

CO₂ Thermal Conductivity Detection in Gas Mixture for Concentration Measurement Using Bridge Configuration of Thermopiles

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Abstract

In this research, improvisation was carried out by modifying the market IR thermopile which functions as a thermal conductivity detector to measure the concentration of CO₂ gas in the gas mixture. Four thermopiles are configured with a Wheatstone bridge with the aim of increasing the accuracy of the measurement system in detecting changes in CO₂ concentration in the gas mixture (N₂ and CO₂). Using the bridge configuration of these four thermopiles, this measurement system can measure changes in CO₂ concentration in small orders. The sensor developed is easy to manufacture, low cost, and has high linearity as evidenced by a correlation coefficient of 0.9943. From the experiments carried out, the sensor works quite accurately in detecting CO₂ concentrations with the sensor's sensitivity of -88.19 Volt/%, the detection range is 0% to 100%, and the RMS error value is 2.25.

Keywords

Thermopile, Bridge Configuration, Thermal Conductivity Detector, CO₂ Concentration

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1. INTRODUCTION

CO₂ is a molecule composed of two oxygen atoms bonded to a carbon atom, which has a molecular weight of 44 grams/mol. Depending on temperature and pressure, CO₂ can be solid, liquid, or gaseous (Ansarizadeh et al., 2015). Several sources of CO₂ production, including; Natural sources: respiration and decomposition of animals and plants, fire, and volcanic activity; Anthropogenic sources: combustion of fossil fuels, industrial activities such as the cement industry and the ammonia industry, processing of natural gas, etc. (US EPA, 2014). Humans indirectly produce CO₂, where all human activities release 70 million tonnes of CO₂ into the atmosphere daily (Driessen, 2013).

CO₂ has been widely used in various aspects of human life, such as CO₂ use for fire extinguishers, pneumatic applications (Binions and Naik, 2013), laser (Oh and Kim, 2012), important reagents in the manufacture of many products, and carbonated drinks (Zosel et al., 2011). CO₂ concentration is one parameter that is widely used in various fields, such as controlling air quality (Kaneyasu et al., 2000; Daisey et al., 2003), and used to reduce energy consumption in heating, ventilation, and air con-

ditioning (HVAC) system (Apte, 2006), controlling industrial processes (Trapp et al., 1998), health diagnostics, and analysis in the field of chemistry (Zhang et al., 2010).

On the other hand, CO₂ concentrations are increasing due to human activities, such as hydrocarbon combustion, industrial processes (Zosel et al., 2011), and carbon-containing fuels (Binions and Naik, 2013). CO₂ is also produced by volcanic activity, where volcanic gases usually contain 10-40% CO₂. Therefore monitoring of CO₂ concentrations produced by volcanic activity can help find out the signs of a volcano, earthquake, or tsunami (Liu et al., 2010).

The demand for CO₂ sensors is always increasing, where CO₂ sensors are expected to be low cost, small in dimension, sensitive, and have reliable performance (Wetchakun et al., 2011; De Luca et al., 2017). There are several methods used by CO₂ gas sensors, such as infrared method, electrochemical method, mass spectrometer, and gas chromatography. These four methods have their advantages and disadvantages. The IR method has several advantages from the four methods, such as high sensitivity, good selectivity, and fast response. The disadvantage of the EC method cannot be used in an explosive

and flammable environment because it requires a large amount of power, while the disadvantages of the GC and MS methods are production costs which are expensive and require a longer working time (Febrina et al., 2019).

In this study, thermopile functions as a thermal conductivity detector to determine the concentration of CO₂ in a gas mixture. The thermal conductivity detection method which is usually called TC sensor has particular advantages such as detecting gas concentrations up to 100% for gases having a thermal conductivity different from the reference gas used (Deng, 2013). Thermopile is an electronic device to convert heat energy into electrical energy. Thermopile consists of several thermocouples that are connected normally in series or, in parallel (Randjelovic et al., 2002; Houlet et al., 2008). Thermocouples' work is based on the Seebeck effect principle, where the output voltage depends on the temperature difference between the thermocouple junction and the reference junction (Lee and Kester, 2016).

Thermopile is usually used as an IR sensor used to measure surface temperature (Schmidt and Schieferdecker, 2003). At present, a thermopile is used in various applications, including spectrometers, remote temperatures (Xu et al., 2017), gas sensors (Liess, 2015), medical applications, household appliances (Schilz, 2001), automation applications, and IR sensors in food processing and farming (Graf et al., 2007).

Thermopile has advantages including thermopile is not affected by ambient temperature, broad spectral response, and easy to operate (Xu et al., 2017). Another advantage of the thermopile is that the thermopile does not have to be chopped or cooled, so it can reduce the complexity of the system. Therefore, the thermopile can be used as a solution to the needs of miniaturized, economical, and efficient electronic components (Graf et al., 2007).

In this study, the thermal conductivity detector is made of four commercial IR thermopiles that have been modified by removing the IR window so that the thermopiles can be directly exposed to the test gas. Modified thermopiles are configured in a bridge configuration to increase the linearity of the sensor so that it can detect changes in CO₂ concentration more accurately. The AC current heats thermopiles and the exposed gas cool the thermopile simultaneously. Based on the principle of work, the thermopile will detect the difference in temperature in the measurement system. The thermal conductivity value of the gas will affect the temperature difference detected by the thermopile, and the concentration of CO₂ gas in the mixture also influences the thermal conductivity value of the gas mixture detected by the thermopile. This principle is used as the basis for developing gas sensors using thermopiles.

The measurement system consists of two aluminum tubes that are a reference gas (N₂) and a gas mixture (N₂ and CO₂). The reference gas and the gas mixture flowed into the aluminum tube at the same time. When the gas passes through the aluminum tube, the thermopile will detect the thermal conductivity of the gas. For different concentrations, the output voltage of the thermopile is also different which is proportional

to the value of the thermal conductivity of the gas. Therefore, this measurement system can determine the concentration of CO₂ gas.

2. DESIGN OF THE SENSOR

The sensor developed was built using two aluminum tubes that are thermally connected, so that the two tubes have the same conditions. One of the tubes is used to drain the carrier gas were in this study using N₂ gas, and the other tube is used to drain the gas mixing device (by using a mixture of N₂ and CO₂). The gas mixing device is specially made for mixing N₂ and CO₂ gases. The gas mixing device is made of acrylic (1 cm thickness) with dimensions of 25×40×10 cm. The maximum pressure that this gas mixing device can hold is 1.2 bar pressure.

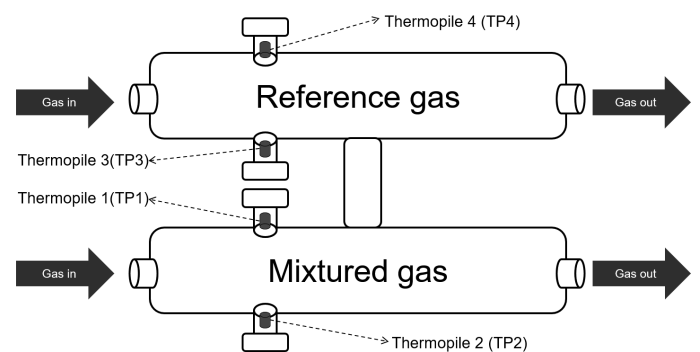


Figure 1. Design of the Sensor

The aluminum tube used has a length of 40 cm and a diameter of 2 cm. The design of the sensors developed can be seen in Figure 1. Thermopile TPiD 1T 0622B was modified by removing its IR window. The carrier gas (N₂) and the gas mixture (CO₂ and N₂) flow with a constant flow rate of 0.2 L/min to the sensor, which is controlled by a flow meter. The carrier gas is detected by two thermopiles arranged in parallel on the tube as well as the gas mixture is detected by two further thermopiles. The four thermopiles are configured in bridge configuration so that the final output voltage of this system is the voltage difference between the thermopile that detects the carrier gas (N₂) and the thermopile that captures the gas mixture (CO₂ and N₂). The output voltage of the sensor system is measured with a digital voltmeter.

3. MEASUREMENT MODEL

Thermopile is a device consisting of many pairs of thermocouples installed in series, and a thermocouple consists of two metals with different Seebeck coefficients (Randjelovic et al., 2002). The thermopile output voltage that has N thermocouple pairs can be written as follows (Weckmann, 1997):

$$V = N\alpha_r\Delta T \quad (1)$$

with N is the pair of thermocouple on the thermopile, α_r is

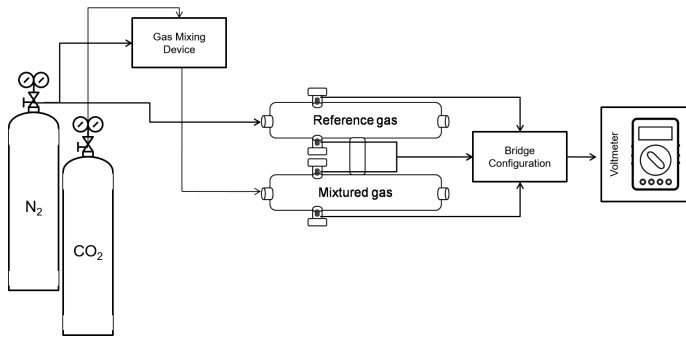


Figure 2. Mechanical Setup for Measuring CO₂ Gas Concentration in Gas Mixture

the thermopile Seebeck coefficient, and ΔT is the temperature difference detected by the thermopile.

The temperature difference (ΔT) is obtained from the thermal conductivity value detected by the thermopile, as defined:

$$\Delta T = \frac{P_e}{K} (1 - e^{-\frac{K}{C}t}), \tag{2}$$

where $\frac{C}{K} = \tau$ (thermal time constant), $K = \frac{A\lambda}{L}$, in which K is thermal contact ($\frac{W}{K}$), λ is thermal conductivity ($\frac{W}{mK}$), A is the contact area, L is the length of contact, P_e is the radiation energy absorbed by thermopile, and C is heat capacity of the thermopile (J/K), and by substituting Equation (2) to Equation (1), the thermopile output voltage can be written:

$$V = N\alpha_r\Delta T = N\alpha_r\frac{P_e}{K}(1 - e^{-\frac{K}{C}t}) = N\alpha_r\frac{P_eL}{A\lambda}(1 - e^{-\frac{K}{C}t}) \tag{3}$$

In this study, CO₂ detection was carried out by using four thermopiles that were electronically connected. The four thermopiles are configured with a bridge configuration such as Figure 3. The use of this bridge configuration aims to measure the difference in voltage produced by the thermopile that detects carrier gas (N₂) and thermopile which detects gas mixtures (N₂ and CO₂).

The output from this configuration can be calculated using Kirchoff's Law (Alexander et al., 2021). From Equation (4) can be said that the sensor output voltage is proportional to the voltage difference from the thermopile that detects the carrier gas with thermopile which detects the gas mixture.

$$\Sigma E = 0$$

$$E_3 + IR_3 + E_4 + IR_4 + IR_2 - E_2 + IR_1 - E_1 = 0$$

At points A and B, then

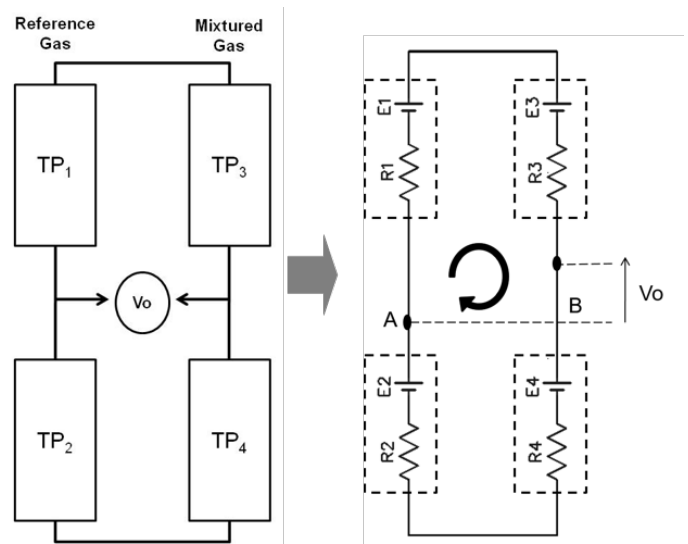


Figure 3. Electronic Model Using Four Thermopiles

$$V_0 = E_4 + IR_4 + IR_2 - E_2$$

$$V_0 = I(R_4 + R_2) + (E_4 - E_2)$$

$$V_0 = I(R_4 + R_2) \cdot \Sigma E$$

$$V_0 \approx \Sigma E$$

(4)

4. EXPERIMENT RESULT AND DISCUSSION

Figure 4 shows the sensor response in the form of voltage changes due to changes in CO₂ gas concentration. The sensor has a linear response with a correlation coefficient of 0.9943. According to Equation (4) and Figure 3, the output voltage V_0 is proportional to the voltage difference ΣE (voltage difference between the two thermopiles), where the voltage difference between A and B will be proportional to $E_4 - E_2$, where E_2 is the voltage at thermopile-2 (thermopile which detects the reference gas), while E_4 is the voltage at thermopile-4 (thermopile which detects the gas mixture). In conditions where there is no gas flowing, there is a voltage difference value between E_2 and E_4 of 2.55 mV. Theoretically, the voltage difference in the initial bridge configuration is 0 (zero), assuming all the values of resistance are the same, but in this experiment, a voltage difference of 2.55 mV in the state of no gas, due to different values of resistance (resistance) in the fourth thermopile.

The thermal conductivity of CO₂ gas is 17.24 mW/mK, while the thermal conductivity of carrier gas (N₂) is 23.4 mW/mK. Based on Equation (3) the output voltage of the thermopile is inversely proportional to the value of the thermal conductivity of the gas. Increasing the concentration of CO₂ will cause the thermal conductivity of the gas mixture to decrease so that the thermopile output voltage that contacts this gas mixture (E_4) will rise.

The graph in Figure 4 is in accordance with the theory explained above (Equation (4)), where V_0 which is the difference

Table 1. The Experimental Data for Measuring the Sensor Output Voltage to Changes in the Concentration of Five Experiments

CO ₂ Concentration (%)	The Output Sensor (mV)					Standard Deviation (×10 ⁻³)
	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	
0.00	2.550	2.552	2.551	2.553	2.552	1.14
9.09	2.432	2.433	2.435	2.436	2.434	1.58
18.18	2.379	2.378	2.381	2.384	2.386	3.36
27.27	2.278	2.277	2.276	2.275	2.275	1.30
36.36	2.159	2.156	2.158	2.156	2.155	1.64
45.45	2.081	2.078	2.082	2.081	2.082	1.64
54.55	1.990	1.992	1.992	1.993	1.989	1.64
63.64	1.850	1.853	1.850	1.853	1.853	1.64
72.73	1.713	1.715	1.716	1.715	1.717	1.48
81.82	1.601	1.604	1.599	1.597	1.603	2.86
100.00	1.453	1.454	1.450	1.454	1.453	1.64

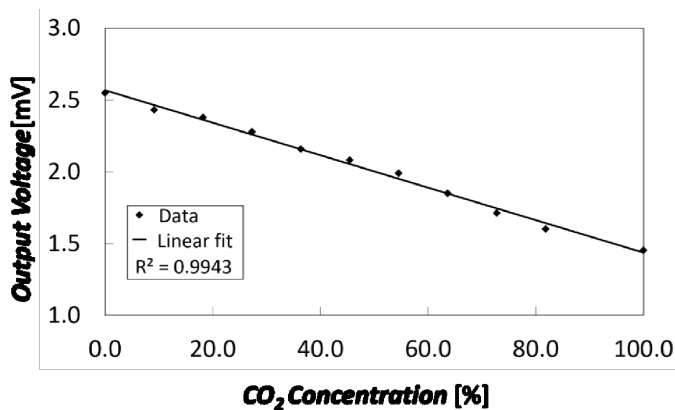


Figure 4. The Experimental Data for Measuring Changes in CO₂ Concentration to the Sensor Output Voltage

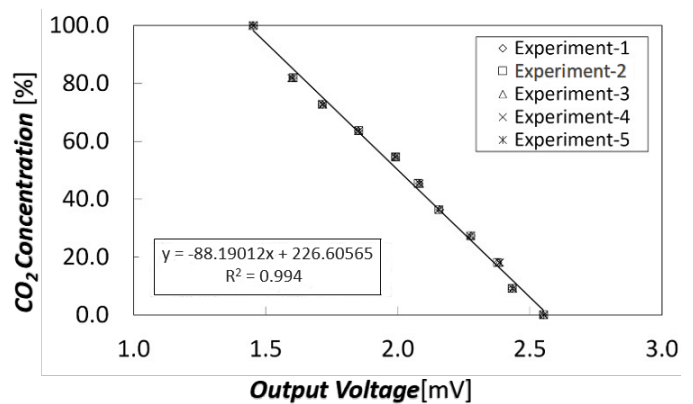


Figure 5. The Inverse Function of the Relationship Between Input and Output Sensor Measurements with the Thermal Conductivity Method

in voltage E_2 and E_4 decreases with increasing concentration. Because of E_4 increases due to the decreased thermal conductivity of the gas mixture due to an increase in CO₂ concentration.

The sensor measurement results are validated by determining the inverse function between sensor input and output. The inverse function results from the comparison of the theoretically obtained CO₂ concentration value (inverse function) with the actual CO₂ concentration value. Figure 5 shows a plot of the inverse function of the test results.

Figure 5 shows the equation of the relationship between the output voltage of the sensor and the value of CO₂ concentration, can be written with the following equation,

$$\text{CO}_2 \text{ Concentration} = -88.19V_0 + 226.60 \quad (5)$$

From the validation results using Equation (5), the sensitivity of the sensor is -88.19 V/%, where with a 1% change in CO₂ concentration, the sensor output voltage is reduced by 88.19

volts. The RMS error is 2.25, with the error value obtained, the built-in sensor can work well in detecting the concentration of CO₂ gas (Fraden, 1994).

The linearity of the system is quite high with a correlation coefficient of 0.9943. This proves that measuring the CO₂ concentration with four thermopiles gives more linear results than testing with one thermopile. This is due to the output of the sensor system that uses four thermopiles is the differential voltage to the change in concentration ($\frac{dV}{dC}$), whereas, in previous studies, the sensor output voltage is directly measured with the output voltage from the thermopile.

Figure 6 shows the percentage of sensor measurement error with the highest measurement error of 2.10% at 54.54% CO₂. The percent error range (δ) is -2.86% < δ < 2.10%.

Figure 7 and Table 1 show the stability and accuracy of the sensor that was developed, in which the experiments were carried out five times resulting in adjacent output values. From five experiments, the sensor standard deviation can be ob-

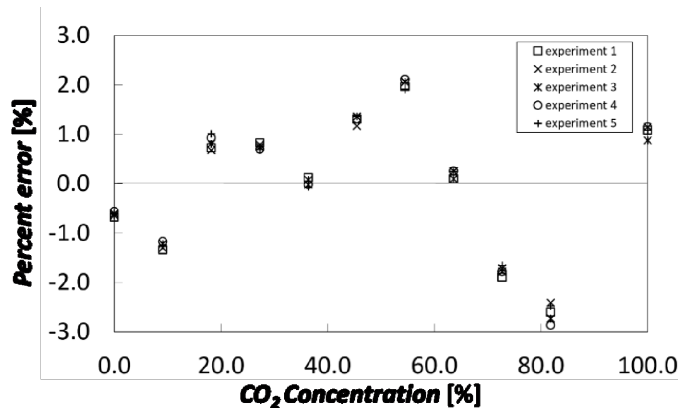


Figure 6. Percent Error from the Sensor Measurement

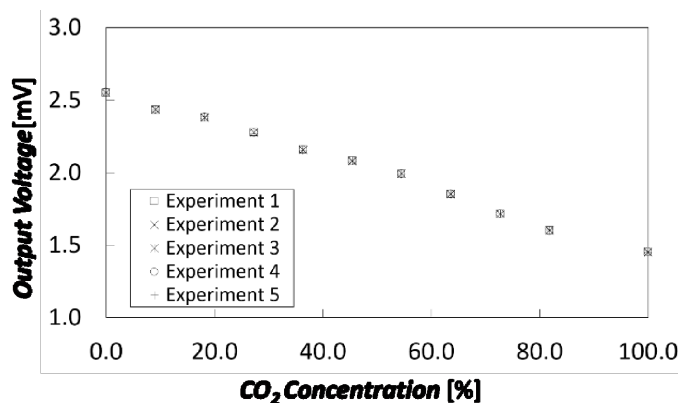


Figure 7. The Stability of Sensor Stability for Five Experiments

tained with a maximum standard deviation of 3.36×10^{-3} mV at 18.18% CO₂. From Table 1, the standard deviation value of the sensor measurement is below 3.36×10^{-3} mV, with this value the sensor can be said to have a good level of precision and stability.

5. CONCLUSION

We have successfully developed a sensor consisting of four commercial IR thermopiles as a thermal conductivity detector to determine the concentration of CO₂ gas in the gas mixture. Four thermopiles are configured in a bridge configuration, so that they can detect changes in CO₂ gas concentrations more accurately. The sensor that has been developed is easily manufactured, low cost, and has high linearity as evidenced by the correlation coefficient of 0.9943. From the experiments conducted, the sensor can detect CO₂ concentrations well from a concentration of 0% to 100% which is evidenced by the RMS error value of 2.25.

6. ACKNOWLEDGMENT

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REFERENCES

- Alexander, C. K., M. N. Sadiku, and M. Sadiku (2021). *Fundamentals of Electric Circuits 7th Edition*. McGraw-Hill Higher Education Boston
- Ansarizadeh, M., K. Dodds, O. Gurpinar, U. Kalfa, T. Ramakrishnan, N. Sacuta, and S. Whittaker (2015). Carbon Dioxide-Challenges and Opportunities. *Oilfield Review*, **27**(2); 36–50
- Apte, M. G. (2006). A Review of Demand Control Ventilation. *LBNL-60170 Report, Lawrence Berkeley National Laboratory, Berkeley, CA, USA*
- Binions, R. and A. Naik (2013). Metal Oxide Semiconductor Gas Sensors in Environmental Monitoring. *Semiconductor Gas Sensors*. Elsevier; 433–466
- Daisey, J. M., W. J. Angell, and M. G. Apte (2003). Indoor Air Quality, Ventilation and Health Symptoms in Schools: an Analysis of Existing Information. *Indoor Air*, **13**(1); 53–64
- De Luca, A., S. Z. Ali, R. Hopper, S. Boual, J. W. Gardner, and F. Udrea (2017). Filterless Non-Dispersive Infra-Red Gas Detection: a Proof of Concept. *2017 IEEE 30th International Conference on Micro Electro Mechanical Systems (MEMS)*; 1220–1223
- Deng, W. (2013). Thermal Conductivity Sensors in Automotive Applications. *Electronic Theses and Dissertations*
- Driessen, B. (2013). Carbon Dioxide: the Gas of Life. *Tiny Amounts of this Miracle Molecule Make Life on Earth Possible*. Washington, DC, USA: Committee for a Constructive Tomorrow (CFACT). 19p; 1–19
- Febrina, M., E. Satria, M. Djamil, W. Srigutomo, and M. Liess (2019). Development of a Simple CO₂ Sensor Based on the Thermal Conductivity Detection by a Thermopile. *Measurement*, **133**; 139–144
- Fraden, J. (1994). *Handbook of Modern Sensors*. Springer
- Graf, A., M. Arndt, M. Sauer, and G. Gerlach (2007). Review of Micromachined Thermopiles for Infrared Detection. *Measurement Science and Technology*, **18**(7); R59
- Houlet, L. F., W. Shin, K. Tajima, M. Nishibori, N. Izu, T. Itoh, and I. Matsubara (2008). Thermopile Sensor-Devices for the Catalytic Detection of Hydrogen Gas. *Sensors and Actuators B: Chemical*, **130**(1); 200–206
- Kaneyasu, K., K. Otsuka, Y. Setoguchi, S. Sonoda, T. Nakahara, I. Aso, and N. Nakagaichi (2000). A Carbon Dioxide Gas Sensor Based on Solid Electrolyte for Air Quality Control. *Sensors and Actuators B: Chemical*, **66**(1-3); 56–58
- Lee, R. and W. Kester (2016). Complete Gas Sensor Circuit Using Nondispersive Infrared (NDIR). *Analog Dialog*, **50**; 10–18
- Liess, M. (2015). A New Low-Cost hydrogen Sensor Build with a Thermopile IR Detector Adapted to Measure Thermal Conductivity. *Journal of Sensors and Sensor Systems*, **4**(2); 281–288
- Liu, Y., Y. Tang, N. N. Barashkov, I. S. Irgibaeva, J. W. Lam, R. Hu, D. Birimzhanova, Y. Yu, and B. Z. Tang (2010). Fluorescent Chemosensor for Detection and Quantitation of

- Carbon Dioxide Gas. *Journal of the American Chemical Society*, **132**(40); 13951–13953
- Oh, H. S. and J. S. Kim (2012). Clinical Application of CO₂ Laser. *CO₂ Laser-Optimisation and Application*. London: *IntechOpen*; 357–78
- Randjelovic, D., G. Kaltsas, Z. Lazic, and M. Popovic (2002). Multipurpose Thermal Sensor Based on Seebeck Effect. *2002 23rd International Conference on Microelectronics. Proceedings (Cat. No. 02TH8595)*, **1**; 261–264
- Schilz, J. D. (2001). Applications of Thermoelectric Infrared Sensors (Thermopiles)
- Schmidt, W. and J. Schieferdecker (2003). Understanding Thermopile Infrared Sensors. *Perkin Elmer*, **5**; 4–7
- Trapp, T., B. Ross, K. Cammann, E. Schirmer, and C. Berthold (1998). Development of a Coulometric CO₂ Gas Sensor. *Sensors and Actuators B: Chemical*, **50**(2); 97–103
- US EPA (2014). *Overview of Greenhouse Gases*. US Environmental Protection Agency
- Weckmann, S. (1997). Dynamic Electrothermal Model of a Sputtered Thermopile Thermal Radiation Detector for Earth Radiation Budget Applications. *Virginia Polytechnic Institute and State University*
- Wetchakun, K., T. Samerjai, N. Tamaekong, C. Liewhiran, C. Siriwong, V. Kruefu, A. Wisitsoraat, A. Tuantranont, and S. Phanichphant (2011). Semiconducting Metal Oxides as Sensors for Environmentally Hazardous Gases. *Sensors and Actuators B: Chemical*, **160**(1); 580–591
- Xu, D., Y. Wang, B. Xiong, and T. Li (2017). MEMS-Based Thermoelectric Infrared Sensors: a Review. *Frontiers of Mechanical Engineering*, **12**(4); 557–566
- Zhang, G., Y. Li, and Q. Li (2010). A Miniaturized Carbon Dioxide Gas Sensor Based on Infrared Absorption. *Optics and Lasers in Engineering*, **48**(12); 1206–1212
- Zosel, J., W. Oelßner, M. Decker, G. Gerlach, and U. Guth (2011). The Measurement of Dissolved and Gaseous Carbon Dioxide Concentration. *Measurement Science and Technology*, **22**(7); 072001