A Computational Model of an Outward Leak from a Closed-Circuit Breathing Device

Kathryn M. Butler

Building and Fire Research Laboratory, National Institute of Standards and Technology,
Gaithersburg, MD 20899-8665
E-mail: kathryn.butler@nist.gov

ABSTRACT

Closed-circuit breathing devices recycle exhaled air after scrubbing carbon dioxide and adding make-up oxygen from a tank of pure oxygen. This equipment provides up to four hours of use before oxygen cylinders and CO_2-absorbent canisters need to be swapped out. Firefighting situations in which these devices would be useful include tunnels, mines, ships, high-rise buildings, and environments contaminated with biological or chemical toxins. Since firefighters may encounter environments containing open flame and high radiant heat, there is concern that a higher concentration of oxygen within the respirator may result in an enhanced possibility of fire ignition in the case of outward leakage around the facepiece.

This study uses computational fluid dynamics (CFD) to investigate the flammability of the environment near a respirator leak from a closed-circuit self-contained breathing apparatus (CC-SCBA) during the breathing cycle. The physical boundary for the computational problem is defined by the combination of headform and respirator geometries obtained from 3D laser scanning. Velocity boundary conditions are defined along a narrow band representing a leak through the gap between respirator seal and head. Oxygen concentration fields and flow streamlines are presented for multiple combinations of fuel and air in the surrounding environment, for pure oxygen and air expelled from the leak, and for both normal and high stress breathing patterns. The flammability diagram for propane is used to estimate the flammable regions as a function of time.

Keywords: closed-circuit SCBA, computational model, respirator leak, flammability, flammability diagram

INTRODUCTION

The open-circuit Self-Contained Breathing Apparatus (SCBA), which vents exhaled air to the atmosphere, is by far the most common respiratory protective device used in firefighting. The standard compressed air cylinders used in these devices contain a limited air supply with a duration of 30 min to 60 min when breathing rates are normal. Under heavy workloads, however, a compressed air cylinder may last as little as 10 min to 20 min. Although this may be adequate for fighting ordinary house fires, longer durations may be necessary in certain situations, including fires in tunnels, mines, ships, high-rise buildings, and environments contaminated with biological or chemical toxins.

An alternative to the open-circuit SCBA is the closed-circuit SCBA (CC-SCBA), which recirculates exhaled air by absorbing carbon dioxide and adding fresh oxygen. Because oxygen needs are only around 5 % of air needs (oxygen consumption rate/ventilation rate), an oxygen cylinder of comparable weight to a compressed air cylinder can sustain the firefighter for a much longer period of time (Kyriazi, 1999a). Closed-circuit SCBAs, also known as rebreathers or four-hour sets, can be used for up to four hours before swapping out cylinders and CO_2-absorbent canisters. This type of equipment is currently used as rescue breathing apparatus in mining operations (Kyriazi, 1999b; DeVries, 2002).

The National Institute for Occupational Safety and Health (NIOSH) is in the process of developing standards for the use of closed-circuit SCBA by firefighters and other first responders after a terrorist attack. In addition to the respiratory protection of first responders in environments containing CBRN agents identified as inhalation hazards, the equipment must be usable under conditions of high heat and open flames. Although a leak is unlikely for a respirator with good fit, the possibility of outward leakage of oxygen in a fire environment is a concern. If the oxygen remains concentrated around the face in the presence of fuel gases and heat, ignition may occur. If the oxygen diffuses rapidly away from the face, however, the possibility of ignition is negligible. The intent of this study was to consider the potential for enhanced danger under worst-case conditions.

Computational fluid dynamics (CFD) numerically simulates fluid flow by solving the equations of motion. The solutions can be obtained in detail that is impossible to achieve in experiments, and for variables that are difficult or impossible to measure in practice, especially in three-dimensional space. A variety of situations, including breathing pattern, leak geometries, and varying concentrations of gaseous components, may be tested. The visualization of the computational results as they vary with time and space enhances our understanding of the flow phenomena.

METHODS

Model Geometry

Experiments using mannequins have demonstrated that a simplified cylindrical geometry is not adequate to represent the flow field near a human face (Anthony et al., 2005). The complex features of the human face combined with the features of a respirator are necessary for an accurate flow model. For this model, the geometries of a headform used in respirator breathing experiments and a respirator facepiece were prepared separately and then combined.

A laser scan of the headform provided a set of points in three dimensions that defined the location of the surface. Image reconstruction software converted this digital point cloud into a set of surface entities that could be used to set up a computational model. Some work was necessary to smooth and clean the geometry and to fill in holes at the mouth, where the physical headform had an opening, and on the top of the head above the path of the scanner. The resulting 3D geometry is shown in Figure 1(a).

A prototypical full facepiece respirator was built from mechanical drawings obtained from a manufacturer. The relative locations of points, curves, and surfaces, as shown in multiple views and cross-sections, were entered into the preprocessor of a finite element CFD program, resulting in the facepiece geometry shown in Figure 1(b). Since this project was concerned only with leaks to the outside environment, the inner mask, which covers the mouth and nose, was not needed. Only half of the facepiece was actually constructed from the mechanical drawings. The other half was obtained by mirroring the points and curves about the plane of symmetry. For final preparation of the model, both the visor and the facepiece hose connector were covered with closed surfaces.

To combine the head with the facepiece, the headform was translated and rotated into the proper position relative to the respirator. Simply merging the two geometries did not provide a good fit. With the chin in good position, the top of the facepiece was not in contact with the forehead and the sides extended inside of the headform. In the real world, of course, the flexibility of the facepiece allows it to fit the shape of the headform as it is put on. In the digital world, a good fit was achieved through adjustment of the facepiece geometry by moving the top toward the forehead, pulling out the sides, and defining the inner and outer seals to follow the contours of the face. Maintaining the correct physical relationships of the facepiece and its flexible seal was not attempted, although an effort was made to prevent gross deformities in shape. After redefining surface entities in contact with each other, such that adjacent surfaces shared a common boundary, the combination of headform and respirator was complete, as shown in Figure 1(c). A leak was defined along the outer seal of the facepiece just above the temple region, where straps would be attached.

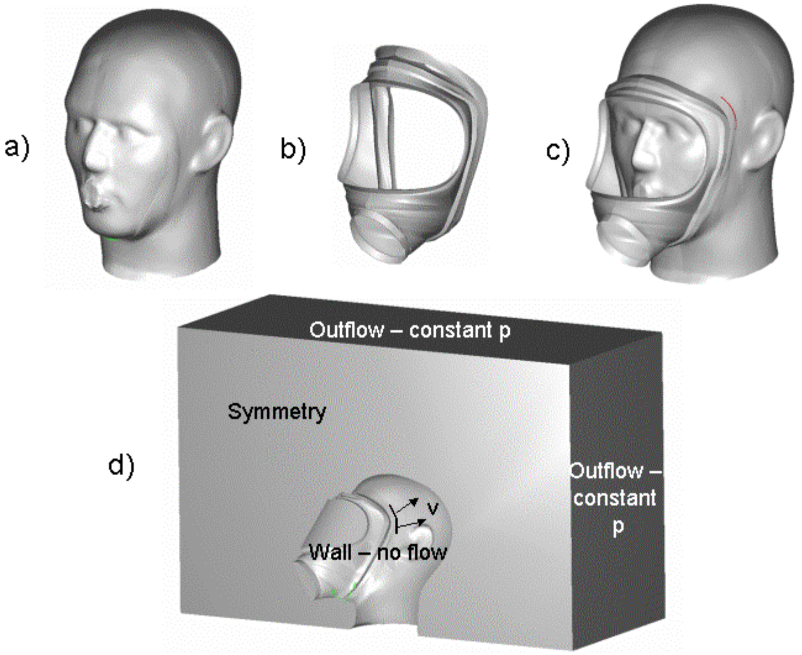

Figure 1. Preparation of model geometry: a) headform, b) respirator facepiece, c) combined headform and facepiece, and d) computational space.

The solution space for the outward leak problem is a volume exterior to the combined headform and respirator facepiece. Because of the symmetry along the centerline of the face and respirator, the size of the computational problem to be solved can be cut in half. Note that using symmetry also means that the outward leak is mirrored on the opposite temple. A rectangular box with the headform / facepiece roughly centered along one side, shown in Figure 1(d), was chosen as the computational space. Tests showed that the rectangular box was large enough that the locations of the walls of the box had a negligible effect on the solution in the immediate vicinity of the leak (Butler, 2007).

Leak Assumptions

Most CC-SCBAs are positive pressure respirators, which maintain positive pressure in the facepiece throughout the breathing cycle. An outward leak is therefore a possibility if a perfect seal between respirator and face is lost. The most likely position and size for an outward leak from a respirator facepiece are not known. For this study, the defined leak was located near the temples and given a size arbitrarily chosen to be 1 mm wide by 43.6 mm long – larger than a pinhole leak but not catastrophic in extent.

The mixture of gases expelled by a leak is determined by the gaseous content of the facepiece. In normal breathing without a respirator, an exhalation contains approximately 16 % O_2 by volume and 4 % CO_2 by volume. When using the CC-SCBA, the exhaled air passes through a canister that absorbs the CO_2 and then into a flexible breathing bag, where, for most types of apparatus, pure O_2 is supplied at a steady rate. The concentration of oxygen within the respirator facepiece must therefore be somewhere between the 16 % of normal exhalation and the 100 % content of the oxygen source. Tests performed by NIOSH on fourteen rescue breathing apparatus showed that, for all but two units, the average inhaled oxygen concentration was much higher than that of the exhaled breath (Kyriazi, 1999b). In fact, average O_2 concentrations were above 60 % for 11 units and above 80 % for six. The danger posed by an outward leak into a mixture that contains flammable gases depends, among other things, on the concentration of oxygen in the facepiece. Since the intent of this study was to investigate a worst-case scenario, and since elevated levels of oxygen have been measured within the facepieces of several CC-SCBA units during operation, the gas expelled through the leak was assumed to be pure oxygen.

A simplified breathing cycle was assumed for this model. For a normal resting breath, the respiratory frequency was taken to be 15 breaths per minute, with inhalation and exhalation cycles each lasting two seconds. The flow during exhalation was considered to be steady over time, with a tidal volume of 0.5 L released over the 2 s duration, a fraction of which was expelled steadily through the leak. During inhalation, the leak was closed. This assumes that the low positive pressure that exists within the respirator facepiece during inhalation is insufficient to keep the leak open.

This study also considered a breathing cycle at high breathing rate and tidal volume, representing breathing under high stress due to exertion. This cycle took the same form as the breath at rest, with a breathing rate of 60 breaths per minute and tidal volume of 3 L, for a minute ventilation of 180 L/min.

Flammability Considerations

The incomplete combustion that takes place in an uncontrolled fire generates smoke and flammable fuel gases that may be transported a distance from the fire. Especially while fighting a fire in the same room, a firefighter may be subjected to high concentrations of flammable gases. It is important to understand what the possible consequences are if oxygen from a respirator leak is introduced into this environment.

For this study, a way was needed to estimate the potential for fire to occur in the vicinity of a leak of oxygen into a fuel/air mixture. The method begins by considering a mixture of a fuel gas with air. A mixture of fuel and air is able to burn only when the concentration of the fuel gas is within a certain range of values, delineated by the lower flammable limit, or LFL, and the upper flammable limit, or UFL. Below the LFL, the mixture of fuel and air is too fuel lean and lacks sufficient fuel to burn. Above the UFL, the mixture is too fuel rich and lacks sufficient oxygen to burn. The ignition of a mixture within the flammable range requires a small source of energy, which can be provided, for example, by a spark due to static electricity.

To estimate the potential for fire to occur in the vicinity of a leak of oxygen into a fuel/air mixture, a flammability diagram was used (Beyler, 2002). Propane, a simple gaseous hydrocarbon fuel, was chosen as the fuel. Dependence of the flammability diagram on temperature and pressure was neglected, and values at standard conditions of 25° C and atmospheric pressure were used.

Figures 2(a)-(d) each show the flammability diagram for propane. In this diagram, concentrations of propane, oxygen, and nitrogen are shown on three axes. Each point within the diagram describes a unique mixture of the three gases. Concentrations are given in percent by volume. Combinations of air with fuel are found along the air/fuel line, which connects pure propane at point D at the top, to pure air at point E at the bottom (79 % nitrogen, 21 % oxygen, and 0 % propane). The LFL and UFL for propane in air are located along this line at values of 2.1 % by volume (point B) and 9.5 % by volume (point A) respectively. The line from point D that is tangent to the flammable region, at point C, is known as the limit line. The mixtures along the limit line have a fixed ratio of oxygen to nitrogen below which flame propagation is not possible for any amount of propane. This line meets the lower axis at the limiting oxygen concentration, LOC, which is 11.5 % by volume for propane.

In pure oxygen, the LFL and UFL have been determined experimentally for several fuels. Values for propane were not found in the literature, but an estimate of 58 % by volume for the UHL in oxygen was obtained using values for other simple hydrocarbon fuels (Butler, 2007). Since the LFL in oxygen is not much different than the LFL in air for most fuels, the LFL in oxygen of propane was estimated as 2.1 % by volume. The LFL and UFL in oxygen are plotted in Figures 2(a)-(d) as points F and G respectively, along the axis with zero nitrogen concentration.

The connection of points F, B, C, A, G in the flammability diagram provide an estimate of the flammable region for propane (Mashuga and Crowl, 1998). All mixtures within this region can be ignited, and mixtures outside of this range cannot.

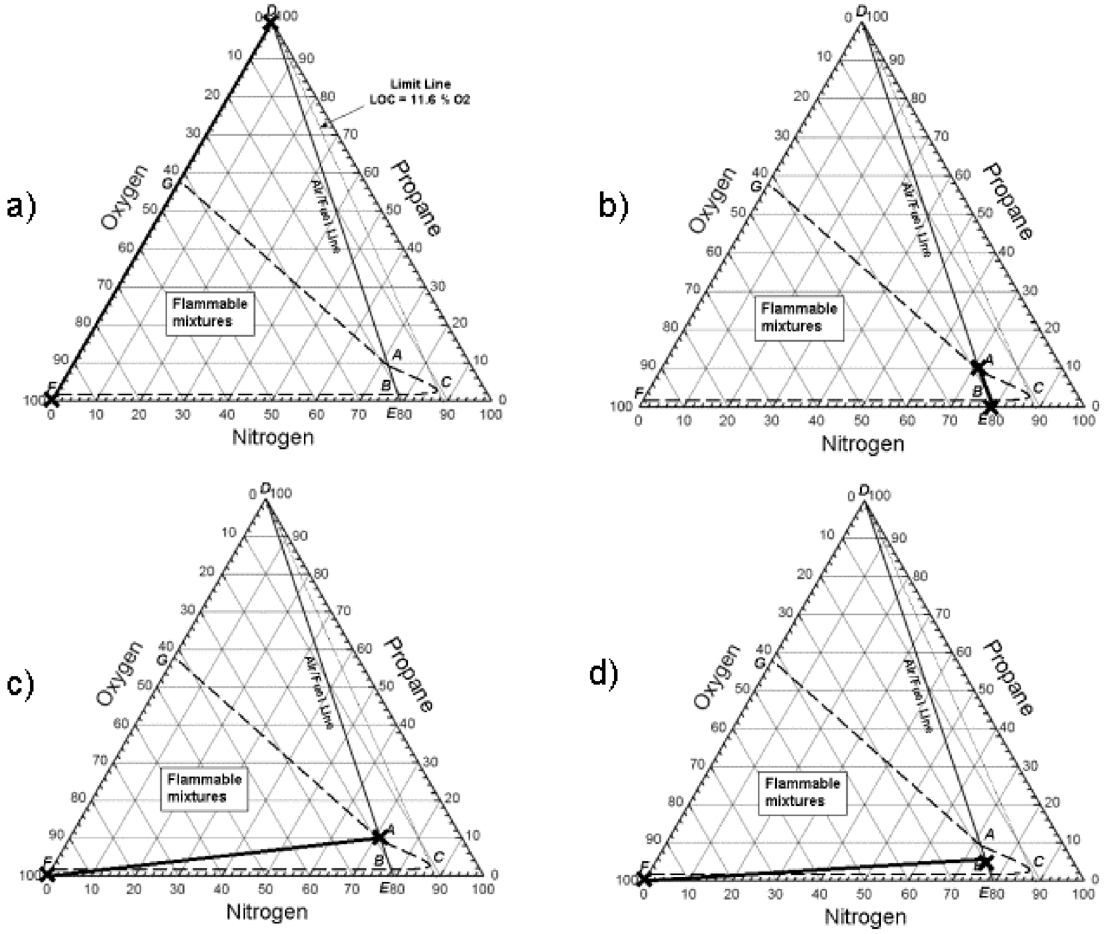

Figure 2. Flammability diagram for propane. Heavy line shows range of mixtures for a) leak of pure oxygen into pure propane, b) leak of air into 10 % propane in air, c) leak of pure oxygen into 10 % propane in air, and d) leak of pure oxygen into 5 % propane in air.

The usefulness of the flammability diagram is in determining the flammable limits between any two mixtures of propane, oxygen, and nitrogen that describe the endpoints in the problem. In this model, the gas emitted from the leak is one endpoint, and the fuel-gas mixture at an infinite distance from the leak (also the external environment at time t = 0 s) is the other. The mixtures encountered within the model are expected to lie on a straight line between the two endpoints. The points at which the line crosses into and out of the flammable region are the LFL and UFL for this particular set of endpoints. In Figure 2(a), the dark line along the left edge (0 % nitrogen axis) of the flammability diagram indicates the range of mixtures for a leak of pure oxygen, marked by an X at the lower left corner, into a pure propane environment, marked by an X at the top of the diagram. The points where this line crosses the flammable region are the LFL and UFL for propane in pure oxygen, 2.1 % by volume and 58 % by volume, as stated previously. In Figure 2(b), a dark line along the air/fuel line marks the range of mixtures for a leak of air, marked by an X at the intersection of the air/fuel line with the 0 % propane axis, into an environment of 10 % by volume propane in air, marked by a second X. This line crosses the flammable region at the LFL and UFL for propane in air, 2.1 % by volume and 9.5 % by volume.

Figures 2(c) and (d) show the ability of this method to provide the flammable limits for arbitrary pairs of mixtures. In Figure 2(c), pure oxygen is leaking into an environment of 10 % by volume propane in air. The points at which the dark line between the mixture endpoints crosses the flammable region are at an LFL of 2.1 % by volume and a UFL of 9.96 % by volume. Note that the UFL is very close to the endpoint of 10 % by volume. This value was calculated crudely as the intersection point between the line describing possible mixtures for this problem and the line between point A, the UFL in air, and point G, the UFL in oxygen. Better knowledge of the boundary of the flammable region in the vicinity of the intersection point would improve the calculation of this important value.

In Figure 2(d), pure oxygen is leaking into a mixture of 5 % by volume propane in air. This propane-air mixture is flammable, and the dark line crosses the boundary of the flammable region only once, at the LFL of 2.1 % by volume.

Model Equations and Boundary Conditions

The flow of gases and liquids can be determined using mathematical equations that describe the conservation of mass, momentum, and energy within the space occupied by the fluid. The terms that are required in the equations depend on the physics and chemistry of the particular problem to be solved. The equations provide only an approximation to reality – the challenge is to make sure that the most important factors are included. In addition to the fluid dynamics equations, the mathematical description of a problem requires the definition of boundary conditions on all boundaries defining the problem space. For a time-dependent problem, initial conditions must also be specified.

The CFD software used to solve this problem is based on the finite volume method. With this approach, the computational space is divided into a large number of cells, also known as control volumes. The cells are arbitrarily shaped triangles or quadrilaterals in two dimensions, and arbitrary 4- to 6-sided volumes in three dimensions. This allows the discretization of complex solution spaces, such as the geometry for the combined headform and facepiece in this model.

The governing equations to be solved are integrated numerically over each computational cell. The average cell value of all dependent variables (such as velocity, pressure, and oxygen concentration) and all material properties (such as density and viscosity) are stored at the cell center. Boundary conditions of fixed value or zero flux are assigned using fictitious boundary nodes for computational cells adjacent to the boundary. A variety of solution schemes is available. First-order upwind differencing in space and the Euler method in time were found to give good results for this problem. At each time step, the solution procedure is repeated until either a specified convergence property is obtained or until a maximum number of iterations is reached. The iterative method used for this problem was the conjugate gradient squared (CGS) equation solver with preconditioning.

The material properties of the gases used in this model were taken from the standard tables of gaseous species. The viscosity for the mixture of gases was calculated using Sutherland’s Law and the mix kinetic theory of gases. The ideal gas law was used to relate density, pressure, and temperature. This model did not account for heat transfer. So although in reality, the mix of fuel and air in the exterior environment take place at elevated temperatures, the material properties used in the analysis were room temperature values. Note that, in practice, the temperatures of the gases cannot be so high that they prohibit the presence of the firefighter.

In this model, oxygen from the leak in the respirator facepiece mixes with the fuel-air mixture in the surrounding environment. This requires the determination of the concentrations of each chemical species as they vary in time and space. To follow each of four chemical species (C_3H_8-propane, O_2-oxygen, N_2-nitrogen, and Ar-argon) separately, a species mass fractions approach was selected. (Although argon was included in the problem, it makes up a small fraction of air and could have been neglected.) In this approach, a transport equation is solved for every chemical species in the problem. The mixing of oxygen from the leak with the fuel-air mixture requires a model for mass diffusion. A constant Schmidt number model was assumed, in which the mass diffusivity is assumed equal to the viscosity divided by a constant, the Schmidt number. The Schmidt number was assumed to equal 0.7 for this model.

For fluid flow problems, the presence of turbulence may strongly affect the transport of mass, momentum, and energy. Turbulence should be taken into account if the Reynolds number Re in the problem exceeds 1000, where $Re = \rho UL/\mu$, ρ is density, U is a typical velocity in the problem, L is a length scale, and μ is viscosity. Turbulence may be a factor if the Reynolds number is above 100. In this problem, the largest velocity and smallest length scale were both found at the leak. For a normal breath, Re is about 50, low enough that turbulence was not necessary for calculations under conditions of normal breathing. If the first responder is breathing more heavily under stress, the velocity at the leak will be significantly higher, and a turbulence model may be advised (although turbulence will still be a factor only close to the leak). A k-epsilon model was chosen for the turbulence model for the high-exertion breathing rate.

Gravity was neglected in this problem. Boundary conditions for the model are shown in Figure 1(d). Outlet boundary conditions of fixed atmospheric pressure were assigned to the open sides, top, and bottom of the box defining the computational volume. Symmetric boundary conditions were assigned to the side of the box along the center plane of the combined headform and respirator. The conditions along this plane of symmetry were zero flux for all variables: velocity, species concentration, and pressure. The exterior surfaces of the combined headform and respirator, with the exception of the leak, were assigned a wall boundary condition. No flow was permitted through these surfaces. Along the leak, the input velocity for a normal resting breath was calculated to be 1 m/s over a two-second time period. For the following two seconds, the leak was closed. Then the leak of 1 m/s was open again for two seconds, followed by another two-second closure, for a total of two breathing cycles. For breathing under exertion, the same pattern was followed, with a leak of 6 m/s for a period of 0.5 s for both exhalation and inhalation.

The initial condition for the model was that at time t = 0, just before the leak due to exhalation begins, the computational volume was filled with the fuel-air mixture of the surrounding environment, and the flow was zero. Still air represents a worst case for oxygen buildup near the respirator, since any flow around the facepiece will act to mix the oxygen with the fuel-air mixture.

RESULTS

Leak of Pure Oxygen into Pure Propane Environment

For a leak of pure oxygen into a pure propane environment, the concentration of nitrogen is zero everywhere. Referring to the flammability diagram in Figure 2(a), the mixtures in this problem all lie along the left boundary, with values from pure oxygen at the lower left corner to pure propane at the top. The flammable mixtures along this line lie between the LFL of 2.1 % by volume for propane in pure oxygen and the UFL of 58 % by volume. Figure 3 shows a close-up of the area near the head at the end of the exhalation portion of the breathing cycle. The results are displayed looking down on a horizontal plane located at the approximate midpoint of the leak, as indicated by the line crossing the image to the lower left. The small contour that extends outward a short distance from the leak is the UFL contour. The LFL contour is very close to the leak. The area between these two contours is the flammable region in this problem.

The gray shading in Figure 3 indicates the oxygen concentration. The values range from 0 % oxygen (100 % propane) in white to 100 % oxygen (0 % propane) in black.

In this case, the flammable region near the head of the person wearing the respirator is small during exhalation and disappears completely during inhalation. Figure 4 shows a time sequence of gas concentrations for these two breathing cycles. The evolution of the oxygen concentration is due to convection and diffusion.

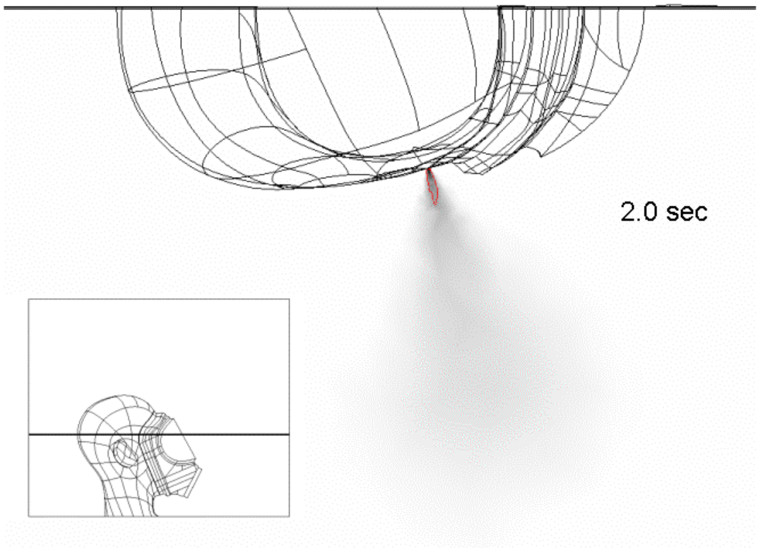

Figure 3. Top view of head and respirator showing oxygen expelled during exhalation into a pure propane environment. Contours mark the UFL and LFL of propane in pure oxygen.

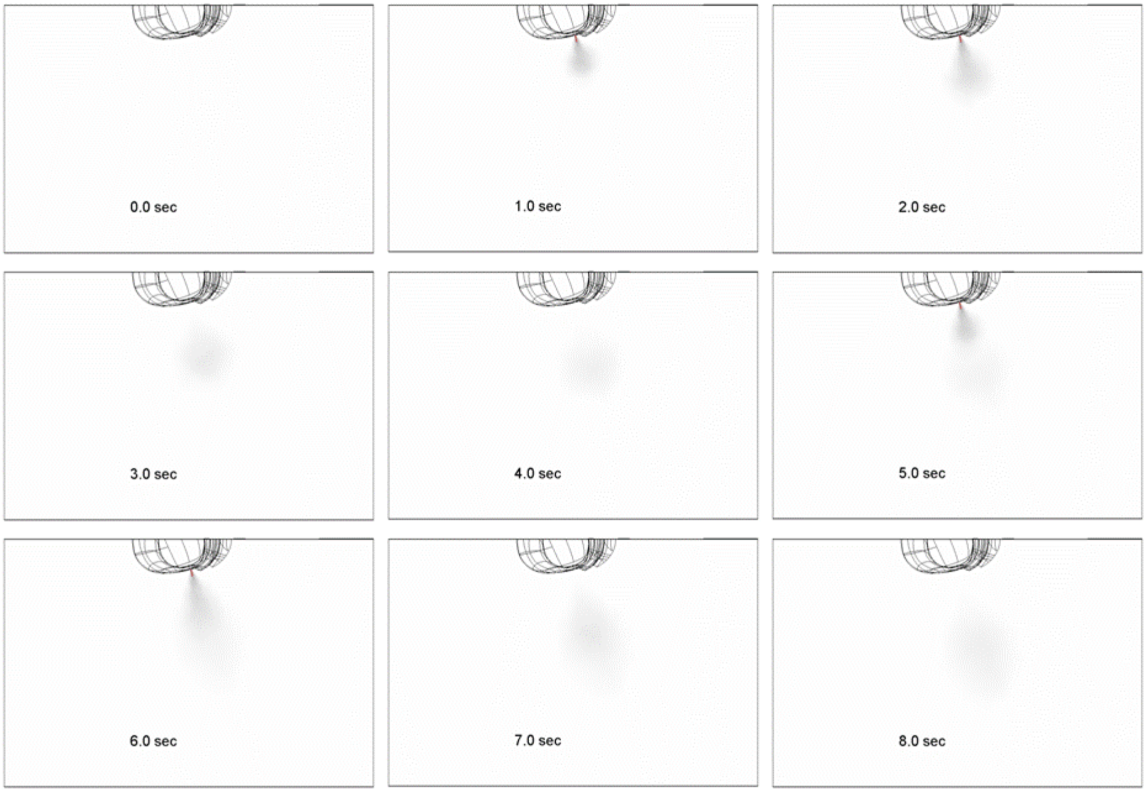

Figure 4. Time sequence of oxygen concentration from pure oxygen leak into pure propane environment.

Leak of Pure Oxygen into 10 % Propane Environment

A much more challenging condition is the leak of breathing gases into an environment in which the fuel level is very close to the UFL but just slightly too fuel rich for flammability. Since the UFL of propane in air is 9.5 % by volume, the value of 10 % by volume is assumed for the fuel/air mixture for this test. The introduction of oxygen into this environment will certainly result in a flammable region – the only question is the size of the region. The range of mixtures in this test is given by the dark line in Figure 2(c), where the LFL was found to be 2.1 % by volume and the UFL 9.96 % by volume.

Figure 5 shows the time sequence for oxygen flowing into the 10 % propane/air mixture. In this case, the LFL contour is still very close to the leak, but the UFL contour has expanded considerably, indicating that there is a large region near the head that contains a flammable mixture. This contour is connected to the head throughout the breathing cycle.

Note that the growth in size of the flammable region over these two breaths is due to the zero leakage before time t = 0, a necessary assumption for starting this transient problem. The flammable region should eventually arrive at an equilibrium size (with some fluctuation over the breathing cycle) in which inflow from the leak is balanced by diffusion.

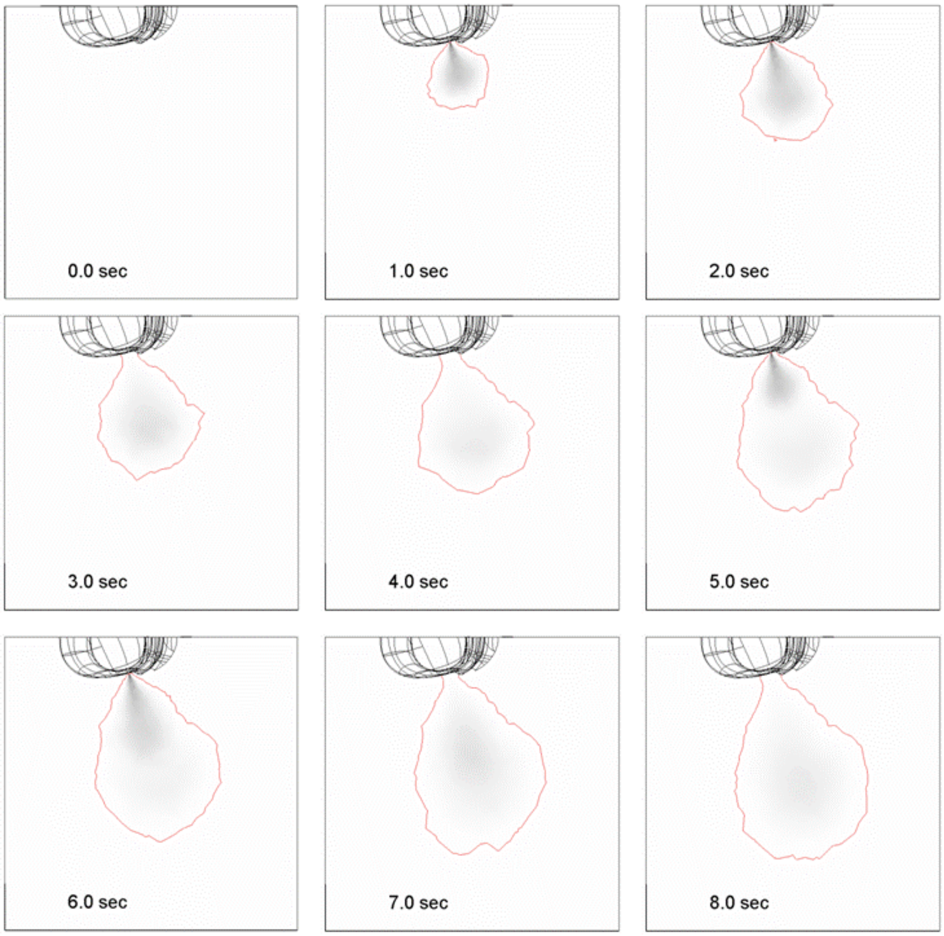

Figure 5. Time sequence of oxygen concentration from pure oxygen leak into 10 % propane environment, showing flammable region.

Leak of Air into 10 % Propane Environment

To evaluate the significance of these results for the use of closed-circuit SCBAs, it is useful to compare the leak from a respirator containing pure oxygen to a leak from a respirator containing air. The latter is a reasonable assumption for a standard open-circuit SCBA using a compressed air tank.

The dark line on the flammability diagram of Figure 2(b) represents the range of mixtures in this problem, from pure air at point E to the 10 % by volume propane point, along the air/fuel line. Since this line lies along the air/fuel line, the points that bound the flammable region are already known to be the LFL and UFL of propane in air, 2.1 % by volume and 9.5 % by volume respectively.

Figure 6 shows the time sequence of gas volume fractions for air leaking into a 10 % by volume propane environment. Comparing this figure to Figure 5 for a pure oxygen leak, it is clear that the flammable regions here are smaller. They detach from the head during inhalation and move away from the head and respirator. It is also clear that this environment is a dangerous environment into which the introduction of oxygen from any source results in a flammable mixture.

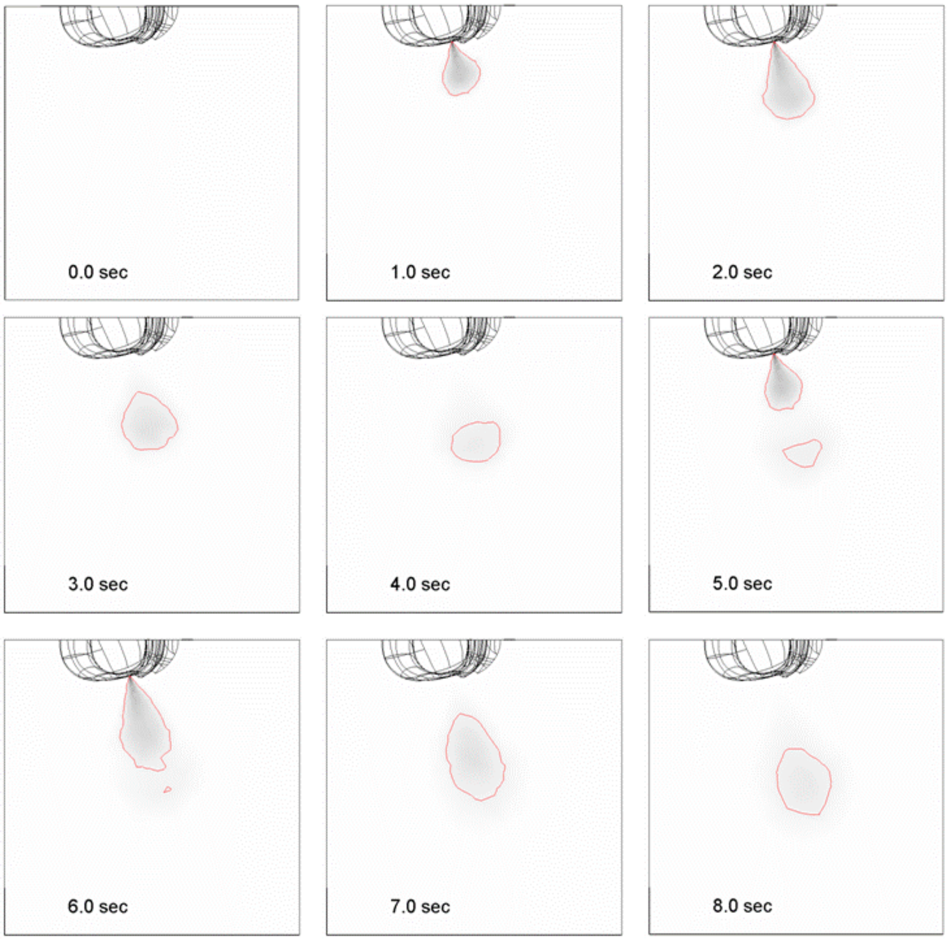

Figure 6. Time sequence of oxygen concentration from leak of air into 10 % propane environment, showing flammable region.

Leak of Pure Oxygen into 5 % Propane Environment

In the case of a leak of pure oxygen into 5 % by volume propane in air, the external environment is already flammable. The range of mixtures for this problem is plotted on the flammability diagram in Figure 2(d). The point at which the line of possible mixtures crosses into the flammable region is at 2.1 % by volume propane, about 24 % by volume N_2, and about 74 % by volume O_2.

Figure 7 shows a close-up of the area near the head at the end of the exhalation portion of the first breathing cycle. The only contour in this plot is an LFL contour that extends outward from the leak by a few millimeters. The space within this contour is the only region in this case that is not flammable.

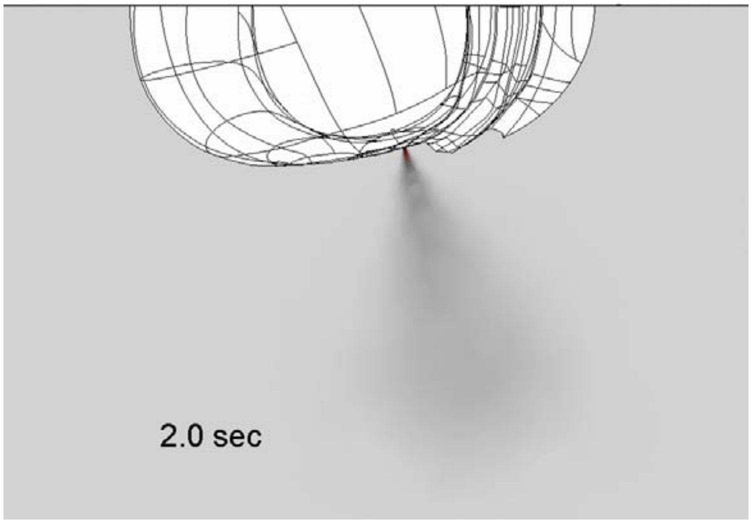

Figure 7. Pure oxygen expelled during exhalation into 5 % propane environment. The contour marking the LFL of propane extends a few millimeters from the respirator.

Leak of Pure Oxygen into 10 % Propane for High Exertion Breathing Rate

For the final problem, the breathing pattern is changed to reflect the higher tidal volume and breathing rate for a person under stress from exertion. The breathing pattern represents a tidal volume of 3 L and breathing rate of 60 breaths per minute. A turbulence model has been added to the problem. The most challenging environment is studied here, with pure oxygen leaking into a 10 % propane environment. The set of possible mixtures is indicated on the flammability diagram of Figure 2(c).

Figure 8 shows the time sequence of oxygen concentration and UFL contours over the first two breaths. The spatial extent of the oxygen jet from the leak into the surroundings is longer when compared with Figure 5 for breathing at rest. The oxygen disperses more quickly into the fuel/air mixture and increases the size of the flammable region.

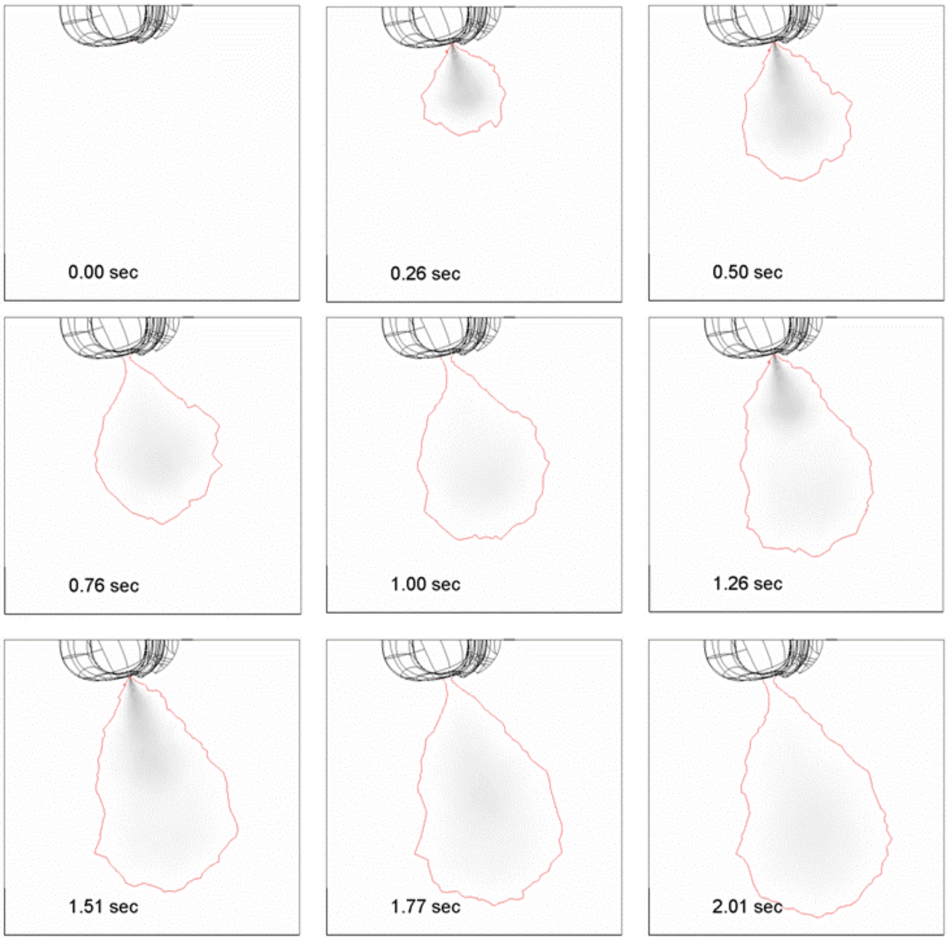

Figure 8. Time sequence of oxygen concentration from pure oxygen leak into 10 % propane environment for breathing during exertion, showing flammable region.

CONCLUSIONS

Under worst-case conditions of an outward respirator leak into a slightly fuel-rich mixture, the flammable region generated by a leak of pure oxygen is considerably larger than that generated by a leak of air. Heavier and more rapid breathing, such as that caused by exertion, increases the flammable region further. This indicates that under these circumstances a leak from a closed-circuit SCBA respirator is more serious than a leak from a standard open-circuit SCBA.

Several assumptions made this a severe test for the CC-SCBA. In this study, the leak is assumed to be pure oxygen, rather than a lower concentration expected in the respirator by the combination of oxygen from the oxygen tank and breathing gases. The mixture of fuel gas and air in the worst-case environment is just above the upper flammable limit, a severe environment in which to be for a firefighter. The surroundings are assumed to be still air, neglecting the flows normally associated with a fire and firefighter movement that will tend to mix the leak gases with the surroundings more rapidly. These flows will lessen the size of the flammable zone.

This study demonstrates the capabilities of CFD to enhance understanding of flow phenomena and communicate the results. Validation of CFD with experimental measurements is recommended to ensure that the results accurately reflect reality. Of equal or greater importance is a better understanding of the actual conditions that may be encountered in the field, including the potential leak size and location, flow rates, and external environment.

Acknowledgments

This work was supported by the Office of Law Enforcement Standards and the National Institute for Occupational Safety and Health. The author would also like to thank John Kovac, Nicholas Kyriazi, Ronald Shaffer, Ziqing Zhuang, and William Newcomb, of NIOSH/NPPTL, Daniel Crowl of Michigan Technological University, and Rodney Bryant and Nelson Bryner of NIST for helpful technical discussions. Dennis Viscusi contributed the 3D laser scans, and Draeger Safety provided technical drawings.

Disclaimer

REFERENCES

Anthony TR, Flynn MR, and Eisner A. (2005) Evaluation of Facial Features on Particle Inhalation. *Annals of Occupational Hygiene* 49: 179-193.

Beyler C. (2002) Flammability Limits of Premixed and Diffusion Flames. In: DiNenno PJ et al., eds. SFPE Handbook of Fire Protection Engineering, 3rd Edition. Quincy, MA: Society of Fire Protection Engineers, Chapter 7.

Butler K. (2007) A Computational Model of Dissipation of Oxygen from an Outward Leak of a Closed-Circuit Breathing Device, National Institute of Standards and Technology, Gaithersburg, MD. NIST Technical Note 1484.

DeVries H. (2002) Mining for Answers, *Fire Chief*, 1 Jan 2002.

Kyriazi N. (1999a) Proposal for Certification Tests and Standards for Closed-Circuit Breathing Apparatus. National Institute for Occupational Safety and Health, Pittsburgh, PA. Information Circular 9449.

Kyriazi N. (1999b) Performance Comparison of Rescue Breathing Apparatus. National Institute for Occupational Safety and Health, Pittsburgh, PA. Report of Investigations 9650.

Mashuga CV and Crowl DA. (1998) Application of the Flammability Diagram for Evaluation of Fire and Explosion Hazards of Flammable Vapors. *Process Safety Progress* 17: 176-183.