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Incident Angle Approach to Sensitivity Enhancement for Ozone Sensor

Michael David[1, a], Tay Ching En Marcus[1, b], Maslina Yaacob[1, 2, c], Mohd Rashidi Salim[1, d], Nabihah Hussin[1, e], Mohd Haniff Ibrahim[1,f], Sevia Mahdaliza Idrus[1, g], Nor Hafizah Ngajikin[1,h] and Asrul Izam Azmi[1, i]

[1]Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

[2]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussien Onn Malaysia, Parit Raja, 86400 Batu Pahat, Johor, Malaysia

[a]mdavid2@live.utm.my, [b]cemtay2@live.utm.my, [c]maslinay@uthm.edu.my, [d]rashidi@fke.utm.my, [e]hussin.nabihah@gmail.com, [f]hanif@fke.utm.my, [g]sevia@fke.utm.my [h]nhafizah@fke.utm.my, [i]asrul@fke.utm.my,

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Abstract. The design and mathematical model of a reflective type optical gas sensor is presented. Light source is radiated at an incident angle for 10 cm gas cell with an internal diameter of 0.4 cm. At an incident angle of 1^o, optical path length obtained is 342.7886 cm, at 27^o incident angle, optical path length is 10.4926 cm and at an incident angle of 28^o, optical path length is 9.9631 cm. The model is most efficient at lower incident angles, precisely between (1^o and 27^o). Effects of variation in diameter and length of gas cell are also demonstrated.

Introduction

In the design of ozone sensor, sensitivity is crucial and hence given due considerations as a performance metric [1-3]. Sensor sensitivity which is in one of the three main specifications for environmental monitoring devices [4] is defined as the minimum input that will generate a readable output change [5]. The safety limit that is recommended for ozone exposure is 0.075 ppm for a period of 8 hours per day [6], which indicates high sensor sensitivity requirements [7]. For an ozone sensor that is built on the principles of absorption spectroscopy, sensitivity (lowest detection limit) [8] of optical gas sensor is enhanced by increasing optical path length of sensor [3, 9-12]. Long absorption path yields higher sensitivity and low sensitivity is associated with short optical path length [13].

Theoretical Background

The mathematical expression for absorption spectroscopy known as Beer-Lambert law states that: if a radiated light intensity I_0 is directed at a sample of concentration c (mol cm^{-3}) in a path length, l (cm), and a radiation of intensity I_t leaves the sample then absorption, A [14]:

$$A = \log\frac{I_0}{I_t} = \varepsilon c l \;=\; \text{Optical density} \tag{1}$$

Where I_t and I_0 are light intensities (in counts) with and without sample respectively and ε (cm^2/mol) is absorption coefficient. The minimum concentration a sensor can measure largely depends upon absorption coefficient and optical path length. Referring to Eq. 1, we make c subject of equation as shown below [15]:

$$c = \frac{A}{\varepsilon l} = \frac{D}{\varepsilon l} \tag{2}$$

Where D is optical density or absorption, A. By increasing the value of denominator of Eq. 2, value of concentration of sample gas measured reduces and hence increasing sensitivity of sensor. i.e.: *when values of* ε*; or* l *is increased; value of c is reduced, which naturally implies decrease in lower detection limit or increased sensitivity[15].*

Methodology

In the conventional design of a transmission type optical sensor, beam of light is radiated parallel to gas cell as shown Fig. 1; hence a transmission type gas cell will have optical path length approximately equal to length of gas cell.

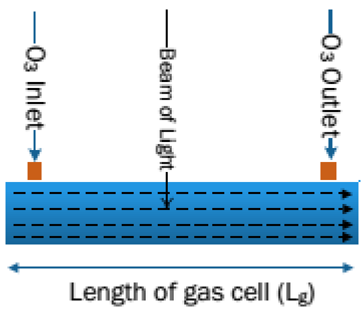

Fig 1: A conventional transmission type gas cell

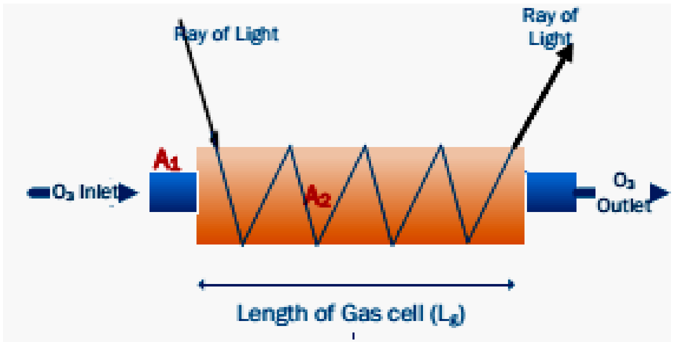

Fig 2: A Basic view of our proposed reflective type gas cell showing propagation of light at an incident angle

For our design, basic laws of reflection are explored which states that angle of reflection equals angle of incidence [16] in combination with factors that favour reduction of head loss in gas flow (sudden enlargement transition is considered) [13]; it is illustrated in Fig. 2. The said design is new and novel and to the best of our knowledge has not been reported in literature for sensing applications. In addition, spectralon with a reflectance that is above 99% in the spectral range between 350 nm to 1700 nm [17] is recommended to be used in coating internal surface of gas cell; and hence, gas cell is considered reflective with beams of light propagated into it at an incident angle. Sensor application will be in the visible spectrum for ozone gas measurement.

Mathematical Model and Design

The sudden enlargement fluid transition is adopted for gas cell design since the dimensions A_1 (gas inlet diameter in cm) and A_2 (internal diameter of the cell in cm) can be effectively chosen such

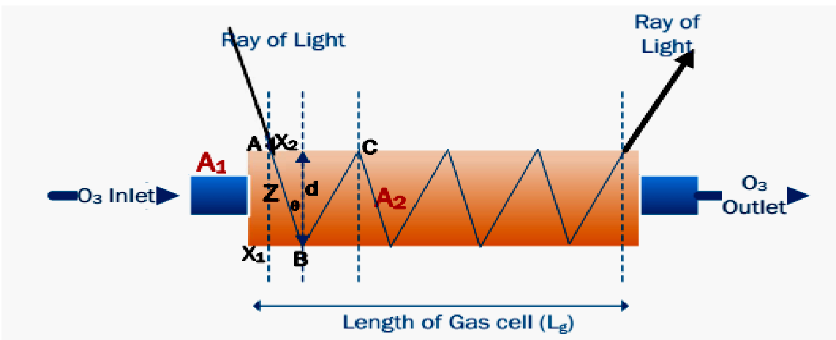

Fig 3: Gas cell diagram for the analysis of our model and design.

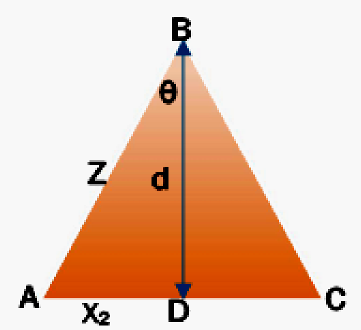

Fig 4: An extracted diagram : part of the ray propagation from fig. 3.

that pressure drop in fluid is minimised. In Fig. 3, for the purpose of our model, all dimension are considered to be in centimeters (cm). AB and BC are incident and reflected rays respectively with dimension Z (cm); d (cm) is diameter of gas cell, while X_1 (cm) is allowable distance between edge of gas cell and the placement of collimating lens for light propagation, X_2 is horizontal equivalent distance travelled by incident or reflected ray and θ^o is incident angle. With reference to Fig. 4; we obtain Eq. 3, 4, 5, 6, 7 and 8.

$$Cos\ \theta = \frac{d}{z} \tag{3}$$

$$Z = d \times \text{Cos}\ \theta \tag{4}$$

$$\tan\theta = \frac{x_2}{d} \tag{5}$$

$$x_2 = d \times \tan\theta \tag{6}$$

$$TotalNumberof\ X_2\ (N_{X_2}) = \frac{L_g - 2x_1}{X_2} \tag{7}$$

$$Optical\ path\ length\ (l) = Z \times N_{X_2} \tag{8}$$

Results and Discussions

Eq. 3 to 8 obtained above are used in computing results shown in Fig. 5, 6 7, and 8. X_1 is assumed to be 2 cm since diameter of a collimating lens is 0.9525 cm and to be able to make provision for tolerance. Fig. 5 shows relationship between incident angle and optical path length for a 10 cm gas cell with 0.4 cm internal diameter. 10 cm gas cell was chosen for initial test running of our model since a minimum of 4 cm tolerance is required to accommodate two collimating lenses.

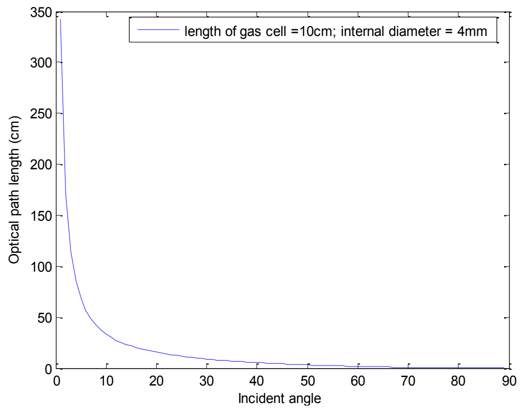

Fig 5: Optical path length at different angle of incidence

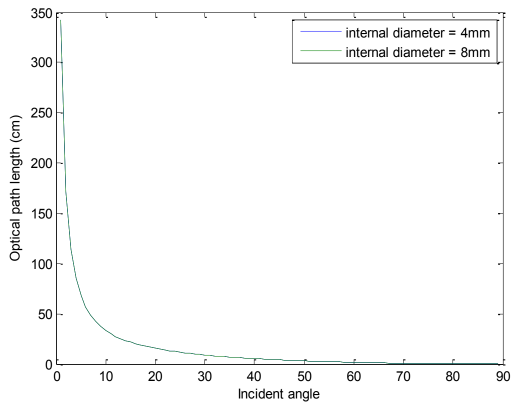

Fig 6: The effect of diameter of optical path length

At incident angle of 1°, optical path length obtained is 342.7886 cm, which is about 34 times the gas cell length. At an incident angle of 27°, optical path length is 10.4926 cm which is about 1.0493 times the length of gas cell. At 28°, optical path length is 9.9631 cm, which is 0.9963 times the length of gas cell. As incident angle increases, optical path length reduces and hence the incident

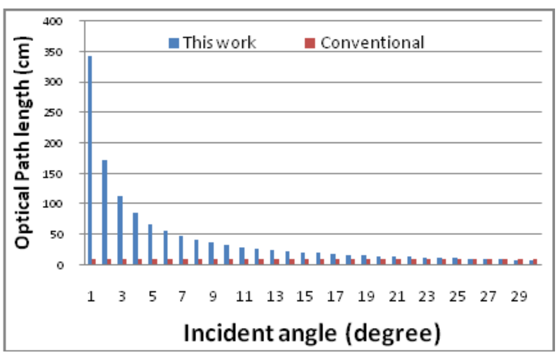

Fig 7. The dependence of optical path length on incident angle for 10 cm gas cell.

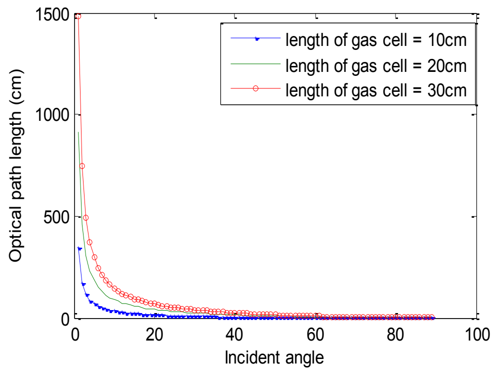

Fig 8. The effect of length variation on optical path length

angle approach is effective only at lower incident angles, precisely in between incident angles of 1^o and 27^o. In Fig.6, internal diameter variation has no effect on optical path. For the two different internal diameters considered, i.e. 0.4 cm and 0.8 cm, optical path length is the same at different values of incident angles.

Fig. 7 compares optical path length for two gas cells, one is the conventional transmission type gas cell and the other is based on our design. The comparison is done for 1^o to 30^o of incidence angle. Conventional transmission type gas cell has constant optical path of 10 cm; whereas, our design has optical path length 9.00 cm for 30^o to 342.7886 cm for 1^o. The effect of variation of length is demonstrated in Fig. 8. For the three different lengths considered (i.e. 10 cm, 20 cm, and 30 cm); at incident angle of 1^o, gas cells of length 10 cm, 20 cm and 30 cm yield optical path length 342.7886 cm, 914.1029 cm and 1485.4171 cm respectively. Similarly, at incident angle of 27^o, gas cells of length 10 cm, 20 cm and 30 cm give rise to optical path lengths 10.4926 cm, 27.9804 cm, and 45.4681cm respectively. Ratio of the optical path lengths at each incident angle for the three lengths of gas cell considered is 1:2.7:4.3. When length of gas cell is increased, optical path length becomes longer. This results in higher sensor sensitivity. The authors [7, 18, 19] accessed 0.05 ppm to 0.3 ppm of changes in ozone concentration by increasing length of reflective gas cell from 40 cm to 63 cm. Thus, result obtained in this work is validated.

Conclusions and Recommendations

The incident light approach in this design is effective only at incident angles between 1^o and 27^o. Within this range, optical path length is longer than effective gas cell length. Variation in internal diameter has no effect on optical path length; however, length of a gas cell is proportional to optical path length. For the 10 cm, 20 cm and 30 cm gas cells considered in this design, the optical path length ratio at any incident angle is 1:2.7:4.6. This shows that the longer the gas cell, the longer the optical path length and the higher the sensor sensitivity (lower detection limit). Use of spectralon to coat internal surface of gas cell for high reflectance, limits application of the sensor to visible spectrum of ozone measurement.

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