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 discernable 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\textsubscript{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 ppm of H\textsubscript{2}S [6], in comparison the safe exposure limit for O\textsubscript{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].

![Diagram of Gas Cell](https://example.com/gas-cell-diagram)

Fig.1: Transmission type 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\(^{-2}\)) and decadic molar absorption coefficient \( \varepsilon \) (cm\(^2\)/mole) [10] is expressed mathematically by the Beer Bouguer- Lambert law as:

\[
T = \frac{I}{I_0} = 10^{-\varepsilon Cl}
\]

(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:

\[
Volume\ rate\ of\ discharge = \frac{V}{t} = \frac{\pi r^2 L}{t} = \frac{L}{t} \times \frac{\pi r^2}{t} = U \times A = Q
\]

(2)

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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:

\[ U_1 \times A_1 = U_2 \times A_2 \]  

(3)

Fig. 2: Flow through a sudden enlargement tube network

<table>
<thead>
<tr>
<th>Method</th>
<th>Length of Gas Cell (cm)</th>
<th>Number of Gas Cell</th>
<th>Internal radius of Gas cell (cm)</th>
<th>Inlet radius of Gas cell (cm)</th>
<th>Response Time (s)</th>
<th>Remarks/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption (UV)</td>
<td>32.49</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[17]</td>
</tr>
<tr>
<td>Absorption (Vis)</td>
<td>50</td>
<td>1</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>[14]</td>
</tr>
<tr>
<td>IBIB-CEAS</td>
<td>14.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
<td>[12]</td>
</tr>
<tr>
<td>Absorption (UV)</td>
<td>63</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>60</td>
<td>[13]</td>
</tr>
<tr>
<td>Absorption (Deep UV)</td>
<td>30</td>
<td>2</td>
<td>0.65</td>
<td>0.5</td>
<td>-</td>
<td>[18]</td>
</tr>
<tr>
<td>Cavity Ring Down</td>
<td>40</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[19]</td>
</tr>
<tr>
<td>Absorption (UV-Visible)</td>
<td>93cm</td>
<td>3</td>
<td>0.31</td>
<td>1</td>
<td>-</td>
<td>[20]</td>
</tr>
<tr>
<td>Absorption (UV - 254nm)</td>
<td>4 - 40</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>[21]</td>
</tr>
<tr>
<td>Absorption (Vis - 600nm)</td>
<td>5</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>[10]</td>
</tr>
<tr>
<td>Absorption (Vis)</td>
<td>150</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>[10]</td>
</tr>
</tbody>
</table>

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 \( \leq 2300 \)) and incompressible flow (Mach number \( \leq 0.3 \)) is assumed.

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

\[ U_2 = \frac{\text{length}}{\text{time}} = \frac{L_2}{t_2} \]  

(4)

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

\[ U_1 \times A_1 = \frac{L_2 \times A_2}{t_2} = \frac{V_2}{t_2} \]  

(5)

Where \( V_2 \) (cm³) is the volume of the gas cell.

Making \( t_2 \) (s) the subject of our equation from “(5),”

\[ t_2 = \frac{V_2}{U_1 \times A_1} = \frac{V_2}{U_1 \times \pi \times r_1^2} = \frac{L_2 \times \pi \times 0.32^2}{U_1 \times \pi \times r_1^2} \]  

(6)

From “(6),” keeping the volume \( V_2 \) (cm³) 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 (\( \leq 0.3 \)) and Reynolds number less than or equals to 2300 (\( \leq 2300 \)), air velocity considered is in the range of 16.79 cm/s to 67.9 cm/s (viscosity of gases is in the order of 1 to 10 \( \mu \)Pa.s.) The analysis is for a gas cell with the following dimensions: length of \( L = 50 \), 40, 30, 20cm, 10cm, and 5cm; internal radius of 0.32cm, and varying inlet radius between \( r = 0.2 \)cm 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 16.79 cm/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 0.8 cm, 0.7 cm, 0.6 cm, 0.5 cm, 0.4 cm and 0.3 cm respectively.

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

Fig. 6 shows the variation of internal diameter on the response time of a 50 cm gas cell with a fixed inlet radius of 0.8 cm; increasing the internal diameter results in longer response time than the targeted 0.5 s and hence it will require 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 ≤ 0.5 s will require a corresponding inlet radius of 0.8, 0.9, 1.0, 1.1 and 1.2 cm respectively.

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

Figure 6: Internal diameter (R = 0.30 - 0.40 cm) for 50 cm 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.
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.

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