Symposium Papers

The History and Physics of Heliox

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Summary

Since the discovery of helium in 1868, it has found numerous applications in industry and medicine. Its low density makes helium potentially valuable in respiratory care applications, to reduce work of breathing, improve distribution of ventilation, reduce minute volume requirement, and improve aerosol delivery. This review includes a brief history of the use of heliox (a mixture of helium and oxygen) and addresses issues related to the physics of gas flow when heliox is used. Specifically covered are the Hagen-Poiseuille equation, laminar versus turbulent flow, the Reynolds number, orifice flow, Bernoulli's principle, Graham's law, wave speed, and thermal conductivity. *Key words: density, heliox, helium, thermal conductivity, viscosity.* [Respir Care 2006;51(6):608–612. © 2006 Daedalus Enterprises]

Introduction

Traditional teaching of respiratory physiology assumes that the breathed gas is air. Likewise, the performance of respiratory care equipment assumes that the gas delivered is a mixture of oxygen and air. Applications of helium in respiratory care are related to its physical properties and not its chemical properties. Being an inert gas, helium is nonreactive with body tissues. It is also relatively insoluble in body fluids. When mixed with oxygen in the inhaled gas (ie, heliox), the density of helium, and to some extent its viscosity, affect flow though the airways.[1–8] The physical properties of helium, including its thermal conductivity, also affect flow through respiratory care equipment,

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including flow meters, nebulizers, and ventilators. This paper reviews the history of the use of heliox and describes the physical principles that determine flow with heliox gas mixtures.

History of Helium and Heliox

Helium was discovered in 1868 by a French astronomer, Janssen, as a bright yellow line with a wavelength of 587.49 nm, in the spectrum of the sun during a solar eclipse.[9] This discovery engendered skepticism in the scientific community, since at that time no element had ever been detected in space prior to being found on earth.[10] Later that year, an English astronomer, Lockyer, confirmed the observation and concluded that it was caused by an unknown element, which he named after the Greek god of the sun, Helios. Assuming that it was a metal, he named it helium. The new element was first isolated on Earth in 1895 by a British chemist, Ramsay. Later that year, Swedish chemists determined its atomic weight.[9–11]

In 1903 the gas from a geyser in Kansas was found to contain 12% of an unidentified gas. In 1907, Cady and McFarland of the University of Kansas published a paper that identified the gas as helium and showed that it could be extracted from natural gas.[12] In 1908, Onnes, a Dutch physicist, first liquefied helium, but failed to cool the gas to a solid state at 0.8° K and atmospheric pressure. In 1926, Keesom used a similar low temperature and solidified helium by applying 25 atmospheres of pressure. In 1938, at a temperature near absolute zero, a Russian physicist discovered that liquid helium has virtually no viscosity, a property called superfluidity.

Helium is a colorless, odorless, tasteless, nontoxic, nearly inert, monatomic element. It heads the noble gas series on the periodic table, with an atomic number of 2 and an atomic weight of 4 g/mol. Helium is the second most abundant element in the universe, but relatively rare on Earth, representing 0.000524% of the atmosphere. With the lowest boiling point and melting point of the elements, helium exists as a gas except in extreme conditions. On Earth, most helium is created by radioactive decay of heavier elements and is trapped with natural gas in concentrations up to 7%. Helium is extracted from natural gas by fractional distillation. The richest sources of helium are found in the United States (Texas, Oklahoma, Kansas, and the eastern flank of the Rocky Mountains), the Middle East, and Russia.

At the time of its discovery, helium had no practical use. This changed during World War I with the introduction of the dirigible. These airships were originally filled with hydrogen, which diffused out as oxygen diffused in, reduced buoyancy, and formed an explosive mixture. After the Hindenburg disaster, helium was used as a substitute for hydrogen. The military interest in helium once made its

use a military secret. Seibel[12] tells the story of the development of helium for military purposes by the United States.

After World War I, the natural gas fields of Kansas, Texas, Oklahoma, and New Mexico were just beginning to be developed. The Petrolia field (Fort Worth, Texas) was rich in helium, and this gas was used to develop the 2 methods for separation of helium devised by the Bureau of Mines. One is to adsorb all but the helium on cooled activated charcoal, and the other is to liquefy the gas and separate the helium by fractional distillation. The latter method is the most economical, but the former was used to some extent to purify the gas obtained when dirigibles were refilled.

Like some other finite national resources, the principal sources of helium, the natural gas fields of the mid-continent, are nearing exhaustion. There is no other source of helium and no substitute for it. But so much helium has been produced in the past that no shortage is envisioned in the near future. Helium occurs only in natural gas, and the United States is fortunate in its relative abundance.

Physical Attributes

Helium at room temperature is an ordinary gas, but it diffuses very rapidly because of its low atomic weight. The problem in helium storage is preventing leakage. Pumps made for other gases are inefficient with helium. Grade A helium is 99.995% pure. Table 1 shows some of the chemical and physical characteristics of helium. Being biologically inert, helium has no known toxic effects, even when used for extended periods. Its low molecular weight and consequent low density allow helium to pass through valves and airways with less turbulence. Helium's diffusion coefficient allows CO_2 to diffuse more rapidly through heliox than through air or oxygen.

Respiratory Care Applications

Mixtures of helium and oxygen (heliox) were first used physiologically to create breathing environments for divers, reducing the formation of nitrogen bubbles responsible for decompression illness (the bends) in divers who work at depth for extended periods. In 1934, Barach[13] noted the biological inertness of heliox; he found no ill effects in mice exposed to a high helium concentration for 2 months.

Table 1. Helium's Chemical and Physical Characteristics of Interest

Biologically inert
Low molecular weight
Low density
High rate of diffusion

Table 2.   Claims of Respiratory Benefits of Heliox

Reduces transpulmonary pressure requirement
Increases tidal volume
Improves homogeneity of gas distribution
Improves elimination of CO_2
Improves aerosol delivery

Table 3.   Target Respiratory Care Clinical Applications of Heliox

Upper-airway obstruction
Post-extubation stridor
Croup
Bronchiolitis
Asthma exacerbation
Chronic obstructive pulmonary disease exacerbation
Pulmonary function testing

Table 4.   Gas Properties

Gas	Density (g/m^3)	Viscosity (μ poise)	Kinematic Viscosity* (Stokes)
O_2	1.429	211.4	147.8
He	0.179	201.8	1,127.4
80% N_2, 20% O_2	1.293	188.5	145.8
80% He, 20% O_2	0.429	203.6	474.6
70% He, 30% O_2	0.554	204.7	369.5
60% He, 40% O_2	0.678	207.5	306.0

*Kinematic viscosity is the ratio of viscosity to density.
1 Stokes = poise × cm^3/g

Those experiments were followed by clinical investigation, with patients, of potential benefits for various disorders, including asthma and infant airway obstruction. Barach noted evidence of relief within 6–10 breaths, with dyspnea returning in as little as 3–4 breaths after discontinuation of heliox.[14–16] After the late 1930s, little was reported about clinical applications of heliox until 1979.[17] Since then, a variety of claims have been made about heliox's respiratory benefits (Table 2) and clinical applications (Table 3). While the clinical benefit of heliox has not been adequately established in all of these applications, there has been increasing investigation in the last 2 decades.

Density and Viscosity

The behavior of a fluid in flow is related to 2 intrinsic properties of the fluid: density and viscosity. The density and viscosity of helium differ from those of air and oxygen. The density of a substance is its mass per unit volume. Because 1 gram molecular weight of a gas occupies a volume of 22.4 L under standard conditions, gas density is its gram molecular weight divided by 22.4 L. The density of helium is thus 0.179 g/L. Oxygen's molecular weight is 32 g, so its density is 1.43 g/L. The density of a heliox mixture with 80% helium and 20% oxygen is 0.429 g/L (ie, 0.8 × 0.179 g/L + 0.2 × 1.43 g/L). Viscosity is an internal property of a fluid. Viscosity causes resistance to flow. A fluid with a high viscosity strongly resists flow. The standard unit for viscosity is poise (dyn · s/cm^2), named for Jean Louis Marie Poiseuille. Table 4 shows the densities and viscosities of helium, oxygen, air, and heliox.

The Physics of Fluid Flow of Heliox

Hagen-Poiseuille Equation

The Hagen-Poiseuille equation describes laminar flow. Laminar flow ($\dot{V}$) is affected by the radius of the conducting tube (r), the pressure gradient (ΔP), the viscosity of the gas (η), and the length of the conducting tube (ℓ):

$$\dot{V} = (\pi r^4 \Delta P)/(8\eta\ell)$$

Note that laminar flow is viscosity-dependent and density-independent. However, laminar flow is efficient in that ΔP varies directly with flow.

Laminar Versus Turbulent Flow

Turbulent flow is less efficient than laminar flow in that ΔP varies directly with $\dot{V}^2$:

$$\dot{V}^2 = (4\pi r^5 \Delta P)/(\rho\ell)$$

where ρ is gas density. Note that turbulent flow is density-dependent and viscosity-independent. In conditions of turbulent flow, a gas with lower density (heliox) is beneficial in that either flow will increase or the pressure required to generate a given flow will decrease.

Reynolds Number

The Reynolds number (Re) is a dimensionless number used to determine the likelihood that a gas will develop a laminar or turbulent flow pattern:

$$Re = (\rho v r)/\eta$$

where ρ is density, v is velocity, r is radius, and η is viscosity. The Reynolds number is the ratio of inertial

forces (density-dependent, viscosity-independent) to viscous forces (viscosity-dependent, density-independent). Laminar flow occurs at a low Reynolds number (Re < 2,000) where viscous forces are dominant, and is characterized by smooth, constant fluid motion. Turbulent flow, on the other hand, occurs at a high Reynolds number and is dominated by inertial forces, producing random eddies, vortices, and other flow fluctuations. The transition between laminar and turbulent flow depends on the flow configuration and must be determined experimentally. Within a range around that transition point there is a region of gradual transition in which the flow is neither fully laminar nor fully turbulent.

Orifice Flow

For gas flow through an orifice (ie, axial acceleration), flow has only weak dependence on the Reynolds number and is affected by density:

$$\dot{V} = (2\Delta P/\rho)^{0.5}$$

In other words, flow through an orifice (eg, constricted airway) increases if the density of the gas decreases (heliox).

Bernoulli's Principle

Bernoulli's principle can be used to describe flow through a partially obstructed airway:

$$(P_1 - P_2) = (\tfrac{1}{2})(\rho)(v_2^2 - v_1^2)$$

where $(P_1 - P_2)$ is the pressure required to produce flow, $(v_2^2 - v_1^2)$, is the difference in velocity between P_1 and P_2, and ρ is the density of the gas. Bernoulli's principle predicts that less pressure is required for a given flow through a partially obstructed airway with heliox than with air or oxygen.

Graham's Law

Graham's law states that the rate of diffusion is inversely related to the square root of gas density:

He diffusion/O_2 diffusion = $\sqrt{O_2 \text{ density}}/\sqrt{He \text{ density}}$

Thus, heliox (80% helium/20% oxygen) diffuses 1.8 times faster than oxygen. This explains why the flow of heliox through an oxygen flow meter is 1.8 times greater than the flow indicated by the meter. It also suggests that heliox will diffuse through a partially obstructed airway faster than air or oxygen.

A gas mixture of 17% oxygen, 5% carbon dioxide, and 78% nitrogen (eg, exhaled gas) has a density of 1.32 g/L. During heliox breathing, the nitrogen is replaced with helium. A gas mixture of 17% oxygen, 5% carbon dioxide, and 78% helium has a density of 0.48 g/L. Thus, 5% carbon dioxide in heliox diffuses 2.75 times faster than carbon dioxide in air, though it is unclear whether this faster diffusion facilitates carbon dioxide clearance. The rate of diffusion is important only if a concentration gradient is present, which requires adequate alveolar ventilation. A P_{aCO_2} decrease in a patient breathing heliox is probably primarily the result of improved gas flow through partially obstructed airways and, thus, improved alveolar ventilation, although increased diffusion may also play a role.

Wave Speed

According to wave speed theory, flow through an airway cannot be greater than the flow at which gas velocity equals wave speed.[18] Wave speed is the speed at which a small disturbance travels in a compliant tube filled with a gas. The wave speed (c) in an airway depends on the cross-sectional area of the airway (A), the density of the gas, and the slope of the pressure-area curve of the airway (dP/dA):

$$c^2 = (A/\rho)(dP/dA)$$

where dP/dA is the slope of the pressure-area curve of the airway. Maximum flow ($\dot{V}_{max}$) is the product of the gas velocity at wave speed and the airway area (cA). If $\dot{V}_{max}$ = cA, then:

$$\dot{V}_{max} = A\sqrt{(A/\rho)(dP/dA)}$$

According to wave speed theory, $\dot{V}_{max}$ increases as gas density decreases, so in patients with flow limitation (eg, COPD), a lower-density gas (heliox) might improve expiratory flow and thus decrease dynamic hyperinflation.

Thermal Conductivity

Thermal conductivity is a measure of a substance's capacity to conduct heat. The coefficients of thermal conductivity for helium and air are 352 μcal/cm/s/°K and 58 μcal/cm/s/°K, respectively. The high thermal conductivity of helium explains why helium affects the accuracy of hot-wire flow sensors, such as those used in some ventilators.

Heat loss occurs if the body is surrounded by heliox rather than by air, because heat conductance is the major factor in skin heat loss. However, respiratory heat loss

depends on heat capacity, not conductance. Although the thermal capacity of helium is higher than that of air, there are fewer molecules of helium in a given volume because heliox is less dense, so heliox's thermal capacity is less than that of the same volume of air. Thus, less heat is lost breathing heliox, so it should not result in hypothermia. If heliox is administered via face mask, however, the face may feel cool.

Why Does Breathing Heliox Cause a Squeaky Voice?

The effect of heliox on the sound of speech is a well-known party trick. A person breathing heliox has a characteristic change in the voice. This makes conducting double-blind studies of heliox difficult. What causes the voice change? Gas moving past the vocal chords causes them to vibrate and produce sound. When breathing air, changes in the pitch of the voice are caused by changing the volume of the oropharynx, which changes the wavelength of the sound; the shorter the wavelength, the higher the frequency and the higher the pitch. The oropharynx thus serves as a resonating cavity (this principle also applies to pipe organs, flutes, saxophones, and other wind instruments). The relationship between velocity, frequency, and wavelength is:

$$\text{velocity} = \text{frequency} \times \text{wavelength}$$

The velocity of sound in a gas is proportional to the square root of the gas density. At 20°C, the velocity of sound is 344 m/s in air and 927 m/s in helium; that is, the sound-wave speed in helium is 2.7 times that in air. Because wavelength is determined by the shape and size of the oropharynx (which is not changed by helium), the frequency must change, which causes the characteristic squeaky voice.[19,20]

Summary

The effect of heliox on gas flow is determined by several physical principles related to density and viscosity. These principles can be used to predict how heliox will affect gas flow in the lungs during various physiologic states. An understanding of these principles can also be used to explain the effects of heliox on the performance of respiratory care equipment.

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