

# Using 3D Head and Respirator Shapes to Analyze Respirator Fit

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**Abstract.** A computational approach to analyzing respirator fit is demonstrated using geometries generated by laser scanning, mechanical drawings, and CAD files. Three fit-related problems that can be solved using computational tools are demonstrated: 1) The study of an outward leak of breathing gases into a near-flammable environment. 2) The study of a flow field inside a half-facepiece respirator. 3) The characterization of the relationship of respirator design and head shape to fit and comfort.

**Keywords:** Respirator fit, digital human modeling, 3D laser scanning, finite element method.

## 1 Introduction

Respiratory protection requires a good fit of the respirator to the individual's face. A poor fit may result in the leakage and inhalation of contaminants, and may also cause discomfort to the user, especially during lengthy operations on the job.

People who need respiratory protection have a wide range of facial shapes and sizes. In order to fit nearly every member of the workplace population, respirator manufacturers typically design a family of sizes for each respirator type. A recent anthropometric survey of US respirator users by the National Institute for Occupational Safety and Health (NIOSH) has identified a fit-test panel encompassing 95 % of the US workforce that can be used to achieve more effective respiratory protection [1]. However, respirators are not infallible – an individual may pass the required fit test but still experience leaks due to improper donning, overbreathing during high work loads, jarring, facial hair, or sweat. Some users may find it difficult to get a respirator that fits well because of facial asymmetry or unusual facial dimensions.

The advent of powerful computational tools provides new methodology to study issues of respirator fit. Laser scanners make it possible to create digital representations of the complex geometries of human heads and respirator facepieces. These three-dimensional images can then be manipulated and subjected to computational analysis of how well a specific respirator operates for a specific user.

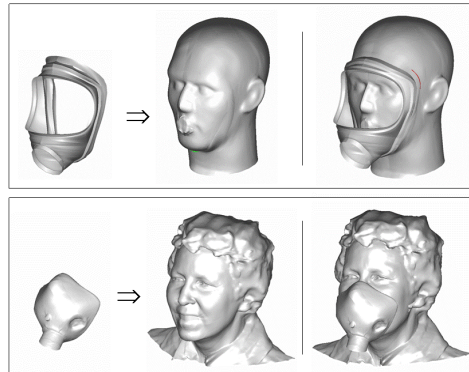
The finite element method (FEM) is the most widely-used numerical technique for solving partial differential equations over complex physical domains. A complex geometry is subdivided into a mesh consisting of elements with nodes at the corners. The elements may be triangular or quadrilateral over a two-dimensional object and

tetrahedral or brick throughout a three-dimensional object. Elements may vary in size and shape and may be concentrated in a region where gradients are high or where a finer solution is desired. Commercial FEM packages provide tools for solving problems involving fluid flow, structural analysis, heat transfer, chemistry, and mechanical contact, among many other phenomena.

This paper discusses the methods used to generate the geometry of heads and respirators and then presents three examples of the use of computational tools to investigate problems of respirator fit.

## 2 Geometrical Representations

To study the fit of a human head to a respirator using FEM, both the geometry of the head and the geometry of the respirator are needed. A 3D laser scanner generates a set of points in three dimensions that defines the location of the surface. Image reconstruction software can then convert the digital point cloud into a set of surface entities that can be used to set up the finite element model. The geometry of the respirator may alternatively be obtained through CAD files or mechanical drawings when these are made available. Figure 1 shows heads and respirators as developed individually and as combined for analysis.



**Fig. 1.** Respirators and heads generated from mechanical drawings (the full facepiece respirator) and 3D laser scanning. To combine the two, each respirator has been distorted to fit the geometry of the head.

All of these methods are time-consuming and subject to inaccuracy. A laser scan requires repair of holes in the point cloud where the scanner does not get good coverage and the cleanup of rough or imprecise regions. Mechanical drawings must be converted by hand into a three-dimensional computational object, and CAD files are not easily converted into a finite element model. Finally, after the creation of the individual geometries for the head and the respirator, the two must be carefully aligned and combined into a single model. In real life, the rubber or silicone respirator seal and the skin of the face both distort during mounting, so the respirator cannot simply be translated in space during assembly. The generation of a complex geometry for a

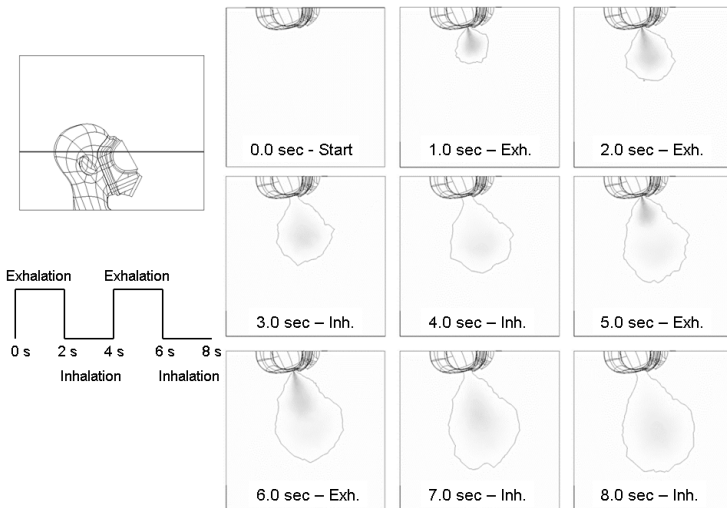
finite element model has a well-deserved reputation for consuming considerable amounts of time, often more than the solution of the model itself. Ways to speed up this process continue to be sought.

### 3 Outward Leak

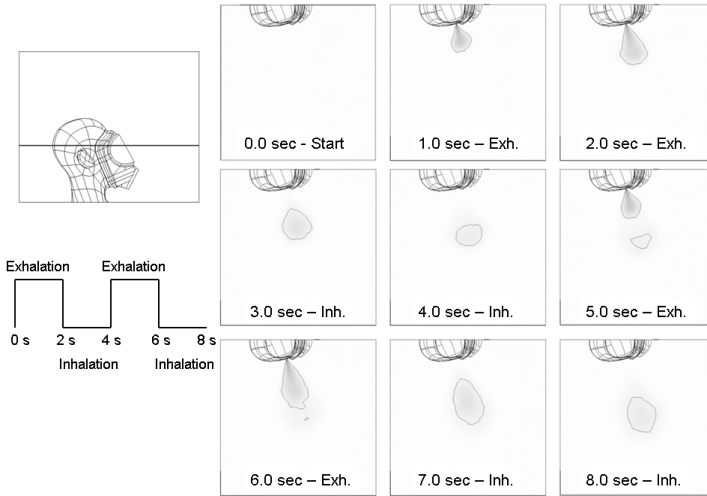
The first of three respirator fit-related problems is a study of an outward leak of breathing gases from a closed-circuit self-contained breathing apparatus (CC-SCBA). This respirator system recirculates the gases breathed by the wearer, chemically scrubbing carbon dioxide and adding oxygen from a storage tank. The advantage is the ability to work for up to four hours without exchanging the tank, as compared to a limit of a half-hour to an hour for the standard compressed air tank carried by fire-fighters. The concern is the accumulation of oxygen within the facepiece, which was measured in laboratory testing at levels as high as 90 % [2], and the potential danger posed by an outward leak into an environment containing flammable gases.

A finite element model was used to determine the difference in size between a flammable region resulting from a leak of air into a near-flammable environment and that resulting from a leak of oxygen [3,4], as a qualitative method to compare hazards. The selected environment was 10 % by volume of propane in air. Since the upper flammability limit (UFL) of propane in air at room temperature is 9.5 % by volume, this mixture is slightly too fuel rich to ignite. Introduction of pure air or oxygen into this mix from a leak creates a flammable mixture in some region surrounding the leak. Temperature was not considered in this problem.

The computational area was defined as a box outside of a head form and mask, as shown in Figures 1 and 2. The leak was defined as a strip 1 mm wide by 43.5 mm long along the interface between head and mask near the temples.



**Fig. 2.** Leak of pure oxygen into a 10 % propane environment over two breathing cycles. The plane shown in the sequence is from the center of the leak region (*upper left figure*).



**Fig. 3.** Leak of air into a 10 % propane environment over two breathing cycles

Figures 2 and 3 show the results for leaks of oxygen and air, respectively. These analyses were carried out for two breath cycles at the typical breathing rate of a person at rest, with flow out of the respirator leak only during the exhalation period. The gray shaded areas indicate the concentration of oxygen. The flammable regions are marked by lines that outline a balloon-like volume cut along a cross-sectional plane. For an oxygen leak at this breathing rate, the flammable region is attached to the respirator during the entire breathing cycle, while for an air leak it detaches during inhalation and moves away from the head.

The flammable region resulting from a pure oxygen leak is significantly larger than that from air. Heavier and more rapid breathing, such as that caused by exertion, increases the flammable region further in both cases. The conditions considered here are worst case conditions: pure oxygen within the facepiece, a near-flammable environment, and still air, so that the results represent an upper bound for the difference in hazard between a leak from a closed-circuit SCBA and a leak from an open-circuit SCBA.

## 4 Interior Flow Field

The second problem is a study of the flow field inside a half-facepiece respirator.

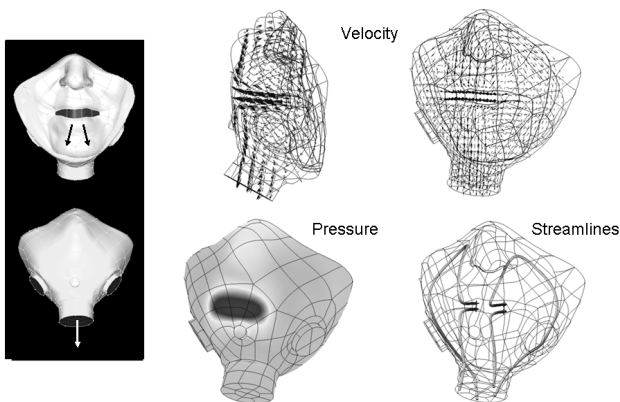
Laboratory investigations of respiratory protection rely on sampling of pressure and aerosol levels using probes mounted within the respirator facepiece [5, 6]. Because of incomplete mixing of the gases and aerosols, measurements vary depending on the location of the probe and the location of any leak [7, 8]. Known as sampling bias, this is also an issue with quantitative fit testing of users using the Portacount, which compares the aerosol particulate levels measured by a probe inside the facepiece to those outside.

Using FEM, or computational fluid dynamics (CFD), to solve for the velocity and pressure fields within the respirator during breathing, allows the determination of the flow within the entire volume. This provides insight into the breathing environment of the respirator user, shows where sampling bias may be a problem, and may suggest a better location within the facepiece to place a probe during testing.

For this problem, the head and half facepiece air purifying respirator (APR) shown in Figure 1 were combined, and the computational space was defined as the space in between those surfaces, as shown in Figure 4. Mouth breathing was assumed, so part of the preparation of the head required opening the mouth by rotating the surfaces of the lower lip and chin about an axis representing the jaw hinge.

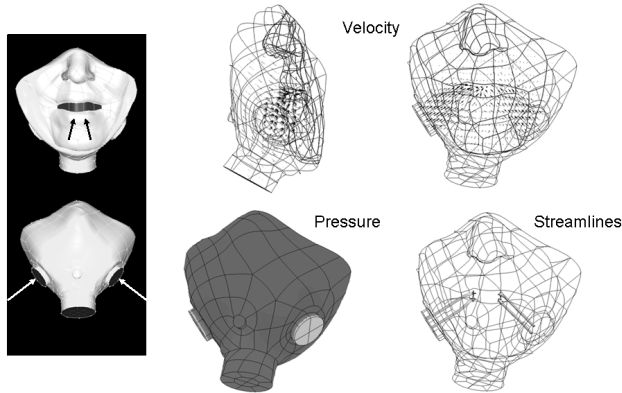
The boundary conditions were dependent on the inhalation or exhalation part of the breathing cycle. During inhalation, the side valves open, and air is drawn in through filters mounted on the respirator (the filters were not considered in the model). During exhalation, the side valves close and the center valve opens to expel the exhaled gases into the surroundings. The geometry of the valve openings was not considered in this model, so the entire area of a valve was free when it was open. The flow was driven by the inlet conditions of the mouth: a uniform positive velocity into the computational space perpendicular to the surface of the open mouth during exhalation, and a uniform negative velocity during inhalation. The magnitude of the velocity was calculated using the flow rate of a resting person divided by the area of the open mouth, and followed a simple sine function from exhalation to inhalation to exhalation.

During exhalation, shown in Figure 4, the center valve of the respirator is open and side valves are closed. The gases exhaled from the mouth impact the wall of the respirator directly in front of the mouth. This causes a region of high pressure that is surrounded by large pressure gradients. A probe located in this volume may be susceptible to sampling bias due to the spatial variability of pressure and velocity. The exhaled gases move away from the wall in all directions, sweeping around the contours of the respirator.



**Fig. 4.** Velocity vectors, surface pressure and streamlines during exhalation

The behavior of the flow during inhalation is quite different, as shown in Figure 5. In this case, the inhaled gases follow a direct path from the open side valves to the mouth. The pressure is uniform around the inner walls of the respirator and jumps to a different value at the side valves. This result would make it difficult to monitor the inhaled gases and particulates, since little mixing appears to take place during this part of the breathing cycle and a probe is not easily placed in the path of the flow.



**Fig. 5.** Velocity vectors, surface pressure and streamlines during inhalation

By running this analysis for a variety of defined leaks, the effects of leaks on the velocity and pressure fields can be studied. It may be possible to determine sensor locations and a monitoring scheme to determine whether respiratory protection has been compromised. By identifying chemical components of inhaled and exhaled gases, this model could also be used to identify dead spaces within the respirator that accumulate carbon dioxide and may be inhaled in subsequent breaths.

## 5 Computational Fit

The third problem uses real material properties of the respirator and skin over bone to characterize the relationship of respirator design and head shape to fit and comfort. The solution of this problem has not yet been achieved, so this paper will report on the approach and the preparation of the initial configuration. The idea is to computationally push the respirator onto the face, distorting its shape as necessary, until the head is "wearing" the respirator. As the respirator is pushed into place, the FEM software determines the areas of contact and contours of stress. Contours of low stress indicate areas where leaks would be most likely, and contours of high stress indicate areas where the respirator would be pulled the tightest to get a good seal, and thus areas of greatest tactile discomfort.

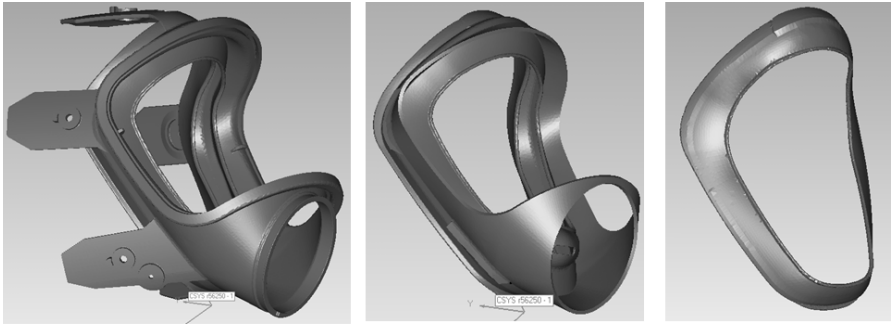
This approach has been successfully tried in the past, in a Phase I SBIR project for the Army Research Laboratory [9]. This project solved a contact problem for a single respirator seal and a nosecup pushed onto a generic face. After reviewing the literature on the material properties of rubber and skin, they selected a hyperelastic model for both

materials. The contact problem included friction between the respirator and skin. The end result of the analysis was a map of contact pressures of the respirator seal against the face that was compared to pressure levels that cause tissue damage and pain.

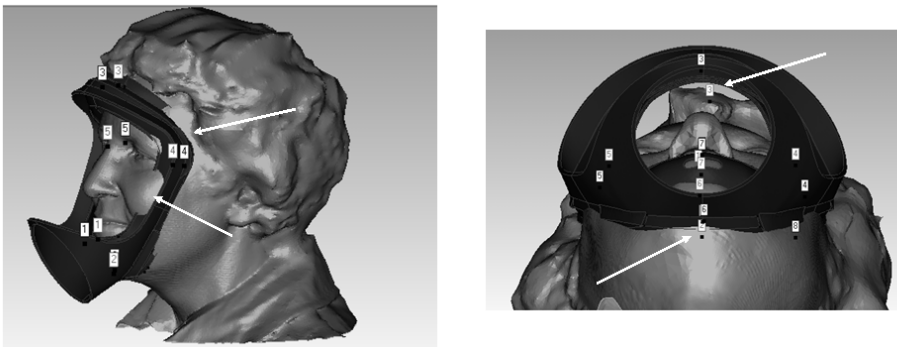
One difficulty with this problem is the thinness of the seal. An accurate representation of material properties requires a thickness of at least three elements, and limitations on the aspect ratio of finite elements will make this a large problem, especially if multiple seals are attempted.

The setup of this model begins with a respirator geometry obtained from a CAD file, shown to the left in Figure 6. The rigid portions of that geometry surrounding the faceshield and valve hardware can be removed and replaced in the model with rigid boundary conditions. The straps are also removed, leaving the multiple seal geometry in the center of Figure 6. Finally, as an initial problem to test the software and determine the feasibility of modeling multiple seals, all seals are removed except the seal closest to the face, resulting in the single seal geometry at the right.

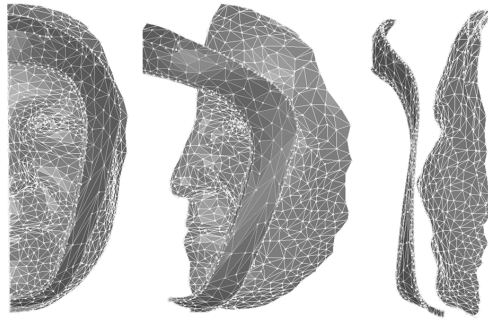
To illustrate the amount of distortion that is required to mount the respirator on the face, Figure 7 shows the combination of the rigid multiple seal geometry with the rigid head. The respirator cuts through cheeks and temple while leaving a wide gap between the top of the respirator and the forehead.



**Fig. 6.** Simplification of CAD file of respirator to a single seal for initial testing



**Fig. 7.** Rigid respirator combined with rigid head. The arrows point out gaps and overlapping areas.



**Fig. 8.** Initial configuration of respirator seal and face

Figure 8 shows an initial configuration for the single respirator seal. The seal is in close proximity to the cheek, the first point on the head that it will encounter. Since the head and respirator are roughly symmetrical, the problem can be cut in half. The skin is created by copying the geometry of the face at a smaller size to generate an inner layer. The thickness of the skin on the face varies with location and the individual. On average, the skin of the forehead is 5 mm thick, the skin of the chin is 9 mm thick, and the skin of the cheek is 21 mm thick [10]. To approximate skin over bone, therefore, the copy of the outer layer of skin is reduced by a different factor in  $x$ -,  $y$ -, and  $z$ -dimensions to approximate these thicknesses on forehead, chin, and cheek. A grid will be created between the inner and outer facial geometries, and the inner surface will be held rigid (the “bone”) during the analysis.

To carry out the analysis, an elastic contact problem will be solved. A load applied to the locations of the base of the straps will pull the respirator seal toward the face until contact is achieved, and the load will be increased until the seal is in contact with the head around its full circumference. For a perfect fit, the contact pressures would be equal over the entire seal. The actual distribution of contact pressures will show where the areas of potential discomfort and leaks would be, and the magnitude of the pressure difference may provide a means to quantify the goodness of fit for this analysis.

The end result of this model could be used as the geometry for the first and second problems discussed in this paper, replacing the arbitrary shaping of the respirator to fit onto the head in each case. The intent of this project includes analysis of multiple heads and respirators and the fit for different facial expressions (e.g. during talking and coughing).

## 6 Discussion

These three examples show some of the investigations into respirator fit and efficacy that can be conducted using computational tools. To fully trust the results, the models need to be validated. It is difficult to visualize the flow field inside a respirator experimentally, but pressure is easily measured and can be used for comparison with the interior flow field model. For the computational fit model, the placement of the respirator on the head can be compared with a 3D scan of the person wearing the respirator.

Computational techniques that significantly improve the speed of creating 3D geometries and converting them to finite element format are needed. As new, more efficient methods for representing human shapes are developed, thought should also be given as to how the geometry will be connected to interfacing geometries, such as the head to a respirator or helmet. Finally, consideration should be made not only to representations of fixed outer surfaces, but to the body in-depth and in motion as well.

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