Oxygen Generating System for Underwater Breathing using Counterflow Diffusion: A Concept

Article *in* International Journal of Scientific and Engineering Research · August 2019

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 04, April-2019

Oxygen Generating System for Underwater Breathing using Counterflow Diffusion: A Concept

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***Abstract*—Conventionally large metal oxygen tanks weighing tens of kilograms are used as apparatus for breathing underwater which decreases the diving time and restricts us from exploring the deeper parts of the sea for a longer period of time. Considering this thesis, this particular research develops an underwater breathing system which is designed based on fish gills. This approach uses the principle of counterflow diffusion to extract dissolved oxygen from surrounding water and supply it directly to the deoxygenated blood coming from the body, eliminating the gas phase in between. A hypothetical system is developed based on the solution provided below. This paper specifically deals with the concept and the mathematical formulations of the phenomena that would be used in the development of this device.**

Keywords—Mass Transfer, Fick's Law, Counter-Flow Diffusion, Underwater Breathing, Artificial Fish Gills, Knudsen flow.

I. INTRODUCTION

The current methods for breathing underwater uses old conventional designs which greatly reduce our productivity. Existing conventional methods of breathing underwater can be divided into two types: Oxygen tanks and surface supplied method. These methods have some limitations like less diving time and large weight. Development of new methods of underwater breathing is therefore required.

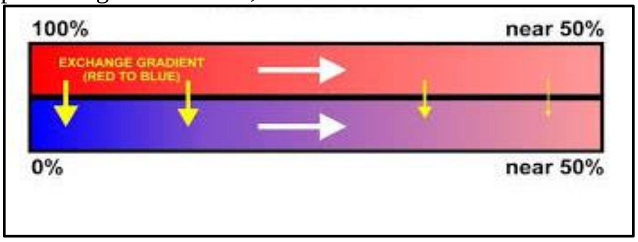
The Oxygen present in atmosphere gets dissolved in water because of the its partial pressure [1] which can be used for breathing underwater. To extract this oxygen, diffusion process is used. Diffusion is mass transfer phenomenon which induces the flow of mass due to concentration difference. The proposed system uses this very principle for exchange of gases between blood and water.

The contents of our research are distributed in the paper as follows: Section I describes introduction, Section II describes the core concept, Section III deals with the mathematical model, Section IV explains the design aspects of the device, Section V describes our hypothetical setup, Section VI sheds light on our future plans for the device.

II. CORE CONCEPT

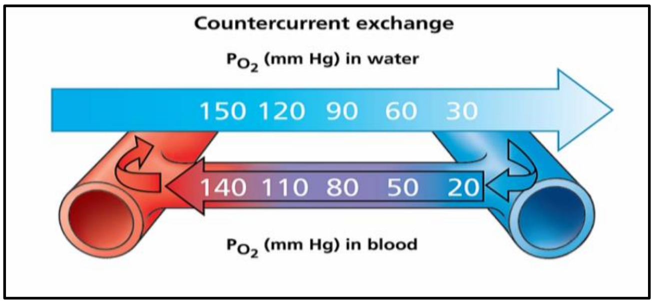
Our system closely mimics the natural structure of fish gills. fish uses the phenomena of counterflow diffusion to absorb oxygen from surrounding water; water flows over the gills and passes through the structure called primary lamellae [2], which consists of sub-structures called secondary lamellae, this is where the diffusion happens. The concentration of oxygen and carbon dioxide [3][4] dissolved in water depends upon the partial pressure gradient of gases between water and atmosphere. Now as the blood and water move in counter current direction in the gills; blood in lamellae and water over it, a partial pressure gradient exist between the deoxygenated blood and oxygen rich water. This results in the diffusion of oxygen into the blood from water. Carbon dioxide on the other hand diffuses from blood into the water because of its high concentration in blood as compared to water [5]. This is how a fish gill works.

The countercurrent flow of blood and water has a reason. Suppose if the blood in the gills and water around it moved in the same direction in the fish gills, that is if they flowed parallel to each other, then the gas exchange occurs until their concentration became equal, since after that no partial pressure gradient exists, no diffusion occurs.



III. MATHEMATICAL MODEL

Gas exchange in fish gills is based on the principle called Counterflow Diffusion.



In the figure above a single element of gas exchange surface of a fish gill is shown, water and blood flow in countercurrent directions. Due to a positive partial pressure gradient of oxygen between water and blood (as indicated by representative values), oxygen diffuses into the blood. Carbon dioxide on the
other hand diffuses from blood to water because of its positive partial pressure gradient between blood and water.
The principle which drives the exchange of gases between the membrane and also governs the workings of fish gills is called the Fick's law [6]. Fick's law can be stated as "Rate of diffusion of oxygen and carbon dioxide through the membrane depends on the partial pressure gradient along the membrane and the area of gas exchange".

Mathematically,

$$Rate\ of\ Diffusion = D * A * \frac{\delta P}{\delta x}$$

Where,

D is the diffusion coefficient,
A is the surface area of gas exchange,
ΔP is partial pressure gradient of gas,
x is the distance in the direction of diffusion of a gas.

Prasoon kumar et al. carried out a computational study of diffusion phenomenon occurring in fish using a two-dimensional model of a secondary lamellae in COMSOL [7], the governing equations they determined in each domain are:

$$U_w \frac{\partial c}{\partial x} = D_w\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\right) \ldots\ldots \text{(Water domain)}$$

$$U_b \frac{\partial c}{\partial x} = D_b\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\right) \ldots\ldots \text{(Blood domain)}$$

$$D_e \frac{\partial^2 c}{\partial y^2} = 0 \ldots\ldots \text{(Epithelial barrier)}$$

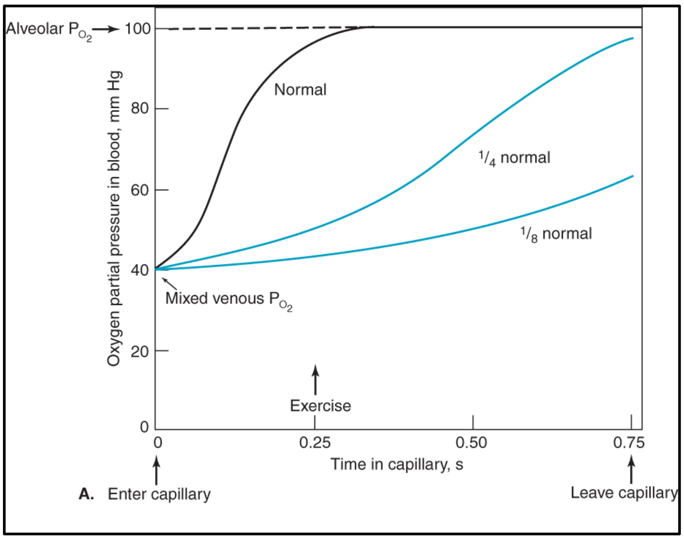
$$N = -D\frac{\partial C}{\partial x} + U_x C$$

Where,
U_w = Average velocity in water channel,
U_b = Average velocity in blood channel,
D_w = Diffusion coefficient of oxygen in water,
D_b = Diffusion coefficient of oxygen in blood,
D_e = Diffusion coefficient of oxygen in epithelial matrix,
C = Concentration of oxygen,
N = Flux.
This model can easily be extrapolated to be applied to humans by inserting appropriate boundary conditions.

IV. DESIGN

A) Length of tubes

This parameter depends only on the partial pressure gradient of the gases that are exchanged through the membrane. With the increase in the length of the tube in the direction of flow of water, the concentration of oxygen in blood increases and saturation occurs. Thus, rendering the remaining length useless. A specific tube length is hence selected based on above phenomenon.
In human lungs, the curve that depicts the increase in concentration of oxygen in blood along the oxygen gradient rise is sigmoidal in nature [8].



Fitting the same curve along the length of breathing device gives the point of saturation of oxygen in blood and hence the length of the membrane tubes.

B) Diameter of tubes

The diameter of these tubes is calculated based on the viscosity of the blood. As the blood is viscous it cannot flow in tubes that are smaller than the critical radius. Another factor that also governs the radius of the tubes is the surface area of diffusion. If the tubes with larger radius are used then the rate of diffusion reduces as the surface area decreases due to the decrease in the number of tubes that can be occupied in the same volume, hence the radius can be reduced to increase the net surface area for diffusion by increasing the number of tubes. Based on these parameters the minimum size of the tubes is calculated.

In a more realistic approach, the resistance in blood vessels from which the diameter of the tube is calculated is modelled based on Thurston's work, but a basic model simulated based on Hagen–Poiseuille equation [9] can be used:

$$\Delta P = \frac{8\mu L Q}{\pi R^4}$$

Where:

ΔP is the pressure difference between the two ends,

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 8 Issue 04, April-2019

L is the length of pipe,
μ is the dynamic viscosity,
Q is the volumetric flow rate,
R is the pipe radius.

C) Flow Rate

The flow rate of water through the system depends upon the oxygen requirement of the person. A specific flow rate supplies a particular amount of oxygen to the blood based upon the concentration of dissolved oxygen in water. If the demand of oxygen increases then the flow rate is increased using a pump. The minimum flow rate required for sufficient diffusion to occur is calculated as shown below:

11 mg/l (ppt) of O_2 in water [10] (On average)
32000 mg of O_2 = 22400 ml (1 mole = 22.4 liter) [Avogadro's law]
11 mg/l = (11/32000) *22400 = 7.7 ml/l (In water)

210 ml of O_2 per liter (In Blood)

210/7.5 = 27 = 30 times more flow
After sometime of swimming the requirement of oxygen is increased hence the concentration of oxygen in blood reduces (<210). To provide sufficient oxygen to the body, this concentration is needed to be maintained at 210 ml/l. Consider this reduced concentration as x.

Delta Concentration(Δ) = (210 - x) ml/l
New required concentration = 210 + Δ
New flow rate of water required = (210 + Δ)/7.7 times of flow of blood

Using this relation, water flow rate can be regulated using the pump.

D) Pore Size in tubes

The maximum size of pores used in the membrane, depend only on the size of molecules that pass through them. During diffusion the only molecules that should pass through this pore are oxygen molecules and carbon dioxide molecules. The molecules that definitely should not pass through this membrane are water and molecules of different components of blood. The size of oxygen [13] is 0.120 nm, size of carbon dioxide molecule [14] is 0.232 nm, size of water molecule [15] is 0.275 nm, and as blood is an organic molecule it is definitely larger than the rest of the molecules. As the size of There are other components present in blood and water, these molecules include salts like NaCl in water and platelets in blood which are organic cells, hence bigger in size. The salts ionize when dissolved in water and form hydrated ions, which means they loosely bond with multiple water molecules hence increasing in size making it impossible for them to pass through holes. Pores should be larger than oxygen and carbon dioxide but smaller than water, so it should be in the range of 0.250 nm to 0.260 nm.

E) Gas flow rate through the pores

When the size of the pore is smaller than the mean free path of the diffusing gas molecule and the density of the gas is low, the molecules collide more with the walls of the pore, this process is known as Knudsen Diffusion [16]. In the diffusion of gases through a membrane when Δ P is less than P_{ave}, then Knudsen flux can be expressed as Volumetric flow rate as

$$Q_K = \frac{\Delta P d^3}{6 l P_{ave}} \sqrt{\frac{2\pi RT}{M_A}}$$

where,
Q_k= Volumetric flow rate in m^3/s,
ΔP= Pressure gradient between the two sides of the pore,
d = Diameter of the pore,
l = mean free path of a gas molecule,
P_{ave}= Average absolute pressure in the system,
R = Universal gas constant,
T = Temperature of the system,
M_a = Molecular mass of gas.

F) Membrane wall thickness

The thickness of the membrane wall depends upon the resistance that the oxygen and carbon dioxide suffer while their flow through the membrane.

The resistance to the flow of gas through a membrane was expressed by James` in [17] as:

$$R_h = \frac{12 \mu L_c}{d^2 A_p},$$

where,
R_h = Hydrodynamic resistance of a pore,
L_c = Length of the pore,
μ = Viscosity of gas,
d = Width of the pore,
A_p = Cross section area of the pore.

This equation was modelled for fish gills but it can be approximated for our device as it works on the same principle.

Thus, the length of the pore or membrane wall thickness can be determined by substituting

$$R_h = \frac{\Delta P}{Q},$$

in the hydrodynamic resistance equation by James.
where,
ΔP= Pressure gradient through the membrane
Q = Volumetric flow rate through the membrane.

G) Membrane Material

Biocompatibility is the most important factor in the membrane material selection. Biocompatibility refers to ability of a material to be in contact with the living system without causing any harm to its function.

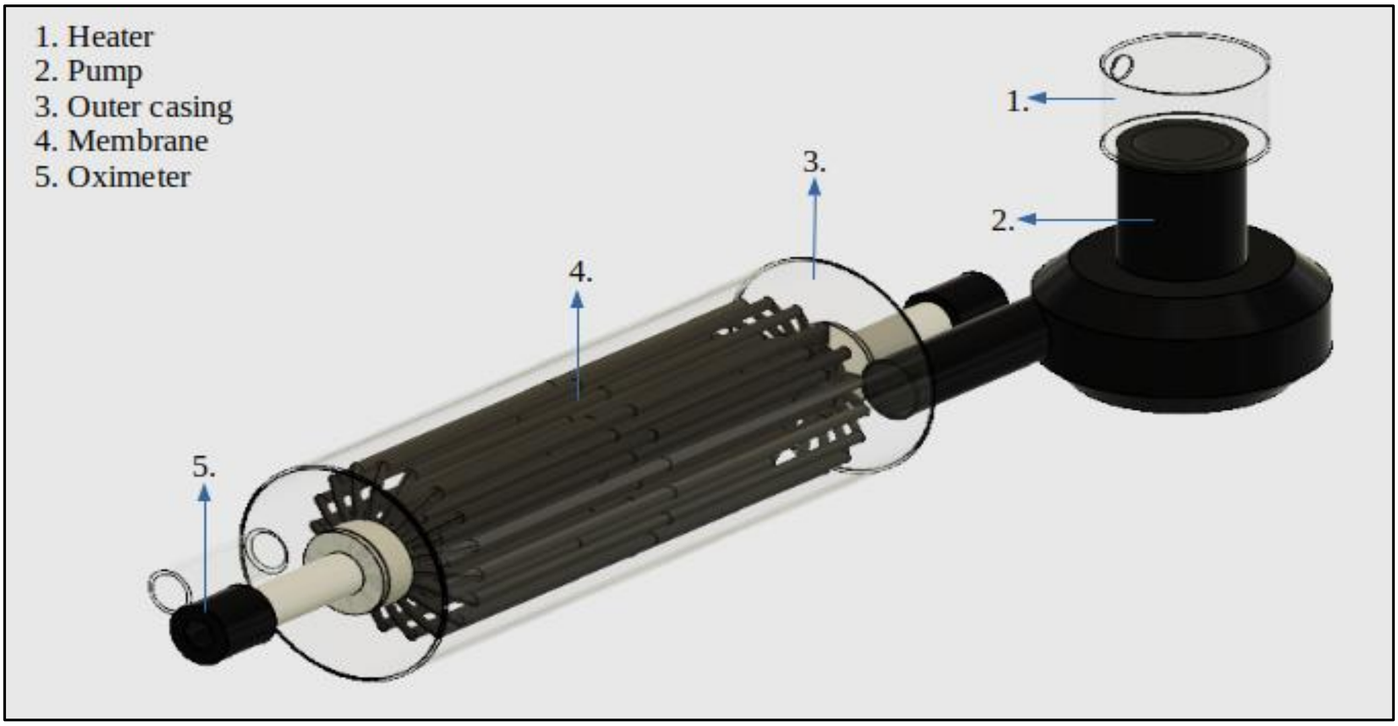
Silicone [17] is a biocompatible material which could be used in the manufacturing of membrane. It is also non-thrombogenic [18] and so it does not react with blood to form clots on the surface.

So, Silicone appears to be a suitable material for the manufacturing of membrane tubes.

V. HYPOTHETICAL SETUP

A) Construction

The device comprises of a cylindrical casing (3) which contains a bunch of tubes made up of membrane (4) with pores diameter of around 0.255 nm. At both the ends there are two oximeters (5) which measures the concentration of oxygen at device's inlet and outlet respectively. In addition to oximeters there is a pump (2) at the inlet which increases the rate of flow of water containing dissolved oxygen. There is a heater besides the Pump to heat the blood and prevent the clotting of blood.



B) Working

Flow of Blood

Deoxygenated blood enters the breathing system from oximeter. In the system, blood and water flow counter current to each other. Blood flows through the membrane tubes and water flows into the outer cylindrical casing. Due to this motion of blood and water a pressure gradient gets established. As a result, oxygen diffuses in the blood from water due to a positive pressure gradient from water to blood and carbon dioxide diffuses from blood to water due to the establishment of a negative pressure gradient from water to blood. Oxygen concentration at the outlet is measured using oximeter. Blood flow will be from host→ oximeter→ breathing system→ oximeter→ host. Hence, the resultant blood will be oxygenated at the end of process.

Flow of Water

Water after flowing through heater enters the casing after passing through the pump. To gain different concentrations of oxygen in blood, the flow of water need to be changed depending on requirement which will be controlled by the pump in the system. Moreover, as this system is to be used for breathing underwater where the temperature is low so to maintain temperature and prevent blood clotting a heater is used that helps in maintaining it. Hence, water flow will be surroundings→ heater→ pump→ cylindrical casing→ surroundings.

VI. FUTURE WORK

The system designed is a theoretical concept right now which can be put to a practical use after some work is done in future. The system uses a membrane with pore size of 0.255 nm which is extremely difficult to manufacture and expensive with the current level of technology. In future the ability of manufacturing machines will increase in terms of precision and make it possible for us to manufacture this membrane. For this system to be put to daily use, there is a need for developing a simple design which makes it easy to integrated the system with human bodies as shown in the diagram below. This work requires close collaboration with medical experts so that we can reduce the risk factor and possibly make it insignificant.

International Journal of Engineering Research & Technology (IJERT)
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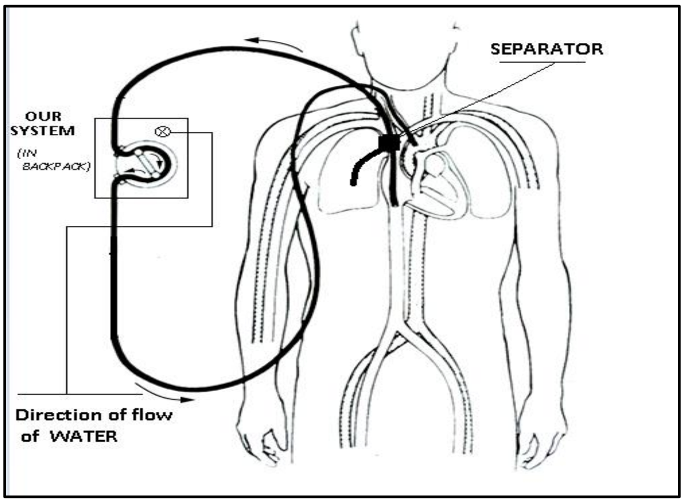

ACKNOWLEDGMENT

We would like to express our sincere gratitude to Dr. D.H Pandya, Head of Department of Mechanical Engineering for allowing us to undertake this work. We would also like to thank Prof. Amit I. Pandey and Prof. Kaushal H. Bhavsar, for their continuous guidance, effort and invertible suggestions throughout the research. Lastly, we would all like to express our sincere appreciation to our parents for encouraging and supporting us throughout the study.

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