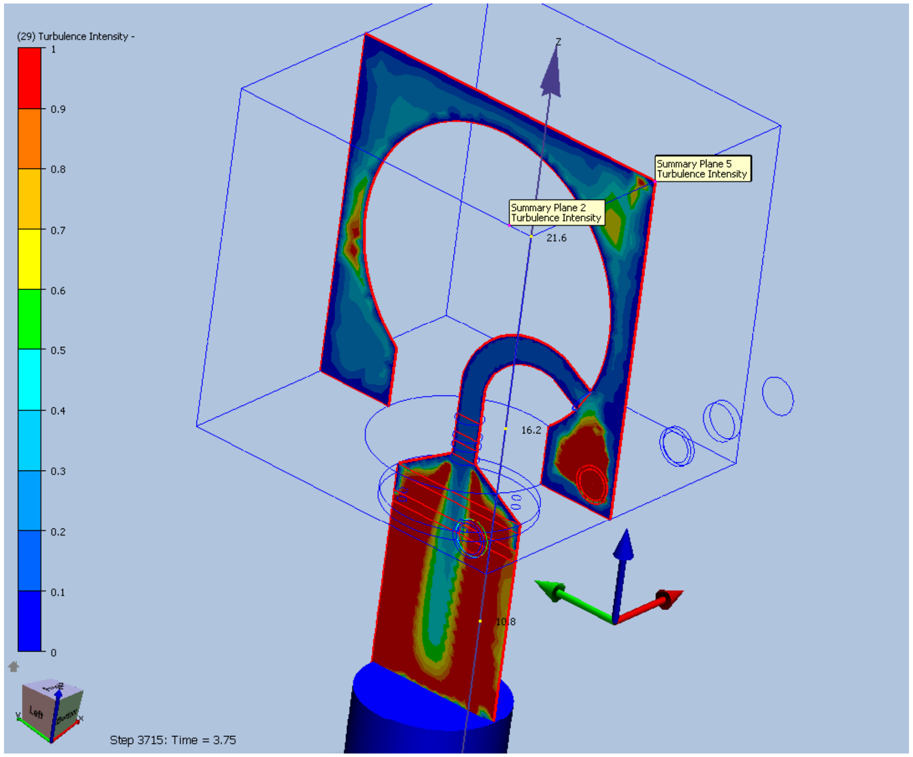
Life Support Helmet CO_2 Transport Modeling

S&T Focus Area



Objectives:

- Investigate CFD helmet CO_2 mixing-transport models.
- Validate CFD models relative to experimental research.
- Explore minimizing CO_2 with minimal flow and power.

Technical Challenges:

- Multi-species flow.
- Laminar and turbulent flow interaction.
- Eddy and molecular diffusion.
- Harmonic problem with relaminarization.

Technical Approach:

- Refine finite difference harmonic mixing zone model.
- Develop inhalation and exhalation steady flow CFD models and correlate CFD results with previous experimental data.
- Develop dynamic breath cycle CFD model and optimize, validate it using experimental data.

Key Performers:

Dr. John Camperman, NSWC-PCD
Robert Hughes, NSWC-PCD
Dr. Rick Smith, NSWC-PCD

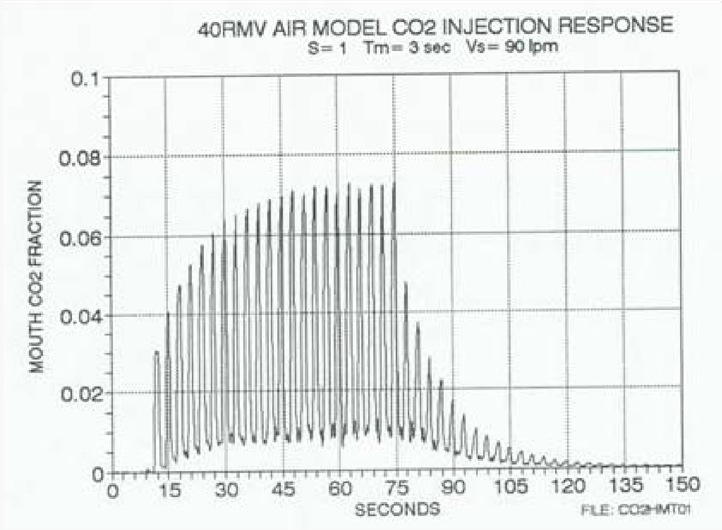
S&T Products:

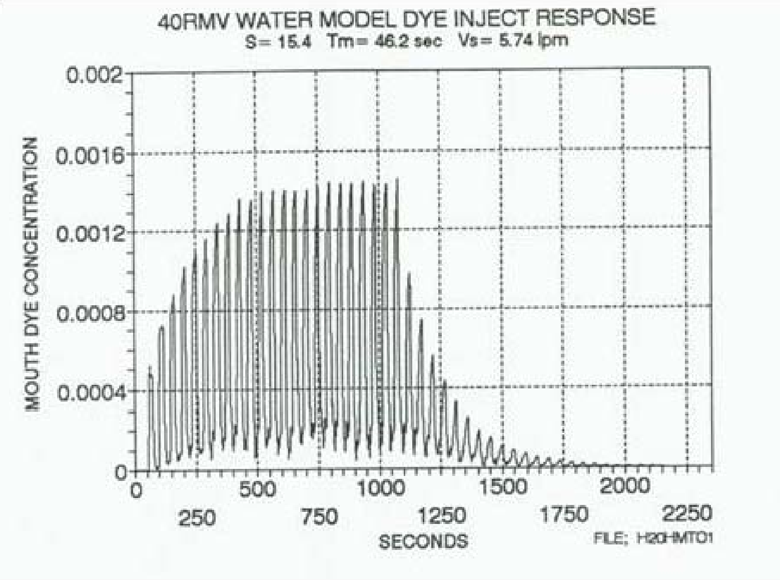
- Assessment of CFD validity for helmet CO_2 transport.
- Investigation of modeling techniques for potential helmet improvements applicable to diving, firefighting, CBRN protection, and aerospace life support helmets.

PROBLEM

- Traditional well mixed assumptions require over 150 liters/min fresh gas flow to maintain average inhaled CO_2 below 2% at one atmosphere.
- High flow generates noise, and consumes excessive gas or blower power.
- Oral-nasal masks control CO_2 but are not desirable.

Previous Experimental Modeling





TWO CYCLE COMPLETE MIXING

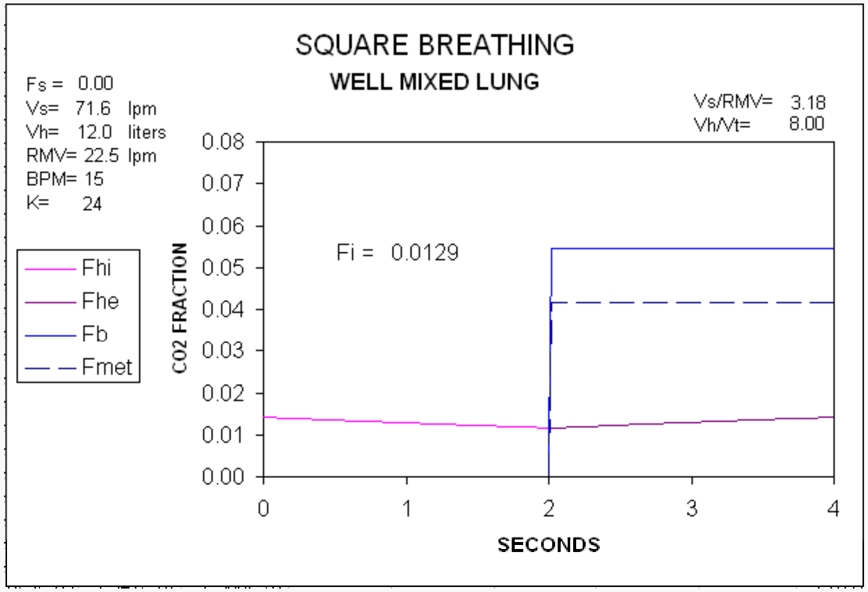
Inhale
$$\dot{F}_{hi} + F_{hi}\frac{\dot{V}_s}{V_h} = F_s\frac{\dot{V}_s}{V_h}$$

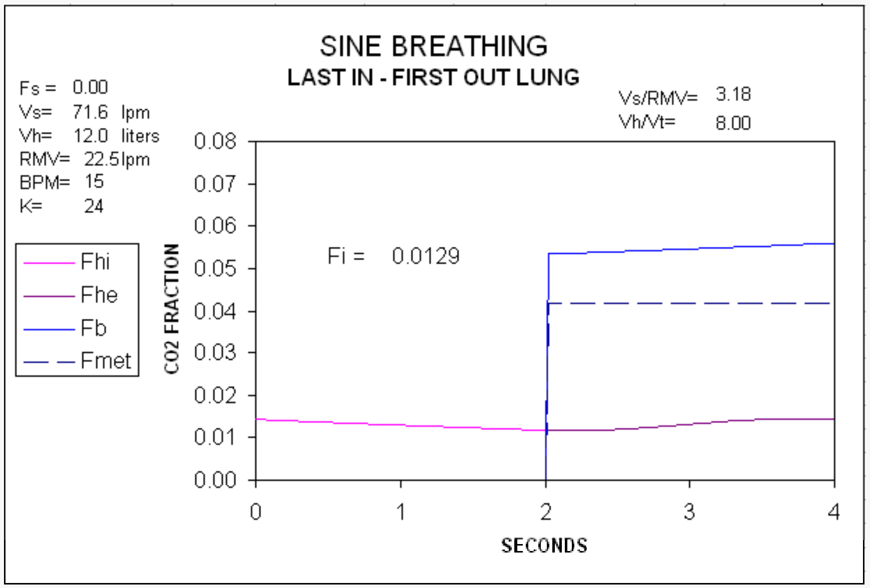
Exhale
$$\dot{F}_{he} + F_{he}\left(\frac{\dot{V}_s-\dot{V}_{be}}{V_h}\right) + F_e\frac{\dot{V}_{be}}{V_h} = F_s\frac{\dot{V}_s}{V_h}$$

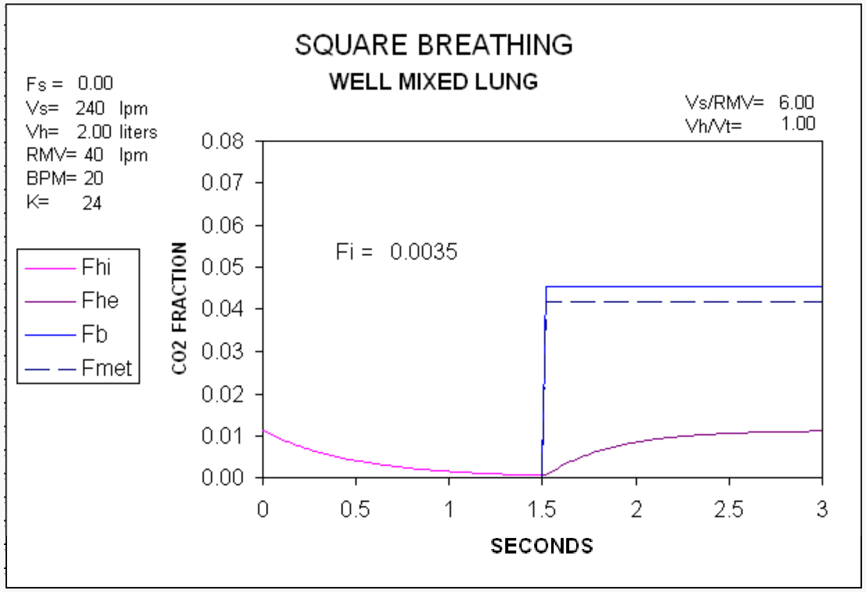
Boundary Conditions (coupling)
$$F_{hi}(0) = F_{he}(T)$$
$$F_{hi}(T_i) = F_{he}(T_i)$$

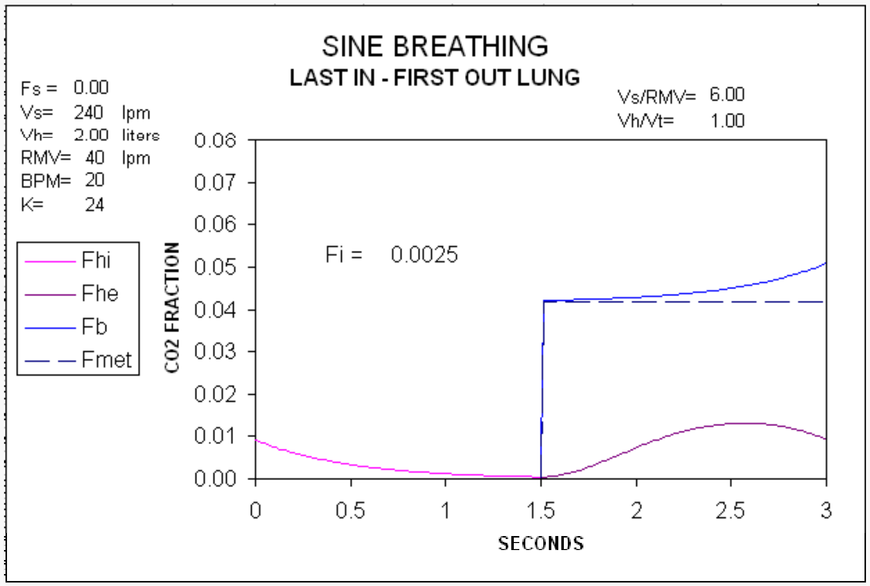
Respiratory CO_2
$$-\int_{Ti}^{T} F_e\,\dot{V}_{be}\,dt = \int_0^{Ti} F_{hi}\,\dot{V}_b\,dt + \dot{V}_{CO2}T$$

Average inhaled CO_2 fraction
$$F_i = \frac{1}{V_t}\int_o^{T_i} F_{hi}\dot{V}_{bi}dt$$


SQUARE BREATHING
WELL MIXED LUNG
Fs = 0.00
Vs= 71.6 lpm
Vh= 12.0 liters
RMV= 22.5 lpm
BPM= 15
K= 24
Vs/RMV= 3.18
Vh/Vt= 8.00
Fi = 0.0129
Fhi
Fhe
Fb
Fmet
C02 FRACTION
SECONDS


SINE BREATHING
LAST IN - FIRST OUT LUNG
Fs = 0.00
Vs= 71.6 lpm
Vh= 12.0 liters
RMV= 22.5lpm
BPM= 15
K= 24
Vs/RMV= 3.18
Vh/Vt= 8.00
Fi = 0.0129
Fhi
Fhe
Fb
Fmet
C02 FRACTION
SECONDS


SQUARE BREATHING
WELL MIXED LUNG
Fs = 0.00
Vs= 240 lpm
Vh= 2.00 liters
RMV= 40 lpm
BPM= 20
K= 24
Vs/RMV= 6.00
Vh/Vt= 1.00
Fi = 0.0035
Fhi
Fhe
Fb
Fmet
C02 FRACTION
SECONDS


SINE BREATHING
LAST IN - FIRST OUT LUNG
Fs = 0.00
Vs= 240 lpm
Vh= 2.00 liters
RMV= 40 lpm
BPM= 20
K= 24
Vs/RMV= 6.00
Vh/Vt= 1.00
Fi = 0.0025
Fhi
Fhe
Fb
Fmet
C02 FRACTION
SECONDS

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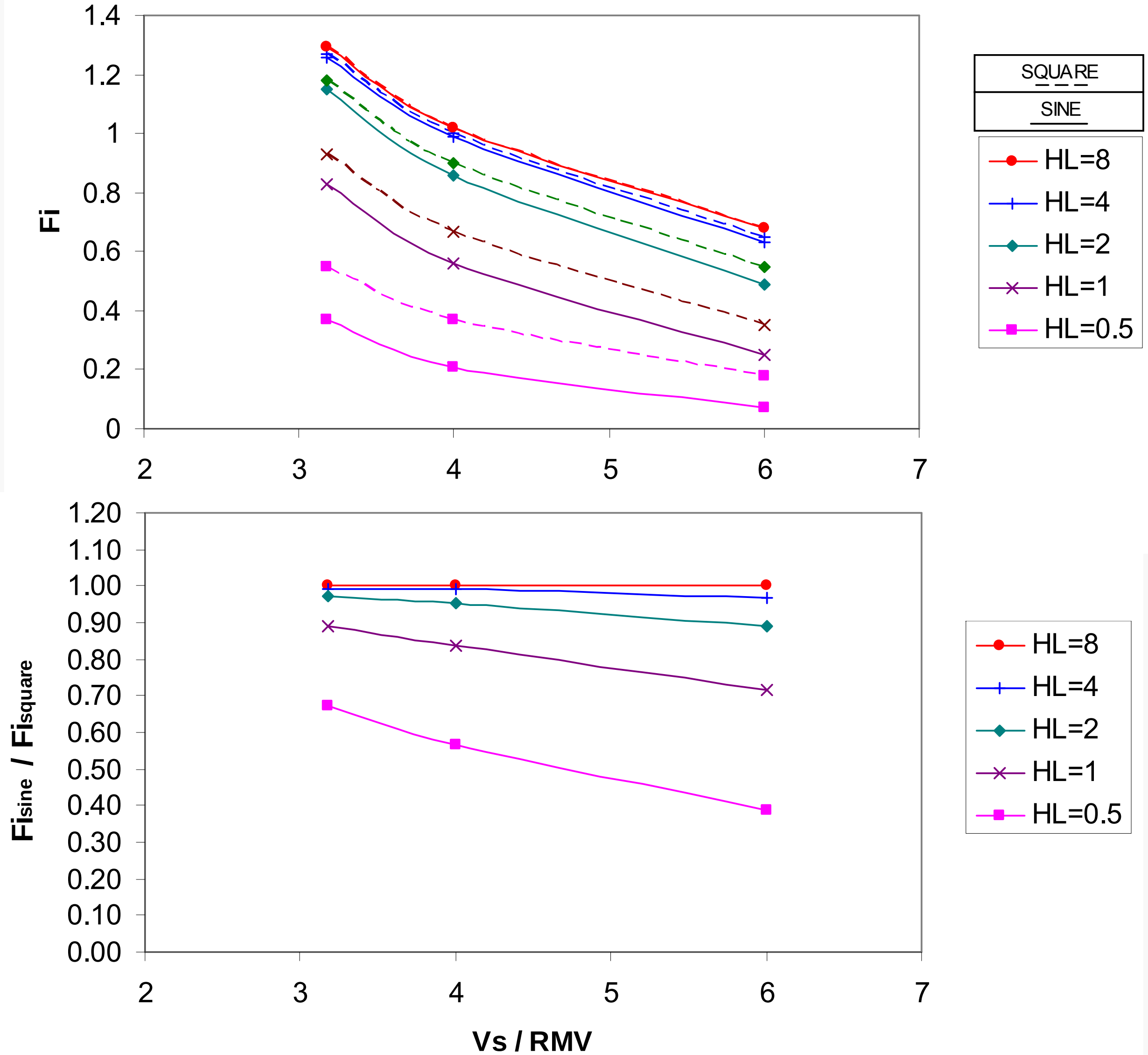
HELMET TWO CYCLE COMPLETE MIXING

Square and Sinusoidal Breathing Inspiratory CO_2

(Finite Difference Model)



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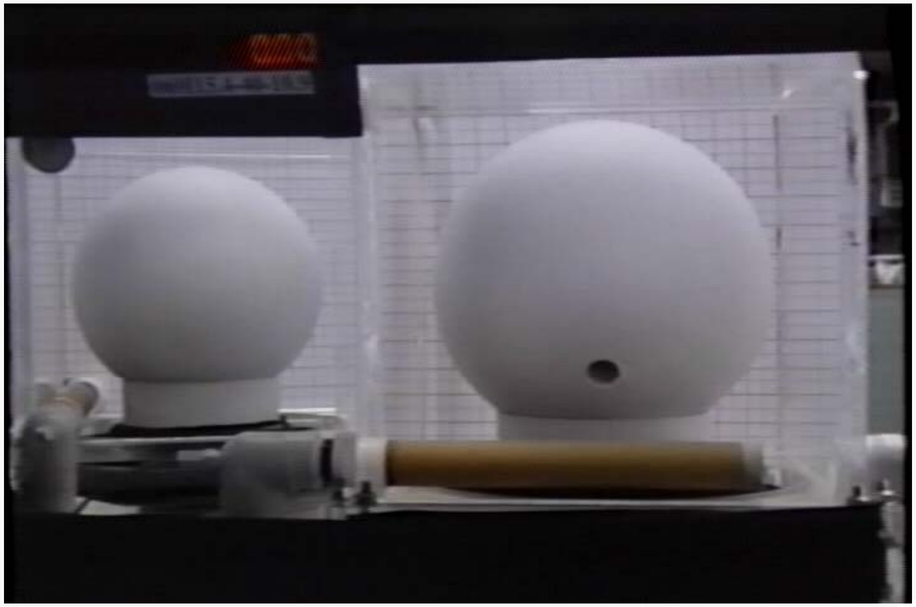
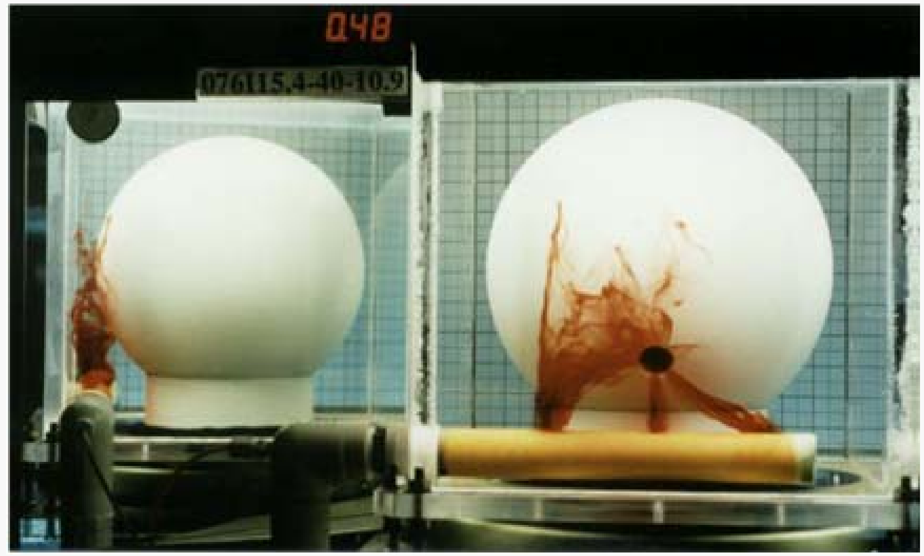
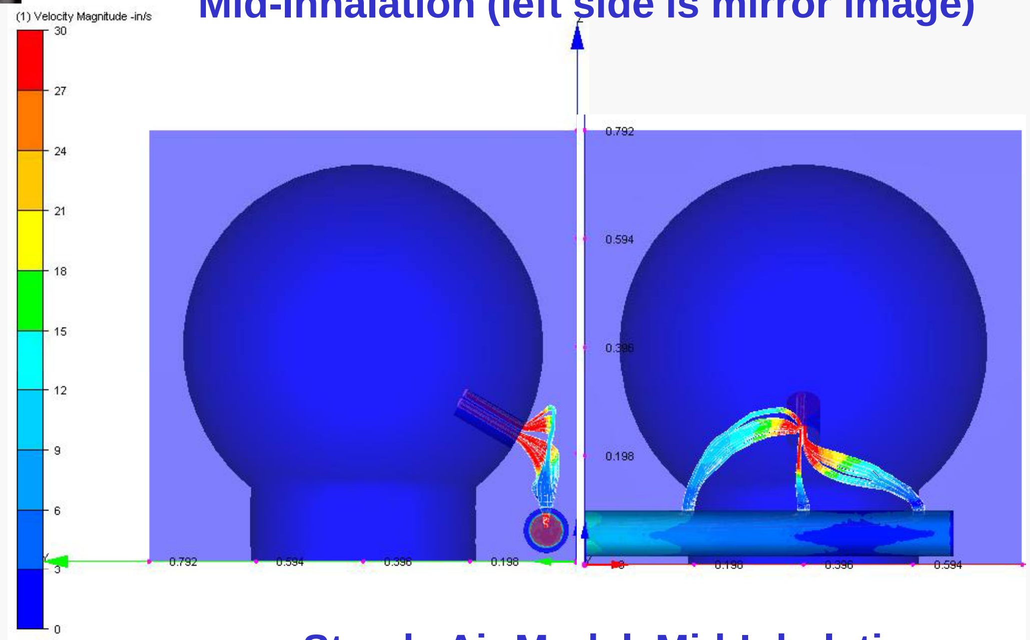
40 RMV Inhalation Streak Lines and Particle Traces

Breath: Supply (lpm) Air 126:170; Water 8.1:10.9



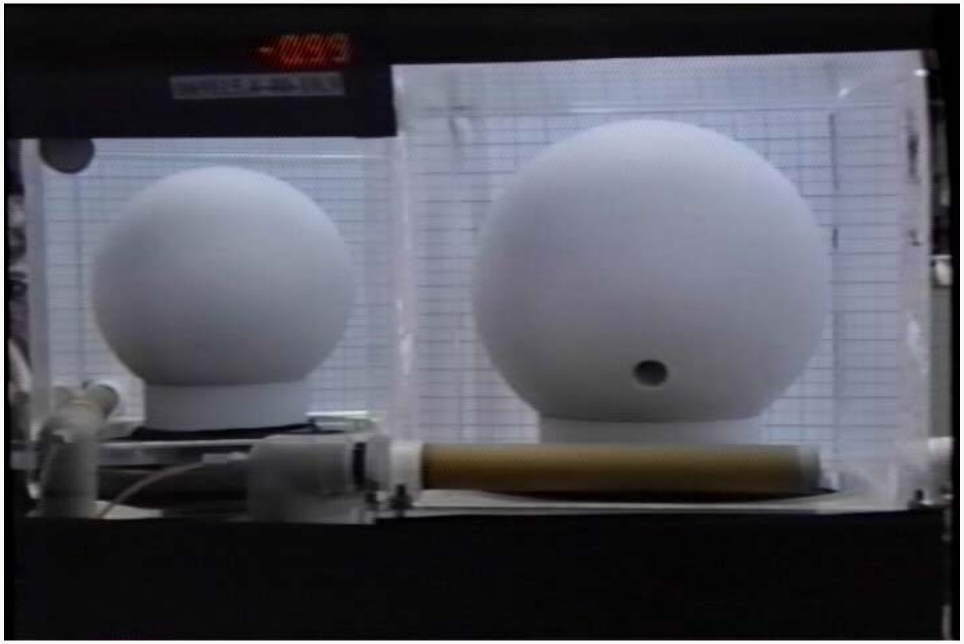


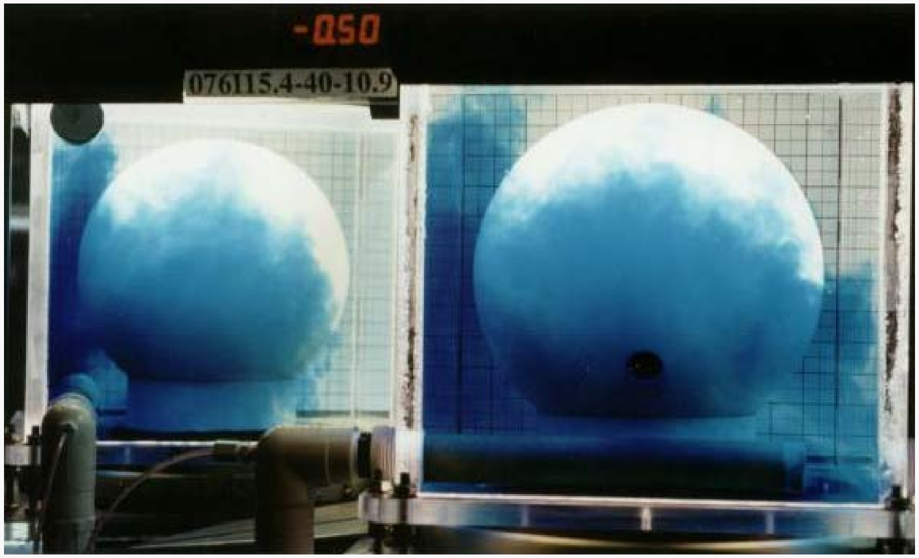
Mid-Inhalation (left side is mirror image)



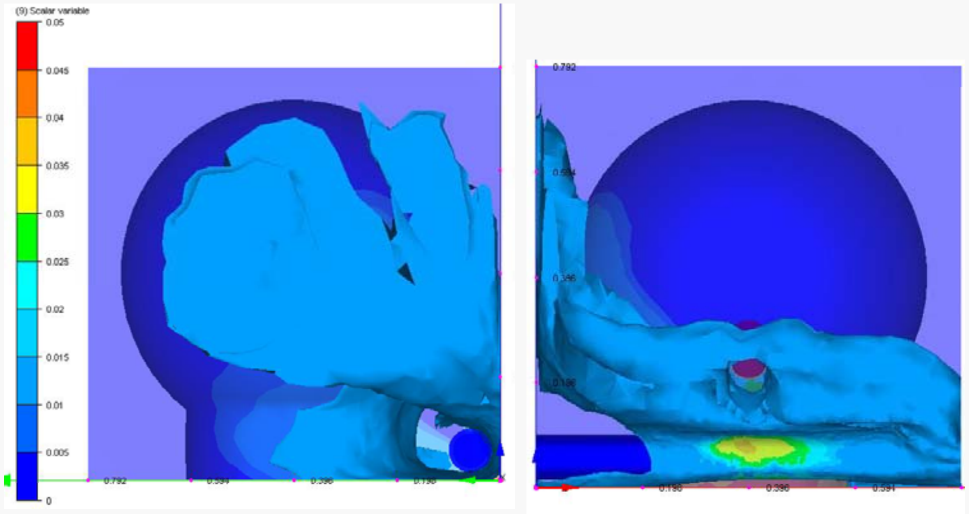
Steady Air Model, Mid-Inhalation

40 RMV Exhalation Breath Plumes
Breath: Supply (lpm) Air 126:170; Water 8.1:10.9





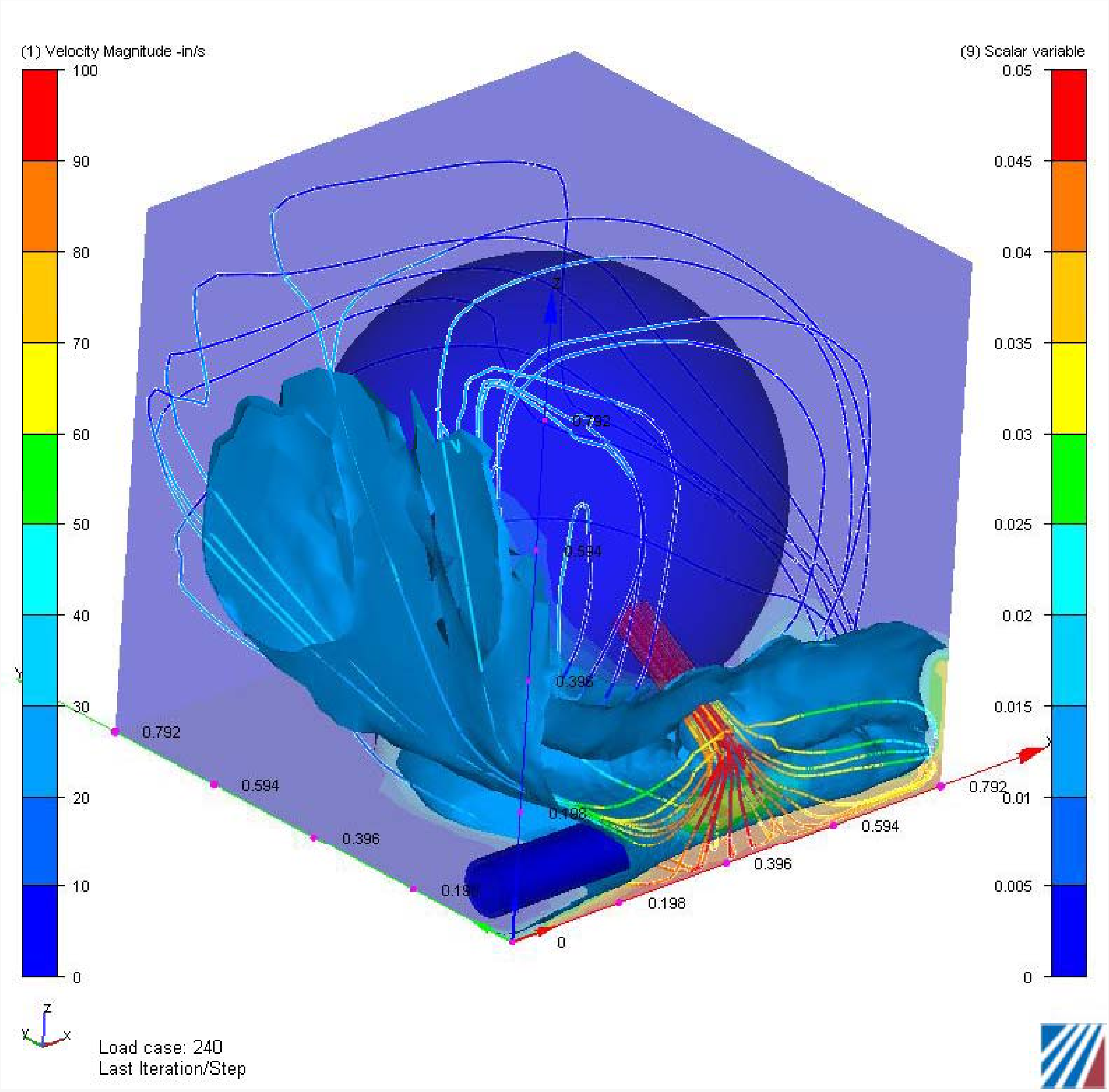
Mid-Exhalation (left side is mirror image)



Steady Air Model, Mid-Exhalation
0.015 CO2 Concentration Surface

40 RMV Mid-Exhalation Steady Air Model

Breath: 126 lpm **Supply:** 170 lpm



Particle Traces and 0.015 CO2 Concentration Surface

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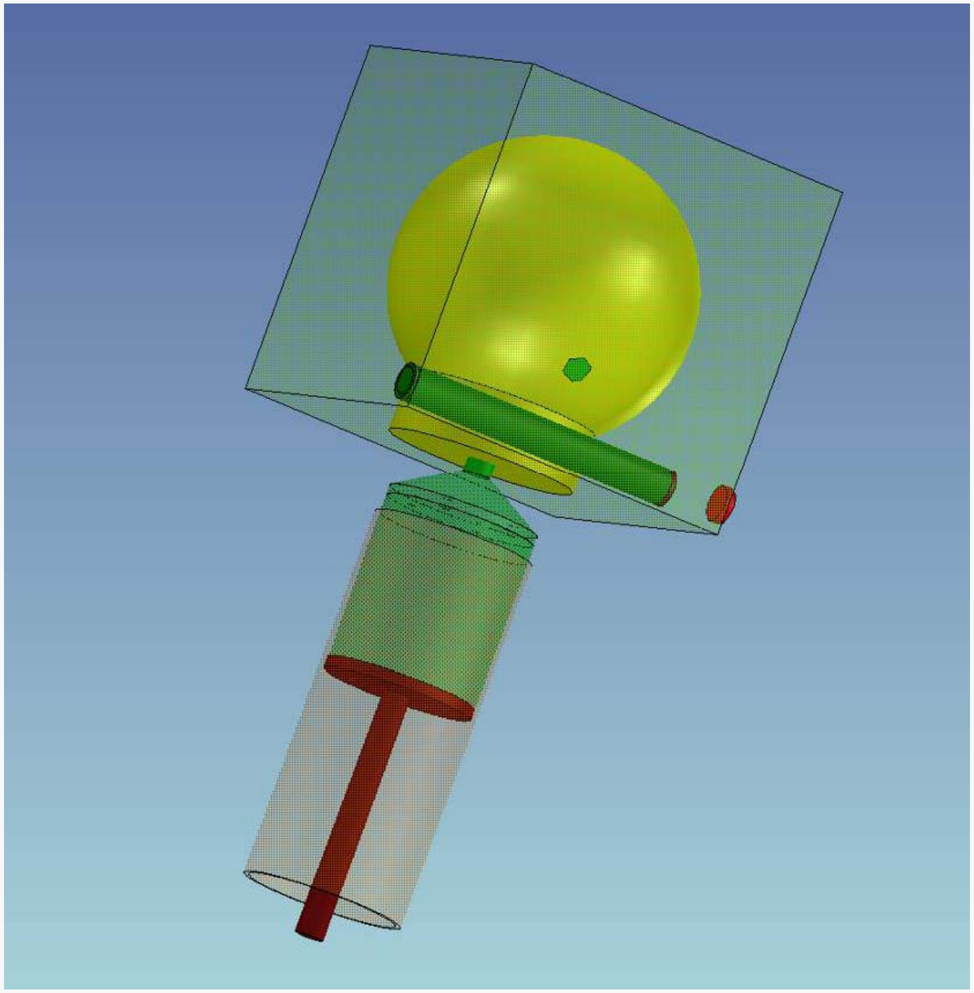
Helmet-Lung Harmonic Air Model Geometry



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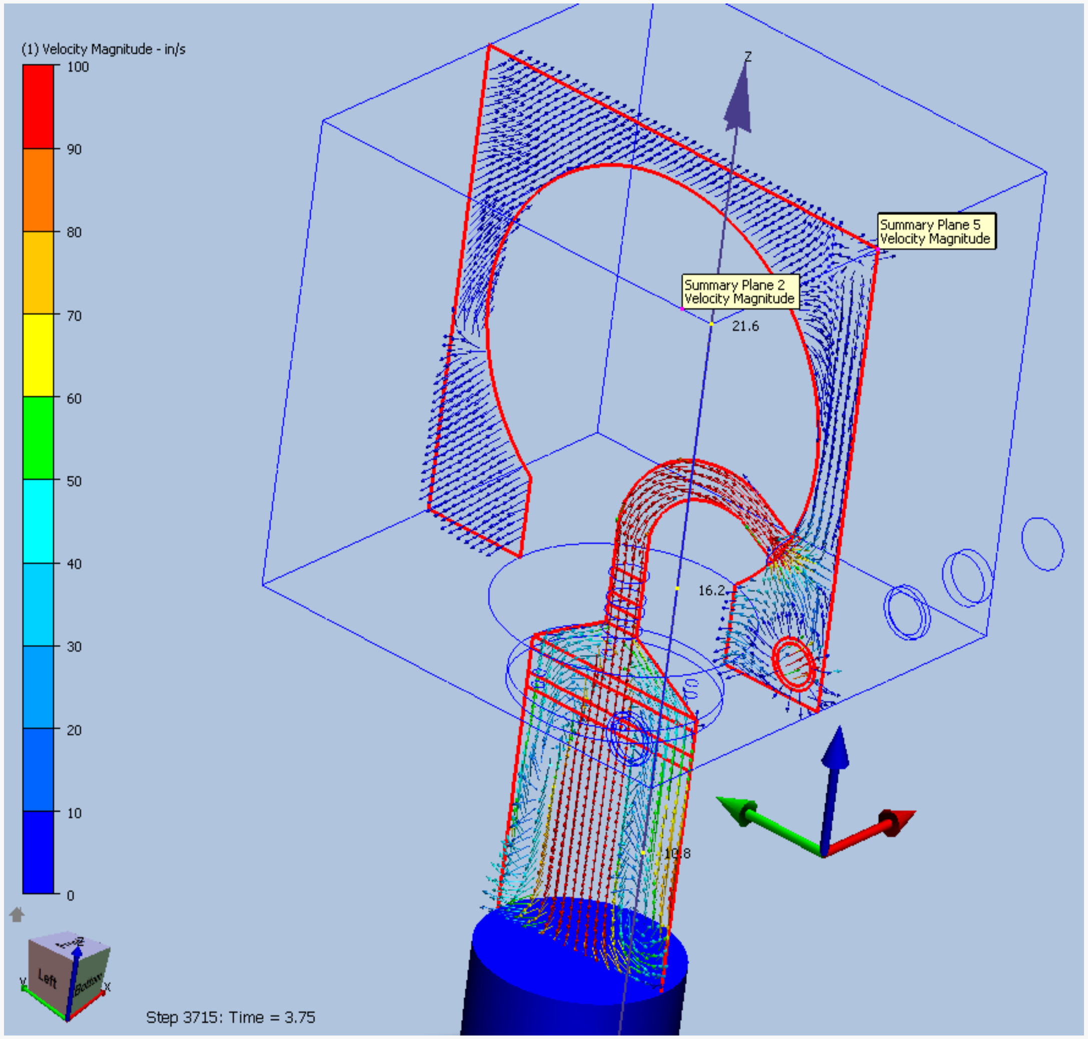
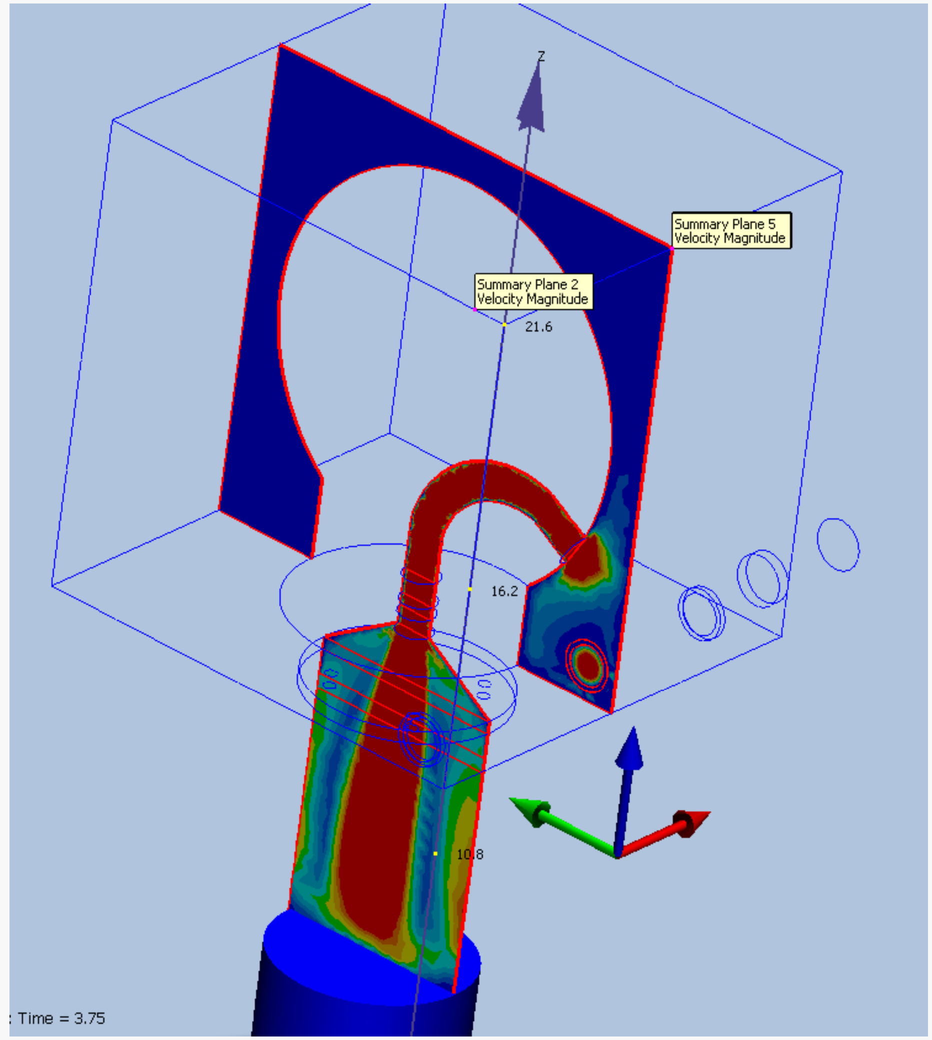
Mid-Inhalation Square Wave Air Model
Breath: ≈126 lpm   Supply: 170 lpm



3D velocity vectors; fixed length, color magnitude.



Velocity contours.

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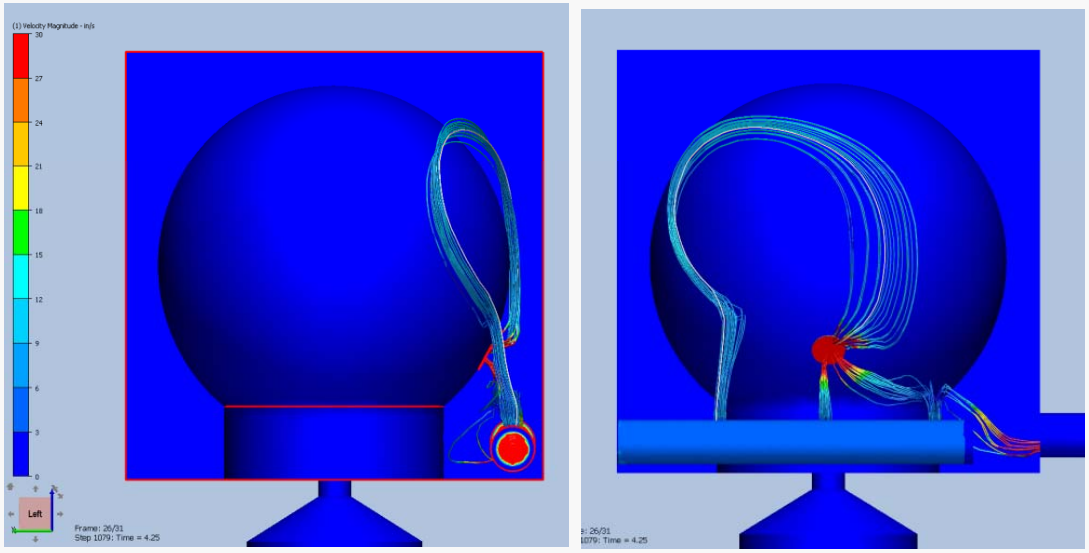
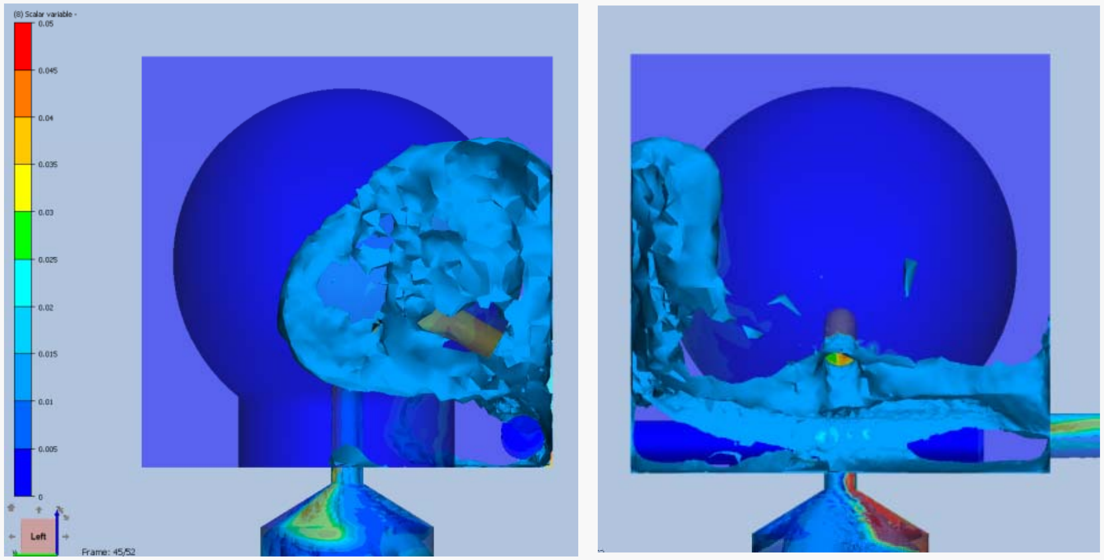
40 RMV Mid-Inhalation Harmonic Air Models
Breath: 126 lpm **Supply:** 170 lpm



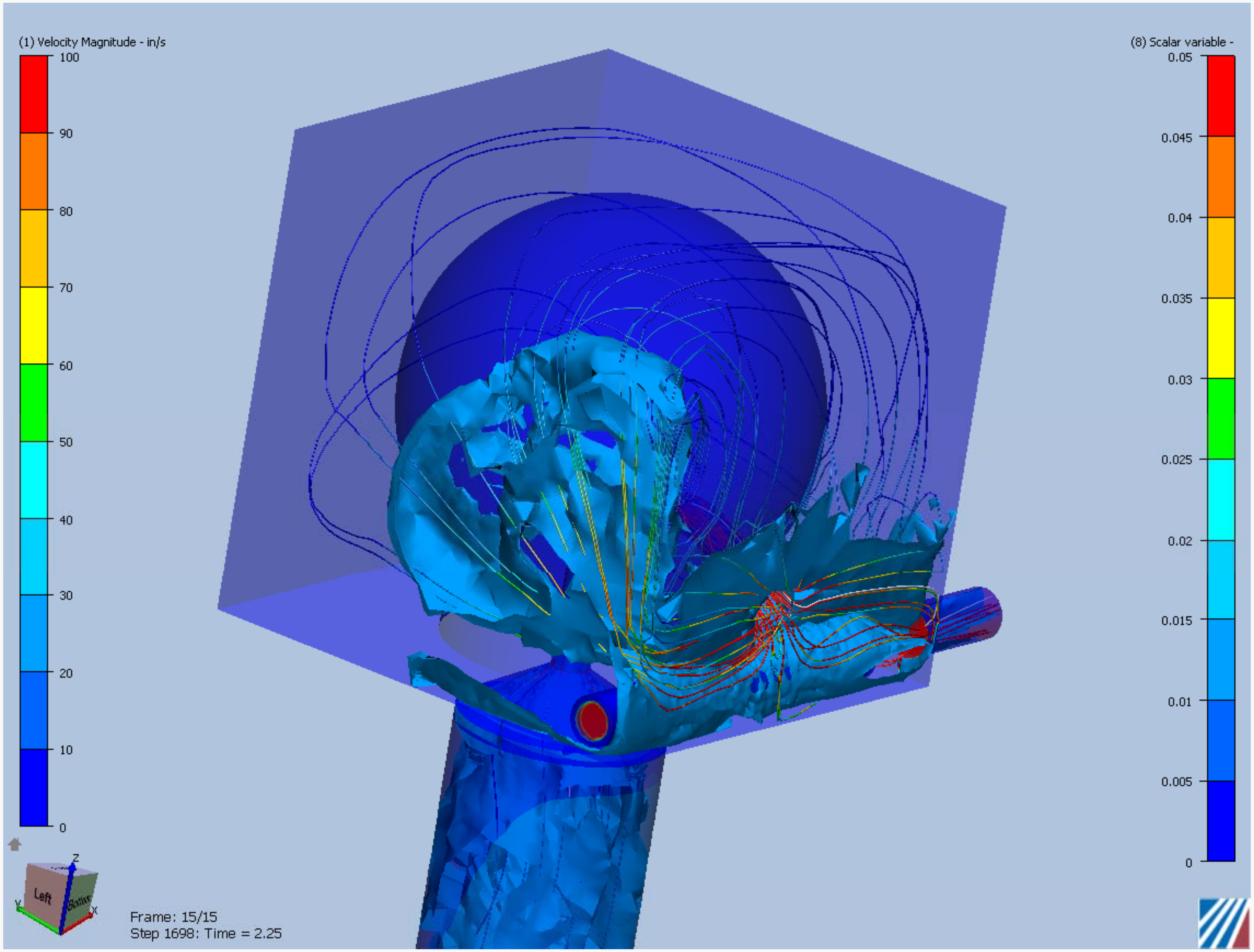
Square Wave Air Model Mid-Inhalation



Sinusoidal Air Model Mid-Exhalation

40 RMV Mid-Exhalation Sinusoidal Air Model

Breath: 126 lpm **Supply:** 170 lpm



FINDINGS

- Finite difference complete mixing model indicates inhaled CO_2 fraction is greatly reduced with sine breathing versus square breathing for small mixing volumes.
- Steady flow CFD simulations represent fundamental harmonic peak flow behaviors.
- Harmonic CFD simulations may be used to model helmet harmonic flows.

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APPLICATIONS

Modeling techniques may guide innovative helmet design geometries that optimize CO_2 transport.

- Navy Flyaway Mixed Gas semi-closed circuit rebreather interface.
- Powered Air Purifying Respirators
- NASA Space Suit Systems