NIST Technical Note 1809

Exploratory Study of Airflow from SCBA Exposed to Elevated Temperatures

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Abstract

This report describes an exploratory set of experiments that investigated the impact of external airflow temperature on the temperature of Self-Contained Breathing Apparatus (SCBA) supply air, and the potential for the supply air to be heated when subjected to an elevated temperature environment during fire fighting operations. For these experiments, an entire SCBA assembly was placed inside an elevated temperature flow loop. The SCBA facepiece was fitted onto a mannequin headform, and a computer controlled breathing simulator provided artificial breathing. The SCBA was exposed to airflows with temperatures ranging between 100 ºC and 200 ºC (212 ºF and 392 ºF) for time durations up to 1200 s (20 min). The temperature of the air from the SCBA was measured in the mannequin's mouth. The results of these experiments demonstrate that the supply air temperature increases when the SCBA is exposed to external conditions of elevated temperatures. The increase in temperature of the supply air was greater for the tests at the higher external airflow temperatures, and the SCBA supply air temperature increased as the duration of exposure to the elevated temperatures increased. A simple energy balance model was developed to characterize the heat transfer process for the breathing air exiting the SCBA cylinder during thermal exposure. This model is used to predict the approximate temperatures of the breathing air as a function of time and external airflow temperature. The model closely predicts the experimental measurements for the three airflow temperatures used in these experiments.

Table of Contents

Introduction 1

Background 1

Testing Procedures 2

Experimental Uncertainty 9

Results 10

Discussion 18

Conclusions 21

References 22

Acknowledgements 22

Appendix 23

Introduction

Fire fighters often face hazardous environments where there are reduced oxygen concentrations or the presence of dangerous contaminants in the atmosphere. To enter and work in these hazardous conditions, fire fighters use a Self-Contained Breathing Apparatus (SCBA). SCBA are portable breathing devices used to provide an individual with a supply of clean breathing air. SCBA are essential gear for search and rescue, fire extinguishment, and other fire fighting operations.

Elevated temperatures are another danger typically present in a fire fighting environment. Exposure to elevated temperatures introduces the potential for temperature increases to the breathing air supplied by the SCBA. Fire fighters have provided anecdotal accounts of the breathing air from their SCBA being heated to uncomfortable temperatures. Questions have been raised, based on recent Line of Duty Death incidents, of the potential for fire fighters to suffer respiratory tract injuries due to breathing hot air from SCBAs. In a given thermal environment, key questions are:

1) How hot can the air in an SCBA become?

2) How quickly can the air in an SCBA heat up?

An exploratory investigation was conducted to examine the impact of environmental temperatures on the temperature of the SCBA supplied air. The experiments provide a preliminary look at the potential for the supply air in an SCBA to be heated when subjected to an elevated temperature environment. For the experiments discussed in this report, an entire SCBA assembly was placed inside an elevated temperature flow loop apparatus and the resulting SCBA air temperature was measured within the facepiece.

Background

SCBAs used by the fire service in the United States are designed to meet the standard requirements set forth by the National Fire Protection Association (NFPA). NFPA 1981: Standard on Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, applies "to all open-circuit SCBA…used by emergency services organizations for respiratory protection of its personnel during fire fighting, rescue, hazardous materials, terrorist incident, and similar operations where products of combustion, oxygen deficiency, particulates, toxic products or other IDLH (immediately dangerous to life or health) atmospheres exist or could exist at the incident scene [1]." NFPA 1981describes various design and performance requirements, including rigorous test specifications, which an SCBA must meet or exceed to obtain certification. Included among the requirements are specifications for heat and flame resistance

performance, detailed in NFPA 1981, Chapter 8.11 Heat and Flame Test. Test methods include subjecting the SCBA to an oven that is pre-heated to a temperature of 95 ºC (203 ºF) for 15 minutes, while operating at a ventilation rate of nominally 40 L/min (1.4 cfm). Immediately following the elevated temperature exposure, the ventilation rate was increased to 103 L/min (3.6 cfm), and the SCBA subjected to 10 s of direct flame impingement. After these exposures, "no component of the SCBA shall separate or fail in such a manner that would cause the SCBA to be worn and used in a position not specified by the manufacturer's instructions," and "no components of the SCBA shall have an afterflame of more than 2.2 seconds." In addition, "the SCBA facepiece pressure shall not be less than 0.0 mm (0.0 in.) water column and shall not be greater than 89 mm (3.5 in.) water column above ambient pressure from the time the test begins until the time the test is concluded" [1]. These requirements are designed to ensure that SCBA manufactured for use by fire fighters perform adequately in a fire fighting environment.

Injuries can occur to the human respiratory tract due to the inhalation of hot gases. When the temperature of the tissue in the respiratory tract increases above 44 ºC (111 ºF), it can result in damage to the tissue [2]. The rise in temperature of the tissue is a complex interaction that varies based on the composition of the gas and the heat capacity of each individual's tissue. Depending on the exposure time, burns to the larynx may occur by breathing dry air at temperatures around 120 ºC (248 ºF) [3]. The addition of humidity, steam, or smoke can increase the thermal capacity or latent heat of the air. Such air at temperatures of 100 ºC (212 ºF) can cause burns if inhaled [3]. The condition of the air, including the temperature and humidity, must be sufficient to cause facial burns in order for thermal burns to the respiratory tract to occur [3].

Testing Procedures

For this exploratory investigation, all tests were completed using a Scott Air-Pak 75 SCBA assembly. The SCBA included a carbon-fiber reinforced aluminum-lined compressed air cylinder, with a maximum working pressure of 31.03 MPa (4500 psi), rated for 45 min. The cylinder was certified to U. S. Department of Transportation (DOT) Special Permit (SP) *DOT-SP 10915, 18th revision* requiring compliance with DOT Basic Requirements for Fully Wrapped Carbon-Fiber Reinforced Aluminum Lined Cylinders, *DOT- CFFC, 5th Revision, March 2007*. Prior to testing, the cylinder underwent the required hydrostatic testing as specified in *DOT-SP 10915*. The SCBA assembly used a Scott AV-3000 facepiece.

An elevated temperature flow loop was used to supply the testing environment for the SCBA equipment. Figure 1 shows a photograph of the NIST flow loop apparatus. The blue arrows show the direction of the air flow. A 50 kW air duct heater located in the flow loop is used to heat the air to the desired temperature to provide convective heat flow. An adjustable

rate electric blower located below the heater circulates the air through the flow loop. The test section of the flow loop provides space for the SCBA equipment to be placed during the high temperature exposure tests. The test section of the flow loop has a 0.91 m by 0.91 m (3 ft by 3 ft) cross sectional area. Thermocouples and bi-directional probes located in the test section provide air temperature and velocity measurements. A return airflow duct carries the air back to the blower, where it is recirculated through the loop. A movable platform located below the test section of the flow loop is used to setup and secure the SCBA equipment and to raise the equipment into the flow loop.

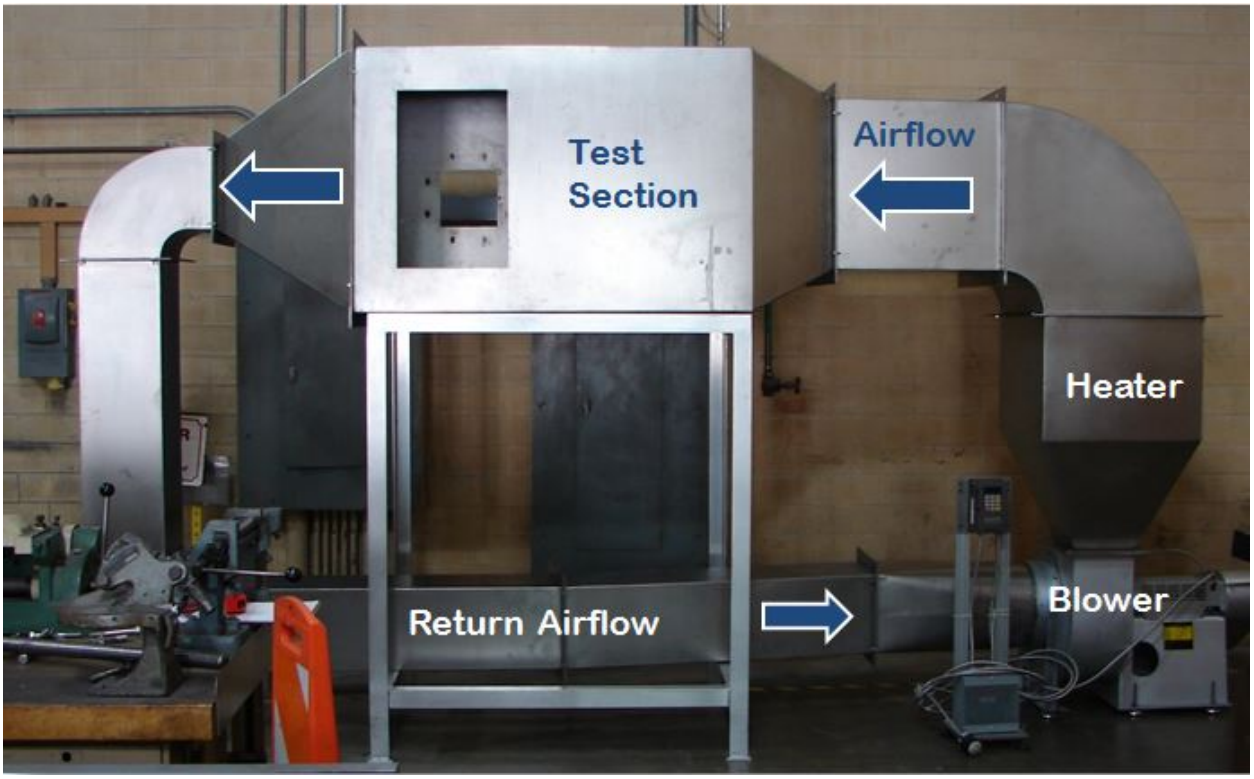

Figure 1 **Side view of NIST Flow Loop**

To perform the elevated temperature exposure tests, the SCBA cylinder and frame assembly was secured in the upright position by a support post mounted to the flow loop equipment testing platform. A mannequin headform was mounted on the testing platform, next to the support post, and the SCBA facepiece was positioned on the headform. Figure 2 shows a photograph of the SCBA equipment setup on the testing platform. For exposure testing purposes, the cylinder and the facepiece were positioned side by side, so that both faced into the oncoming airflow when raised into the flow loop. A protective fire fighting hood made of aramid was placed on the mannequin headform over the SCBA facepiece, as would typically be worn by a fire fighter.

Figure 2 **SCBA equipment on the flow loop testing platform**

The mannequin headform used for this investigation is of the same type as specified in NFPA 1981, Section 8.1 Airflow Performance Test, 8.1.4.1 [1]. A photograph of the mannequin headform is shown in figure 3. The headform is equipped with a nominally 38 mm (1.5 in) breathing passageway through its mouth, with an opening on the underside of the headform. This passageway may be connected to a mechanical breathing apparatus to allow for simulated breathing. When an SCBA facepiece is placed on the headform, air may be drawn through the SCBA to simulate breathing while wearing an SCBA. A pressure measurement probe is located in the headform, in the location of the left eye. This pressure probe was connected to a pressure transducer to monitor the pressure inside the SCBA facepiece.

Temperatures were measured using type-K bare-bead thermocouples. The sampling rate for all temperature measurements was 1 Hz. Two thermocouples were located inside the mouth opening of the mannequin head, to measure the temperature of the airflow through the mouth. This measurement is representative of the temperature of the air breathed by a fire fighter wearing an SCBA. The thermocouples inside the mannequin's mouth can be seen in the photograph of the headform in Figure 3. The thermocouples were located at the mid-height of the mouth, 1.0 cm ± 0.2 cm (0.39 in.) in from the right and left sides, and 1.0 cm ± 0.2 cm (0.39 in.) deep inside the passageway of the mouth.

Figure 3 **Mannequin headform with thermocouples inside mouth.**

Two thermocouples were attached to the SCBA facepiece. One was placed on the outside of the face piece, positioned along the centerline of the lens, 3.0 cm (1.2 in) below the silicon rubber gasket. The other thermocouple was placed on the inner surface of the lens, directly opposite the first thermocouple, centered and 3.0 cm (1.2 in) below the silicon rubber gasket. The thermocouples were secured in place with fiberglass tape. Figure 4 shows a photograph of the mannequin headform wearing the SCBA, along with the aramid heat-resistant protective hood. The thermocouples are visible on the facepiece. A thermocouple was also located on the outside of the SCBA cylinder, in order to record the temperature of the outer cylinder wall. This thermocouple was located along the centerline at the midway point of the cylinder, For some tests, an additional thermocouple was placed on the outside of the SCBA air hose, 25.4 cm (10.0 in.) below the connection between the hose and the regulator, at the midpoint of the hose facing the airflow.

Figure 4 **Thermocouples placed on SCBA facepiece**

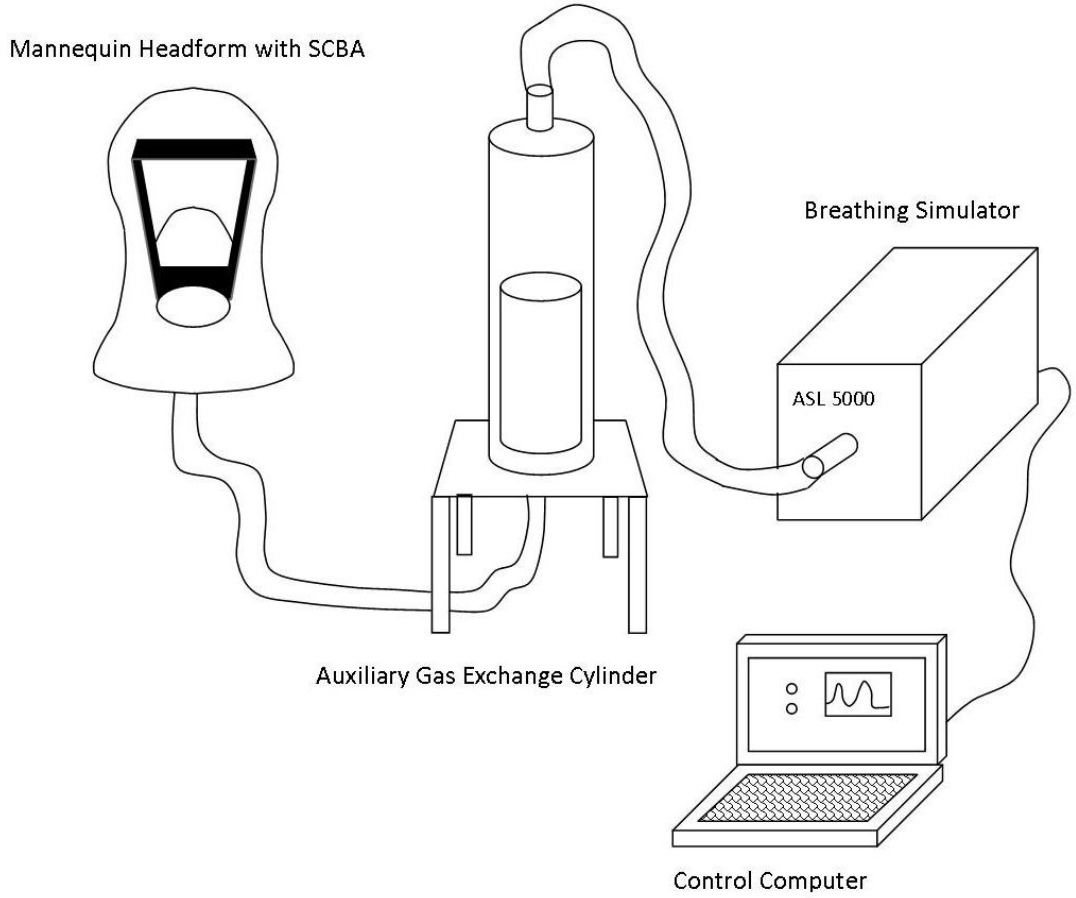

Figure 5 ASL 5000 Breathing Simulator System

The mechanical breathing operation for the mannequin head was provided using the Active Servo Lung 5000 (ASL 5000) Breathing Simulator. The ASL 5000 is a computer controlled system designed to provide the mannequin head with precisely controlled and repeatable artificial breathing. An electronic drive motor operates a piston to control airflow into and out of a cylinder to simulate breathing. A diagram of the ASL 5000 setup is shown in Figure 5. An Auxiliary Gas Exchange Cylinder with a bellows inside was used in-line between the breathing simulator and the mannequin head to protect the internal components of the breathing simulator from possible elevated temperatures. The ASL 5000 software was used to designate a controlled breathing profile with a sinusoidal waveform at a rate of nominally 40 L/min (1.4 cfm) for all tests. This breathing volume work rate is the lower of the two testing work rates as described in NFPA 1981 [1].

The SCBA cylinder was filled to its maximum capacity of 31 MPa (4500 psi) with compressed breathing air prior to the start of each test. The temperature of the cylinder was allowed to equilibrate to ambient room temperature. The full cylinder was installed in the SCBA frame assembly, and the whole SCBA assembly was secured to the support on the flow loop equipment testing platform, as shown in Figure 2. The SCBA face piece was positioned on the mannequin headform and secured in place with the facepiece straps. The facepiece was then connected to the rest of the SCBA assembly. Prior to each test, a breathing check was performed on the apparatus using the ASL 5000 breathing simulator. This check ensured that everything was properly connected, that the SCBA, mannequin, and breathing machine were operating correctly, and that there was no leakage from the SCBA or the facepiece.

For each test, an airflow temperature was selected and the testing section of the flow loop was pre-heated to the desired temperature. Tests on the SCBA were conducted at air flow temperatures of nominally 100 ºC (212 ºF), 150 ºC (302 ºF) and 200 ºC (392 ºF). The air speed inside the flow loop was set to the maximum blower speed of 1.4 m/s ± 0.3 m/s (3.0 mph). When the testing section of the flow loop reached the desired temperature, the equipment testing platform was then raised into the flow loop, exposing the entire SCBA assembly to the heated airflow. During the elevated temperature exposure, temperatures were recorded at all thermocouple locations at a data rate of 1 Hz.

Experimental Uncertainty

Uncertainties identified for the measurements in this report are described below and are a result of evaluating the Type A and Type B standard uncertainty as specified in [4]. Type A uncertainties are evaluated using statistical methods, and the Type B uncertainties are determined by estimating the upper and lower limits of uncertainty for the measurements.

The temperature measurements for these tests were made using bare-bead thermocouples, with bead diameters of nominally 1 mm. The thermocouples used type-K standard thermocouple wire manufactured by Omega Engineering. The manufacturer lists the standard uncertainty for this type of thermocouple wire as ± 2.2 ºC for the temperature ranges encountered in this investigation [5]. The thermocouples are subjected to some measurement uncertainty due to radiative heating from the flow loop. The combined standard uncertainty for the thermocouple measurements is estimated to be ± 8 %. The total expanded uncertainty for the thermocouple measurements with a coverage factor of two and a confidence level of 95 % is ± 16 %.

There are uncertainties associated with the reported measured location for the instrumentation used in these tests, including the placement position of the thermocouples. The component standard uncertainty for each location measurement is estimated to be ± 7 %. The combined standard uncertainty for the position of the instrumentation is ± 12 % and the total expanded uncertainty with a coverage factor of two and a confidence level of 95 % is ± 24 %.

The uncertainty in the flow velocity measurement is dependent on the accuracy of the instrumentation and the variations of measurement due to flow repeatability. The standard uncertainty due to accuracy of the velocity probes is ± 10 % [6]. The uncertainty due to the repeatability of the flow measurement is ± 11 %. The combined standard uncertainty of the flow velocity measurements is ± 15 %. The total expanded uncertainty with a coverage factor of two and a confidence level of 95 % is ± 30 %.

Results

A total of seven elevated temperature tests were performed on the SCBA. The first test was conducted with the SCBA exposed to an airflow temperature of nominally 100 ºC (212 ºF) for 1200 s (20 minutes). Four tests were conducted at airflows of nominally 150 ºC (302 ºF), two tests for 900 s (15 minutes) and two for 1200 s (20 minutes). The final two tests were performed with the SCBA equipment exposed to an airflow temperature of 200 ºC (392 ºF) for 1200 s (20 minutes). Because of the safety controls in place during these experiments, 200 ºC was the maximum temperature at which these experiments could be conducted in the NIST flow loop apparatus. When multiple tests were conducted at the same air flow temperature, the results were very repeatable. Measured temperatures were within ±5 ºC for repeat tests, which is less than the uncertainty in the measurements. Table 1 lists the tests performed, the nominal airflow temperature for each test, and the low and high temperatures recorded in the mannequin mouth at different times during the high temperature exposure. A temperature range is reported because the measured temperatures varied over the 10 s interval about each time, depending on whether the mannequin was inhaling or exhaling. The mean ambient temperature measured in the mannequins mouth prior to each test was 24 ºC (75 ºF) with at standard deviation of 1 ºC.

Table 1. Gas Temperature Measured at Mouth of the Mannequin

Test Number	Nominal Airflow Temperature	Mouth Temperature Range as Function of Time Exposure Low and High over 10 s interval			
		300 s	600 s	900 s	1200 s
1	100 ºC	34 ºC to 41 ºC	42 ºC to 50 ºC	46 ºC to 57 ºC	51 ºC to 60 ºC
2	150 ºC	45 ºC to 51 ºC	60 ºC to 65 ºC	65 ºC to 73 ºC	N/A
3	150 ºC	44 ºC to 50 ºC	55 ºC to 65 ºC	62 ºC to 73 ºC	N/A
4	150 ºC	45 ºC to 50 ºC	55 ºC to 65 ºC	63 ºC to 73 ºC	70 ºC to 80 ºC
5	150 ºC	42 ºC to 51 ºC	55 ºC to 68 ºC	63 ºC to 79 ºC	68 ºC to 85 ºC
6	200 ºC	47 ºC to 61 ºC	65 ºC to 84 ºC	76 ºC to 99 ºC	84 ºC to 110 ºC
7	200 ºC	48 ºC to 60 ºC	66 ºC to 85 ºC	78 ºC to 101 ºC	86 ºC to 110 ºC

Figure 6 shows a graph of the average temperature measurements as a function of exposure time for each of the thermocouples located inside the mannequin mouth during the test of SCBA equipment exposed to a nominally 100 ºC (212 ºF) airflow. This was the first test completed in this series, and it demonstrates an increase of temperature in the air supplied by the SCBA when it is exposed to elevated temperatures. For this test, the temperatures that were measured in the mouth began increasing after just 35 s of exposure to the 100 ºC (212 ºF) environment. The temperature inside the mouth increased steadily, reaching an average temperature of 40 ºC (104 ºF) after approximately 400 s. After 1200 s (20 min) of continuous exposure to 100 ºC (212 ºF) airflow, the average temperatures measured in the mannequin mouth reached approximately 55 ºC (131 ºF).

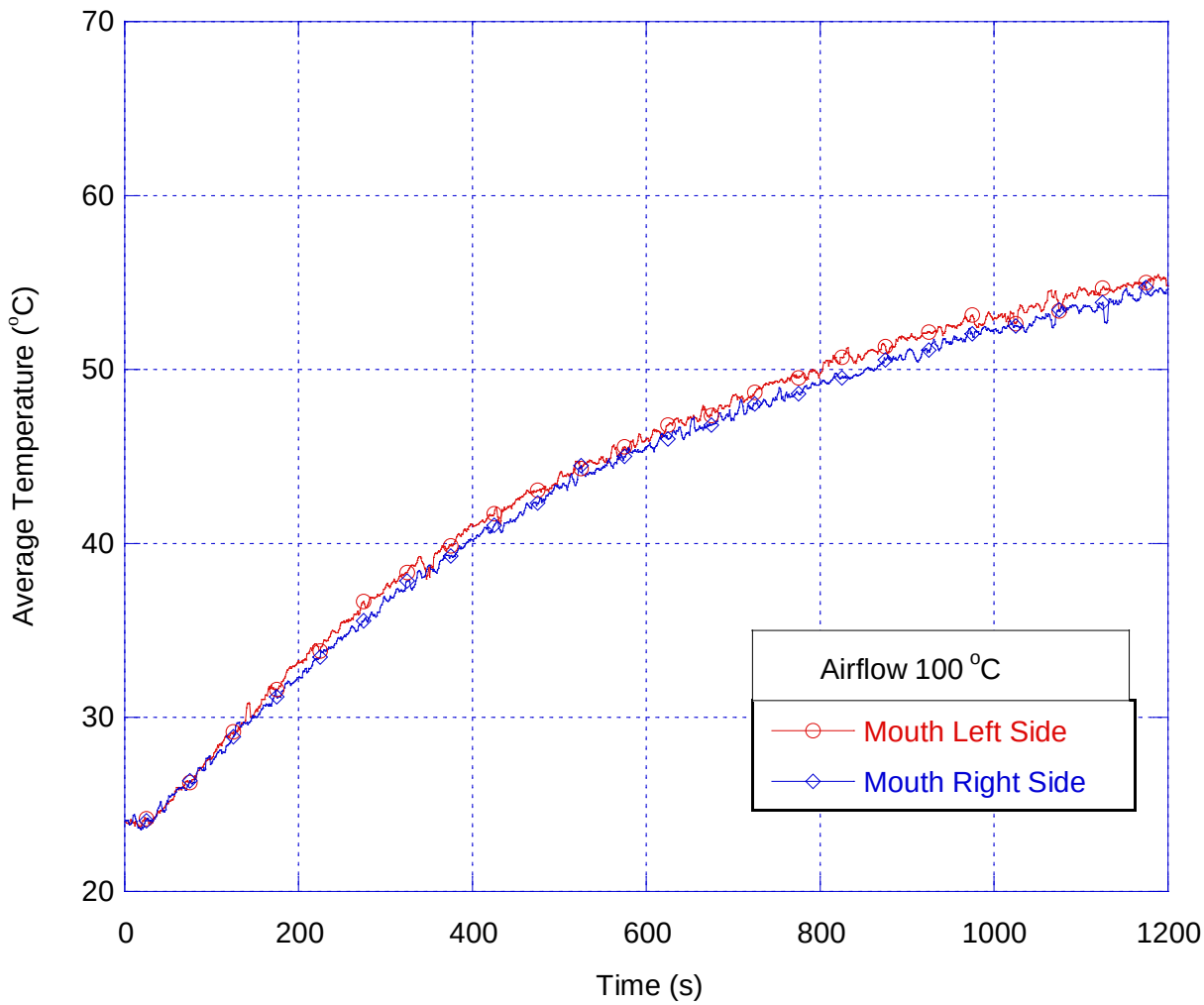

Figure 6 **Average Temperatures measured in the mannequin mouth for 100 °C exposures.**

The graph in Figure 7 shows the average temperatures measured inside the mannequin mouth for a test in which the SCBA was exposed to a nominally 150 ºC (302 ºF) airflow. Temperatures measured in the mannequin mouth rose at a faster rate than for the 100 ºC (212 ºF) exposure, reaching an average of 40 ºC (104 ºF) after just 210 s, and reaching an average of 52 ºC (126 ºF) after 400 s. Average temperatures reached above 75 ºC (167 ºF) after 1200 s of continuous exposure at 150 ºC (302 ºF).

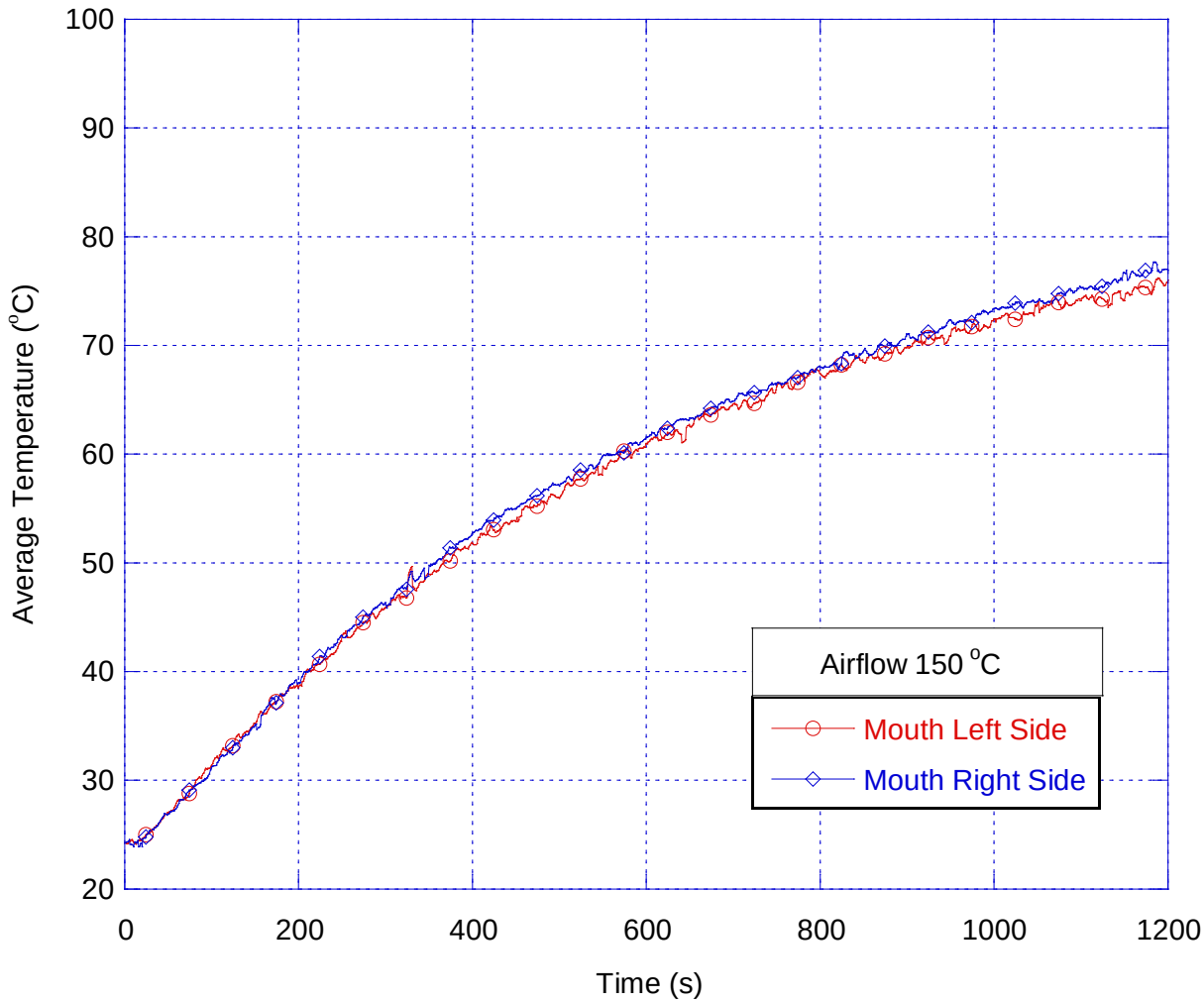

Figure 7 **Average Temperatures measured in the mannequin mouth for 150 °C exposure.**

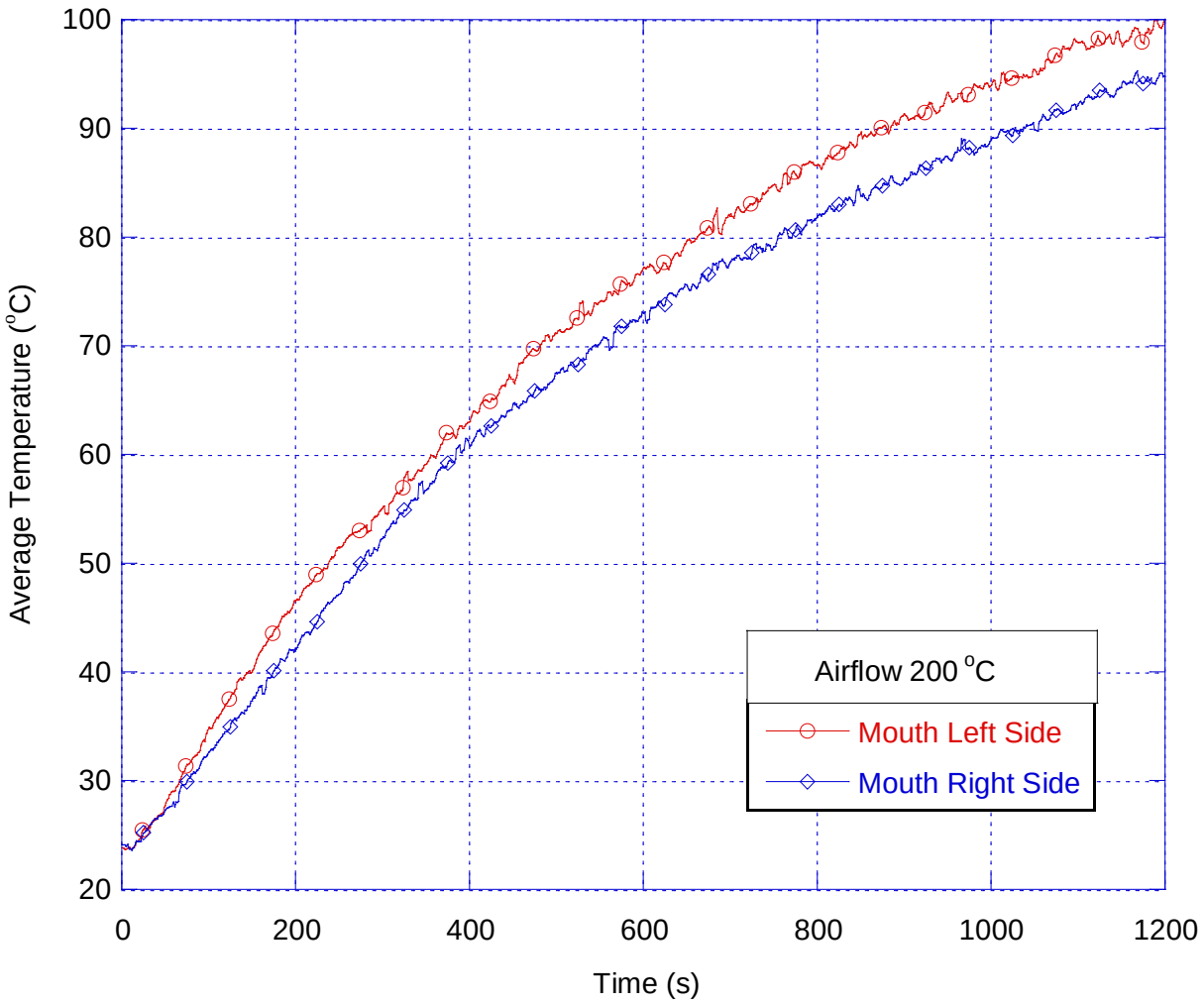

Figure 8 **Average Temperatures measured in the mannequin mouth for 200 °C exposure.**

For this exploratory investigation, the maximum external airflow exposure for the equipment was nominally 200 ºC (392 ºF). Figure 8 shows the average temperatures measured inside the mannequin mouth for one of the 200 ºC (392 ºF) exposure tests. At this exposure, temperatures on both sides of the mouth reached an average of 40 ºC (104 ºF) after just 175 s. By 400 s, average mouth temperatures exceeded 60 ºC (140 ºF). For both of the tests completed at an airflow exposure of 200 ºC, the temperature measured on the left side of the mouth was slightly higher than on the right side of the mouth, by up to 5 ºC. This difference is likely due to the exact placement of the thermocouples inside the mannequin's mouth, and is within the uncertainty of the thermocouple measurements.

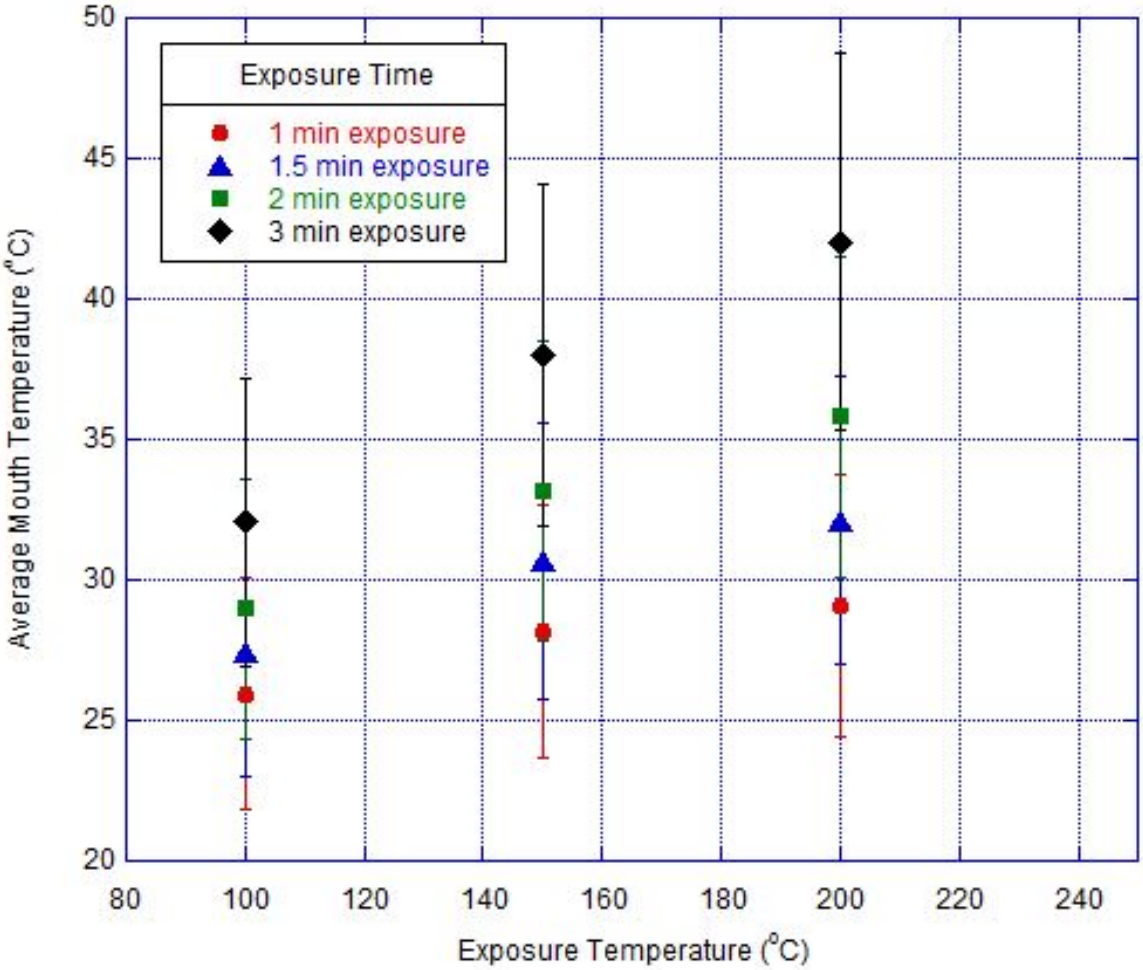

Figure 9 **Average Gas Temperatures at SCBA Mouth as a Function of External Exposure Temperature**

For this investigation, the SCBAs were tested at three external airflow exposure temperatures, 100 ºC (212 ºF), 150 ºC (302 ºF) and 200 ºC (392 ºF). Figure 9 shows the average temperatures measured in the mannequin mouth as a function of the airflow exposure temperature. The averages of the temperatures were computed at 1 min, 1.5 min, 2 min, and 3 min, for each of the airflow exposure temperatures. At 3 min of exposure at 100 ºC (212 ºF) airflow temperature, the average mannequin mouth temperature was 32 ºC (90 ºF), just 8 ºC above of the ambient temperature of 24 ºC (75 ºF). At 3 min of exposure at the 200 ºC (392 ºF) airflow, the average mannequin mouth temperature was 42 ºC (108 ºF), which is 18 ºC above the ambient temperature.

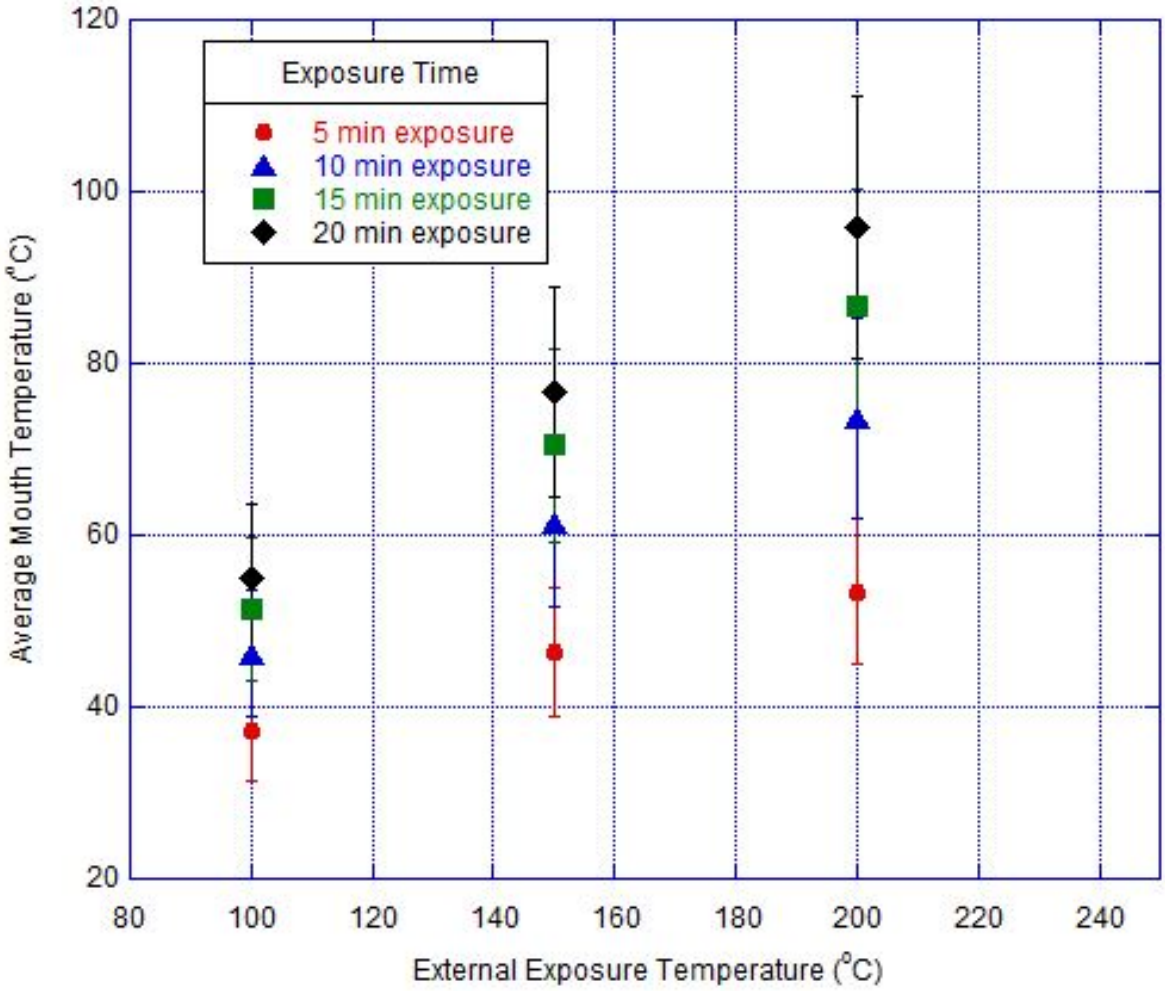

Figure 10 **Average Gas Temperatures at SCBA Mouth for SCBA Exposure Times beyond 5 minutes**

Figure 10 shows the average temperatures measured in the mannequin mouth as a function of the airflow exposure temperature, for SCBA equipment operation at time durations of 5 min, 10 min, 15 min, and 20 min. For 5 min of exposure to the 100 ºC (212 ºF) airflow temperature, the average mannequin mouth temperature was 37 ºC (99 ºF), and at 20 min of exposure at the 100 ºC airflow, the average mouth temperature was 55 ºC (131 ºF). A 5 min exposure at 200 ºC (392 ºF) airflow temperature resulted in an average mannequin mouth temperature of 53 ºC (127 ºF). At 20 min of exposure at the 200 ºC airflow, the mouth temperature was 96 ºC (205 ºF). This represents a 72 ºC increase over the average ambient temperature.

Figure 11 shows a plot of the temperatures measured on the surface of the facepiece for the three airflow temperatures to which the SCBA equipment was exposed. The temperature of the facepiece rose quickly during the initial phase of each test, and then had a moderate rate of increase for the remainder of the exposure time.

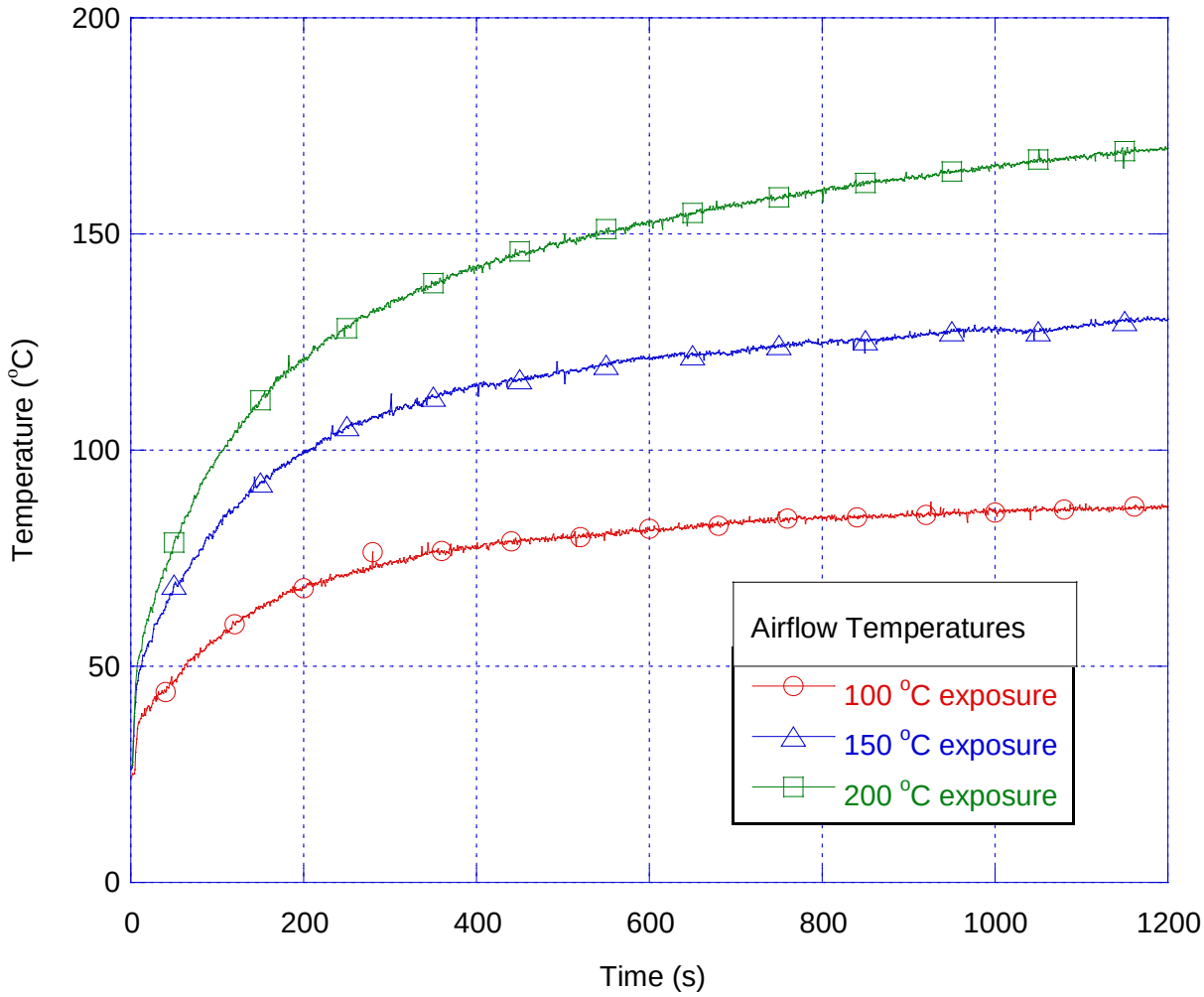

Figure 11 **Temperature of the Outer Surface of the Facepiece**

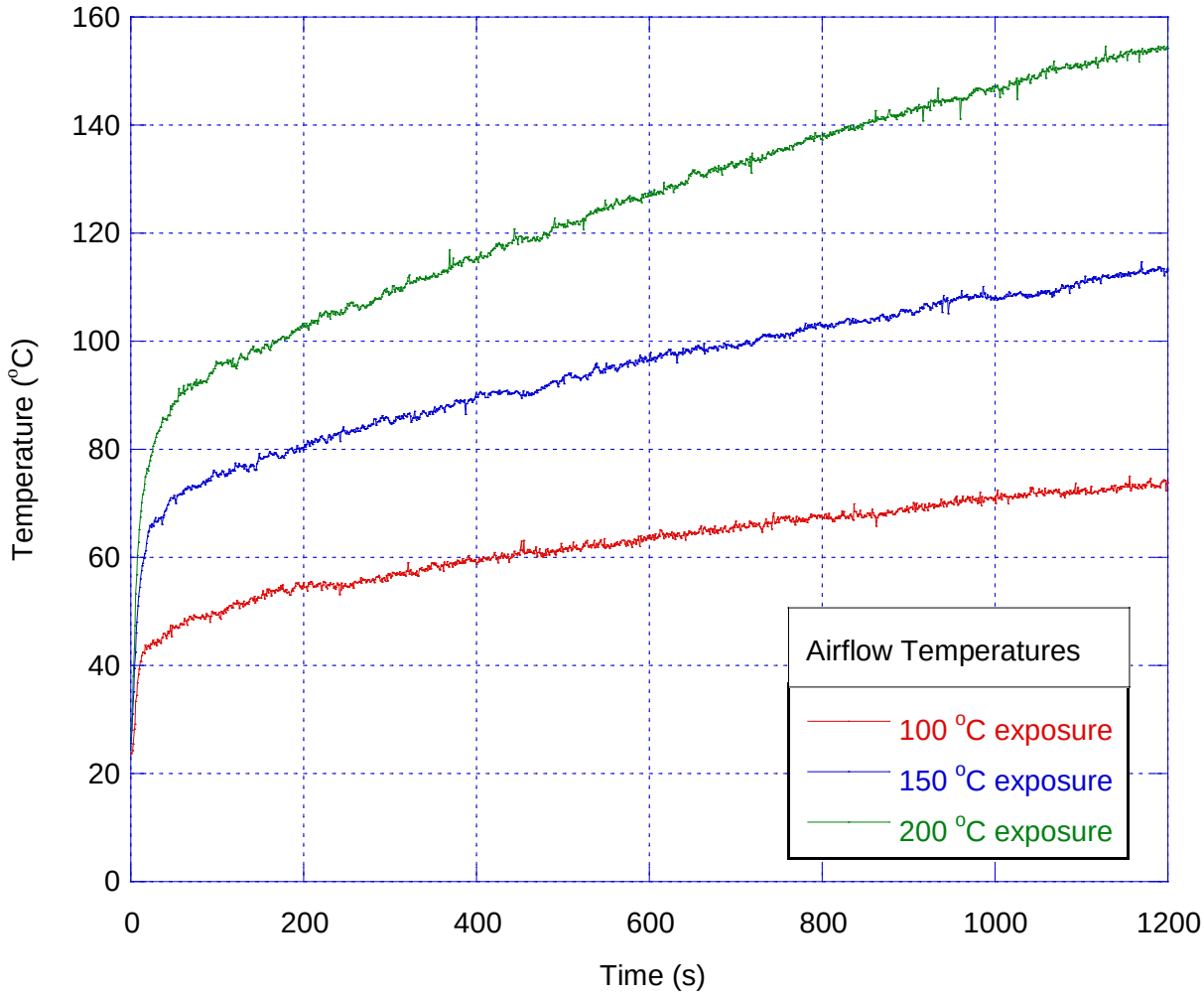

Figure 12 **Temperature of the Outer Surface of the Cylinder for Increasing Airflow Temperatures**

Temperature measurements were taken on the outside surface of the cylinder, at the mid-point of the cylinder on the side facing the oncoming airflow. The results of these measurements are shown in Figure 12. After a quick initial rise, the temperature on the outer surface of the cylinder continued to increase through the exposure time. The heating rate was slightly more for the 200 ºC (392 ºF) exposure, as show in Figure 12. Uncertainties in temperature measurements are ± 16 %.

Discussion

The results from these experiments clearly show that the external temperature of the environment in which an SCBA is operating has an effect on the breathing air that emerges from the SCBA. The temperature measurements inside the mannequin's mouth show that when the SCBA is exposed to an external environment with an elevated temperature, the temperature of the air supplied by the SCBA can increase. The amount of temperature increase depends on both the environmental airflow temperature and the time duration of exposure to the airflow.

The results shown in Figure 6 for the test at the 100 ºC (212 ºF) airflow, show that after 400 seconds, the average gas temperature inside the mannequin's mouth was above 40 ºC (104 ºF). This demonstrates that even for a relatively low exposure temperature, the breathing air inside the SCBA can increase 16 ºC above the ambient temperature in less than seven minutes. After 20 min of exposure to 100 ºC (212 ºF), the average temperature in the mannequin mouth reached approximately 55 ºC (131 ºF). This is a shorter time duration at 100 ºC (212 ºF), than that of Thermal Class I (25 min at 100 ºC), where fire fighters may routinely be expected to work [7], indicating that fire fighters may often be exposed to elevated temperature SCBA breathing conditions during routine operations.

For the 150 ºC (302 ºF) airflow exposure, Figure 7, the average gas temperatures in the mouth of the mannequin reached 40 ºC (104 ºF) after just 210 s, significantly faster than for the 100 ºC exposure test. As expected, at the greater airflow temperature, the temperature of the air in the SCBA increased faster, especially during the initial heating.

Figures 9 and 10 show the average mannequin mouth temperature plotted as a function of the exposure temperature, for various time durations. Figure 9 shows that for short time exposures of 3 minutes or less at airflow exposure temperatures up to 200 ºC (392 ºF), the average air temperature in the mannequin mouth stayed at 42 ºC or less. This temperature is 18 ºC above the ambient temperature of 24 ºC. Although these results indicate an increase in the temperature of the air from the SCBA, for the time durations and temperatures shown in Figure 9, the average mouth temperature stayed well below 100 ºC (212 ºF), the temperature where burns to the internal tissue could occur [3].

In Figure 10, results are shown for longer airflow exposure times of 5 minutes to 20 minutes. Some of the airflow temperature and time duration combinations that are shown in this plot may represent conditions that are not survivable for fire fighters; however the data are reported to show the results for operating the equipment at these conditions. For an external airflow temperature of 200 ºC, and a time exposure of 1200 s (20.0 min), the average temperature in the mannequin's mouth measured 96 ºC (205 ºF). Breathing humid air at 100 ºC (212 ºF) has been shown to cause thermal burns to the respiratory tract [3].

To characterize the heat transfer process for the SCBA cylinder during thermal exposure in the flow loop, a simplified model was developed. The model approximates the system by disregarding the tubing and facepiece sections, as well as the periodic cycles of the breathing apparatus, and treats the breathing air as a constant flow out of the cylinder. An energy balance is used to model the heat transfer into the system as the breathing air leaves the system. A detailed derivation of the model is given in the Appendix. Using the simplified model, the temperature of the air exiting the system, T_1, which corresponds to the temperature of the breathing air measured in the mannequin's mouth, can be represented with the following equation:

$$T_1 = \frac{1}{(\mathrm{St}_1 + \gamma - 1)} \left\{ \mathrm{St}_1 T_\infty - \left[\mathrm{St}_1 T_\infty - (\mathrm{St}_1 + \gamma - 1) T_{1,bi} \right] \left[\frac{N_{1,i} - K_1 t}{N_{1,i}} \right]^{(\mathrm{St}_1 + \gamma - 1)} \right\}$$

The temperature, T_1, in the equation above is solved as a function of the time, t. The other terms of the equation are defined in the Appendix, including the dimensionless heat transfer Stanton number, St_1 [8]. This simplified model can be used to predict the approximate temperatures of the cylinder air exiting the system, which effectively represent the breathing air temperatures that would be measured in the mannequin's mouth. A graph of the predicted temperatures of the air exiting the cylinder system as computed using this model is shown in Figure 13. The temperature, T_1, was computed using the three external airflow exposure temperatures that were used in the experiments, 100 ºC (212 ºF), 150 ºC (302 ºF) and 200 ºC (392 ºF). A Stanton number of St_1=3 is used for the calculations plotted in Figure 13, and the constant terms used are given in Table A2 of the Appendix. Graphs showing the comparisons of the model with the measured results are shown in Figures A2, A3, and A4 of the Appendix.

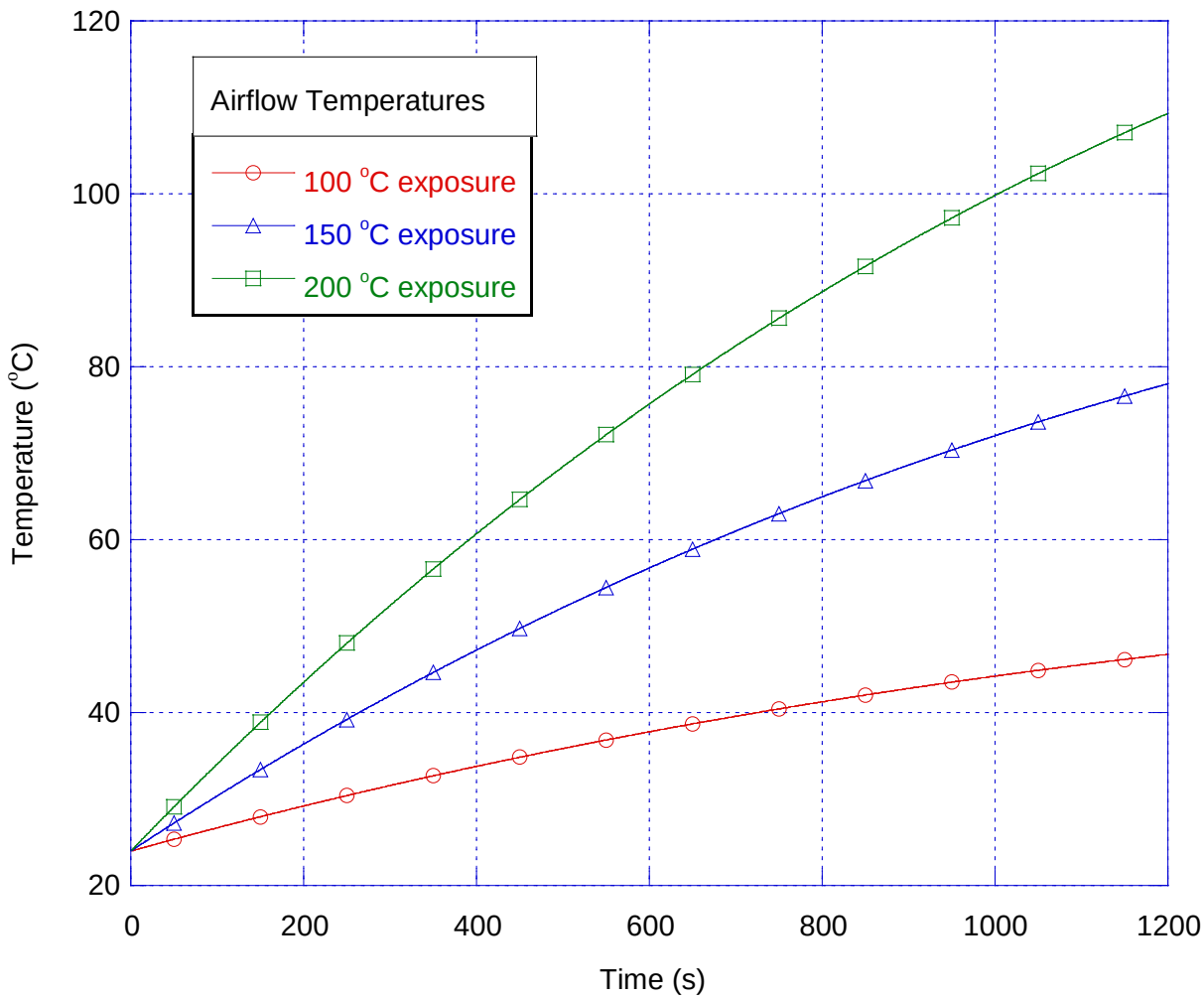

Figure 13 **Computed temperature exiting the system, (mannequin mouth temperature), calculated using the simplified model, with St_1 = 3**

In this exploratory set of experiments, the intent was to investigate the possibility of temperature increases in the SCBA air supply and to measure temperature increase rates. It is recognized that during these experiments, the SCBA equipment was exposed to some temperatures and time duration combinations that may not be survivable for living persons, even absent of a temperature increase of SCBA breathing air. These tests were intended to collect temperature data for the SCBA equipment and to characterize temperature rate increases for the SCBA equipment and the air it would supply under various temperature conditions.

For this investigation, the SCBA unit was taken as a whole, and the entire assembly was inserted into the test section during each test. The air temperature ultimately measured in the mannequin's mouth is the result of heating of the air as it passed through the entire SCBA, from

inside the cylinder, through the regulators and tubing connections, and through the face piece, before reaching the mouth. During this exploratory look, no attempt was made to identify or quantify temperature increases that may have occurred in each section of the SCBA. Instead, the focus was on the final temperature that would be experienced by a user at the mouth inlet of the SCBA face piece.

This exploratory investigation yielded initial results regarding the effect of the environmental temperature on the SCBA supply air temperature, but there are other variables that may impact the SCBA and would be useful to explore in future research. For future work, experiments could be conducted to examine the heat transfer at external flow velocities greater than the 1.4 m/s (3.0 mph) used in these experiments. Thermal flows in fire environments have been measured in the 6 m/s to 9 m/s (13 mph to 20 mph) flow range, and these flows could increase the heat transfer rate significantly. Another issue for future work could be to investigate the heat transfer contributions of the different components of the SCBA, and their impacts on the air supply temperature. Other variables to consider would be different breathing flow rates, and the effects of pre-heating of a closed SCBA system before use. Radiant heating of the SCBA equipment, and flame impingement on the cylinder are two more issues that may affect the SCBA supply air temperature, and should be considered in future testing.

Conclusions

This exploratory set of experiments investigated the impact of elevated external temperatures on the temperature of the breathing air supplied by a Self-Contained Breathing Apparatus. For these experiments, the SCBA assembly was placed inside an elevated temperature flow loop, and was exposed to airflows with temperatures between 100 ºC (212 ºF) and 200 ºC (392 ºF), for time durations up to 1200 s (20 min). The results show:

1) Breathing air supplied by the SCBA increases in temperature when exposed to an elevated temperature environment.

2) The increase in temperatures of the SCBA supply air became greater as the external airflow temperatures increased.

3) The SCBA supply air temperature increased as the duration of exposure to the elevated external temperature increased.

4) For the maximum time exposure, 1200 s, and the maximum external airflow temperature, 200 ºC, for this set of tests, the average SCBA supply air temperature measured 96 ºC (205 ºF).

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Appendix

A simplified model was developed to describe the thermal exposure process for the SCBA cylinder during thermal exposure in the flow loop. Figure A1 shows an idealized representation of the SCBA cylinder exposed to the elevated temperature airflow. The breathing air in the cylinder is considered to be a system (System 1). As a first approximation, the short periodic disruptions of the airflow during the inhaling and exhaling cycles of the breathing simulator are ignored, and the model assumes a continuous airflow out of the SCBA cylinder. The temporal temperature variation at the exit of the cylinder is assumed to represent the temperature within the SCBA facepiece and is used to compare with the experimental measurements.

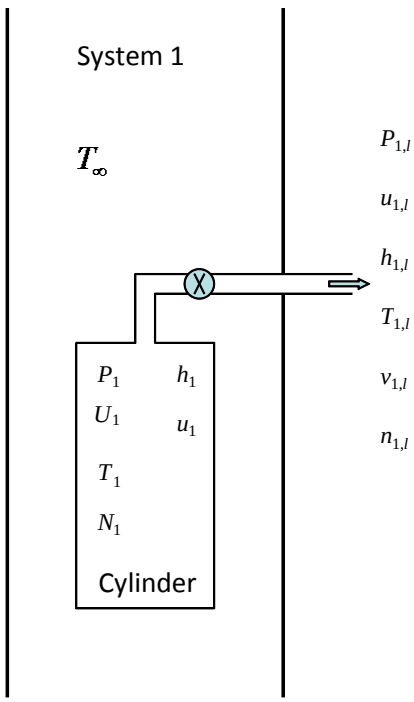

Figure A1. Simplified model for thermal exposure of SCBA cylinder.

Table A1. Table of Terms for Model

	Description	Units
T_∞	Temperature of air surrounding the cylinder	K
U_1	Total internal energy of the air cylinder	J
P_1	Pressure in cylinder	Pa
T_1	Temperature of air in the cylinder	K
N_1	Total number of moles in the system	mol
h_1	Molar enthalpy of system	J/mol
u_1	Molar internal energy of system	J/mol
$P_{1,l}$	Pressure at the cylinder outlet	Pa
$T_{1,l}$	Temperature of air at the cylinder outlet	K
$h_{1,l}$	Molar enthalpy at the cylinder outlet	J/mol
$v_{1,l}$	Molar volume at the cylinder outlet	m^3/mol
$u_{1,l}$	Molar internal energy at the cylinder outlet	J/mol
$n_{1,l}$	Molar output of the system	mol
t	Time	s

For this simple approximation, the gas flow rate out of the cylinder is assumed to be constant. The system under consideration, System 1, is the breathing air in the cylinder. From the First Law of Thermodynamics for a simple open system (air cylinder) [9],

$$dU_1 = \delta Q_1 - \delta W_1 - h_{1,l}\, d\, n_{1,l} \qquad (1)$$

where U_1 is the total internal energy of the air cylinder (System 1), Q_1 is the heat added to the cylinder from the surroundings, W_1 is the work done by the system, $h_{1,l}$ is the molar enthalpy at the cylinder outlet, and $n_{1,l}$ is the molar output from the system.

With $\delta W_1 = 0$, Eq. (1) can be written as

$$d\,U_1 = \delta\,Q_1 - h_{1,l}\;d\;n_{1,l} \tag{2}$$

Taking the time derivative of Eq. (2),

$$\frac{dU_1}{dt} = \frac{\delta Q_1}{dt} - h_{1,l}\,\frac{dn_{1,l}}{dt} \tag{3}$$

Eq. (3) can be expressed in terms of molar internal energy, u_1, of System 1 and the total number of moles in System 1, N_1.

$$\frac{d\left(N_1 u_1\right)}{dt} = N_1\,\frac{du_1}{dt} + u_1\,\frac{dN_1}{dt} = \frac{\delta Q_1}{dt} - h_{1,l}\,\frac{dn_{1,l}}{dt} \tag{4}$$

A mole balance of the system results in

$$-\frac{dN_1}{dt} = \frac{dn_{1,l}}{dt} \tag{5}$$

If a constant molar flow rate out of the cylinder, K_1, is assumed, then

$$-\frac{dN_1}{dt} = \frac{dn_{1,l}}{dt} = K_1 \tag{6}$$

Integrating Eq. (6),

$$N_1 = N_{1,i} - K_1 t \tag{7}$$

where $N_{1,i}$ is the initial total number of moles of air in the cylinder.

Substituting Eq. (6) and Eq. (7) into Eq. (4),

$$\left(N_{1,i} - K_1 t\right)\frac{du_1}{dt} + u_1 K_1 = \dot{Q}_1 - h_{1,l}\, K_1 \tag{8}$$

with $\frac{\delta Q_1}{dt} = \dot{Q}_1$ as the heat transfer rate to the system from the surroundings.

Substituting for the molar enthalpy, $h_{1,l}$, gives

$$\left(N_{1,i} - K_1 t\right)\frac{du_1}{dt} + u_1\, K_1 = \dot{Q}_1 - (u_{1,l} + P_{1,l} v_{1,l})\, K_1 \tag{9}$$

where $u_{1,l}$, $P_{1,l}$, and $v_{1,l}$ are the molar internal energy, pressure, and molar volume of the air at the cylinder outlet, respectively.

If the gas is treated as ideal, then the molar internal energy of an ideal gas can be expressed as

$$u_1 = u_0 + c_v\,(T_1 - T_0) \text{ and } u_{1,l} = u_0 + c_v\,(T_{1,l} - T_0) \tag{10}$$

where u_0 is the molar internal energy at some reference temperature T_0 and c_v is the molar specific heat at constant volume, assuming c_v does not change significantly with temperature over the temperature range of interest. Eq. (9) can be rewritten as an ideal gas,

$$c_v(N_{1,i} - K_1 t)\frac{dT_1}{dt} - c_v K_1 T_1 = \dot{Q}_1 - K_1 c_v T_{1,l} - K_1 R T_{1,l} \tag{11}$$

where R (= 8.314 J/mole K) is the universal gas constant.

Treating the pressure regulator of the cylinder as a throttling device (a constant enthalpy process), then

$$h_1 = h_{1,l}$$

$$(u_1 + P_1 v_1) = (u_{1,l} + P_{1,l} v_{1,l})$$

$$u_0 + c_v(T_1 - T_0) + RT_1 = u_0 + c_v(T_{1,l} - T_0) + RT_{1,l}$$

$$T_1 = T_{1,l}$$

Equation (11) becomes

$$(N_{1,i} - K_1 t)\frac{dT_1}{dt} = K_1\left[\frac{U_{1,HT} A_{1,t}}{K_1 c_v}(T_\infty - T_1) - \frac{R}{c_v}T_1\right] \tag{12}$$

The $\dot{Q}_1$ term in Eq. (11) can be conveniently expressed in terms of an overall heat transfer coefficient, $U_{1,HT}$, the heat transfer area of the cylinder, $A_{1,t}$, and the temperature difference between the surrounding temperature, T_∞, and the cylinder temperature, T_1. The use of a constant overall heat transfer coefficient simplifies the detailed analysis of heat transfer from the surroundings to the cylinder surface, and from the cylinder to the interior through the composite cylinder wall. Equation (12) can be rewritten as

$$(N_{1,i} - K_1 t)\frac{dT_1}{dt} = K_1\left[\mathrm{St}_1 T_\infty - (\mathrm{St}_1 + \gamma - 1)T_1\right] \tag{13}$$

where $\gamma = c_p / c_v = (c_v + R)/c_v$ and c_p is the molar specific heat at constant pressure, and

$\mathrm{St}_1 \equiv \dfrac{U_{1,HT} A_{1,t}}{K_1 c_v}$, which can be considered a form of the dimensionless heat transfer Stanton number [8]. $\mathrm{St}_1 = 0$ corresponds to adiabatic condition, and $\mathrm{St}_1 \to \infty$ corresponds to infinitely fast heat transfer. Integrating Eq. (13) with the initial condition at t = 0, $T_1 = T_{1,i}$ (the initial temperature of the air in cylinder) obtains

$$\frac{\mathrm{St}_1 T_\infty - (\mathrm{St}_1 + \gamma - 1)T_1}{\mathrm{St}_1 T_\infty - (\mathrm{St}_1 + \gamma - 1)T_{1,i}} = \left[\frac{N_{1,i} - K_1 t}{N_{1,i}}\right]^{(\mathrm{St}_1 + \gamma - 1)} \tag{14}$$

$$T_1 = \frac{1}{(\mathrm{St}_1 + \gamma - 1)}\left\{\mathrm{St}_1 T_\infty - \left[\mathrm{St}_1 T_\infty - (\mathrm{St}_1 + \gamma - 1)T_{1,i}\right]\left[\frac{N_{1,i} - K_1 t}{N_{1,i}}\right]^{(\mathrm{St}_1 + \gamma - 1)}\right\} \tag{15}$$

Equation (15) represents the temporal air cylinder temperature during each breathing cycle. Note that in Eq. (15) when $\mathrm{St}_1 \to \infty$, $T_1 \to T_\infty$. That is, for infinitely fast heat transfer, the cylinder temperature would attain thermal equilibrium with the surroundings.

The calculations were performed using the values listed in Table A1. Figures A2, A3, and A4 show the comparisons of the calculations with the experimental measurements, using different values of St_1. The graphs show that using St_1 values of 3 or 4, with the simplified model, closely predicts the experimental measurements for the three experimental conditions.

Table A2. Numerical Values for Model Computations

$N_{1,i}$	Initial total number of moles in cylinder	117.3 mol
$T_{1,i}$	Initial temperature of air in cyliner	23 ºC (296 K)
T_{∞}	Temperature of air surrounding the cylinder	100 ºC (373 K) 150 ºC (423 K) 200 ºC (473 K)
K_1	Molar flow rate out of cylinder	2.98×10^{-2} mol/s
γ	Ratio of molar specific heat at constant pressure to molar specific heat at constant volume	1.4
R	Universal gas constant	8.314 J/mol K

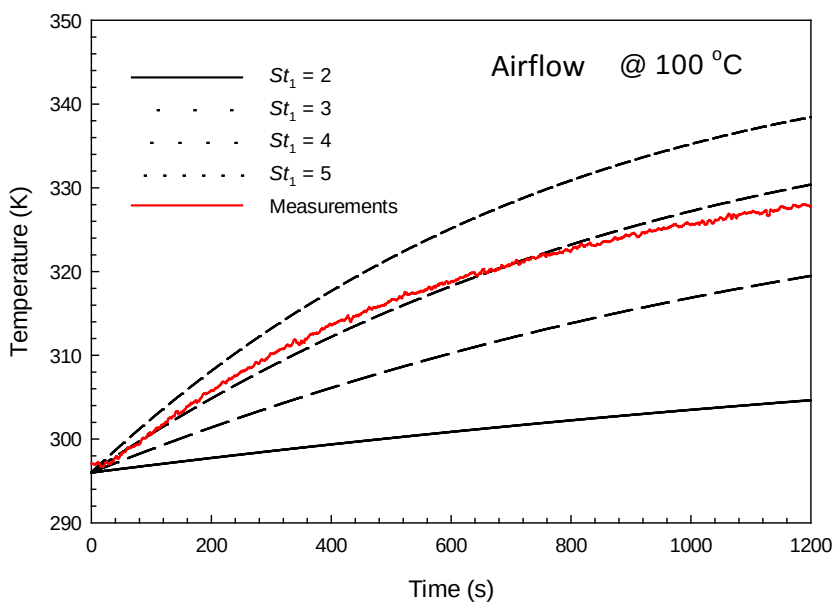

Figure A2. Comparison with measurements using different St_1 at 100 ºC.

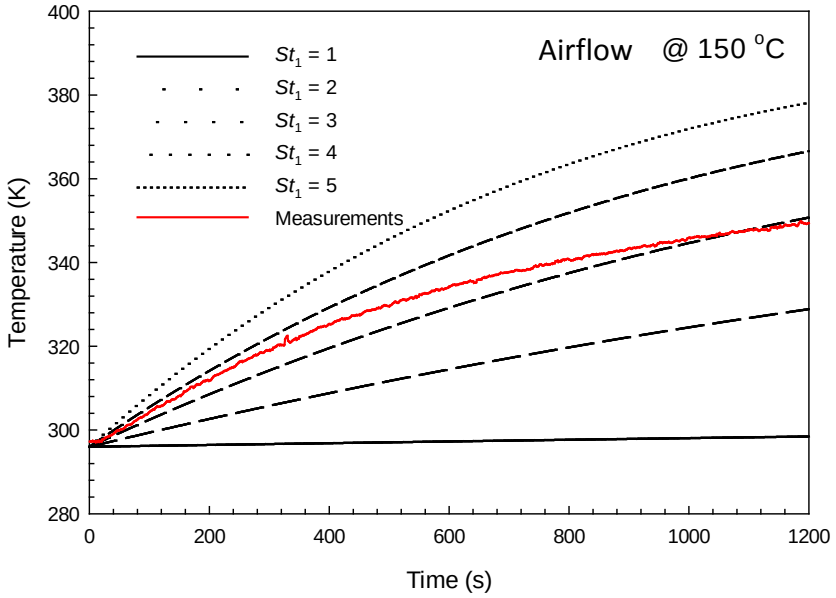

Figure A3. Comparison with experimental measurements using different St_1 at 150 ºC.

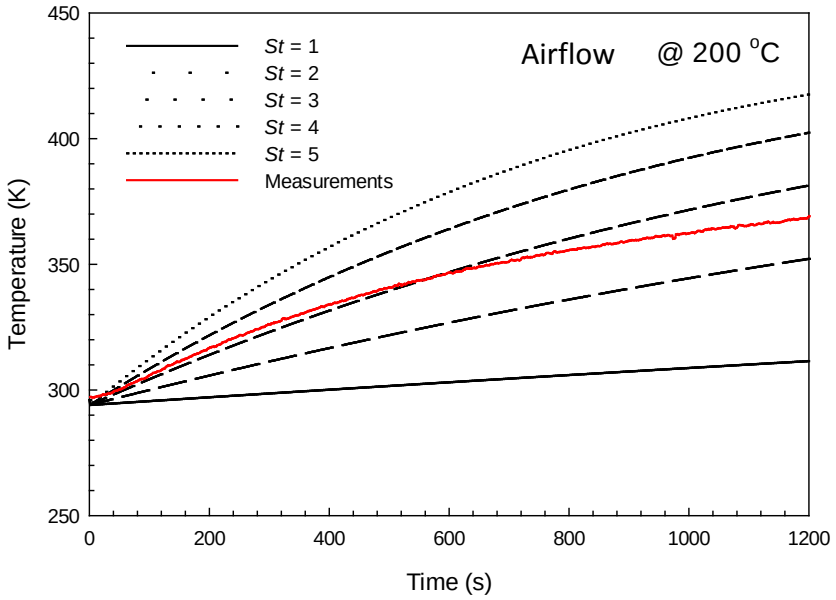

Figure A4. Comparison with experimental measurements using different St_1 at 200 ºC.