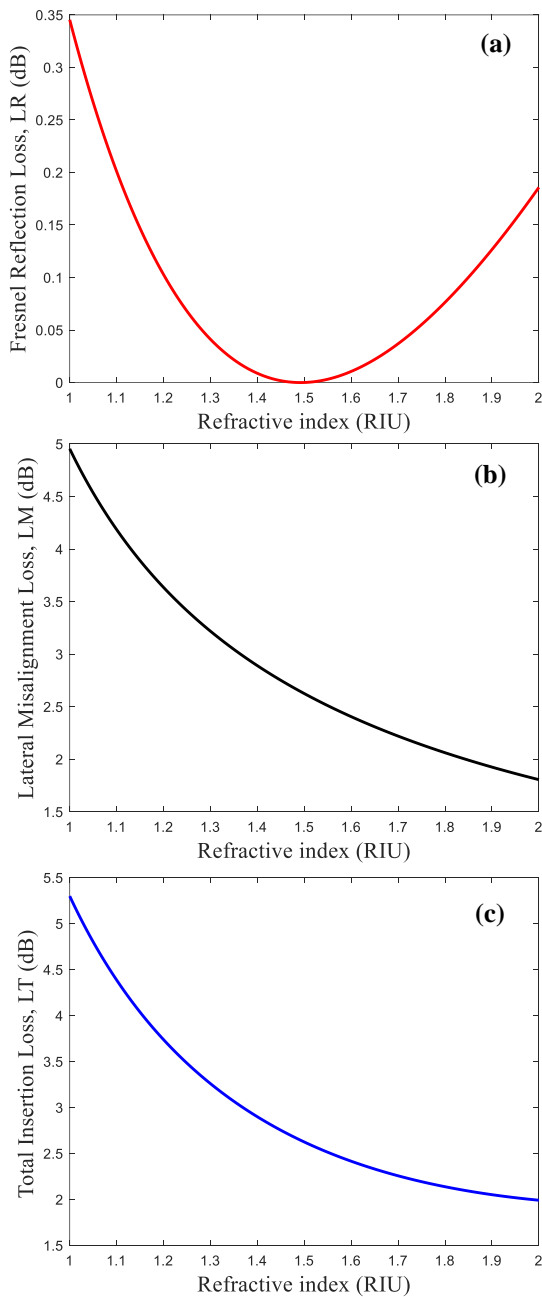


Figure 2. (a) L_R , (b) L_M , and (c) L_T versus refractive index of the medium.

As shown in Figure 2, the losses decrease depending on the refractive index value increasing according to the humidity, water vapor, and water formation in the environment. The decrease in losses means an increase in the optical power at the sensor output.

3. EXPERIMENTAL SETUP

Figure 3 shows a schematic representation of the fiber optic sensor system with the biogas reactor's main parts. The description of the main components is given in Table 1.

Table 1. Description of the main parts of the biogas reactor.

No	Explanation
1	Fertilizer mixer motor that can work back and forth in the biogas reactor.
2	Biogas reactor manure loading door.
3	Biogas discharge outlet valve on the biogas reactor.
4	PH and ammonia measurement probe inlet valve on biogas reactor.
5	Biogas sampling pipe valve on the biogas reactor.
6	Waste discharge valve inside the biogas reactor.
7	PH and ammonia measurement probe in the biogas reactor.
8	Manure mixer shaft and connected apparatus.
9	Biogas reactor legs.
10	Fiber optic sensor measuring probe inlet valve.
11	Fiber optic humidity sensor measurement tip inside biogas reactor.
12	PH and ammonia measurement probe inlet valve on biogas reactor.

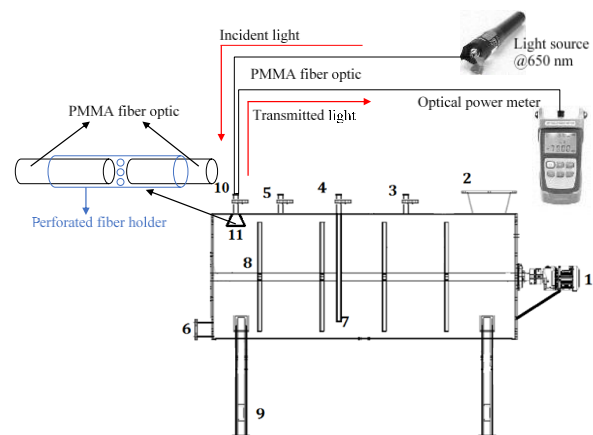


Figure 3. Biogas reactor main parts with fiber optic sensor probe.

FDPF4002EH 1mm Polymer Fiber in 2.2 mm PE Jacket is used as fiber optic cable. The gap length between the two polished fibers is fixed at 2 mm. The core radius of the fibers is 980 µm. Typical Attenuation @ 650 nm 0.14dB/m. It has operational temperature values of -40 to +75°C. The optical source is an LED that produces visible red light at 650 nm wavelength. Finally, an optical power meter was used to measure the optical power at the output.

4. RESULTS and DISCUSSION

Simultaneous measurement results during biogas production are shown in Figure 4. Accordingly, coupling losses are reduced due to water droplets' formation due to humidity, water vapor, and condensation in the reactor's air gap, respectively. Because the environment where the sensor probe interacts at the beginning is air (n₀=1), humidity increases during production and creates water vapor and water droplets. This situation is also compatible with the effect of index matching gels added to eliminate fiber coupling losses. The relationship between fiber losses and input/output power,

$$L_T = 10 \log \left(\frac{P_{incident}}{P_{transmitted}} \right) \quad (8)$$

it is given by [14]. From Equation (8), the output power is finally obtained as in Equation (9).

$$P_{transmitted} = P_{incident} \times 10 \quad (9)$$

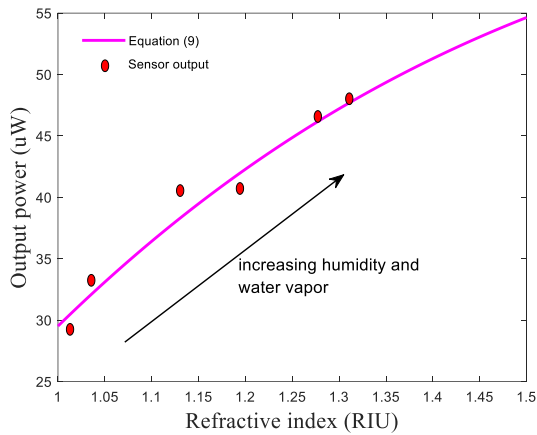


Figure 4. Sensor output power according to the refractive index change (When the input power is 100 µW).

The groups of bacteria named fermentative and hydrolytic bacteria break down carbohydrates, proteins, and fats. They are the three essential elements of organic matter. They convert CO₂, acetic acid, most of them into soluble volatile organic substances. The main component contributing to moisture, water vapor, condensation, and in-tank moisture is water added to organic waste for anaerobic fermentation. The power transmitted to the second fiber in the presence of humidity air between the two aligned fibers forming the measurement zone has been described in detail in the Golnabi study [16]. The

data obtained according to the repeated measurement results have been shown in Figure 5.

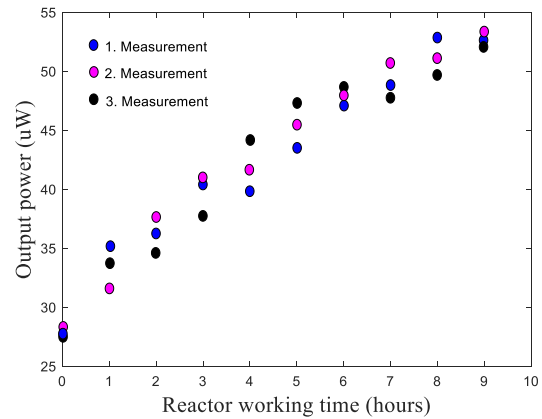


Figure 5. Repeated measurement results.

Since the outside of the biogas reactor is insulated, there is no interaction with the environment outside the reactor. Anaerobic fermentation takes place in an oxygen-free environment. Therefore, the temperature inside the reactor has been kept constant at 38°C for the survival and efficient operation of mesophilic bacteria. Since there is anaerobic fermentation in the reactor, there is no temperature change in the environment. The data obtained from an experimental study with a humidity meter by taking the average of the repeated measurement results are shown in Figure 6 by comparing them. The values of the relative humidity meter used to determine the amount of humidity in the reactor, accuracy is ± 2%, measurement range 0-100% RH, response time 4 s, repeatability ± 0.1% RH, discrimination is 0.1% RH, probe operating temperature is from -40 to +120° C.

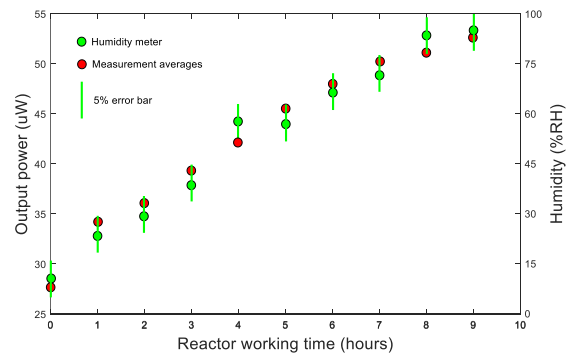


Figure 6. Comparison of humidity meter results with the average fiber optic measurement results (with %5 error bar).

Experimental measurements are related to the refractive index. Humidity change in the biogas reactor is also a crucial parameter and does not interact with the environment outside the reactor. Since anaerobic fermentation must occur in an oxygen-free environment, the environment outside the reactor is not affected by humidity and temperature changes.

5. CONCLUSION

Fiber optic sensors are manufactured to remain robust in areas with an abrasive material or excessive moisture and are resistant to electrical noise. Also, they contain no electrical circuits or moving parts to work safely in biomass power plants, which is a flammable and explosive environment. Humidity and water vapor detection system formed with PMMA based plastic optical fiber has been applied to biogas reactors. The experimental verification of the high sensitivity and fast response sensor has been performed. In this direction, the process of water vapor in the reactor increasing and converting to water droplets during biogas production has been determined. Based on fiber reflection and alignment losses, an equation is obtained that gives the relationship between output power and losses. It was seen that the results obtained from the equation and the sensor output were compatible.

ACKNOWLEDGEMENT

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DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Murat ŞAHİN: Prepared the experimental setup of the biogas reactor and performed the experiments.

Şekip Esat HAYBER: Performed the experiments, analyse the results, and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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