Movement of Respired Gas in Manned Space Enclosures

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The minimum atmosphere movement required for human respiratory support has never been determined since man's earliest thoughts of space flight. The purpose of this paper is to present research to aid in determining the movement and dispersion of respired gas in manned space enclosures during weightless flight. This research is based upon mathematical analysis and human and model experimentation. The effects of atmosphere movement produced only by respiration and diffusion are analyzed. This is the condition that exists in manned spacecraft without forced atmosphere movement during weightless flight for a sleeping or restrained astronaut. The determination considers an astronaut in an infinite space enclosure. The exhaled gas is considered to be injected into the infinite medium as two pulsating jets from a fixed source. Due to viscosity and momentum effects, the exhaled gas is slowed down by the surrounding fluid until the only means of gas dispersion is due to molecular diffusion. The amount of carbon dioxide which is inhaled is dependent upon the position and dispersion of the previous exhalations due to the effects of momentum, viscosity, and diffusion. The techniques of dimensional analysis and model theory are used to provide an experiment in the earth laboratory which represents the movement and dispersion of respired gas in a weightless space enclosure.

THE MINIMUM ATMOSPHERE movement required for human respiratory support has never been determined since man's earliest thoughts of space flight.

The lack of convection during weightless flight has caused much concern as to the movement and dispersion of respired gas in spacecraft. Some researchers speculate that without forced atmosphere movement the expired gas will remain in front of the nose of the astronaut. Other researchers speculate the astronaut will surround himself with a layer of his own expiratory gases. Still other researchers speculate that formations of localized bodies of gas will occur containing deficiencies of oxygen and abundancies of carbon dioxide which could cause suffocation.

The purpose of this paper is to present research to aid in determining movement and dispersion of respired gas in manned space enclosures during weightless flight. This research is based upon mathematical analysis and human and model experimentation. The effects of atmosphere movement produced only by respiration and diffusion are analyzed. This is the condition that exists in manned spacecraft without forced atmosphere movement during weightless flight for a sleeping or restrained astronaut.

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and dispersion of the previous exhalations due to the effects of momentum, viscosity, and diffusion.

The techniques of dimensional analysis and model theory are used to provide an experiment in the earth laboratory which reasonably represents the movement and dispersion of respired gas in a weightless space enclosure. The design of the experiment is based upon the results of human exhalation with smoke to determine the correct angles of dispersions and the exhalation flow patterns. The theoretical and experimental analyses have been integrated to investigate the minimal atmosphere movement required for life support during manned space flight.

DIMENSIONAL ANALYSIS

The purpose of this mathematical analysis is to determine how the position of exhaled gas depends upon the variables which characterize the fluid flow behavior of the pulsating jets. The exhaled gas is considered to be divided into two portions. Each portion emanates as a jet from a fixed nostril. The dimensions of these variables directly influence the analysis such that this approach is termed dimensional analysis.

The variables of fluid flow behavior and their dimensions are given by the following table.

Variable	Symbol	Dimension
Distance from nostril	h	L
Time	t	T
Mass of fluid	m	M
Viscosity	u	$ML^{-1}T^{-1}$
Density	p	ML^{-3}
Velocity	v	LT^{-1}
Effective diameter of nostril	l	L

The distance of the gas from the nostril is expressed as a function of the variables as given below.

$$h = f(t, m, l, u, p, v)$$

The theory of dimensional analysis provides a technique for obtaining a suitable equation for the previous function by forming dimensionless groups. The general group is designated as (A) and the specific groups are designated at A_1, A_2, A_3, . . . etc. Since there are seven variables and three basic dimensions, the theory of dimensional analysis predicts that there will be four dimensionless groups. The theory of dimensional analysis also requires that

$$f(A_1, A_2, A_3, A_4) = 0.$$

The general group (A) is defined as a dimensionless product of the variables where each variable is raised to an exponential value as given by the following equation.

$$A = (h^a)(t^b)(m^c)(l^d)(u^e)(p^f)(v^g)$$

The basic dimensions are substituted into the general group to obtain the following equation.

$$A = (L)^a (T)^b (M)^c (L)^d (ML^{-1}T^{-1})^e (ML^{-3})^f (LT^{-1})^g$$

The following equations are set up which take into account the basic dimensions, the exponents and the theorem that (A) must be dimensionless.

$$c + e + f = 0$$

$$a + d - e - 3f + g = 0$$

$$b - e - g = 0$$

Various values are assigned to the exponents a, b, c, and d to solve the above equations for the exponents e, f, and g. The exponent values obtained by this technique determine the terms for the specific dimensionless groups of A_1, A_2, A_3, and A_4.

The specific dimensionless groups are then determined to be given by the following equations.

$$A_1 = (h)(u^{-1})(p)(v) = hpv/u$$

$$A_2 = (t)(u^{-1})(p)(v^2) = tpv^2/u$$

$$A_3 = (m)(u^{-3})(p^2)(v^3) = mp^2v^3/u^3$$

$$A_4 = (l)(u^{-1})(p)(v) = lpv/u$$

The theory of dimensionless analysis therefore yields the following equation.

$$f\left(\frac{hpv}{u}, \frac{tpv^2}{u}, \frac{mp^2v^3}{u^3}, \frac{lpv}{u}\right) = 0$$

This equation is solved for (h) by a rearrangement which involves a new function as shown below.

$$\frac{hpv}{u} = \phi\left(\frac{tpv^2}{u}, \frac{mp^2v^3}{u^3}, \frac{lpv}{u}\right)$$

$$h = \frac{u}{pv}\,\phi\left(\frac{tpv^2}{u}, \frac{mp^2v^3}{u^3}, \frac{lpv}{u}\right)$$

The function ∅ must be determined by experimentation.

MODEL THEORY ANALYSIS

A technique based on model theory can be used to solve problems which are otherwise too complicated for mathematical or graphical solution.

The purpose of this analysis is to provide a model of the actual exhalation and inhalation of human breathing. This model can be obtained if the four specific groups A_1, A_2, A_3, and A_4 are satisfied. To obtain model and prototype similarity, the dimensionless group for the model must equal the dimensionless group for the prototype. The following equations must be obeyed to achieve similarity.

$$\left(\frac{hpv}{u}\right)\text{ model} = \left(\frac{hpv}{u}\right)\text{ prototype}$$

$$\left(\frac{tpv^2}{u}\right)\text{ model} = \left(\frac{tpv^2}{u}\right)\text{ prototype}$$

$$\left(\frac{mp^2v^3}{u^3}\right)\text{ model} = \left(\frac{mp^2v^3}{u^3}\right)\text{ prototype}$$

$$\left(\frac{lpv}{u}\right)\text{ model} = \left(\frac{lpv}{u}\right)\text{ prototype}$$

A full size model can be constructed using water as the model fluid. Thus

$$l \text{ model} = l \text{ prototype}$$

and

$$h \text{ model} = h \text{ prototype}$$

It is assumed that the tidal volume for inspiration and expiration is 500 cc at sixteen respirations per minute. One half the tidal volume emanates on exhalation from each nostril. The inspiration phase lasts 1.55 seconds which is followed immediately by expiration which lasts 1.55 seconds. A rest phase of 0.65 seconds occurs between the phases of expiration and inspiration. Experiments were also performed without the rest phase. Both types of experiments indicated that there is no meaningful rebreathing of previous exhalations.

The following model times can be obtained from the dimensionless groups to simulate respired gas in space enclosures of 300 mm Hg oxygen at 80°F and 760 mm Hg air at 80°F. The calculations are based on water as the model fluid.

A. Prototype Space Enclosure of 300 mm Hg oxygen 80°F

Model Time of Inspiration	67 seconds
Model Time of Expiration	67 seconds
Model Time of Rest	28 seconds

B. Prototype Space Enclosure of 760 mm Hg Air at 80°F

Model Time of Inspiration	26 seconds
Model Time of Expiration	26 seconds
Model Time of Rest	11 seconds

DIFFUSION ANALYSIS

The effects of molecular diffusion become apparent during dispersion after the effects of momentum become negligible. These effects can be determined if the exhaled fluid is considered to be injected into an infinite medium as an instantaneous source. The diffusing fluid is assumed to be initially distributed uniformly through a sphere of radius (a).

If the amount of diffusion fluid is deposited within a sphere at time t = o, the concentration (c) at radius (r) and time (t) can be determined by the following equation (Ref. 1).

$$C = \tfrac{1}{2}C_0\left[\operatorname{erf}\frac{a+r}{2\sqrt{Dt}} + \operatorname{erf}\frac{a-r}{2\sqrt{Dt}}\right] - \frac{C_o}{r}\sqrt{\frac{Dt}{\pi}}\left[e^{\frac{-(a-r)^2}{4Dt}} - e^{\frac{-(a+r)^2}{4Dt}}\right]$$

where

C_o = uniform initial sphere concentration
C = concentration at r for t
a = radius of initial sphere
r = radius at time t
t = time
erf = error function which is an extensively tabulated mathematical function
D = diffusion coefficient

Examination of the instantaneous spherical source diffusion equation shows that concentration is dependent upon the dimensionless term $\left(\frac{Dt}{a_2}\right)^{1/2}$. Since this term is dimensionless, the model theory technique is used to obtain the same concentration at radius (r) for time (t) for similar spherical sources. This similarity is given by the following equations.

$$\left(\frac{Dt}{a^2}\right)^{1/2}_{\text{model}} = \left(\frac{Dt}{a^2}\right)^{1/2}_{\text{prototype}}$$

Since the model is full size

(a) model = (a) prototype

and

(Dt) model = (Dt) prototype

The diffusion coefficient for the model fluid will be considered as self diffusion for water in water. This diffusion coefficient is a function of viscosity and density and is given by the following equation.

$$D = \frac{u}{p}\ \left({}^{ft^2}/_{hr}\right)$$

The diffusion coefficient for the prototype gases can be determined from the following equation (Ref. 2).

$$D = \frac{(0.0069)\,T^{3/2}}{P(V_A^{1/3} + V_B^{1/3})}\sqrt{\frac{1}{M_A} + \frac{1}{M_B}}$$

where

D = diffusion coefficient (ft²/hr)
T = absolute temperature (°R)
M_A, M_B = molecular weight (lbm)
P = total pressure (atm)
V_A, V_B = molecular volume (ft³)

The time for similar diffusion to occur during the model rest phase, as it does for the protype rest phase, can be obtained from the aforementioned diffusion coefficients and the model-prototype diffusion relationship. It can be shown that the model time for diffusion corresponds to the model time for momentum as previously determined by dimensional analysis for the rest phase. A model experiment can therefore be designed which considers both momentum and diffusion effects of the movement and dispersion of respired gas in manned space enclosures.

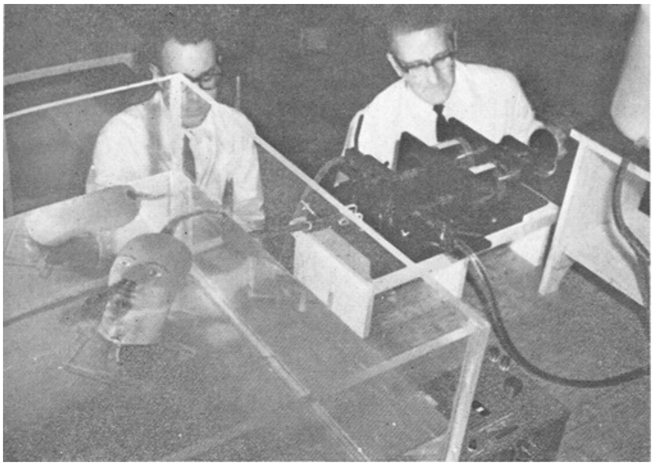

Fig. 1. Model Experiment.

EXPERIMENTAL ANALYSIS

The purpose of this analysis is to provide a valid experiment based upon the results of the previous analyses.

The experiment consists of a replica of a full size human head, an enclosure, and a simulated respiration pumping system which incorporates a dead fluid space of 150 cc. The components of the experiment are shown in Figure 1.

The enclosure is filled with water and allowed to stand in an air conditioned room to attain a uniform temperature throughout the fluid. After several hours the fluid comes to complete rest without any convection currents. A water-dye solution of the same density and temperature of the fluid within the enclosure is then pumped through the simulated dead fluid space and the immersed model head. The water-dye solution enters the enclosure fluid as two jets from the nostrils of the model head.

The tidal volume for the model experiment is 500 cc on inhalation and exhalation. The first 150 cc of fluid which is exhaled is the last 150 cc which was previously inhaled. The model times for the phases of inhalation, exhalation, and rest correspond to the model times which were given in the model theory analysis. It is seen that the movement and dispersion of respired gas in any spacecraft atmosphere can be simulated in the model experiment by changing model times. The model tidal volume, dead fluid space, and the head replica would remain full size. The viscosity and density of the model fluids would remain the same for all experiments if the model temperature is kept constant.

The model experiment reasonably simulates the movement and dispersion of respired gas in spacecraft under weightlessness. This is done in the earth laboratory under controlled conditions by horizontally injecting a fluid into a surrounding fluid of the same temperature and density. The injected fluid will neither rise nor fall. The only effects of movement and dispersion will, therefore, be due to momentum, viscosity, and molecular diffusion. The effects of gravity have been cancelled since convection has been minimized.

An engineering replica of a human nose is an important component of the experiment. The nose is an integral part of the head replica and affects the flow and movement of fluid during the phases of exhalation and inhalation.

The design and fabrication of the nose replica was determined after extensive experimentation with human subjects and smoke. Human subjects were placed within a partially sealed enclosure and instructed to exhale cigarette smoke through their nostrils as shown in Figure 2. Analysis of the exhaled smoke patterns indicated that the angle of spread between the two gas jets is approximately 30 to 40 degrees. The angle between the gas jet and the neck is approximately 40 degrees. The conical angle of dispersion for each gas jet is approximately 24 degrees.

The nostrils were determined to be elliptical with the dimensions of ⅜ inches x ⅝ inches. The angle between nostrils was determined to be approximately 60 degrees.

The nose was designed and fabricated to deliver fluid jet flow with the aforementioned angles. The jet flow emanating from each nostril has the form of an elliptical cone.

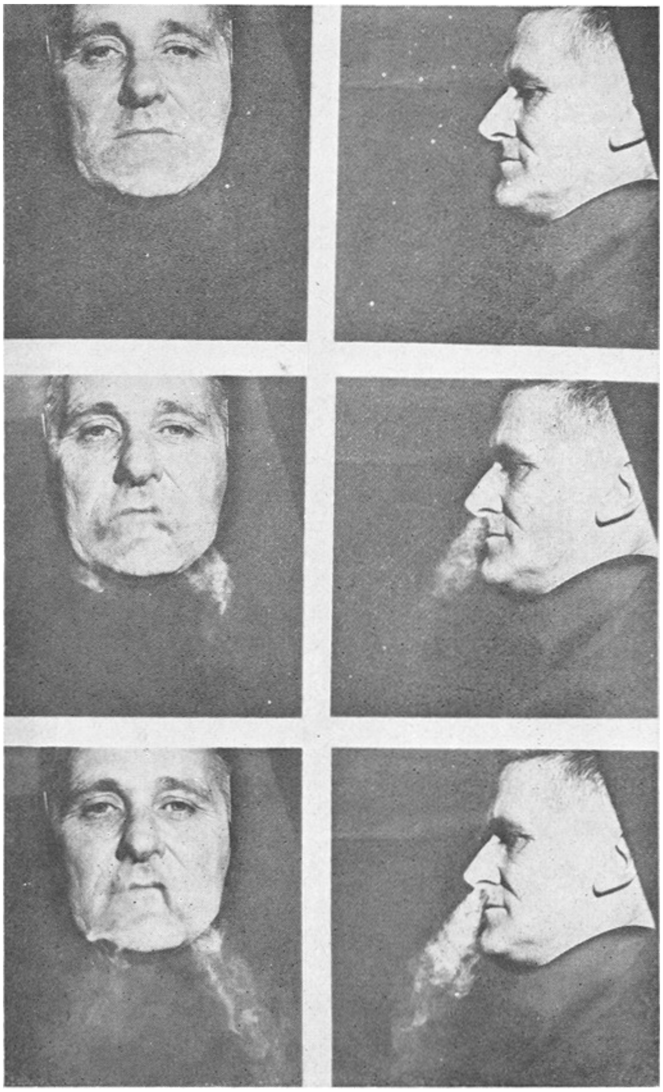

Fig. 2. Exhaled Smoke Pattern.

CONCLUSIONS

Model experiments were performed using the techniques which were described in the previous analyses. Water was used as the enclosure fluid and a water-potassium permanganate solution was used as the injected fluid to simulate carbon dioxide. For practical purposes, both fluids were of the same density at 75°F.

The model experiments were performed to simulate spacecraft atmospheres of oxygen at 300 mm Hg and 80°F, and air at 760 mm Hg and 80°F. Fluid sampling was performed in the dead fluid space and in the enclosure. The technique of spectrophotometry was used to analyze the simulated carbon dioxide concentrations which the fluid samples represented. The samples were taken from the dead fluid space on inhalation as soon as inhaled enclosure fluid passed the sample location. Samples were taken from the center of previous exhalations in the enclosure fluid immediately after the end of the exhalation and rest phases.

The simulated carbon dioxide concentrations for the simulated pure oxygen experiment were less than 3 mm Hg in the dead fluid space on inhalation and less than 7 mm Hg in the center of the exhaled fluid immediately after the end of exhalation. The simulated carbon dioxide concentrations for the simulated air experiment were less than 1.5 mm Hg in the dead fluid space on inhalation and less than 3.7 mm Hg in the center of the exhaled fluid immediately after the end of exhalation.

Simulated dead space fluid sampling was also performed at the end of the inhalation phase. This sampling indicated that less carbon dioxide was being inhaled at the end of the inhalation phase than at the beginning. Simulated sampling in the enclosure indicated that less carbon dioxide was present in the exhaled fluid at the end of the rest phase than at the beginning of the rest phase.

The model experiments clearly indicated that a previous exhalation was not inhaled. The fluid which was inhaled was that fluid in the immediate vicinity of the nostrils.

The exhaled fluid was shown to emanate from the nostrils as two elliptical cones. Each cone entered the surrounding enclosure fluid until viscosity effects transformed the conical form into an approximate spherical form. It was apparent that surrounding enclosure fluid was being entrained with the exhaled fluid during the exhalation phase. The effects of momentum were shown to be much greater than the effects of molecular diffusion during the fluid dispersion. It was apparent that previous exhaled fluid still had momentum during the following rest and inhalation phases. These effects caused the last 350 cc of exhaled fluid, which simulated respired gas with a carbon dioxide concentration of 40 mm Hg, to be dispersed to carbon dioxide concentrations well within the safe range. The first 150 cc of exhaled fluid simulated carbon dioxide concentrations equivalent to the carbon dioxide concentration within the surrounding enclosure fluid in the immediate vicinity of the model head.

The results of initial model experimentation indicate that an astronaut will not poison himself because of lack of atmosphere movement. The exhaled fluid did not accumulate before the model nose nor did the exhaled fluid surround the model head. Formations of localized bodies of fluid containing representative deficiencies of oxygen and abundancies of carbon dioxide which could cause suffocation did not occur within the model experiment enclosure.

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