

Flow Based Oxygen Leak Detection System in Self-Contained Breathing Apparatus

Prakash Chapain, Omar Bekdash, and Arthur T. Johnson*

Department of Bioengineering, University of Maryland, College Park, MD

* Corresponding author & E-mail: artjohns@umd.edu

ABSTRACT

Even though closed-circuit self-contained breathing apparatus (CC-SCBA) used in firefighting and other combustible atmospheres can possibly improve physical performance of the wearer and have increased service times by recycling the exhaled air, there exists a serious burn hazard to the wearer due to oxygen-enriched air leaking from the positive-pressure facepiece area of the CC-SCBA. NIOSH has imposed a long-standing advisement against the use of oxygen-based closed-circuit respirators in high radiant or open flame environments. The purpose of this study was to develop and employ a flow sensing system to be installed on a SCBA unit with a goal of minimum oxygen leak detection and quantification. Three flow sensors were placed and adapted at various locations of the oxygen flow loop, and the flow data, taken on a breathing machine and headform, were acquired to determine the magnitude of the various leaks induced on the facepiece area. Five different leak sizes were induced during normal breathing by installing different diameter tubes on the periphery of the face piece of the CC-SCBA allowing for air to escape at different rates that increased with increasing diameter of the tubes. Flow measurements were performed for seven different conditions: no leak, no leak repeated, and 5 different leak sizes. For each sensing unit, total flow and mean flow rates were calculated and the information was used to determine the magnitude of total leaks. Results indicated two major conclusions: i) Mean flow rates of inhalation and exhalation decreased with increasing leak sizes, ii) Calculated leaks increased with increasing induced leaks. Both of these analytical observations validated the theoretical assumption under which the experiments were performed. A less than 5 % difference was observed between two no leak conditions; and between no leak and the smallest leak conditions, a more than 20 % difference was observed indicating a sufficient sensitivity of the system necessary to differentiate a leak from a no leak scenario. There was a greater than 350 % difference calculated between the biggest induced leak and no leak condition. Results were limited by the reproducibility of the breathing waveform. However, given that restriction, the obtained positively indicate that a flow based sensor system for oxygen leak detection can be employed for developing safer CC-SCBA units to be used in combustible environments.

Keywords: closed circuit self-contained breathing apparatus, respirator fit, respiratory protection, oxygen leak

INTRODUCTION

A closed circuit self-contained breathing apparatus (CC-SCBA) is used in IDLH (Immediately Dangerous to Life and Health) situations for the purpose of supplying breathable air to the wearer. CC-SCBA can recycle exhaled air by removing carbon dioxide, but saving oxygen and inert gases. This process of recycling directly augments the portion of oxygen in the compressed gas cylinder, which benefits the wearer in two ways. It allows either extended service times with the same size cylinder or the same time and lighter weight with a smaller cylinder. It has also been reported that CC-SCBA wearers can improve their physical exertion by breathing oxygen-enriched air (Williams, 1998). Many CC-SCBA without oxygen enrichment are, however, used by firefighters in combustible environments. Even though the use of oxygen enriched air in the air tank of the CC-SCBA contributes to extended service times, oxygen enrichment is currently prohibited for CC-SCBA used in firefighting or other combustible atmospheres due to wearer burn hazards because of the possibility of oxygen rich mixtures leaking from the positive pressure facepiece (NIOSH, 1985). Relevant tests have been done to reveal that the facepiece fit accounts for the biggest problem for a closed circuit respirator to provide adequate protection against oxygen leaks (Rehak, 2008). Because of the risks involved, NIOSH has imposed a long-standing advisement against the use of oxygen-based closed-circuit respirators in the presence of high radiant heat or open flames based upon concerns of user burn injury from the potential oxygen enriched atmospheres in the vicinity of the facepiece leaks (Rehak, 2008). There are several possible ways to detect oxygen leaks from an CC-SCBA. Nevertheless, attention should be directed to leak detection from the periphery of the facepiece because it represents the most likely site of leakage. Wherever the location of the leak, one method of such leakage determination is monitoring the flow of oxygen to and from the facepiece. Pneumotachometers can be placed at various locations in the airflow loop and the flow of gas can be monitored at different stages of the airflow. This allows us to acquire the necessary flow information to detect and calculate leaks from a closed-circuit SCBA. The main objective of this work was to assess if this approach could be employed to detect oxygen leaks from a CC-SCBA and thereby, empirically find the minimum possible detectable leak.

METHODS

This study of the use of flowmeters to detect and identify leaks from a CC-SCBA was completed over a series of steps as detailed in the following sections.

Flowmeter-Transducer Selection

The first phase of the research involved the selection of flowmeters with the required sensitivities that could be adapted and retrofitted to the CC-SCBA. Together with transducers, these flowmeters would serve as the flow sensing units. There were three main constraints for the selection of the flowmeter-transducer system: 1. Range of flow 2. Size and adaptability 3. Speed. Based upon these constraints, a pneumotachometer was used as the main flow detecting unit that detects and measures flow by converting flow to pressure. A differential pressure transducer was then used to convert the differential pressure to voltage. Two pressure taps from the pneumotachometer were connected to higher and lower pressure taps of the differential pressure transducer respectively by the use of flexible plastic tubing thereby creating a flow sensing unit. Two Hans Rudolph pneumotachometers (Hans Rudolph, Inc., Shawnee, KS, Series 3700, 0-160 L/min) and one Fleish type # 2 pneumotachometer (Phipps and Bird, Richmond, VA, 0200 L/min) were used with three differential pressure transducers (All Sensors, Inc., Morgan Hill, CA, Part number: 0.25 INCH-D-4V) for the study.

Flowmeter Calibration

The flowmeters were to be located in different locations of the CC-SCBA, and flow differences would need to be taken in order to detect leaks. Care must be taken to assure that flow differences reflect real values and not just differences due to flow device tolerances or manufacturers' inaccuracies. Hence, flowmeter calibration to determine exact flows from each of the devices was necessary. All three flowmeters were calibrated for a flow scale of -80 L/min to +80 L/min, considered adequate for flows within CC-SCBA. A Gilmont flowmeter (Gilmont Instruments, Inc., Model F-4001, Tube Size 4) was used with known flow rates for linear scales for the calibration purposes. The pneumotachometers were placed in series to assure that the same air flow rate was experienced by each flow device. Air was supplied by pressurized air supply through the Gilmont flowmeter and three pneumotachometers in series at increasing flow rates based on the linear scales on the Gilmont flowmeter. For each flow rate, voltage readings were obtained from the 3 differential pressure transducers connected to their respective three pneumotachometers. Thus, a flow to voltage relationship was achieved for each pneumotachometer-transducer (PT-TD) pair for a full calibration range. Flowmeters are sometimes sensitive to pressures at their inlets and outlets. Thus, the calibration process was repeated 5 more times by switching the positions of the three pneumotachometer-transducer pairs for all permutations of the series arrangement. Calibration curves for the three flowmeters were not found to change with change in relative position.

System Setup and Placement of Flowmeters

The experimental system setup comprised the following components: CC-SCBA, breathing pump, manufacturer-designated medium-sized headform, data acquisition unit, computer, and data analysis programs. A Biopak 240R Revolution (Biomarine, Inc., Exton, PA) was the closed-circuit rebreather used during all of the experiments of leak detection. A motorized syringe (Vacu-Med, Ventura, CA, Model No. 857-001) was employed as a mechanical breathing pump for the purpose of eliciting a continuous reproducible breathing waveform. The breathing pump was connected to the mouth orifice of a metal headform using plastic tubing. The facepiece portion of the rebreather was applied to the head form following proper directions from the rebreather manual to ensure a tight leak-free fit. Modeling clay was used around the mask periphery to assure a complete seal between the facepiece and the head form. The three pneumotachometers were placed at three different locations of the breathing loop (Figure 1). One flowmeter (#2 in the Figure) was located in the oxygen supply hose, a second flowmeter (#3) was located in the return hose, and a third flowmeter (#1) was located at the syringe, in the position normally occupied by the mouth when the CC-SCBA is worn. The position and placement of the three sensors was of particular significance to the overall leak detection. Voltages were acquired by a National Instruments (Austin, TX) USB-6008 data acquisition board via three channels, one for each flow sensor. In addition to being the principal data acquisition unit, the NI USB-6008 also provided two other vital applications. The most important task was to serve as an analog to digital converter for the signal. Secondly, it provided the excitation voltage necessary for the functioning of the pressure transducers. The data acquisition unit was connected to a computer (Dell, Inc., Model Inspiron 17, Round Rock, TX) by a USB cable and port. LabView (National Instruments, Inc., Austin, TX), MATLAB (Mathworks, Inc., Natick, MA), and Excel (Microsoft, Inc., Redmond, WA) programs were installed in the computer and used to analyze the data.

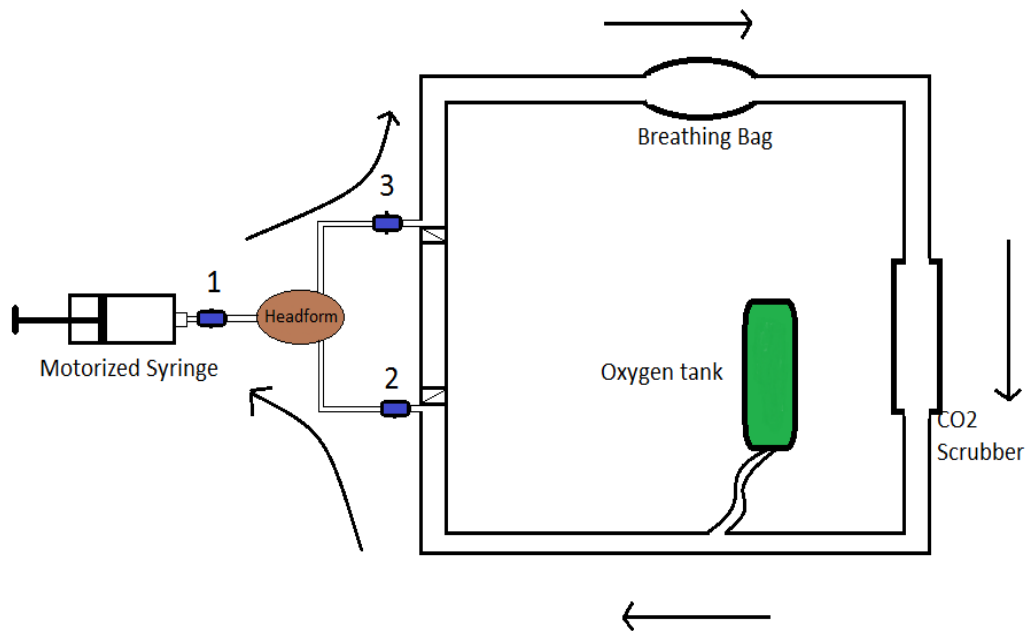


Figure 1. Placement of three flowmeters in the breathing loop. The arrows represent the flow direction.

Induced Leaks

A major portion of the tests involved taking flow measurements from the sensors embedded at various locations in the system while different sized leaks were introduced. A total of five different leaks were used by employing varying internal diameter plastic tubes (1.2, 1.6, 3.2, 4.8, and 7.94 mm, or 3/64, 1/16, 1/8, 3/16, and 5/16 inches). Prior to the induction of leaks into the system, volumetric flow rates for each of the leaks were experimentally determined. Since leaks result because of pressure differences inside the facepiece and the atmosphere, average pressure inside the facepiece was determined first in order to find the flow rates through each tube used for leak induction.

A tube with internal diameter of 7.94 mm (5/16 inch) was inserted inside the facepiece and its other free end was connected to a manometer (Dwyer Instruments, Inc., Michigan City, IN, Model 40-1) for pressure sensing. The entire system was turned on and allowed to equilibrate and pressure inside the facepiece was read from the manometer. This pressure was found to be 0.03 cm of water. Flow rate determinations for various leak sizes that followed were based on this pressure reading.

Each of the tubes was attached to a "T" connection with one port of the "T" connected to the manometer while the other to a manually operated 3L syringe pump. The syringe was then pulled to fill up the 3L volume while keeping the pressure at the previously determined value of 0.03 cm of water. The time taken to draw the full 3L volume was noted for each of the five tubes. Three trials were performed for each tube. Using the empirically determined times and the total volume of 3L, flow rates for each of the five tubes were calculated (Table I).

These leaks were later introduced into the system at different times by inserting each tube on the periphery area of the facepiece directly (Figure 2). Proper caution was taken not to create unintended leaks because of tube insertion by sealing the tube-facepiece interaction region with modeling clay.

Table I. Five Different Profiles for Induced Leaks

Leaks	Tube Diameter (mm and inches)	Flow Rates (L/s)
1	1.2 (3/64)	0.003
2	1.6 (1/16)	0.005
3	3.2 (1/8)	0.036
4	4.8 (3/16)	0.069
5	7.9 (5/16)	0.075

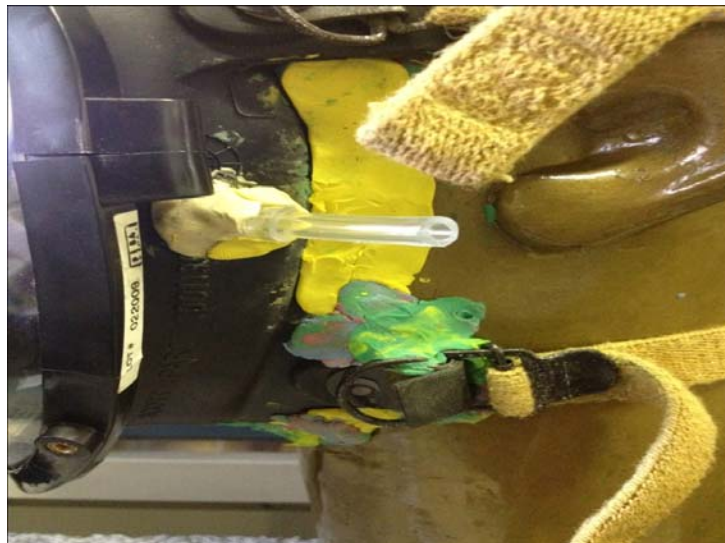


Figure 2. A tube inserted inside the facepiece to induce a leak. Clay was used to seal off unintended leaks.

Experiments and statistical analysis

The experimental phase consisted of running the system for seven different conditions. The first two conditions involved flow measurements from the sensors without any deliberate leaks within the breathing loop and the system. These conditions were appropriately named 'no-leak 1' and 'no-leak 2' for nomenclature purposes. The no-leak condition was repeated in order to determine the reproducibility of the measurement system without any induced changes. The remaining five conditions involved different sized induced leaks in the facepiece area of the CC-SCBA. Leaks consisted of various diameter plastic tubes inserted under the periphery region of the facepiece (Figure 2) and allowed for air to continuously escape *ad libitum*.

The motorized pump was set to 1 L tidal volume and 15 breaths per minute (br/min). The total time for each testing and recording session was 12 seconds, which represented three breathing cycles. Numerical integration of the flow curves using MATLAB was performed for each flowmeter to obtain tidal volumes of gas that passed through each over the time period of 12 seconds. Mean flow rates for the inhalation and exhalation sensors were also calculated over the same time interval for each condition.

RESULTS

The first phase of the research involved the calibration of the pneumotachometer-transducer (PT-TD) system for known flow rates for a particular range. A voltage to flow relationship was obtained for each pair after calibration. Figure 3 shows the relationship curves for all 3 sensors.

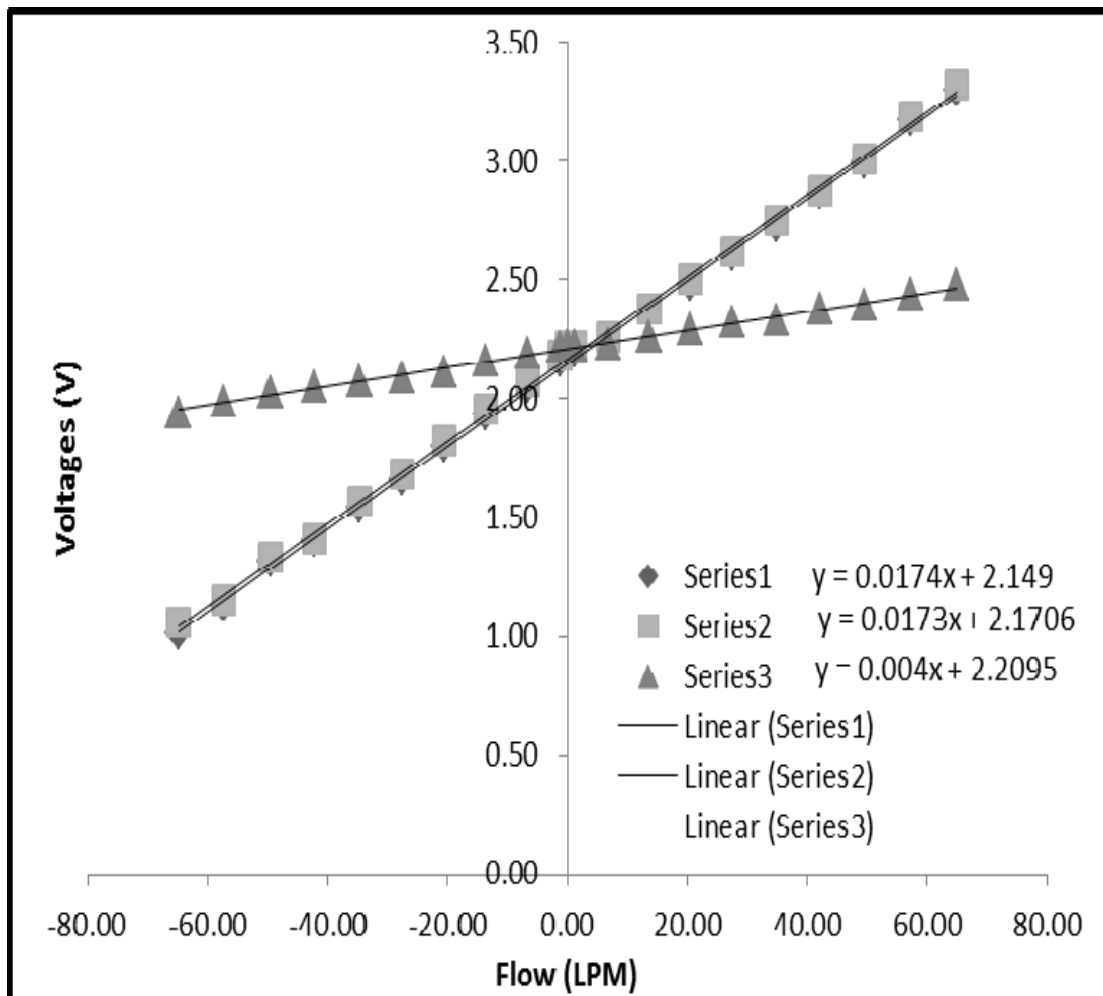


Figure 3. Voltage-flow relationship curves for three flow sensors. The two Hans-Rudolph pneumotachometers (series 1 and 2) gave almost identical calibration curves. The Fleisch pneumotach (series 3) had a different calibration.

To assess the validity of the calibration results and accuracy of the three sensor systems, the three PT-TD pairs were subjected to a range of flows individually and the obtained voltage outputs were converted to flows using the determined voltage-flow relationship equations. Output of each sensor was plotted against the other two to correlate the output flows from each sensor (Figure 4).

After the calibration of the sensors, and proper placement and adaptation into three different points of the breathing loop, the system was tested for seven different conditions. Flow waveforms from all the three sensors were generated and acquired for the first two no-leak conditions, and the following five with induced leaks of various magnitudes. Figures 5 through 7 show the resulting flow waveforms

over an interval of 12 seconds representing three breathing cycles for three different conditions of no-leak 1, Leak 1 (the smallest induced leak), and the biggest induced Leak 5. The graphs were plotted with the raw data obtained from the sensors without any filtering, or intermediate processing.

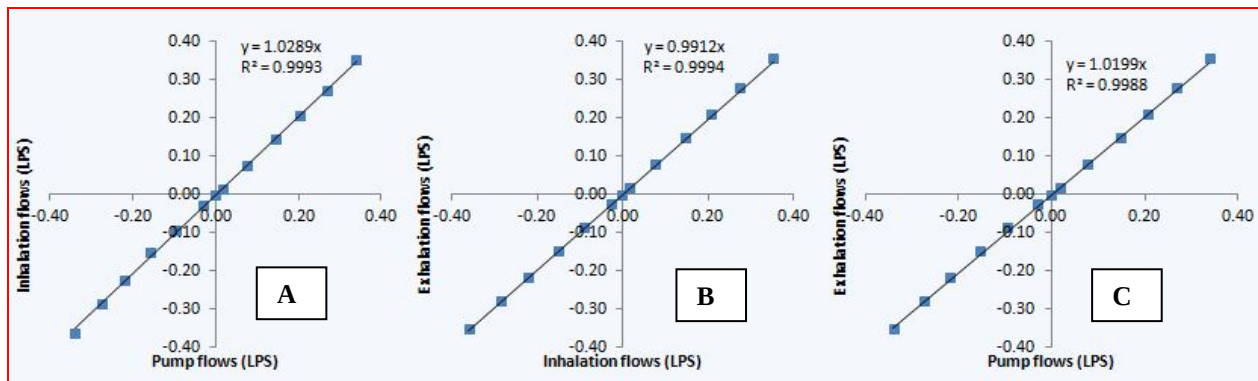


Figure 4. Output relationship curves between three sensors after calibration: A. Flowmeter 1 vs Flowmeter 2, B. Flowmeter 2 vs flowmeter 3, C. Flowmeter 1 vs flowmeter 3. These lines demonstrate that flow rate differences between any two pneumotachometers can be made accurately and precisely.

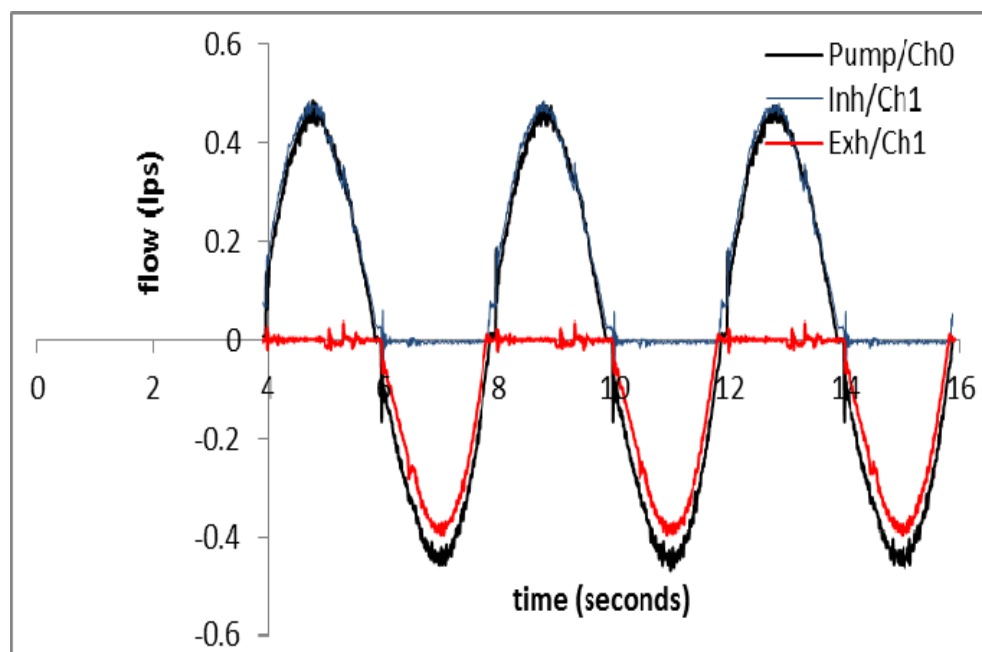


Figure 5. Flow waveforms generated for three sensors for No Leak 1. Pneumotach 1 (in black) senses pump flow, pneumotach 2 (in blue) senses inhalation flow, and pneumotach 3 (in red) senses exhalation flow.

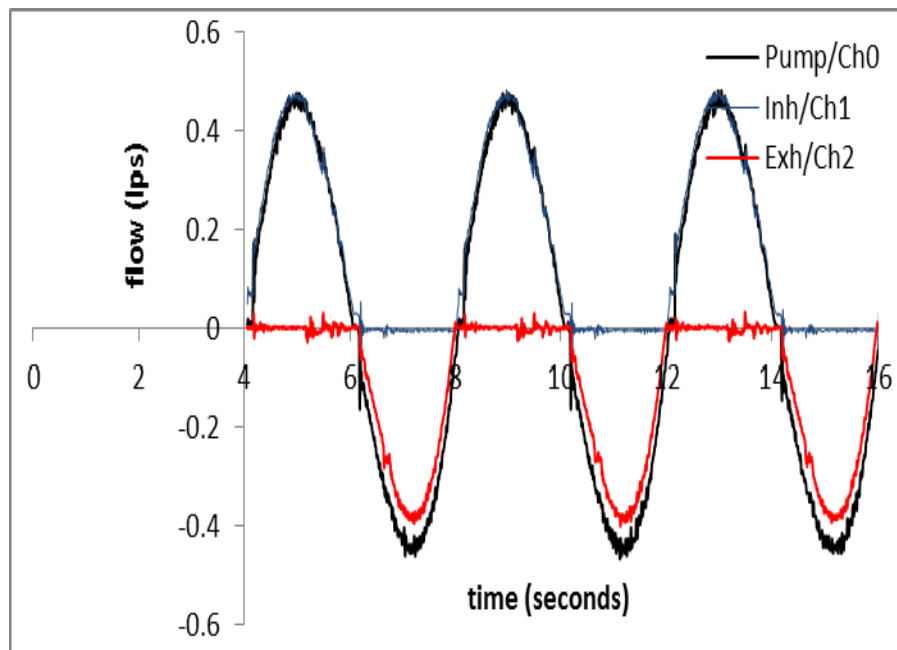


Figure 6. Flow waveforms generated for three sensors for Leak 1 (1.2 mm). Pneumotach 1 (in black) senses pump flow, pneumotach 2 (in blue) senses inhalation flow, and pneumotach 3 (in red) senses exhalation flow.

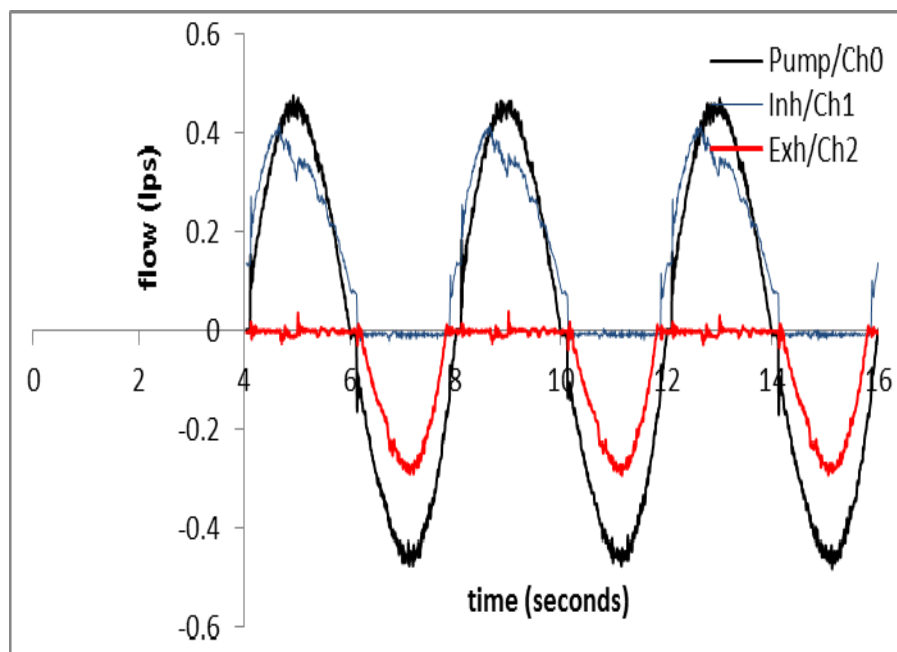


Figure 7. Flow waveforms generated for three sensors for Leak 5 (4.8 mm). Pneumotach 1 (in black) senses pump flow, pneumotach 2 (in blue) senses inhalation flow, and pneumotach 3 (in red) senses exhalation flow.

The waveform data from the flows through the sensors were taken and integrated over the whole period of 12 seconds and total flow volumes through each of the flowmeters were calculated for each of the seven conditions.

Leak detection was based on flow data acquired from the sensors during the seven different trials. Total flow data from the three sensors was used to calculate leaks from the following equation:

$$\text{Leak} = \text{Pump Flow} - (\text{Inhalation Flow} + \text{Exhalation Flow})$$

Total leaks in each case were determined by subtracting total volumes from inhalation (#2) and exhalation (#3) sensors from the volume of the pump sensor (#1). Table II illustrates all the flows calculated for each sensor for each test condition over a fixed time of 12 seconds and the leaks determination thereafter.

Table II. Calculated Total Flows Through Each Sensor and Overall Leak Calculation for Each Test

Test Condition	Flowmeter 1: Pump (L)	Flowmeter 2: Inhalation (L)	Flowmeter 3: Exhalation (L)	Leak (L)
No Leak 1	3.46	1.9	1.39	0.17
No Leak 2	3.47	1.9	1.39	0.18
Leak 1	3.5	1.91	1.38	0.21
Leak 2	3.45	1.88	1.31	0.26
Leak 3	3.46	1.88	1.23	0.35
Leak 4	3.47	1.88	1.17	0.42
Leak 5	3.49	1.82	0.9	0.77

It can be seen that with increased induced leaks the magnitude of calculated leaks also increased. However, for the first two test conditions in which no leaks were induced, some small leak was detected anyway. From the graph presented in Figure 8 and the data in Table II, it was not easy to differentiate a relatively small leak from a no-leak condition. The calculated leaks data were utilized to calculate the percent differences between each induced leak and the no-leak condition (Table III).

Table III. Percent Differences in Leaks Calculated between a No Leak and a Leak Test Condition

Condition	Leaks (L)	% Difference
No leak 1	0.17	-
No Leak 2	0.18	3.37
Leak 1	0.21	24.4
Leak 2	0.26	53.9
Leak 3	0.35	107
Leak 4	0.42	146
Leak 5	0.77	355

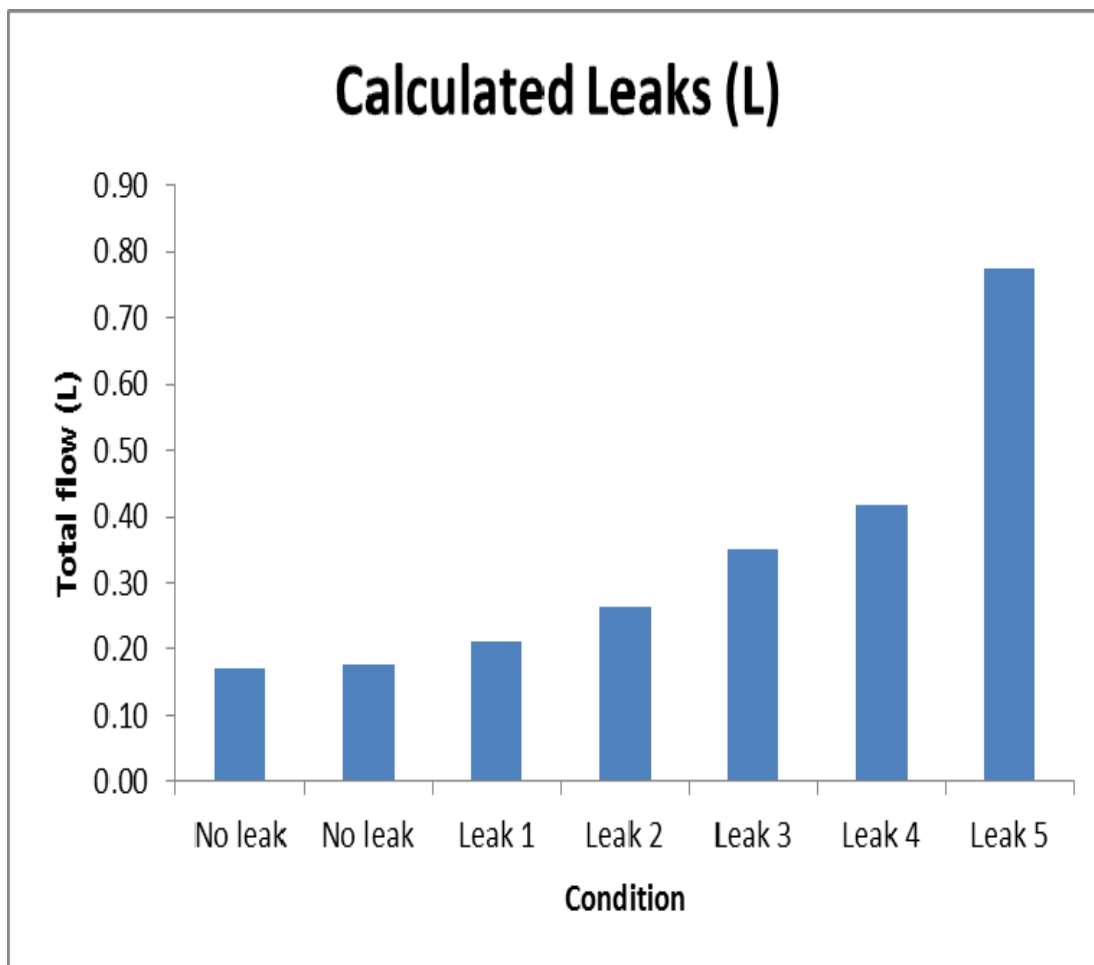


Figure 8. Total leaks calculated for each test condition.

A difference of 3.37% was found between the two no-leak trials. However, the percent difference jumps to almost 25% between the first no-leak and induced leak 1 test conditions. Between the first no-leak and the largest induced leak scenario, a percent difference of greater than 350% was found. In addition to the total flows through each sensor, mean flow rates for the inhalation and exhalation sensors were also derived over the total time period of measurement (Figure 9). The decrease in mean flow rates for the exhalation sensor (#3) was found to be greater than for the inhalation sensor (#2). Greater decreases of mean flow rates indicate higher rates of leakage. The results show that there was a greater amount of leakage during the exhalation phase of the breathing cycle than during the inhalation phase. However, for both the inhalation and exhalation sensors, a decrease in mean flow rates was observed between the first no-leak and the largest leak scenarios.

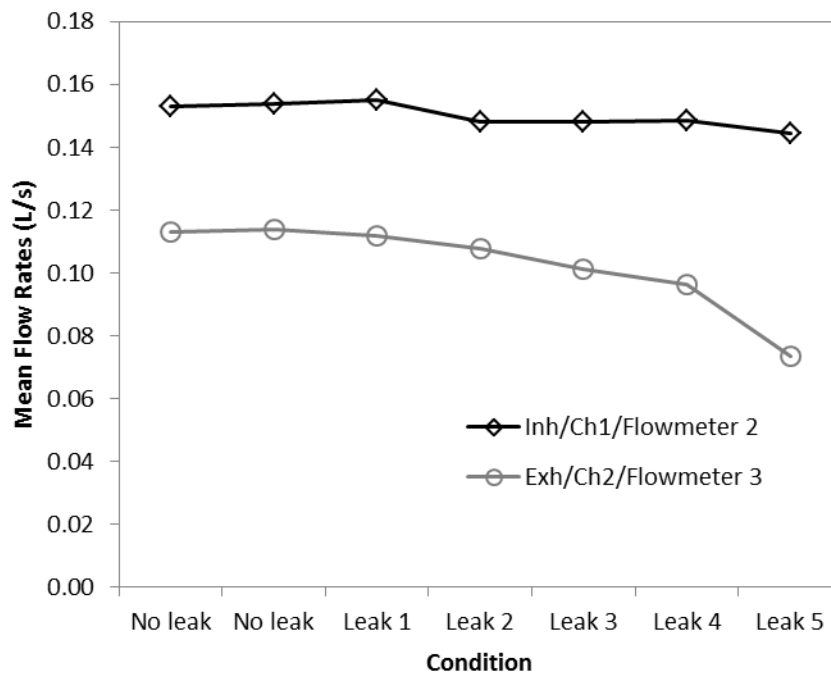


Figure 9 Calculated mean flow rates for inhalation and exhalation sensors for each test condition.

DISCUSSION

An approach to leak detection in CC-SCBA by the employment of flow sensors was presented. There are multiple benefits of using the flow approach to detect leaks. The proposed flow sensors are small, fast, portable, sensitive and can be more easily retrofitted to an existing CC-SCBA than other possible sensors. The presented placement of flowmeters allows for monitoring of the entire flow loop, not just the facepiece region. The direct benefit of this methodology is that detection of leaks is not limited to the facepiece periphery leaks.

Prior to the placement and adaptation of the flow sensors at various locations in the system, proper calibration was performed. Results in figures 3 and 4 are strongly indicative of good calibration. Voltage-flow relationships were acquired for all three sensors for a full range of flow considered adequate for our purposes. When subjected to the calibration check, output flows for the three sensors linearly correlated with a coefficient of very close to 1. This calibration of the sensors allowed eliminating errors in experimental measurements. Any flow differences obtained from two different sensors at any point during experimentation would reflect real values and not differences due to the use of different devices.

Even without any leak induction in the system, a minimal amount of leak was detected. In Figure 5, it can be observed that the flow curves for pump sensor (#1) and exhalation sensor (#3) do not completely overlap, which suggests a leak in the system during the exhalation cycle of breathing even when no leak was induced. In order to separate a leak from a no leak condition, the trial was repeated with no induced leak and a percent difference of 3.37% was calculated. The first induced leak resulted in a percent difference of almost 25% from the No leak 1 condition suggesting a strong leak detecting capability of the sensor system. With increasing size of induced leaks, greater leaks were calculated and

significant percent differences were observed. For the biggest induced leak, a percent difference of greater than 350% was noticed.

Results from the mean flow rates for sensors #2 (inhalation) and #3 (exhalation) suggest both decrease with increasing leaks. However, it is noticed that the magnitude of leaks were higher during exhalation than during inhalation. Mean flow rates for exhalation sensor decrease at a higher rate with increasing leak sizes than that for inhalation sensor.

As mentioned throughout, a total of three sensors were used to in detecting oxygen leaks in CC-SCBA. However, it can be argued that we might have achieved similar results by employing only two sensors instead of all three. If able to do so, it would prove useful especially during leak detection experiments and real world situations involving human CC-SCBA wearers. The insertion of a flowmeter to detect the breathing flow rate of a wearer might be difficult and the removal of that particular sensor would be desirable. However, unlike breathing machines, human breathing waveforms are not guaranteed to be repeatable, so including a sensor comparable to our pneumotach #1 would be required to calculate total breathing flows.

CONCLUSIONS

Total leaks were able to be calculated from the flow information from the three sensors strategically placed at three different points of the breathing loop. Calculated leaks increased linearly with increasing induced leaks in the system. Total leaks were higher during exhalation than during inhalation. However, with increasing leaks, mean flow rates decreased for both the inhalation and exhalation sensors. The results strongly indicate that flow sensors placed correctly in the CC-SCBA flow circuit could be employed on a CC-SCBA system for oxygen leak detection.

Acknowledgements

The authors gratefully acknowledge that work in this paper was supported by NIOSH contract 200-2010-32954, Detection of Oxygen Leaks for Self-Contained Breathing Apparatus (SCBA).

REFERENCES

- NIOSH, 1985, NIOSH/MSHA Testing and Certification of Positive-Pressure Closed-Circuit Self-Contained Breathing Apparatus, Federal Register vol. 50 (222) pp. 47456-47457 (18 November).
- Rehak, T. (2008) NIOSH O₂ Prohibition, NIOSH Public Presentation, Sheraton-Station Square, Pittsburgh, PA.
- Williams, B. E. (1998) The effects of oxygen-enriched air on firefighter job performance, National Fire Academy Executive Fire Officer Program Report (Feb), pp. 113-154.
http://www.usfa.fema.gov/downloads/pdf/tr_98bw.pdf.