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Enhancement of the Response time of a Reflective Type Sensor for Ozone Measurements

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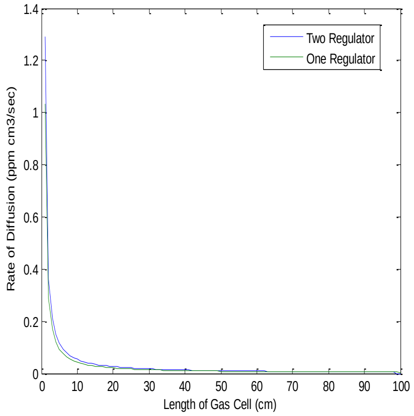
Graphical abstract



The effect of gas cell length on the
Rate of concentration.

Abstract

Sensor response time *T (90)* or speed of response is mathematically a function of the rate of diffusion of a gas sample in an absorption spectroscopic gas cell. Increasing the rate of diffusion increases the speed of response and vice versa. In this article, we present the design and analytical results on the response time of a reflective type ozone gas sensor. The variables of length and cross sectional area were interplayed to optimise the rate of diffusion. Two optical reflectors were employed in increasing the path length of the sensor; this resulted in the simultaneous reduction of the effective cell length and an increase in the diameter of the gas cell (cylindrical structure). Ozone diffusion in the 30 cm length of gas cell has been simulated to be 0.01713 ppm cm^3/secs in comparison to 0.01023 ppm cm^3/sec for a single reflector gas cell, which shows an enhancement of the sensor response time.

Keywords: Optical path length; optical recto-reflectors; ozone; sensitivity; response time; gas cell length; cross sectional area and rate of diffusion

■1.0 INTRODUCTION

The response time of a sensor is a crucial and a necessary sensor performance indicator especially for sensors that are employed for safety applications; as delay could be costly and even life threatening [1-3]. As a performance index, response time is categorised as one of the two major indices for systems considered as been real-time [4] and one of the three main specifications for environmental monitoring devices [5] and besides, higher partial sensor resolution are a direct results of reduction in sensor response time [6].

Ozone as a trace gas in the atmosphere has been rated as very essential [7]; it has also been described as Dr Jekyll and Mr Hyde because of its dual role[8] that is, while it is very useful in application, yet at the same time can pose to be a potential threat to human health in general [9-11]; and hence ozone gas monitoring devices can be considered as safety devices. Chemiluminescence and the UV method have been classified as standard methods for ozone measurements [12, 13]. The detection of ozone gas by means of optical absorption spectroscopy has been in use and is widely accepted [14].

Ozone sensing with spectroscopic methods witness a great revolution with the advent of fibre optics [15] and optical methods are characterized by ease of automation, minimal error, good sensitivity, moderate cost uncomplicated installation and a very good speed of response [16]; and hence has become a preferred method for sensing ozone gas.

Recent works has revealed that increasing the length of a gas cell which produce better sensor performance in terms of absorption spectroscopic optical sensor sensitivity, lower detection limit and resolution, however results in longer or slow response time [17, 18], and hence the need to improve upon sensor speed for long optical gas cells [17, 18]. In this work we proposed by means of sensor design and analysis, a reflective type ozone gas sensor with an improvement in the rate of diffusion which in turn reduces sensor response time, while at the same obtaining desired optical path length by taking advantage of the light propagation pattern of a retro-reflector. There are three internal surfaces in an optical retro-reflector, incident rays of light at right angles to it are reflected by this three surfaces and the rays return parallel to the incident rays [19].

Light transmission in a gas cell is however, regulated by Beer's law; which states that: the transmittance T of a monochromatic light with a path length of light l (cm), through a gas sample with a concentration *C* (mole cm^{-3}) and decadic molar absorption coefficient $\mathcal{E}$ (cm^2/mole) [20] is expressed mathematically by the Beer Bouguer- Lambert law as:

$$T = \frac{I_t}{I_0} = 10^{-\varepsilon Cl} \tag{1}$$

Where I_t and I_0 are the light intensities (in counts) with and without the sample respectively.

■2.0 SENSOR RESPONSE TIME

The response time of a sensor is the time taken by the output from the sensor to change from its initial state to a final settled value [21], conventionally, the final standardised settled value refers to *T* (90); which is the time when 90%-of the maximum concentration is indicated [2]. Low response time has been attributed to the slow natural diffusion of ozone gas in filling long optical gas cell [17, 18]. The authors of [22] has also highlighted that speed of response is a function of diffusion and this has also been validated by the authors of [2].

Mathematically the rate of diffusion is expressed as:

$$\frac{\boldsymbol{dn}}{dt} = - \frac{SD(n_2-n_1)}{l} \tag{2}$$

Where:

- *S= cross sectional area* (cm^2)
- *D= Diffusion Constant* (cm^2/sec) [23]
- $n_2 - n_1$ = *Concentration gradient* (ppm)
- *l= length of gas cell* (cm) [24, 25]

■3.0 METHODOLOGY AND SENSOR DESIGN

Let the rate of diffusion $\frac{d_n}{d_t} = R_t$ and hence

$$R_t = -\frac{SD(n_2-n_1)}{l} \tag{3}$$

Differentiating the diffusion rate with respect to S *and* l while keeping other variables constant [26]:

For R_t with respect to l:

$$\frac{\partial R_t}{\partial l} = \frac{\partial}{\partial l}\left[-\frac{SD(n_2-n_1)}{l}\right]$$

$$\frac{\partial R_t}{\partial l} = \frac{\partial}{\partial l}[-SD(n_2-n_1)l^{-1}]$$

$$= SD(n_2-n_1)l^{-2} \tag{4}$$

For R_t with respect to S:

$$\frac{\partial R_t}{\partial S} = \frac{\partial}{\partial S}\left[-\frac{SD(n_2-n_1)}{l}\right] = -\frac{D(n_2-n_1)}{l} \tag{5}$$

For every little increment δl *and* δS there will be a corresponding small increment δR_t in the rate of diffusion [26] given as:

$$\delta R_t = \frac{\partial R_t}{\partial l}\delta l + \frac{\partial R_t}{\partial A}\delta S \tag{6}$$

Substituting Equation 4 and 5 in Equation 6 we obtain:

$$\delta R_t = SD\frac{(n_2-n_1)}{l^2}\delta l - D\frac{(n_2-n_1)}{l}\delta S \tag{7}$$

The direct application of the equation 3 above in our design, implies that rate of diffusion is enhanced by designing a sensor with a larger cross sectional area and shorter length; this is also affirmed to be valid by the authors of [10]. Hence, length and the cross sectional area are considered as variables. The proposed sensor takes advantage of light propagation principle in an optical retro-reflector.

Figure 1 An external view of retro-reflectors [27]

In our design, the first item considered is the retro reflector shown above in Figure 1; its dimension are given in Table 1. The novel ozone sensor designed by [28, 29] with only one retro reflector in a gas cell of 40cm, a light path length l of 2 × 40cm (80cm approximately) was achieved; the concentration measured was stated as 0.1ppm, the cross sectional area of a gas cell of 40cm in length, going by the diameter of the retro-reflector and tolerance and applying the area of cylindrical shape as shown in Equation 8 is approximately between 0.39147cm^2 -0.40280cm^2. Hence in our design our target is to obtain a path length equal to or greater than 80cm, and a cross sectional area greater than 0.4026cm^2.

$$Area = \pi r^2 \tag{8}$$

With two retro – reflectors align as shown Figure 2; to obtain a path length of light equals or greater to 80 cm; will be 80 ÷ 3 = 26.6667cm; however we choose 30cm to make for better sensitivity and to accommodate the tolerances.

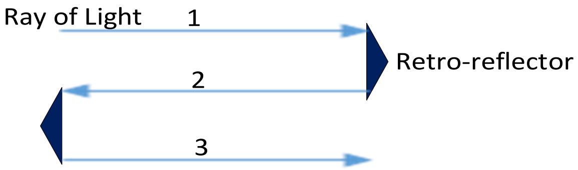


Figure 2 Ray diagram for two retro reflectors

Table 1 Retro-reflector dimensions[27]

Description	Dimension / Remarks
Diameter	0.716 cm
Diameter Tolerance	+0/-0.010 cm
Height	0.610 cm
Height Tolerance	±0.05 cm
Surface Accuracy (λ)	1/10
Surface Quality	20-10
Angle Tolerance	10 arc seconds
Substrate	UV Grade Fused Silica
Coating	Uncoated
RoHS	Exempt

Figure 3 74 UV collimating lens[30]

The next item considered is the 74 UV collimating lens shown in Figure 3; this is important because it is coupled directly to the gas cell and hence its external thread dimensions (3/8- 24) is directly incorporated in the sensor design. The dimensions and specifications taking into considerations are outlined in Table 2. The sensor designed based on the formulations above are as shown in Figure 4.

Table 2 Specifications of the collimating lens[30]

Item	Diameter	Focal length	Material	Range	Operating Temperature	Connector
74-UV	5 mm	10 mm	f/2 fused silica Dynasil	200 – 2000 nm	150 °c	SMA 905, 0.635 cm ferrule, 3/8-24 external thread

■4.0 COST ANALYSIS

The cost analysis considered is for the retro-reflector. With reference to Edmund Optics Catalogue for 2014 [31], an uncoated retro-reflector with the stock number #65-250 employed in our design is S$ 178.25 (Singaporean Dollar) which is 140.56 US Dollar as at 3rd April, 2014; hence our design with two retro-reflectors will require an extra amount of 140.56 USD for the retro reflector. While, there is an extra cost, it is however important to emphasise that in our design, safety which depends on response time is prioritise and is not been traded-off with cost.

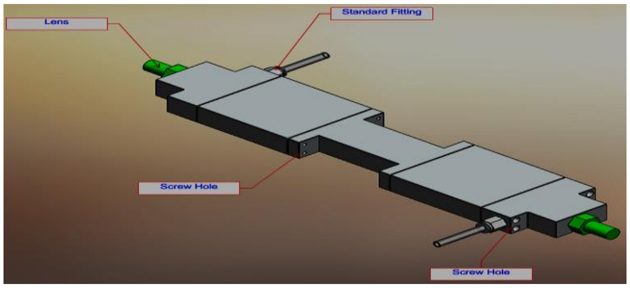


Figure 4(a) Proposed ozone gas cell showing the external features of the sensor. (Fabrication drawing by[32])

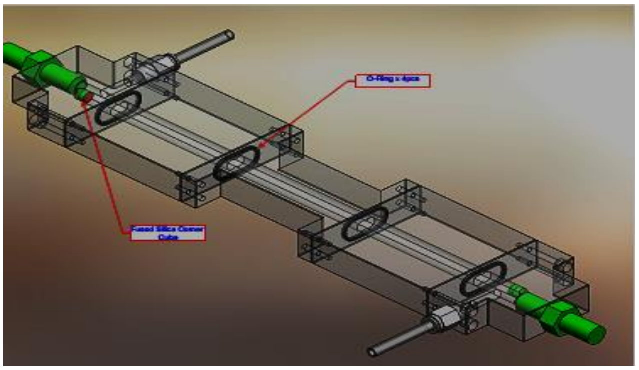


Figure 4(b) Proposed ozone gas cell showing the interior of the sensor. (Fabrication drawing by[32])

■5.0 RESULTS AND DISCUSSION

The analysis below considers a gas cell of length 30cm as depicted in Figure 4. With the two reflector design, the cross sectional obtained is approximately 0.50350cm^2. In Figure 5, the path length achievable is about 90cm. For the rate of diffusion' since diffusion constant is temperature and pressure dependent, we assumed the same condition of temperature and pressure for both a one and two retro-reflector design; and hence the only variables are the length and the cross sectional area of the gas cell.

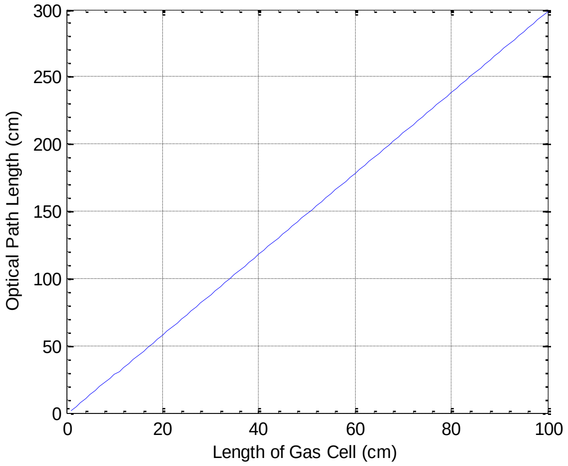


Figure 5 Achievable optical path length for various length of gas cell

Figure 6 shows that for the 30cm gas cell diffusion rate is approximately 0.017132 ppm cm^3/secs in comparison to 0.01023 ppm cm^3/sec for the single reflector cell of 40cm length; which is about 1.67534 times faster. At shorter optical path length it is even much faster and hence the shorter the length of the gas cell the faster the rate of diffusion and the lower the response time of the sensor or the faster the sensor response speed for this type of design.

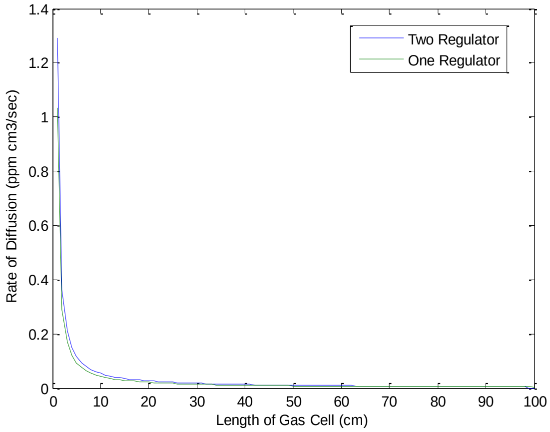


Figure 6 The effect of gas cell length on the Rate of concentration

Figure 7 compares the two cross sectional areas of the one reflector and two reflector gas cells. For both design the cross sectional area in comparison to the length of gas cell is constant; however the two reflector gas cell has a wider cross sectional area and thus favouring faster diffusion of the gas inside the sensor. The cross sectional area of the sensor can further be increased by increasing the number of the retro-reflectors for the sensor or by employing retro-reflectors with wider diameters.

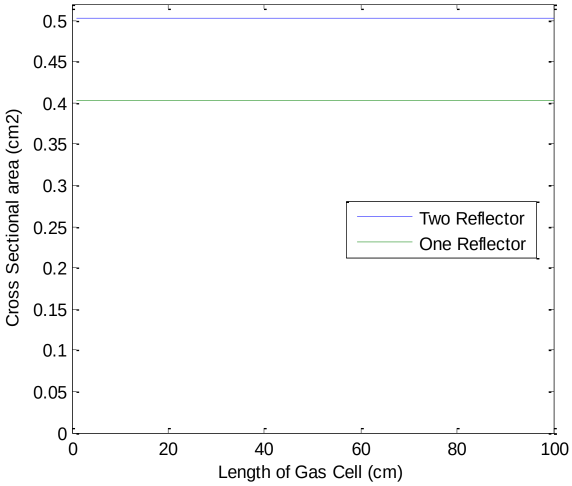


Figure 7 Relating Area of gas cell and length of gas cell

In Figure 8, fluid flow rate (R_f) in both the one and two reflector design is compared using the Poiseuille's equations. According Poiseuille, fluid flow rate in a cylinder is a function of pressure difference, fluid viscosity and the radius and length of the cylinder [24]. It is expressed as:

$$R_f = \frac{\pi R^4 (P_1 - P_2)}{8\eta l} \qquad (9)$$

Where

- R = Radius of cylinder (cm)
- l = Length of cylinder (cm)
- η = *Viscosity* (Pa . secs)
- P_1- P_2 = Pressure difference (Pa)

The volume flow rate for the proposed gas cell in terms of the radius and the length of the cylindrical structure is 0.00109 Pa cm^3/sec. while that of the single reflector design is 0.00016 Pa cm^3/sec. This is a confirmation of the results obtained with the diffusion model, confirming that the flow is faster with a wider diameter and a shorter length.

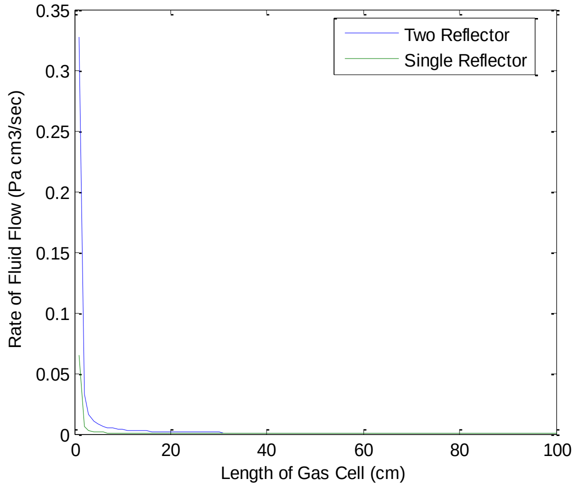


Figure 8 Fluid flow rate in Pascal centimetre cube per seconds using the Poiseuille's equations

6.0 CONCLUSION

The design and analysis of the optical reflective type gas cell is aimed at reducing the gas diffusion time which in turn reduces the time taken for the gas cell to be filled with a gas sample and thus enhanced the sensor response time. Using two reflectors to achieve an optical path length of approximately 80cm reduces the effective gas cell length from 40cm (used in previous work) to 30cm and increases the cross sectional area from $0.40280cm^2$ to $0.50350cm^2$. The two variables of length and diameter considered as factors that favours faster diffusion are simultaneously enhanced; while there was an increment in the gas cell internal diameter, the effective length of the sensor was reduced. For the 30cm gas cell, diffusion rate is approximately 0.01731 ppm cm^3/secs in comparison to 0.01023 ppm cm^3/sec for a single reflector cell; approximately 1.67533 times faster; which thus yields a faster sensor response.

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