Investigation of the Effect of Inlet Radius on the Response Time of a Transmission Type Ozone Sensor

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Abstract— **The effect of inlet radius of a transmission type optical gas cell on its response time is reported. Six gas cells of varying lengths, and internal radius of 0.32cm were considered at first and then other internal diameters were also investigated afterwards. The effect of inlet radius is easily discernible at all velocities considered; however it is more pronounced at lower flow rates. At a velocity of 16.79cm/s of ozone gas, and for a target sensing time of ≤ 0.5 seconds; we observed that the inlet radius requirements for gas cells of varying lengths and varying internal diameters is not the same for a specific target sensing speed. The length and the internal radius of a gas cell are proportional to its inlet radius.**

Keywords— ***Optical path length; inlet diameter; internal diameter; response time; flow rate***

I. INTRODUCTION

Ozone (O_3,) though a trace gas and a principal greenhouse gas [1-3] is nevertheless evolving in relevance. It is now been considered for the removal of pesticide left over in strawberry [4] and the removal of Bisphenol-A from Water [5]; thus it is essential to improve on its detection because of its rise in utilization and also because of the side effects associated with undue exposure to its toxicity. Whereas loss of consciousness or even death is the consequence of exposure to 500 to 1000 parts per million (ppm) of H_2S [6], in comparison the safe exposure limit for O_3 is 0.075ppm for 8 hours per day[7]. Indoor application will require a fast and frequent monitoring to ensure personnel's safety at all times [8, 9].

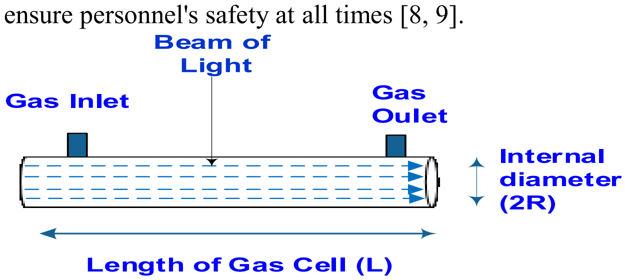

Fig.1: Transmission type gas cell

The sensitivity, lower detection limit and the resolution of an absorption spectroscopic ozone sensor are proportional to its optical path length and thus longer gas cells yields better operations in terms of sensitivity, resolution and lower detection limits [10-12]; this however results in unsatisfactory sensing speed [13, 14]. In this study, we investigate the effect of the inlet diameter of a transmission type optical gas sensor on the sensing speed of an optical sensor.

There are basically three important dimensions associated with an absorption spectroscopy gas cell in the literature; these are the length of the gas cell, internal diameter and inlet diameter as depicted in fig. 1. Table 1 shows that while the first two are often mentioned in literature the third is rarely considered and often omitted and hence in this study we examine how the inlet radius of a transmission type gas cell impacts on its sensing speed of a specific length of a gas cell.

II. METHODOLOGY AND MODELLING

Gas detection by absorption spectroscopy requires the simultaneous transmission of both light and the gas sample into the gas cell. The transmission of light in the fiber optic cable is governed by total internal reflections; light transmission in the 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) [10] is expressed mathematically by the Beer Bouguer- Lambert law as:

$$T = \frac{I_t}{I_0} = 10^{-\varepsilon Cl} \qquad (1)$$

Equations of diffusion as well as Poiseuille's equations [15] can be used to study the flow of gas in a tube; however in this study we have employed continuity equation to both model and study the time dependence of gas flow in the gas cell. When a gas flow through a tube, the velocity changes according to the equation of continuity [15, 16]. For a given volume of gas flowing through a gas cell the volume rate of discharge can be express as the velocity rate of discharge Q (cm^3/s) , given as:

$$Volume\ rate\ of\ discharge = \frac{V}{t} = \frac{\pi r^2 L}{t} = \frac{L}{t} \times \pi r^2 = U \times A = \mathrm{Q} \qquad (2)$$

Universiti Teknologi Malaysia: grants number: 4F565, 05J60, 4F317, and 04H35; MOE and ETF- Nigeria

Where:

V = Volume of fluid (cm^3)

t = time (s)

L = length of the gas cell (cm)

$U = \frac{L}{t}$ = velocity of fluid (cm/s) [17]

$A = \pi r^2$ = area of cross section at entry or exit (cm^2)

When a gas transits through either a sudden enlargement (fig.2) or a sudden contraction using equation 2, the velocity rate of discharge is related and express as:

$$U_1 \times A_1 = U_2 \times A_2 \quad (3)$$

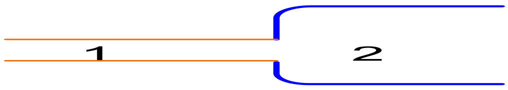

Fig. 2: Flow through a sudden enlargement tube network

Table 1: Dimensions of a Gas Cell and Inlet diameter

Method	Length of Gas Cell (cm)	Number of Gas Cell	Internal radius of Gas cell (cm)	Inlet radius of Gas cell (cm)	Response Time (s)	Remarks/ Reference
Absorption (UV)	32.49	1	-		-	[17] optical path length was 90cm
Absorption (Vis)	50	1	0.4		-	[14]
IBB-CEAS	14.4	-	-		0.1	[12]
Absortion (UV)	63	1	-		60	[13]
Absorption (UV)	30	2	-	0.65	0.5	[18]
Absorption (Deep UV)	4 and 40	1	-		-	[19]
Cavity Ring Down	93cm	3	0.31		1	[20]
Absorption (UV-Visible)	Range 4 - 40	1	-		-	[21]
Absortion	40	1	-		-	[22]
Absorption (UV -254 nm)	5	1	-		1	[10]
Absorption (Vis – 600nm)	5	1	-		Significantly lower	[10]
Absorption (Visible)	150	1	-		-	[10] length was increase to increase resolution
Absorption (Vis)	5	1	0.4		-	[23]

In fig. 3, the typical connection of our aluminum gas cell labeled 2 and a silicon tube labeled 1 is shown, where *L* (cm) is the length of the gas cell. For the purpose of modeling, the gas cell is considered to be a large section of the silicon tube. Streamline flow (Reynolds number ≤ 2300) and incompressible flow (Mach number ≤ 0.3) is assumed.

Applying continuity equation to fig. 3, with the velocity U_2 expressed as:

$$U_2 = \frac{length}{time} = \frac{L_2}{t_2} \quad (4)$$

Substituting "(4)" in "(3)," we obtain equation 5:

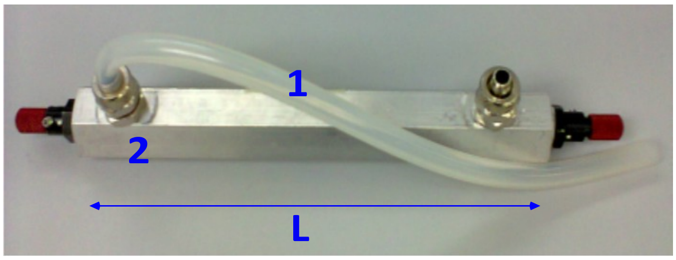

Figure 3: A transmission type gas cell with a silicon connected to its inlet.

$$U_1 \times A_1 = \frac{L_2 \times A_2}{t_2} = \frac{V_2}{t_2} \quad (5)$$

Where V_2 (cm^3) is the volume of the gas cell.

Making t_2 (s) the subject of our equation from "(5),"

$$t_2 = \frac{V_2}{U_1 \times A_1} = \frac{V_2}{U_1 \times \pi \times r_1^2} = \frac{L_2 \times \pi \times 0.32^2}{U_1 \times \pi \times r_1^2} \quad (6)$$

From "(6)," keeping the volume V_2 (cm^3) of the gas cell and the velocity U_1 (cm/s) of the gas, constant; the time taking t_2, to fill the gas cell is inversely proportional to the square of the radius r_1, of the silicon tube, thus the bigger the inlet diameter, the shorter the time taken by the gas to fill the gas cell and the faster it is to attain *T* (90,) the time in seconds (s) taken to attain a stable value of 90% which is the sensor response time [6, 24].

III. Results and Discussion

Ozone is a trace gas in the atmosphere and hence when an ozone sensor is placed for environmental monitoring either outdoor or indoor, it is not ozone gas only that enters into the gas cell but the entire constituent gases in the air, however at a wavelength of 253.7nm (UV) or 603nm (visible) [10] ozone gas is selectively detected. Hence the speed of sound in air (which is 340m/s at standard temperature and pressure) [16] is considered for this analysis. To achieve a Mach number less than or equals to 0.3 (≤ 0.3) and Reynolds number less than or equals to 2300 (≤ 2300), air velocity considered is in the range of 16.79 cm/s to 167.9 cm/s (viscosity of gases is in the order of 1 to 10 μPa.s.) The analysis is for a gas cell with the following dimensions: length of *L* = 50cm, 40cm, 30cm, 20cm, 10cm, and 5cm; internal radius of 0.32cm, and varying inlet radius between *r* = 0.2cm to 1.2 cm at a step of 0.1cm.

Fig. 4 is the sensing time for a 50cm in relation to the velocity of ozone at different dimensions of inlet radius. The effect of inlet radius is discernible at all velocities considered; however its effect is more pronounced at lower flow rates. This is also justified by the authors of [14, 25]; inlet radius is inversely proportional to the speed of response.

The sensing speed requirements for ozone sensors is in the range of 0.02 to 1.0 seconds [26]. Analysis with excel spread sheet, two-way analysis of variance and Matlab at a velocity of 16.79cm/s (since slow response is often associated with lower flow rates or velocity) and a target response time of ≤ 0.5 seconds as depicted in fig. 5. The rate of gas flow in each gas cell is independent of the flow in other gas cells; the required inlet radius for a gas cell with lengths of (41 to 50) cm, (31 to 40) cm, (21 to 30) cm, (14 to 20) cm, (8 to 13) cm, and (4 to 7) cm are 0.8cm, 0.7cm, 0.6cm, 0.5cm, 0.4cm and 0.3cm respectively.

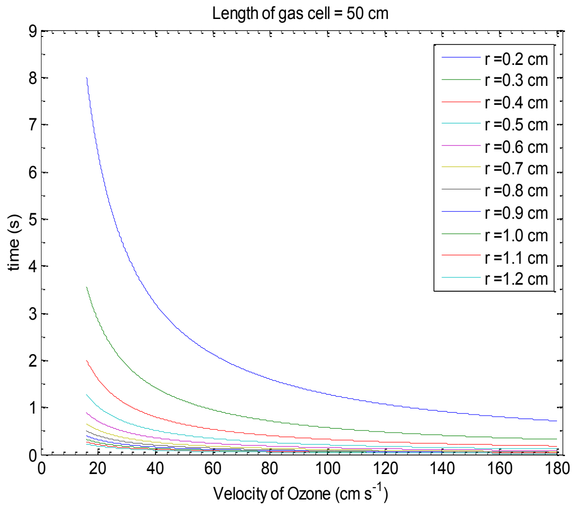

Fig. 4: The effect of varying inlet r on the response time t of an ozone gas sensor with a path length of 50cm.

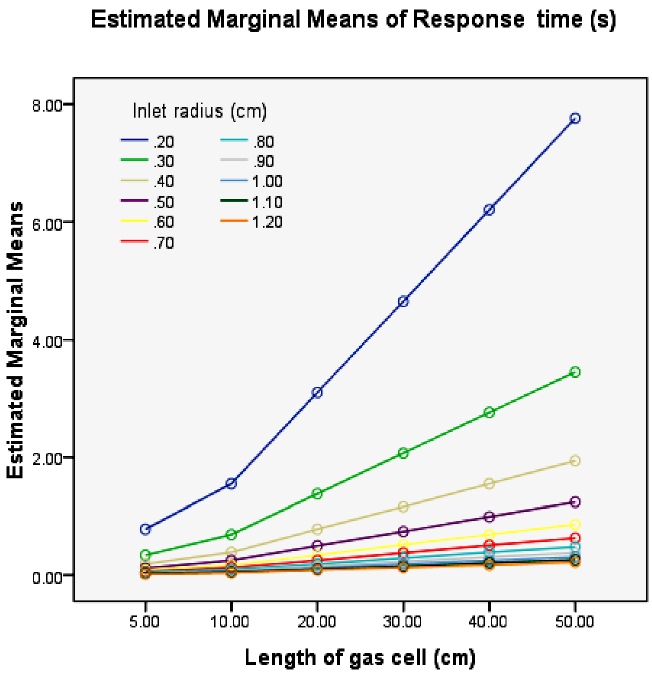

Figure 5: Two-way Analysis of Variance of response time.

Fig. 6 shows the variation of internal diameter on the response time of a 50cm gas cell with a fixed inlet radius of 0.8 cm; increasing the internal diameter results in longer response time than the targeted 0.5s and hence it will requires that increasing internal diameter should have a corresponding increase in the inlet diameter to be able to satisfy the 0.5 s targeted response time for our analysis. Fig.7 is the variation of the internal radius for a 50 cm gas cell and inlet diameter to obtain a target of 0.5 s response time. A 50 cm gas cell with internal radius between (0.30 and 0. 33), (0.34 and 0.38), (0.39 and 0.42), (0.43 and 0.46) and (0.47 and 0.50) cm, for a target response time of ≤ 0.5s will require a corresponding inlet radius of 0.8, 0.9, 1.0, 1.1 and 1.2 cm respectively.

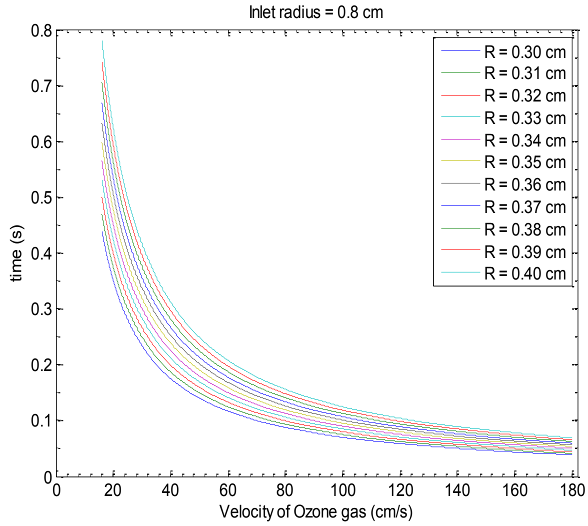

Fig. 6: Internal diameter (R =0.30 - 0.40 cm) for 50cm gas cell with an inlet radius of 0.8 cm

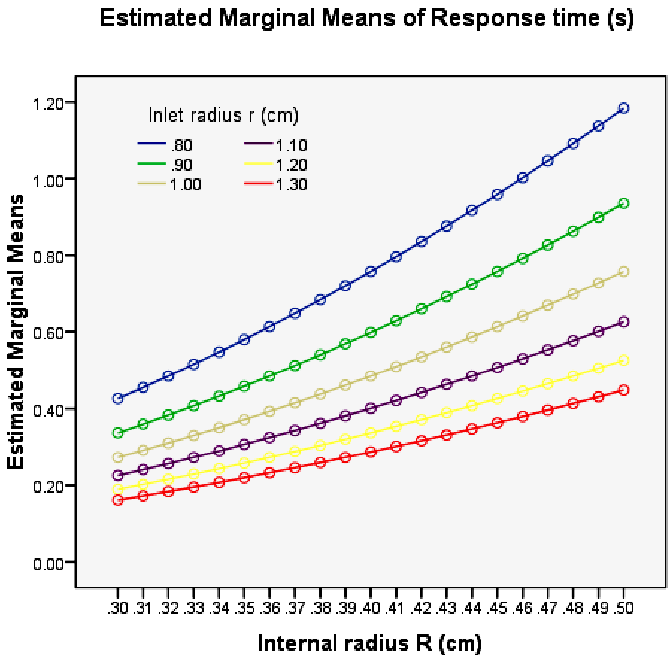

Figure 7: Two-way Analysis of Variance of the effect of internal diameter on response time.

IV. CONCLUSION

The continuity equation has been applied in modeling the ozone flow in a transmission type gas cell. Results have been analyzed using excel spreadsheet, two-way analysis of variance and Matlab. The effect of inlet diameter on the response time for gas cells with length of 50cm, 40 cm, 30cm, 20cm, 10cm and 5cm and internal diameter of 0.64 cm was found to be inversely proportional. For a target time of ≤ 0.5 seconds and ozone flow velocity of 16.79cm/s, the effective inlet radius are in the range of 0.3 cm to 0.8 cm respectively for 5cm to 50cm length of gas cells. Similarly, increasing the internal diameter of the 50 cm gas cell in range between 0.30 to 0. 50 cm, will require a corresponding increase in the inlet radius to between a range of 0.8 to 1.2 cm respectively.

ACKNOWLEDGMENT

The authors would like to thank Universiti Teknologi Malaysia (UTM) for sponsoring this publication under Research University Grant (RUG) Scheme, grant no: 05J60 and 04H35; and Fundamental Research Grant Scheme (FRGS) grant no: 4F317 and 4F565. The Ministry of education (MOE) Malaysia is also acknowledge and the Nigerian Education Trust Fund (ETF) for the financial support giving inform of Tertiary Education Trust Fund (TET-Fund).

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