



Non-Dispersive Near Infrared Gas Flow Cell Design for Oxygenator-Exhaust Capnometry

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Abstract

Non-dispersive near-infrared technique is widely used nowadays for the detection of gases, especially in harsh environments. In this study, an optical gas cell was designed for oxygenator exhaust capnometry. A computer-based simulation was used for the analysis of air flows for model selection. ANSYS Discovery 2020 R2 was used for model simulation. The gas flow cells were tested using a custom-made gas rig to measure the fraction absorbance of carbon dioxide gas at the detector. Two gases were used, nitrogen gas as a reference gas (0%) and 9% carbon dioxide. Three gas cells with the following optical path lengths were tested: 31mm, 36mm, and 40mm. The results showed that all gas flow cells produced laminar flow and small pressure drop across the inlet and outlet of the cell (11~12 Pa). Further, the minimum velocity is obtained in the 40mm gas flow sensor and it is located at the gas outlet path away from the effective optical gas path. The simulation and experimental results indicate that the gas flow cell of 40mm optical path length is more suitable for the intended application as it offers a maximum effective absorption path compared to the stagnation areas, and as a result, it provides the maximum fraction absorbance.

Keywords: Oxygenator Exhaust Capnometry, NDIR, Gas Flow Cell, Gas-Flow Simulation, ANSYS Discovery.

تصميم خلية غاز خاصة بتقنية الاشعة تحت الحمراء الغير مشتتة لغرض

الاستخدام في جهاز الكابنوميتر الخاص بمؤكسج الدم

بسمه عبد الصاحب فيحان ، زياد طارق الدهان، حسين حسن الزبيدي

الخلاصة:

تستخدم تقنية الاشعة تحت الحمراء الغير مشتتة في قياس نسب الغازات. في هذا البحث ، تم تصميم خلية تدفق الغاز خاصة بالغازات الخارجة من مؤكسج الدم لغرض تصميم جهاز الكابنوميتر. تمت دراسة جريان الغاز باستخدام برنامج المحاكاة ANSYS Discovery 2020 R2 وتم اختبار خلايا تدفق الغاز باستخدام منظومة غازات مخصصة لهذا الغرض لحساب نسبة امتصاص الغاز للاشعة تحت الحمراء. استخدم غاز النايتروجين لغرض تصفير الاشارة واستخدم غاز ثاني اوكسيد الكربون بنسبة 9٪ كأعلى نسبة ممكن قياسها من الغاز المنبعث من مؤكسج الدم. تم اختبار ثلاث اطوال من خلايا تدفق الغاز: 31 ملم، 36 ملم، و 40 ملم. اثبتت النتائج جريان الغاز بشكل صفائي ونسبة فقدان الضغط قليل (11~12 Pa) للاطوال الثلاثة. ايضاً، تم الحصول على السرعة الدنيا في مستشعر تدفق الغاز 40 ملم ويقع عند مخرج مسار الغاز بعيداً عن مسار الغاز البصري الفعال. اثبتت نتائج المحاكاة والنتائج العملية أن خلية تدفق الغاز بطول المسار البصري 40 ملم أكثر ملاءمة للتطبيق المقصود لأنها توفر اطول مسار امتصاص فعال مقارنة بمناطق الركود، ونتيجة لذلك ، فإنها توفر أقصى نسبة امتصاص للغاز.



1. Introduction

Measuring carbon dioxide (CO₂) concentration in breathing gases is known as capnometry [1]. It is a common method for monitoring pulmonary function noninvasively for emergency situations, intensive care, anesthesia, and for membrane oxygenators used in extracorporeal life supports such as cardiopulmonary bypass (CPB) [2]. The measurement of CO₂ removal is achieved by placing a CO₂ sensor at the exhaust port of the CPB oxygenator for perfusion monitoring and evaluating the oxygenator performance [3]–[5]. This is usually done by comparing blood gases before and after the oxygenator to exhaust blood gas analysis due to the lack of a standard technique for detecting CO₂ in the oxygenator's exhaust [3]. Optical gas sensors offer a higher selectivity and are less hazardous than contact gas sensors like semiconductor gas sensors [6]. The non-dispersive infrared (NDIR) gas sensor, for example, has a compact volume, robust against volatile organic compounds [7], and high practicality, making it ideal for detecting gases with asymmetric molecule structures like CO₂. The working principle of NDIR sensors can be described by Beer-Lambert Law [8]:

$$I = I_0 e^{-\alpha CL} \quad \dots (1)$$

Where α is the absorption coefficient of the CO₂ gas and filter, C is the CO₂ concentration, and L is the optical path length between the source and detectors. NDIR sensors consist of an IR source, a detector with an optical filter placed in front of it, and an optical gas chamber, as shown in Fig.1. The incident IR intensity is absorbed by the gas entering the cell. The reduction in IR intensity can be measured using Equ.1 and can be used to measure the gas concentration. The functions of the optical gas cell are: ensuring that the emitted IR reaches the detector properly; providing an adequate absorption light route for the target gas; and providing a solid and practical structure for the source and detectors.

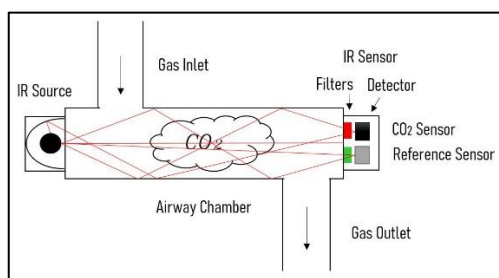


Figure (1): NDIR CO₂ gas cell.

Gas detection in various situations may be accomplished by designing an optical gas chamber and installing an appropriate IR light source and detector.

There are two types of gas flow cells; mainstream and sidestream. In the mainstream design, the gas flows directly from the exhaust port to the gas flow cell, whereas gas samples aspirated to the measuring device in the sidestream design. It requires a pumping mechanism, flow stabilization components [9], disposable tubes and a water trap. Therefore, it ends

up with a more complex system and requires more space than mainstream design. Further, there is a chance of diluting the exhaust gases with room gas [10]. Optical software is frequently used by researchers to simulate and imitate light pathways and fluxes [11]–[13]. D. S. Shah created a cylindrical optical gas cell with a length of 25mm and a diameter of 20mm, and used Zemax software to examine the light in the chamber. The detection range is from 0 to 30000ppm [14]. In the optical path length designed by Sieber, the emitted IR light experiences triple reflections before being projected on the detector. The results are based on computer-aided design techniques [15]. With two concave mirrors, J. Park created an optical cavity structure. The simulation results indicate that the light generated by the IR source is reflected twice and projected on the detector in a converging state. In the optical air chamber, the light path length is 65mm. The optical gas chamber has a capacity of 4.5cm³, and the detection range is from 0 to 2000ppm [16]. J. Hodgkinson designed an optical gas cell with a composite parabolic collector. Zemax simulation results show that the IR light experiences a twice reflection before being projected onto the detector, and the average effective optical path length is 32mm [17].

The thermopile NDIR gas sensor has a significant advantage over other optical gas sensor types in terms of size and mobility and the ability to be used in a high mechanical noise and humidity environments, such as the exhausted gas from the CPB oxygenator.

All the above-mentioned studies designed NDIR sensors for low CO₂ concentration aimed to be used in outdoor or indoor applications for air quality monitoring; therefore, the gas velocity is not considered when designing the optical path length. In this paper, a simulation and practical experiment are performed to verify the gas cell design required for the mainstream oxygenator exhaust capnometry sensor.

2. Materials and Methods

Design criteria:

The gas flow cell (GFC) should provide the following design criteria:

1. The gas flow cell (GFC) should not add any extra resistance to the oxygenator to avoid the generation of gas bubbles;
2. The GFC should not induce turbulence flow between the IR source and detector;
3. The operating theater, in general, and the perfusion section, in particular, is so crowded. Therefore the device should be as small as possible, i.e., less than or equal to the pediatric oxygenator diameter (~60 mm).

Design specifications:

To accomplish the first criteria, the diameter of the GFC is equal to the exhaust port diameter. Also, the exhaust port is connected to the GFC via a plastic



tube to the ground. In this way, the added pressure due to the tube length is equalized. Three gas flow cells made from Aluminum with the following optical path lengths: 40mm, 36mm, and 31mm were tested (Fig. 2). ANSYS Discovery 2020 R2 was used for fluid flow analysis. SolidWorks 2019 was used for drawing the GFCs.

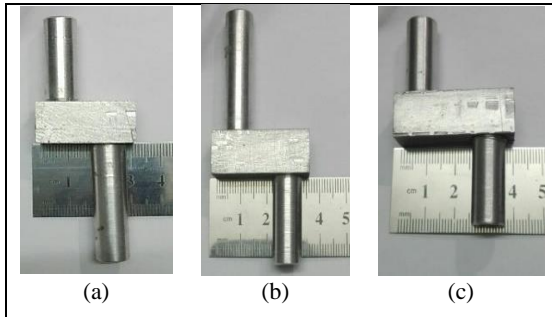


Figure (2): Gas flow cells, a: 31mm cell, b: 36mm cell, and c: 40mm cell.

The maximum gas flow rate during CPB is about 6L/min, and the exhaust port radius is 8mm; therefore, the velocity is about 2m/s. The default temperature is set at 34°C (which is the average temperature at the oxygenator exhaust), and the outlet temperature at 22°C (operation theater temperature). The gravity effect is excluded. The fluid material is changed to air, and the associated properties are left as default (Fig.3) as the following:

- Density: 1.16 kg/m³
- Viscosity: 1.832e-5 PaS
- Thermal expansion Coefficient: 0.00333 1/K
- Isotropic thermal conductivity: 0.02582 W/m.K
- Specific heat: 1021 J/kg.K

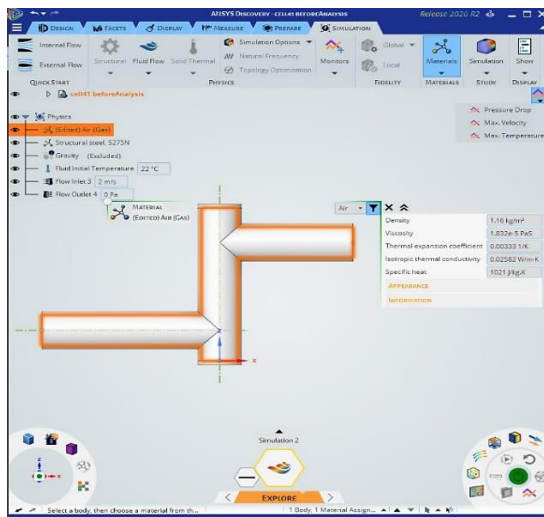


Figure (3): ANSYS Discovery 2020 R2 screenshot showing the boundary conditions (upper left side) and the material (air) properties (middle right side).

To verify our selection, the three GFCs were tested for 0% CO₂ by means of nitrogen gas (N₂) and 9% CO₂ (for hypercapnia, CO₂ concentration is about 7% [14]) using a custom-made gas testing rig, as shown in Fig. 4 and 5. The pulsable IR source EVF-5550 and HTS-E21-F3.91/F4.26 detector were fitted in the gas flow cell. The IR is modulated with a 3Hz, 30% duty cycle using Attiny85 microcontroller and F5305S Mosfet module.

The gas testing rig consists of pressure control valves (without heater) integrated with rotameters. Gas temperature was controlled using SHT31-D temperature humidity sensor and an insulated heating wire (AC 220V, 0.9A, 1.5m length, Heraeus, Germany) connected via a relay to the controller (Arduino UNO). FS1012 flowmeter (Renesas, Integrated Device Technology, Japan) was used for measuring the inlet gas flow via STM32F103C8T6 microcontroller, which is also used to record the signals from the CO₂ sensor. The data from both microcontrollers is sent serially with 115200 baud rate through USB cables to the computer. MATLAB R2019b was used for data recording and processing. Signals from the CO₂ detector were filtered using moving average filter with a window size of 48.

The experiment is done at 25°C and relative humidity of 34%. The gas flow rate is set as 1L/min. The fraction absorbance of CO₂ can be computed as:

$$\text{Fraction Absorbance} = \frac{V_0 - V}{V_0} \quad \dots (2)$$

V₀ and V are the output voltage at zero gas (N₂) and 9% CO₂, respectively.

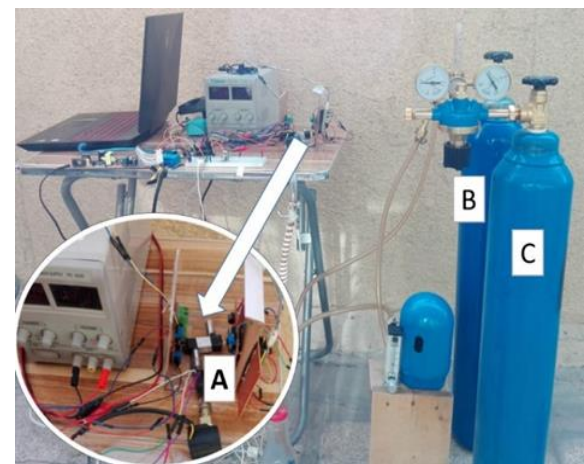


Figure (4): A custom-made gas testing system, a: GFC (40mm), b: 9% CO₂ gas cylinder, and c: N₂ gas cylinder.

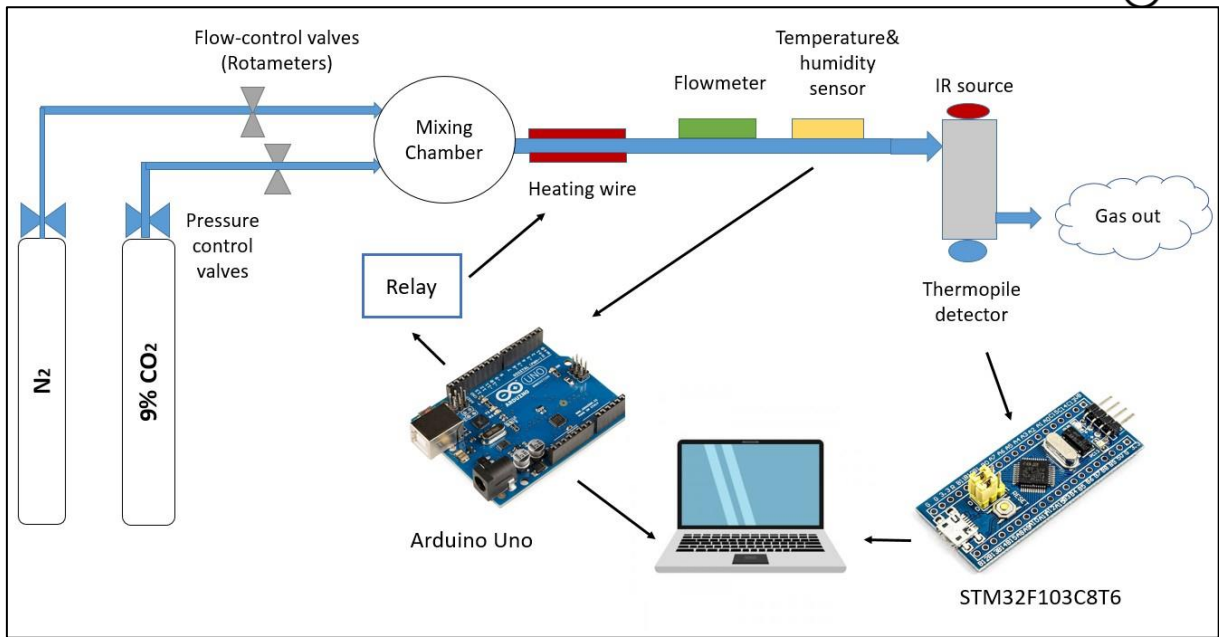


Figure (5): Schematic diagram of the sensor Calibration bench.

3. Results and discussion:

The flow simulations of the three GFCs illustrating the regions of high flow velocities are shown in Fig. 6-8. The fraction absorbance and the maximum flow velocities of the GFCs are listed in Table.1.

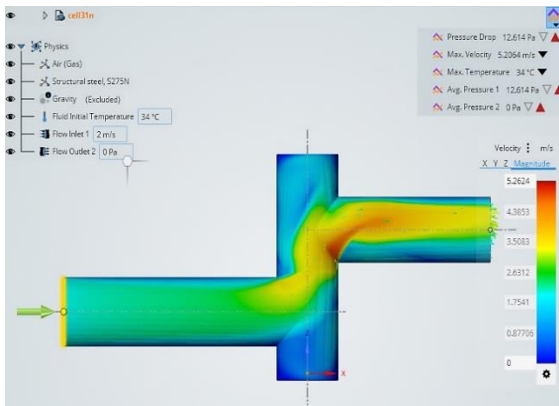


Figure (6): The analysis results showing the velocity distribution for 31mm GFC.

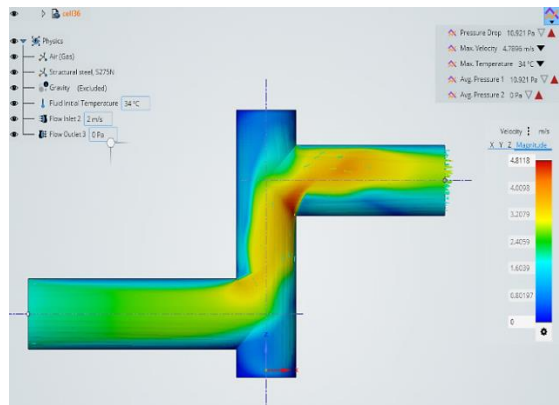


Figure (7): The analysis results showing the velocity distribution for 36mm GFC.

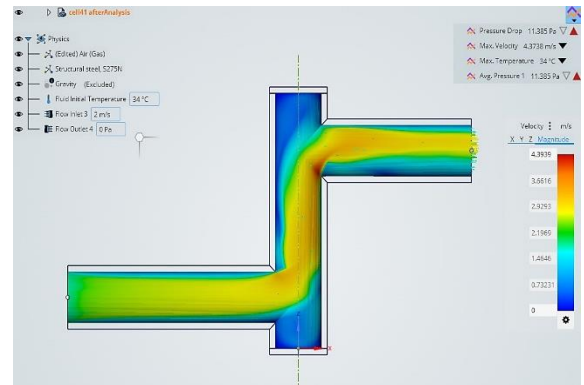


Figure (8): The analysis results showing the velocity distribution for 40mm GFC.

Table (1): The maximum velocity (m/s), the average pressure drop (Pa), and the fraction absorbance of the GFCs.

Measured Parameters	GFC Length		
	31mm	36mm	40mm
Maximum Velocity (m/s)	5.206	4.789	4.373
Average Pressure Drop (Pa)	12.614	10.921	11.385
Fraction Absorbance	0.793	0.799	0.851

In this study, we evaluated the optical path length of the mainstream NDIR capnometry both experimentally using a custom made gas testing rig that simulates CO₂ gas concentrations during CPB, and by using flow simulation software to explore the turbulent and stagnation regions. The mainstream gas cell was the candidate design as it offers a simpler design, requires no additional disposable tubing and



water trap. More importantly, it can be used for high flow rates ($> 0.21/\text{min}$) [9].

The fluid analysis shows that the maximum velocity is at the point where the fluid changes its flowing direction, far from the detector; therefore, the red flow region has no effect on the optical path, i.e., no turbulent flow occurs between the source and the detector path. The blue areas near the source and the detector represents stagnation regions. The ratio between flow and stagnation regions of 40mm cell is more than that in 36mm and 31mm. Therefore 40mm cell is considered the best of the three cells as it offers a more extended absorption area for the NDIR sensor. The results are consistent with [18] as they suggested increasing optical path length for improving NDIR sensor performance.

Furthermore, in practice, the maximum fraction absorbance was obtained when using 40mm GFC. The results show that the path length has nearly no effect on the pressure drop (11~12 Pa).

4. Conclusion:

This study demonstrated the effect of optical path length on NDIR CO₂ sensors aimed to be used for CPB oxygenators. Our results showed that GFC of 40mm is better than 36mm and 31mm in terms of maximum fraction absorbance, larger effective optical path length for IR absorption, and the maximum velocity generated at the exit is minimum. Therefore, a GFC with a 40mm optical path length or higher is recommended for the intended application.

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