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ISTANBUL TECHNICAL UNIVERSITY

Control and Automation Engineering

KON305E – Programming Techniq.in Control

# Term Project

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# INTRODUCTION

The ECMO machine replaces the function of the heart and lungs. People who need support from an ECMO machine are cared for in a hospital's intensive care unit (ICU). Typically, people are supported by an ECMO machine for only a few hours to days, but may require it for a few weeks, depending on how their condition progresses. There are many overlaps and differences between the use of ECMO in children and adults.

The ECMO machine is connected to a patient through plastic tubes. The tubes are placed in large veins and arteries in the legs, neck or chest. The ECMO machine pumps blood from the patient's body to an artificial lung that adds oxygen to it and removes carbon dioxide. Thus, it replaces the function of the person's own lungs. The ECMO machine then sends the blood back to the patient via a pump with the same force as the heart, replacing its function.

In this project, a simulation environment containing the human cardiopulmonary system model for an ECMO device in Simulink / MATLAB and a closed loop control system is formed to assist a critical patient suffering from COVID-19 infection.

# A. PRELIMINARIES

## 1. [p, z, k]=PoleZeroGain(Gs) Function

Aim of the function “PoleZeroGain” is to find poles, zeros and gain of the transfer function. To do this, transfer function should be separated as numerator and denominator. After this, both numerator and denominator should be solved by “solve” command in MATLAB environment. To find gain value, “Final Value Theorem” should be applied. The code of the function is given below.

```
function [p, z, k]=PoleZeroGain(Gs)
    [ num , den ] = numden(Gs);
    try     %if num elements contains only number vpa does not
work
        z = vpa(solve(num),4);
    catch   %to catch error its used try/catch errror handling
method
        z = 'No zeros' ;
    end
    p = vpa(solve(den),4);
    k = limit(Gs,0);
end
```

When the transfer function entered to “PoleZeroGain” function, the output is returned as;

```
p =                     z =                         k =

-10.0                  'No zeros'                  2/25
-3.125
```

## 2. y=Amplitude(u) Function

Fast Fourier Transform is used to find amplitude of input signal. Fast fourier transform of the signal is taken by scaling along the length This is because the fast fourier transform of the incoming signal also provides fourier transform in discrete time.the signal. The result will give us amplitude. Since we can not manage dynamic memory in the matlab function blocks in Simulink, we have been obliged to examine the signal in a frequency region, not on time basis, to include all its time. When the fast fourier transform is scaled by taking the length of the signal, the signal is defined for each frequency region and their sum is defined to give the signal. In short, the system will give the sum of the coefficients in one frequency region, in short, the amplitude. The value here is not clear and there is a margin of error. The reason for this is that continuous-time functions are given by keeping them in a discrete time in the MATLAB. Dynamic memory management is essential to eliminate the margin of error, but it could not be used here.

```
function y = Amplitude(u)

y= abs(fft(u,length(u));
```

## B. RESPIRATORY SYSTEM MODEL

Respiratory system is modeled in 3 main headings in this report. These are respectively; lung model, alveoler gas exchange model and tissue gas exchange model.

### 1. Lung Mechanics Model

Human's lung mechanics model can be represented as circuit analogy. It can be seen at figure 1.

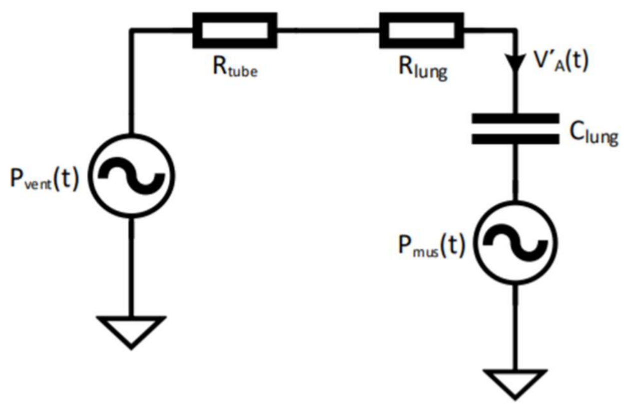


*Figure 1 The Lung Mechanics Model*

The elements of circuit are controlled voltage source, resistor and capacitor. $P_{vent}(t)$ represents the pressure provided by the ventilator ($cmH_2O$). $P_{mus}(t)$ represents the pressure provided by the respiratory muscles ($cmH_2O$). In this report $P_{mus}(t)$ is taken as zero. $V'_A(t)$ represents alveolar airflow. $R_{lung}$ represents the total lung resistance and $C_{lung}$ represents the total lung compliance, $R_{tube}$ represents the resistance due to the endotracheal tube, which connects the ventilator to the patient.

a) The lung mechanics model is remodelled in MATLAB Simulink environment by using Simscape Library, the Simulink Model is shown in figure 2. The pulse generator's parameters is given in figure 3.

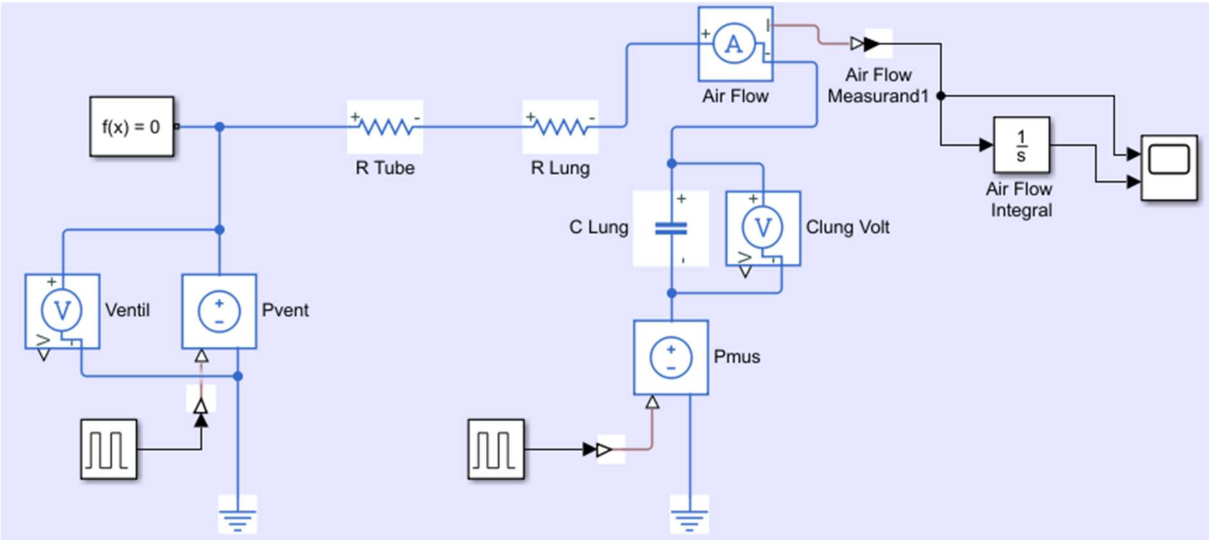


*Figure 2 The Lung Mechanics Model in Simulink*

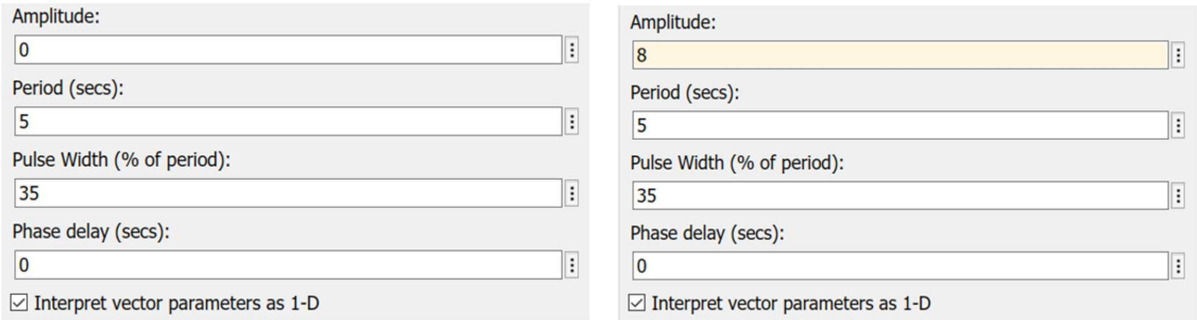


*Figure 3 Pvent(t) Parameters (Left), Pmus(t) Parameters (Right)*

For getting smother signal, a filter added between $P_{vent}(t)$ and $P_{vent}(t)$'s pulse generator, the filter is shown in figure 4.

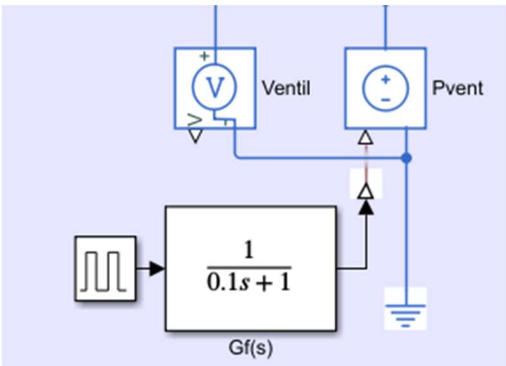


*Figure 4 Gf(s) Filter*

b) Airflow, Tidal Volume and $P_{vent}(t)$(mechanical ventilator) graphs are observed with scope which is given below.

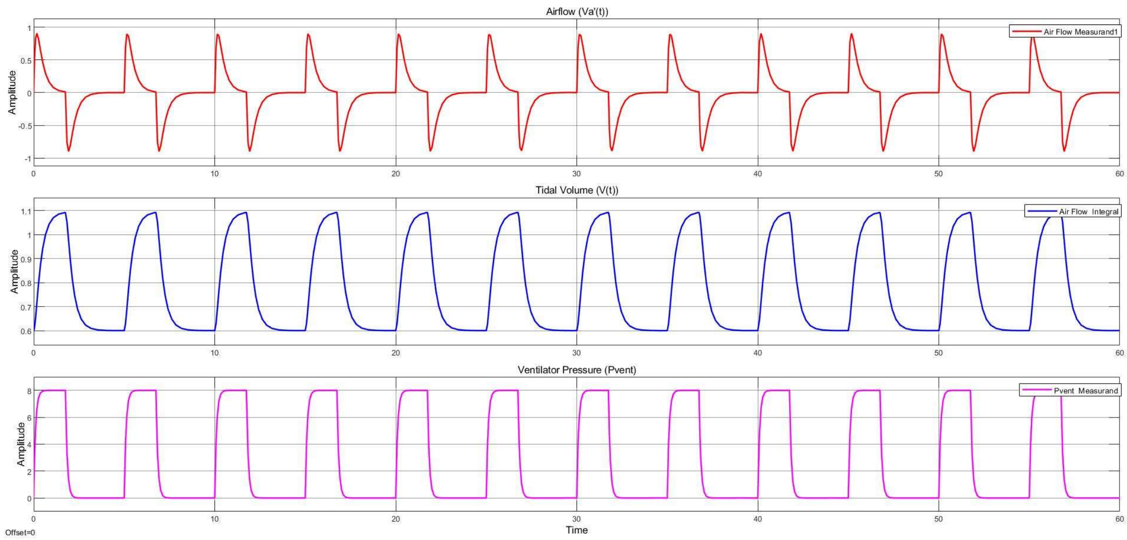


*Figure 5 Output Signals Graph*

c) Lung Mechanic math model's equation is given below.

$$P_{vent}(t) = (R_{tube} + R_{lung})V'(t) + \frac{1}{C_{lung}}\int_{t_0}^{T} V'(t)\,dt$$

$$\Big\downarrow \mathcal{L}$$

$$P_{vent}(s) = (R_{tube} + R_{lung})sV(s) + \frac{1}{sC_{lung}}\,sV(s)$$

From this equation, transfer function is obtained as,

$$G(s) = \frac{V(s)}{P_{vent}(s)} = \frac{C_{lung}}{(R_{lung} + R_{tube})C_{lung}s + 1}$$

$$G_{ol}(s) = G(s)G_f(s) = \frac{C_{lung}}{((R_{lung} + R_{tube})C_{lung}s + 1)} \cdot \frac{1}{(0.1s + 1)}$$

d) Finding K parameter on PI controller by magnitude condition code is given below. The root locus graph of forward path gain of system is given in figure 6.

```
syms s k;
Gf=(1)/(0.1*s+1);
Gs=(0.08)/(0.32*s+1);
Pi=(s+3.125)/s;
E=Gf*Gs*Pi;      % forward path gain
E_tf=syms2tf(E);
rlocus(E_tf)     % desired root is s = -5 +- 1.97i

% via root locus magnitude condition |E(jw+sigma)|=1/K
K=(vpa(abs(subs(E,s,-5-1.98*i)),4))^(-1)
```

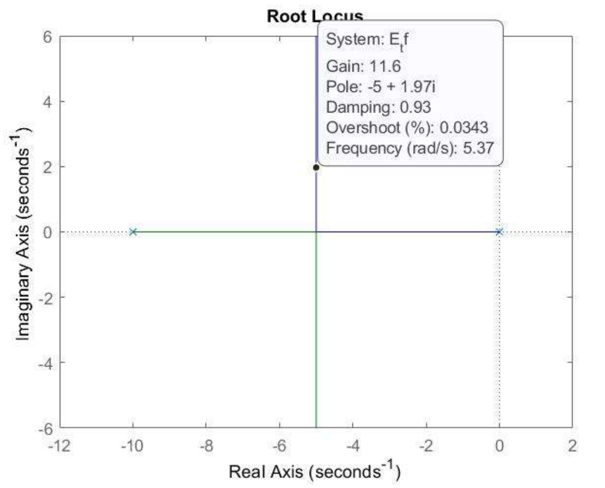


*Figure 6 Root Locus*

e) After designing the controller, the graphs of airflow, tidal volume and Pvent are given in figure 7. The system is working correctly with the controller.

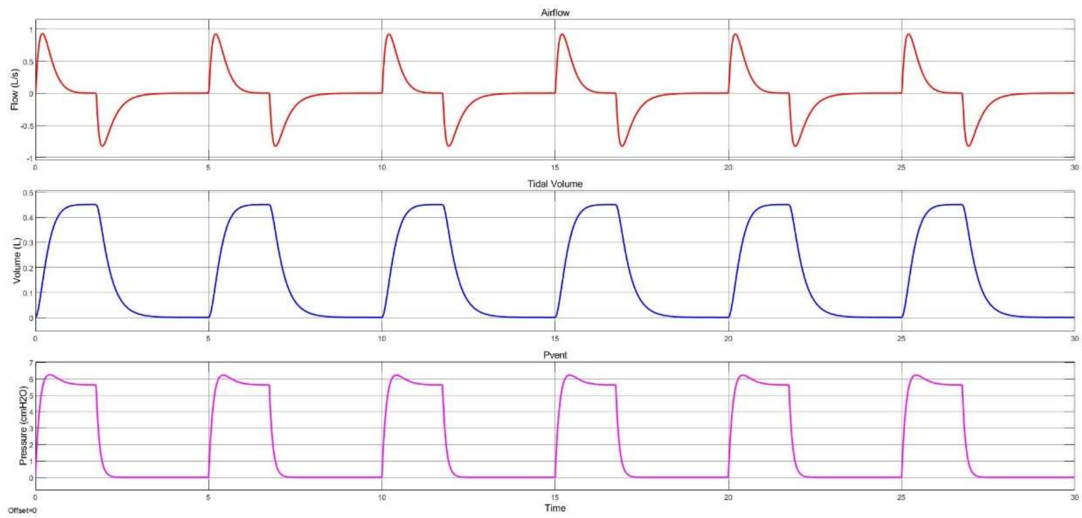


*Figure 7 Output Signals Graph with Controller*

## 2. Dead Space And Alveolar Gas Exchange Model

a)

The space where there is no gas exchange in the air transmission path is called "dead space". For this reason, the partial pressure of oxygen and carbon dioxide changes until they reach the alveoli. If the alveolar airflow $V_A$'(t) is greater than zero, "I" equations should be used. Otherwise, "O" equations should be used.

I: $$V_D \frac{dP_{dO}\ (t)}{dt} = V'_A(t)[P_{IO}\ (t) - P_{dO}\ (t)]$$

$$V_D \frac{dP_{dCO2}(t)}{dt} = V'_A(t)[P_{ICO2}(t) - P_{dC}\ \ (t)]$$

O: $$V_D \frac{dP_{dO2}(t)}{dt} = V'_A(t)[P_{dO}\ (t) - P_{AO}\ (t)]$$

$$V_D \frac{dP_{dCO2}(t)}{dt} = V'_A(t)[P_{dCO2}(t) - P_{ACO2}(t)]$$

Here, $P_{AO2}(t)$ and $P_{ACO2}(t)$ are partial pressure of $O_2$ and $CO_2$ in alveoli. To obtain $P_{AO}\ (t)$ and $P_{ACO}\ (t)$ the equations given below should be used.

$$P_{IO_2} = (P_{atm} - P_{ws})F_{IO_2}$$ $P_{atm}$ (Atmospheric Pressure)=760mmHg

$$P_{ICO_2} = (P_{atm} - P_{ws})F_{ICO_2}$$ $P_{ws}$ (Vapour Pressure of Water)=47mmHg

The Simulink Model of dead space equations is shown in figure 8.

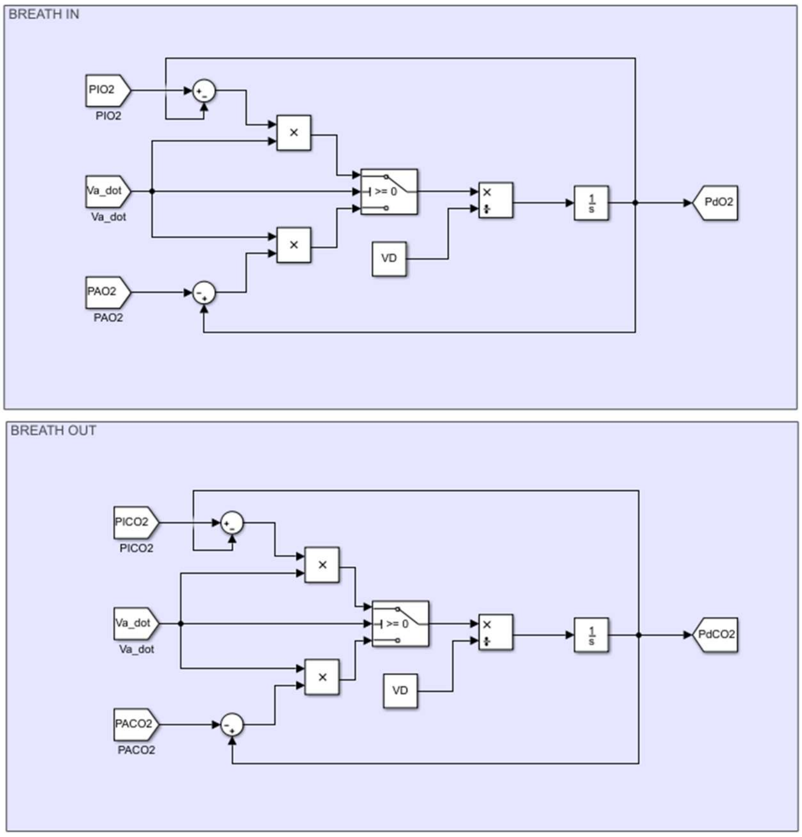


*Figure 8 Dead Space Simulink Model*

$P_{ICO2}$ will be taken as zero because $F_{ICO}$ (0.004) is negligible. Alveolar gas exchange equations are given below.

**I:**

$$V_{LO_2}\frac{dP_{AO_2}(t)}{dt} = 863F_{pp}(t)\left[C_{vO_2}(t-\tau_{TL}) - C_{AO_2}(t)\right] + V'(t)\left[P_{dO_2}(t) - P_{AO_2}(t)\right]$$

$$V_{LCO_2}\frac{dP_{ACO_2}(t)}{dt} = 863F_{pp}(t)\left[C_{vCO_2}(t-\tau_{TL}) - C_{ACO_2}(t)\right] + V'(t)\left[P_{dCO_2}(t) - P_{ACO_2}(t)\right]$$

**E:**

$$V_{LO_2}\frac{dP_{AO_2}(t)}{dt} = 863F_{pp}(t)\left[C_{vO_2}(t-\tau_{TL}) - C_{AO_2}(t)\right]$$

$$V_{LCO_2}\frac{dP_{ACO_2}(t)}{dt} = 863F_{pp}(t)\left[C_{vCO_2}(t-\tau_{TL}) - C_{ACO_2}(t)\right]$$

The Simulink Model of alveolar gas exchange equations is shown in figure 9.

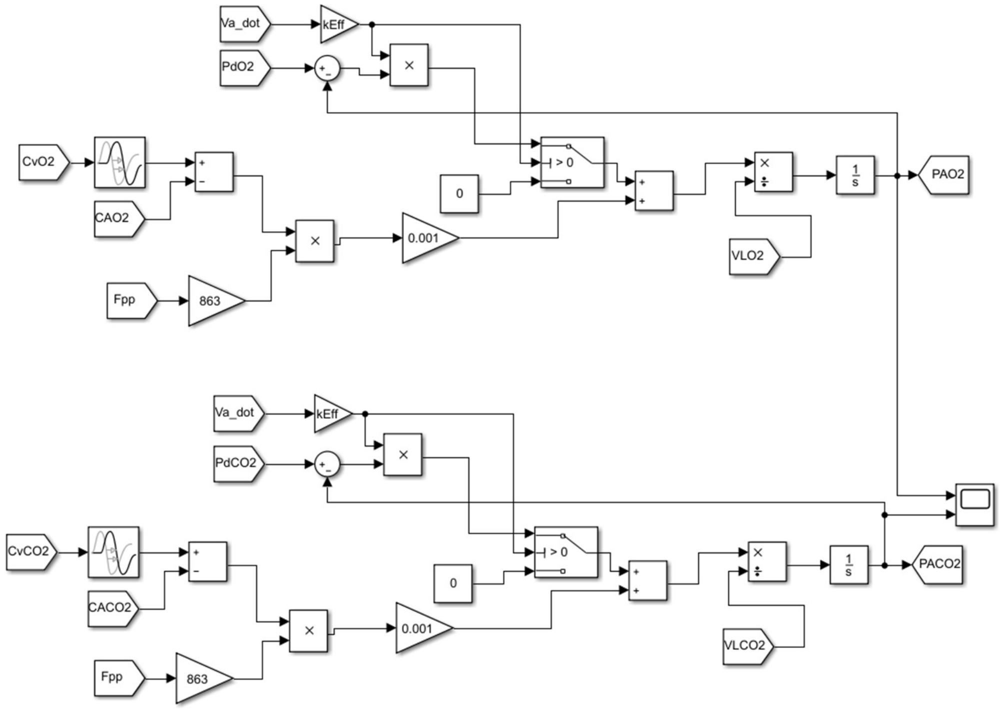


*Figure 9 Simulink Model of Alveolar Gas Exchange*

In the model, transport delay used due to blood transportation. The switch block is for determine the magnitude of efficient airflow; if magnitude of airflow is greater than zero, "I" equations is used otherwise "O" equations is used. The gain block which has the value of "0.001" is used for unit transform of $F_{pp}$ (the pulmonary blood flow) which will be explained later. $V_{LO2}$ and $V_{LCO2}$ refer to lung storage volumes for oxygen and carbon dioxide. $C_{VO2}$ and $C_{VCO2}$ refer to concentration of oxygen and carbon dioxide in venous blood. $C_{AO2}$ and $C_{ACO2}$ refer to concentration of oxygen and carbon dioxide in alveoli.

$$V_{LO_2} = V_{L0} + V(t) \qquad F_{pp}(t) = (1 - shunt)F_p(t)$$
$$V_{LCO_2} = 1.28\, V_{LO_2} \qquad F_{ps}(t) = shunt\ F_p(t)$$

When the two equations above replaced, $C_{AO2}$ , $C_{ACO2}$ ,$C_{VO2}$ and $C_{VCO2}$ are obtained. Gas Exchange in Lung and Tissues is shown in figure 10.

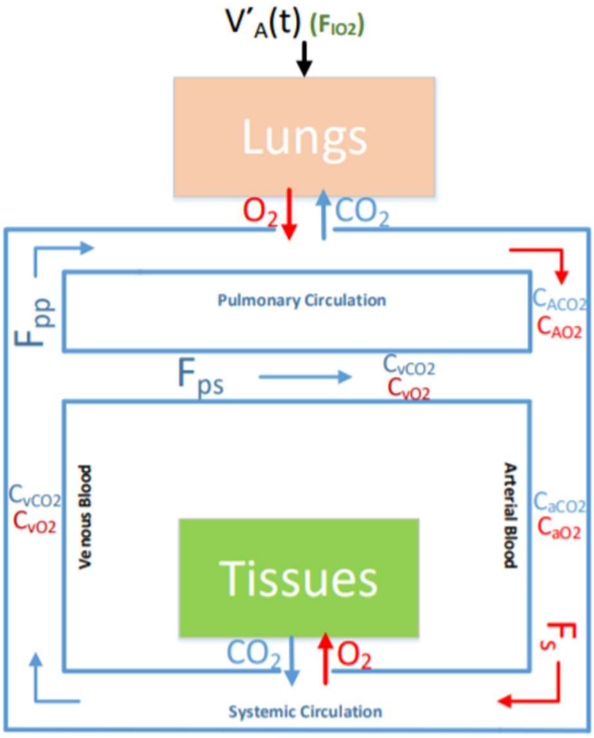


*Figure 10 Gas Exchange in Lung and Tissues*

When breathing under normal conditions, 21% oxygen in the air passes into the blood. Oxygen high blood is called clean blood. Clean blood goes to the lungs and undergoes gas exchange in the alveoli. Meanwhile, oxygen-poor blood is formed. This blood is called dirty blood. Then this blood is cleared through the heart.

Alveolar Oxygen and carbon dioxide concentrate are found by following equations. The Simulink models of following equations are shown in figure 11.

$$C_{AO_2} = C_{satO_2} \frac{\left(P_{AO_2} \frac{1 + \beta_1 P_{ACO_2}}{K_1(1 + \alpha_1 P_{ACO_2})}\right)^{1/h_1}}{1 + \left(P_{AO_2} \frac{1 + \beta_1 P_{ACO_2}}{K_1(1 + \alpha_1 P_{ACO_2})}\right)^{1/h_1}}$$

$$C_{ACO_2} = C_{satCO_2} \frac{\left(P_{ACO_2} \frac{1 + \beta_2 P_{AO_2}}{K_2(1 + \alpha_2 P_{AO_2})}\right)^{1/h_2}}{1 + \left(P_{ACO_2} \frac{1 + \beta_2 P_{AO_2}}{K_2(1 + \alpha_2 P_{AO_2})}\right)^{1/h_2}}$$

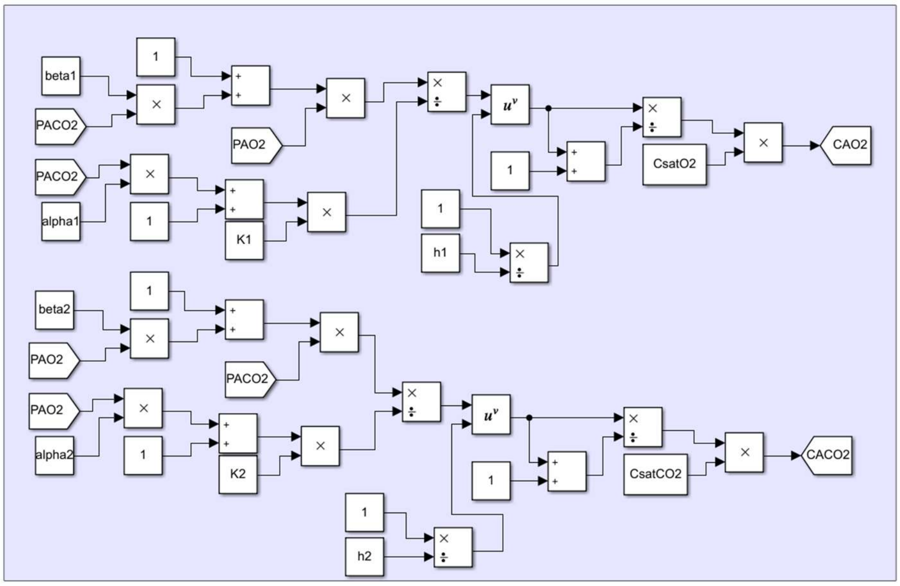


*Figure 11 Alveolar Gas Concentrations*

Arterial oxygen and carbon dioxide concentrate are found by following equations. The Simulink models of following equations is shown in figure 12.

$$C_{aO_2} = \frac{F_{pp}(t)\, C_{AO_2}(t) + F_{ps}(t) C_{vO_2}(t)}{F_{pp}(t) + F_{ps}(t)}$$

$$C_{aCO_2} = \frac{F_{pp}(t)\, C_{ACO_2}(t) + F_{ps}(t) C_{vCO_2}(t)}{F_{pp}(t) + F_{ps}(t)}$$

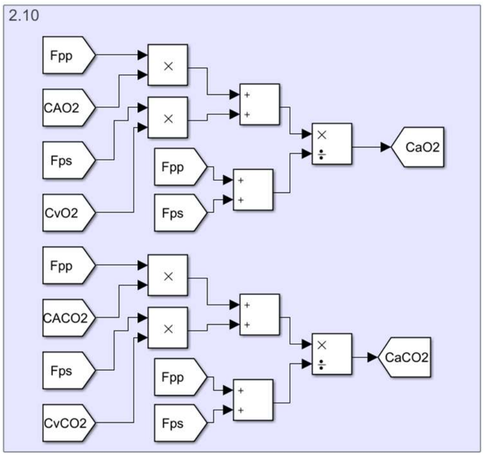


*Figure 12 Arterial Oxygen and Carbon Dioxide Concentration*

Finally, oxygen and carbon dioxide partial pressures is given below:

$$P_{aO_2} = \frac{K_1(1+\alpha_1 P_{aCO_2})}{1+\beta_1 P_{aCO_2}}\left(\frac{C_{aO_2}}{C_{satO_2} - C_{aO_2}}\right)^{h_1}$$

$$P_{aCO_2} = \frac{K_2(1+\alpha_2 P_{aO_2})}{1+\beta_2 P_{aO_2}}\left(\frac{C_{aCO_2}}{C_{satCO_2} - C_{aCO_2}}\right)^{h_2}$$

Simulink model is given in figure 13.

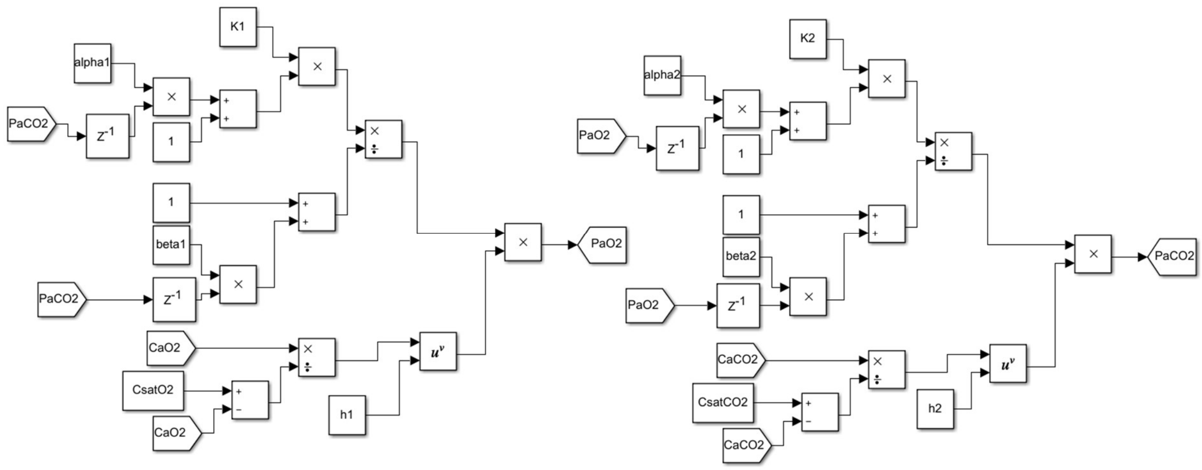


*Figure 13 Arterial Partial Pressure of Oxygen and Carbon Dioxide*

The model in Figure 13 was created with the mathematical expression of the equations. Mathematical expressions such as multiplication, division and addition are used. Alpha, beta and K values are taken from Model Workspace. The delay statement was used before the pressures entered the model. This is to prevent the Algebraic Loop error. When delay expressions are not used, signals overlap on a time basis and solver cannot solve this situation.

$$V'(t) = k_{eff} V_A'(t)$$

Since tissue gas exchange model is not modelled yet, $C_{VO2}$ and $C_{VCO2}$ are used as constant from model workspace and shunt equals zero, that means there is no blood flow for tissues.

b)

For healthy subject $P_{AO2}$ and $P_{ACO2}$ graphs are shown in figure 14.

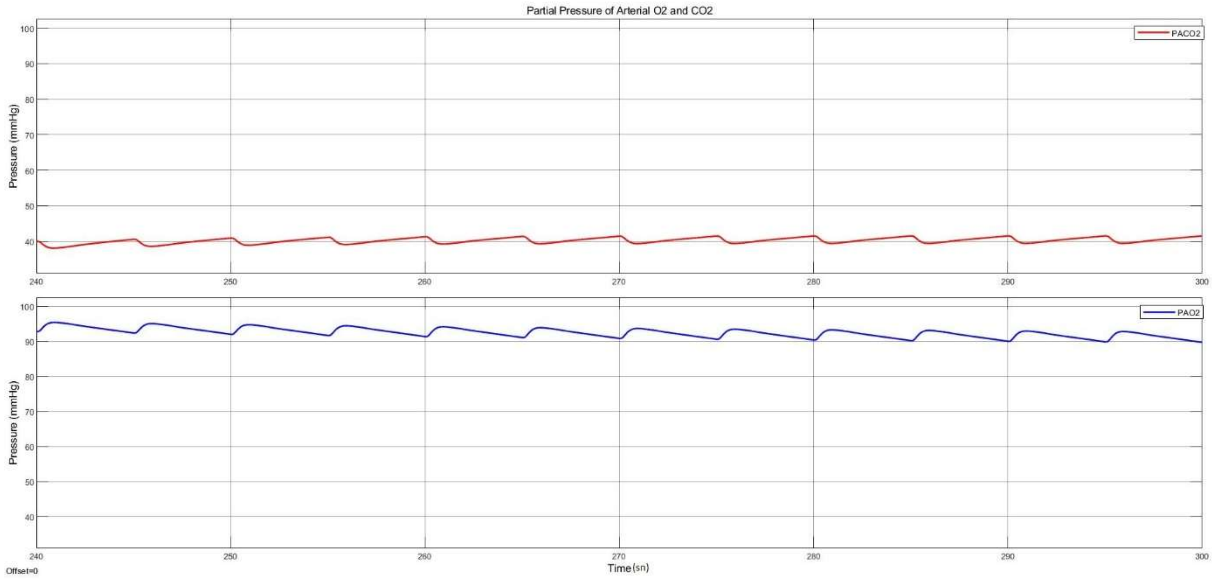


*Figure 14 $P_{ACO2}$ and $P_{AO2}$ (Fp=75ml)*

c)

Normally, $F_P$ and $F_S$ should be obtained from cardiovascular system. Since cardiovascular system will be not modelled in this report, the following equations are used instead of cardiovascular system. The equations also modelled in Simulink, which can be seen at figure 15.

$$F_p(t) = \begin{cases} 1 + 460\sin\left(\frac{\pi}{0.25}t\right)^{1.55}, & 0 \le t \le 0.25 \\ 1 & , \ 0.25 < t \le 0.84 \end{cases}$$

$$F_s(t) = \begin{cases} 1 + 670\sin\left(\frac{\pi}{0.19}t\right)^{2}, & 0 \le t \le 0.19 \\ 1 & , \ 0.19 < t \le 0.84 \end{cases}$$

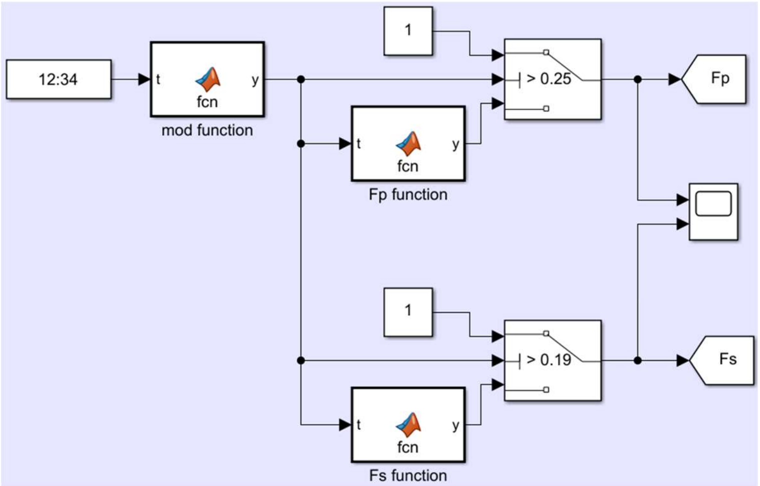


*Figure 15 Fp and Fs Functions*

First, clock block is implemented to get time info. Then periodicity is provided by mod function. The functions' code is given below and output graph is given in figure 16.

```
function y = fcn(t) % mod function
    period=mod(t,0.84);
y = period;
```

```
function y = fcn(t) % Fp function
y = (abs((sin(pi*t/0.25)))^1.55)*460+1;
```

```
function y = fcn(t) % Fs function
y = (abs((sin(pi*t/0.19)))^2)*670+1;
```

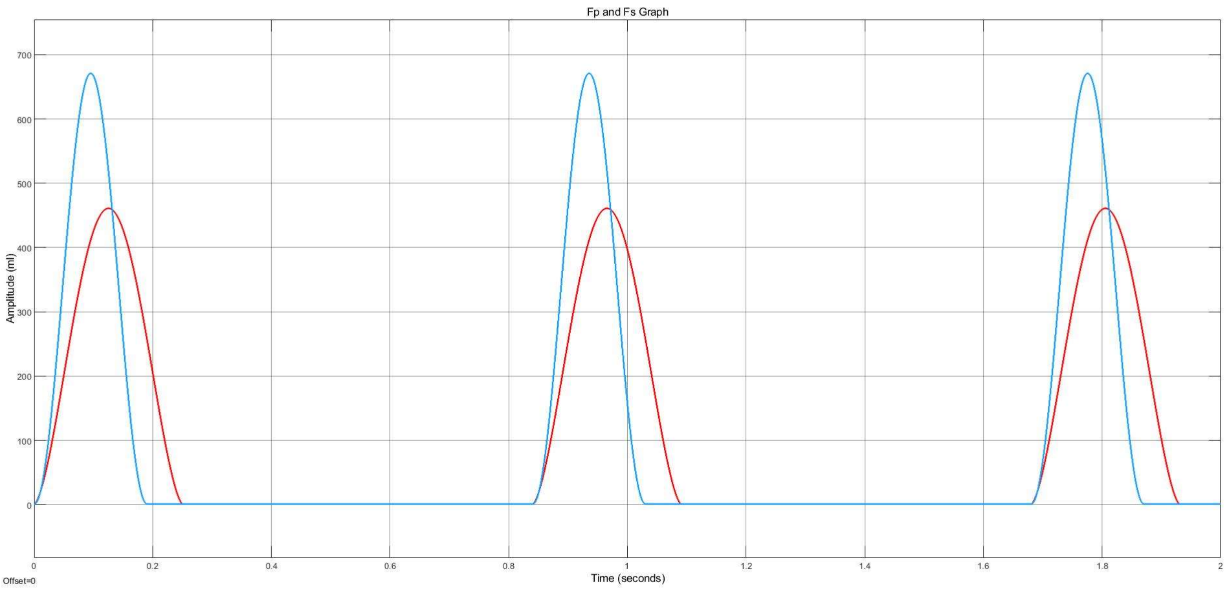


*Figure 16 Fp and Fs Graph*

d)

Blood volume pumped to the body per beat equals 64.49 in each period. The created Simulink model to calculate blood volume pumped to the body per beat is given in figure 17.

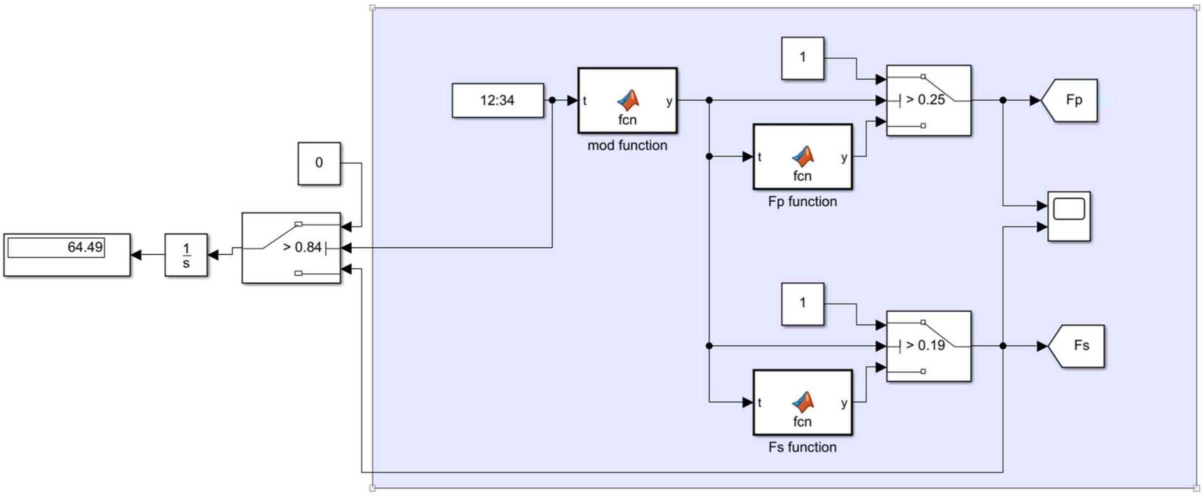


*Figure 17 Blood Volume Pumped to the Body Per Beat in Each Period*

## 3. Tissue Gas Exchange Model

$V_{TO_2}$ and $V_{TCO_2}$ represent the body's storage volume. As the body breathes and breathes, the cells take the oxygen necessary for its work from the blood and the resulting carbon dioxide is returned to the blood. This is called metabolic consumption and metabolic production. In short, while the metabolic consumption of oxygen is seen, the metabolic production of carbon dioxide is seen. The expressions $MR_{O_2}$ are used to represent the metabolic consumption of $O_2$ and $MR_{CO_2}$ is used to represent the metabolic production of $CO_2$.

$$V_{TO_2}\frac{dC_{vO_2}(t)}{dt} = -MR_{O_2} + F_s(t)\left[C_{aO_2}(t-\tau_{LT}) - C_{vO_2}(t)\right]$$

$$V_{TCO_2}\frac{dC_{vCO_2}(t)}{dt} = MR_{CO_2} + F_s(t)\left[C_{aCO_2}(t-\tau_{LT}) - C_{vCO_2}(t)\right]$$

The shunt value for this step is taken nonzero because the transition to blood in previous equations was not taken into account. The shunt value represents the amount of blood transitions here. These equations are implemented in Simulink, which is given in figure 18.

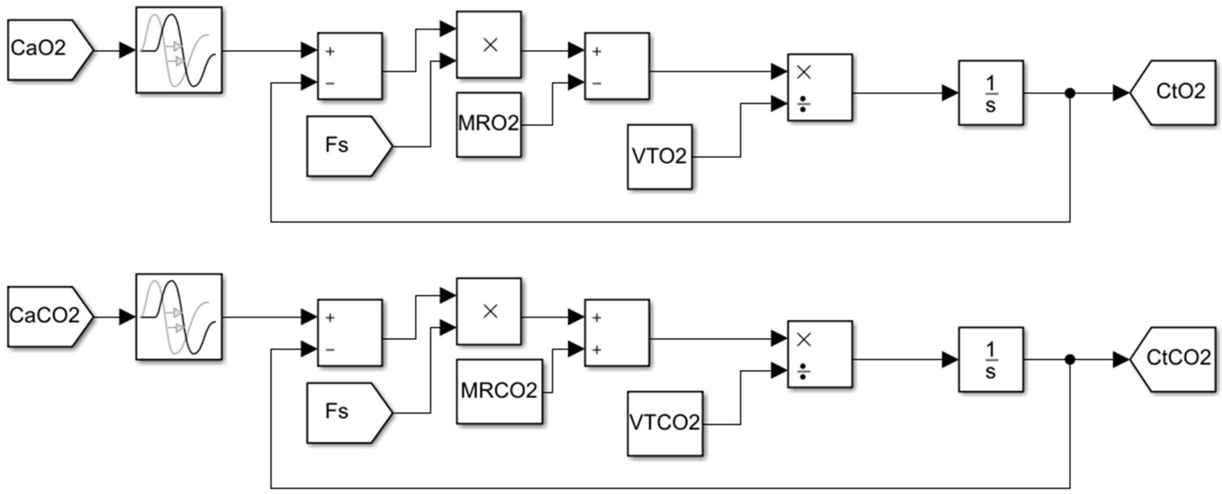


*Figure 18  Tissue Gas Exchange Model*

a)

From now on $C_{vO2}$ is defined and shunt does not equal to zero; therefore, $P_{aO2}$ and $P_{AO2}$ are not equal. $P_{aCO2}$, $P_{ACO2}$ are not equal either. $C_{vO2}$, $C_{tCO2}$ and $C_{vCO2}$, $C_{tCO2}$ are equal. The model obtained in Simulink was run with the parameters obtained from the healthy_prm.m file. The aim here is to examine how the lungs of a healthy person work. The values obtained in this context were compared with the reality and the operation of the system was confirmed. “τ” parameter is used by delay blocks to delay the blood. The output graphs of $P_{aO2}$ and $P_{aCO2}$ is given in figure 19.

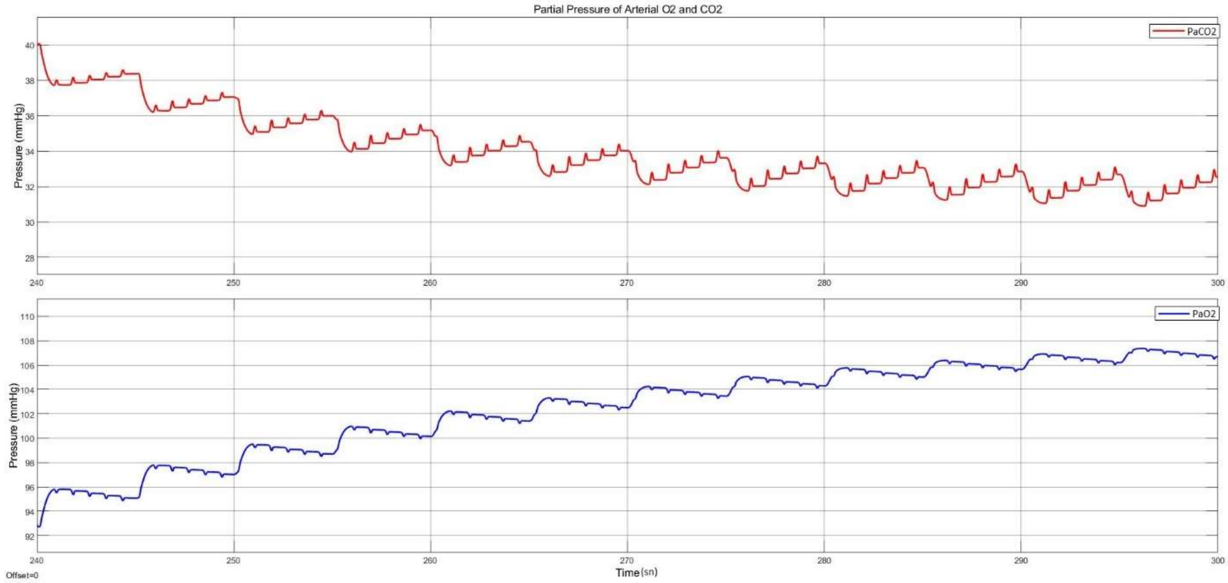


*Figure 19 Partial Pressure of Arterial O2 and CO2 (Healthy Person)*

The pressures of $O_2$ and $CO_2$ are in the correct positions. $C_{vO2}$ and $C_{vCO2}$ equals to 0.1376 ml/ml and 0.5936 ml/ml respectively.

b)

After $MR_{O2}$ and $MR_{CO2}$ are set to 150% system simulated 20 minutes and $P_{aCO2}$,$P_{aO2}$ is increased. Since human body oxygen consumption increased. In reality, in addition to this breath frequency should be increased as well as $P_{aO2}$ and $P_{aCO2}$. The graph is given in figure 20.

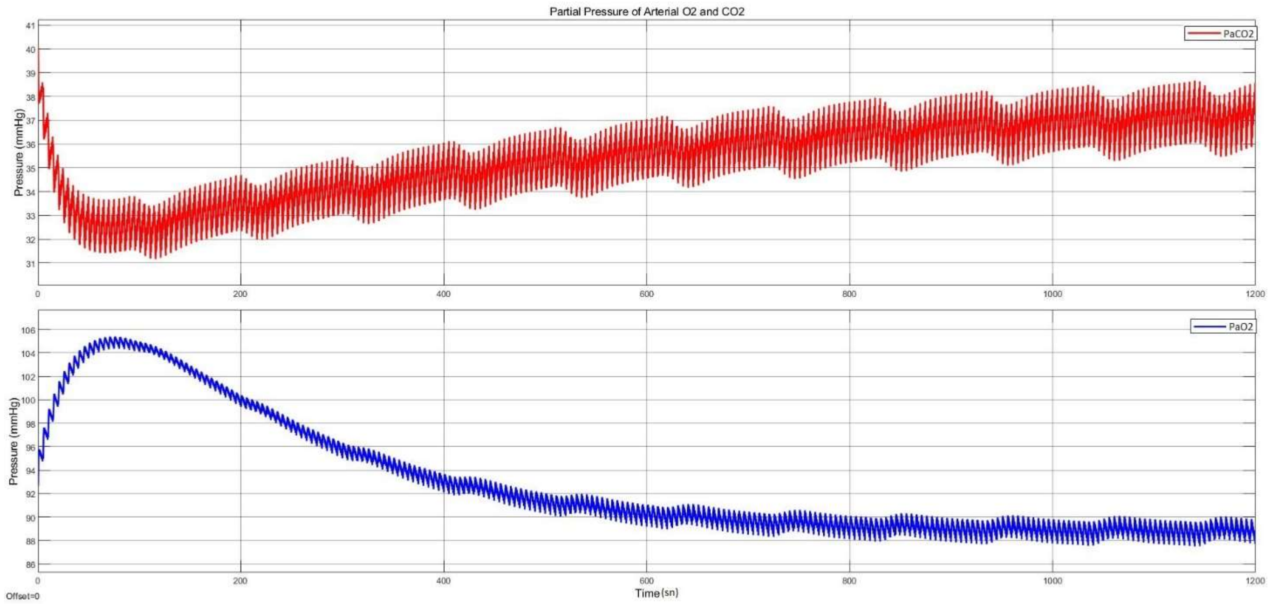


*Figure 20 Partial Pressure of Artial O2 and CO2 (with change of $MR_{O2}$ and $MR_{CO2}$)*

c)

The system was simulated for 10 minutes. The results obtained based on the last 60 seconds are reflected on the graph. Now $V^{ref}$ is changed to 650ml; therefore, Figure 21 shows partial pressures of $O_2$ and $CO_2$ when human is taking deep breath.

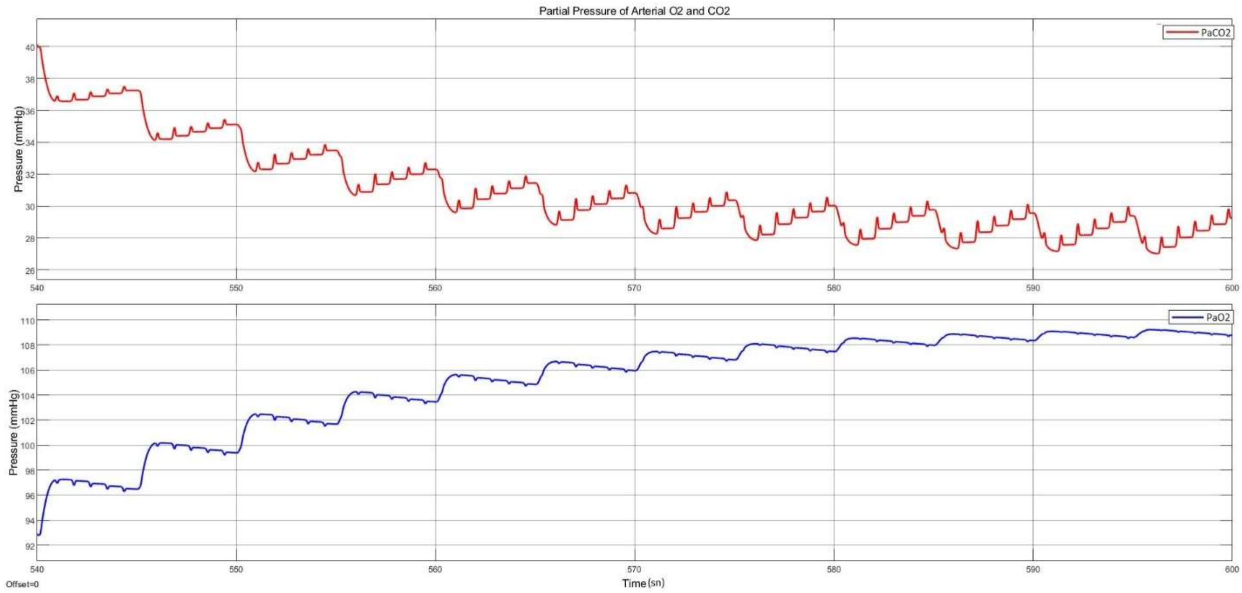


*Figure 21 Partial Pressure of O2 and CO2 (with Vref=650ml)*

d)

The given system was simulated for 20 minutes in Simulink environment. The output parameters obtained during simulation were recorded in the file named “xFinalDisease”. During the simulation, keff, which is one of the input parameters, was taken as 0.6, shunt value was taken as 16.5%. Partial pressure of oxygen is decreased and carbon dioxide is increased because as “Keff” is increased blood flow which is going to the lungs is decreased. The graph of Partial Pressure of O2 and CO2 can be seen at figure 22.

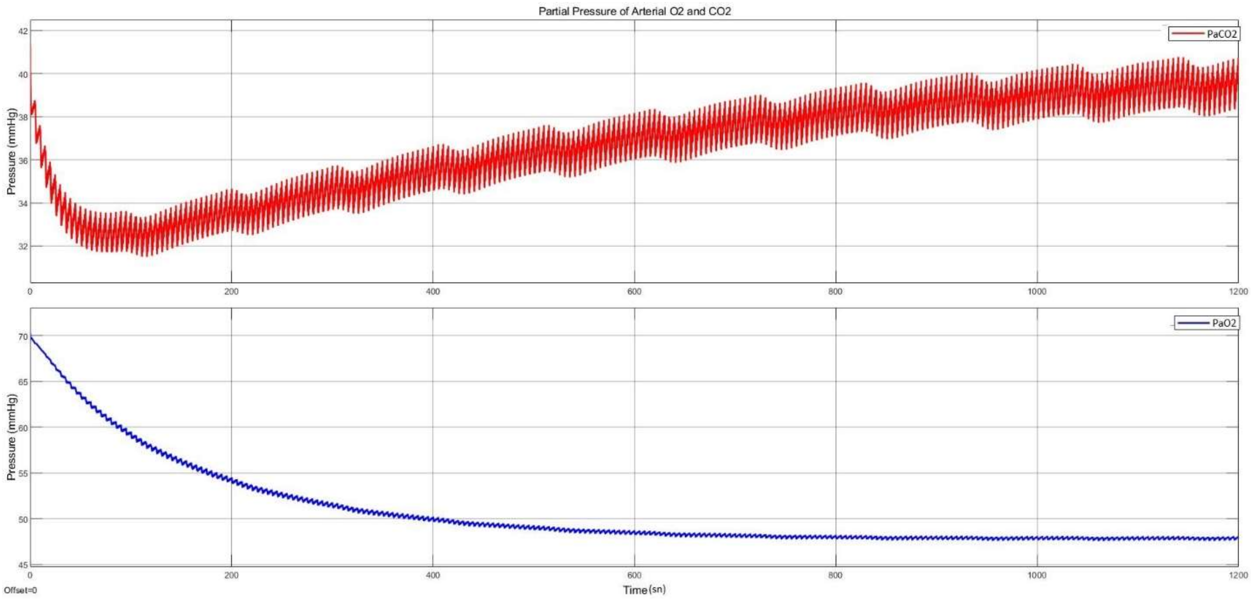


*Figure 22 Partial Pressure of O2 and CO2 (Diseased Lungs)*

## e)

Using the parameters in the xFinalDisease file, this system was simulated by Simulink for 30 minutes. Even if the amount of oxygen in the air which is 21% in normal conditions, is 70%, the amount of arterial oxygen has not reached a sufficient level. Tidal volume amount was taken as 650mL. Nevertheless, no appreciable normality in values was below the expected level. The measurement results are shown in Figure 23.

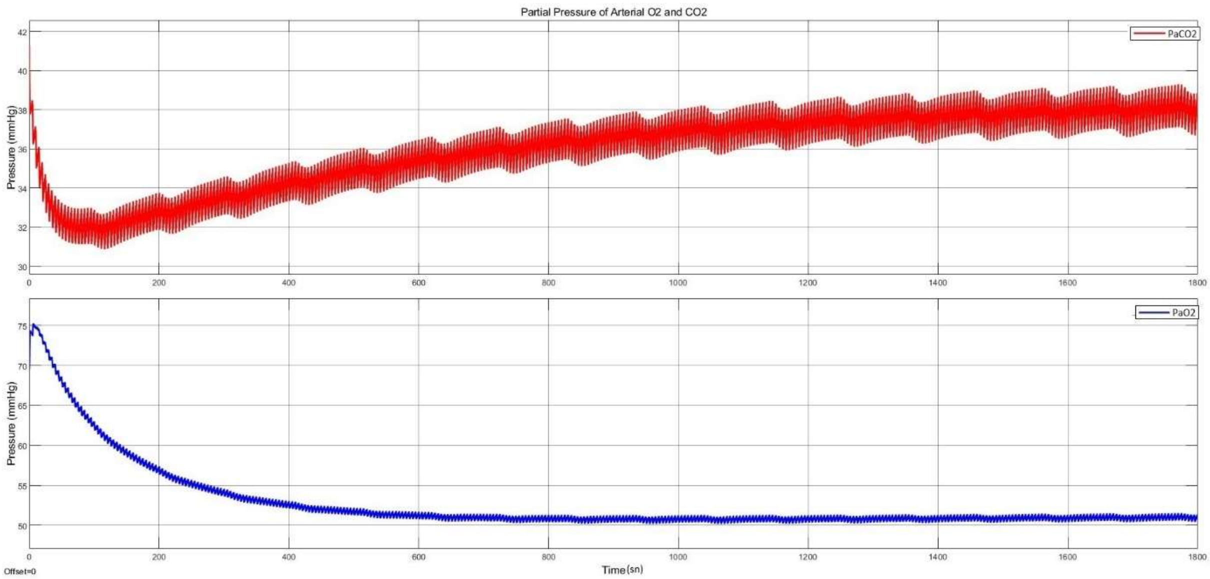


*Figure 23 Partial Pressure of O2 and CO2 (Diseased Lungs with 70% Oxygen)*

## f)

Oxygen pressure in the artery was below the desired level for people suffering from COVID-19 disease regardless of the amount of oxygen in the air. The values obtained after simulating the system for 20 minutes after being implemented in the Simulink environment are shown in Figure 24. The data in Figure 24 are for values where the oxygen concentration in the air is 21%. The same system is simulated when the oxygen concentration in the air is 100%. Said outputs are given in Figure 25. The main problem here is that arterial oxygen is low despite the oxygen concentration in the air. The “diseased_prm.m” MATLAB file was used to obtain the parameters of the diseased person.

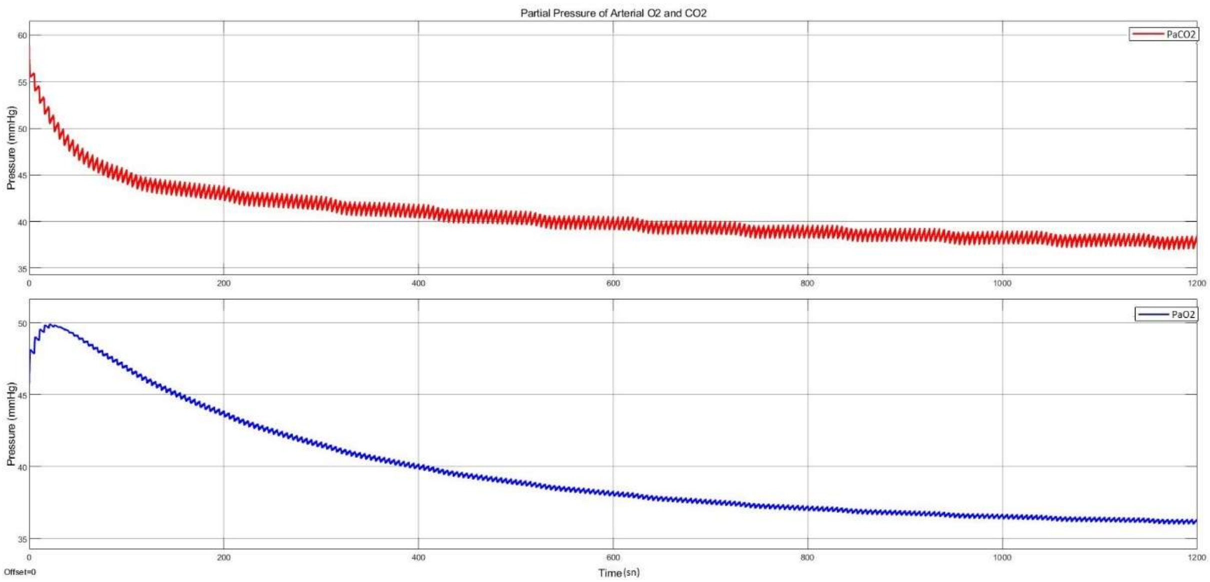


*Figure 24 Partial Pressure of O2 and CO2 (Diseased Lungs with 21% Oxygen)*

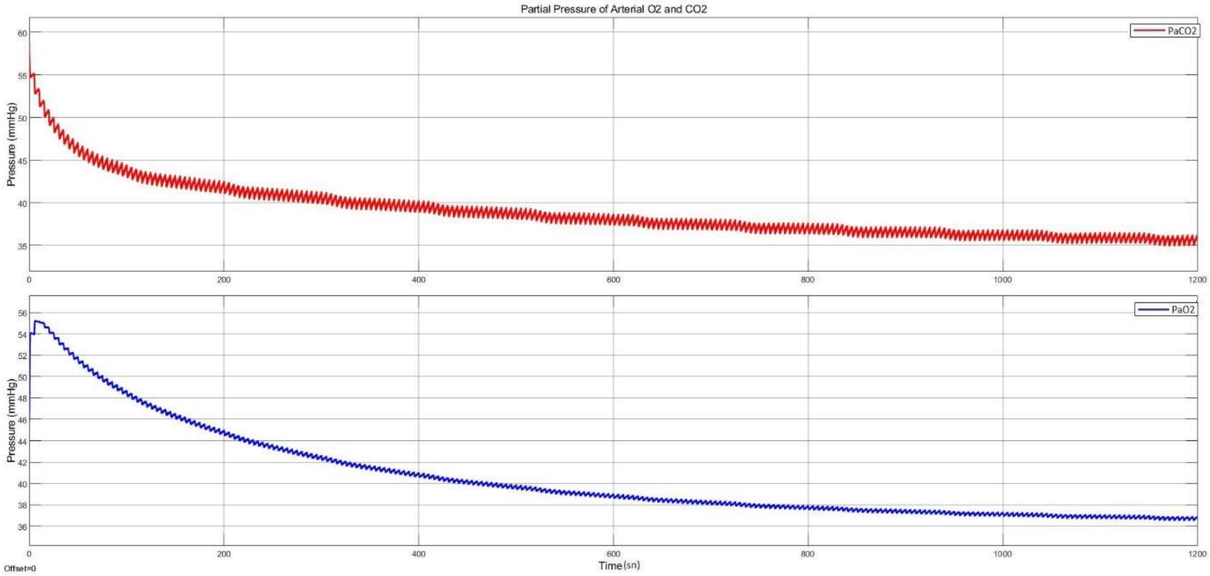


*Figure 25 Partial Pressure of O2 and CO2 (Diseased Lungs with 100% Oxygen)*

## C. EXTRACORPOREAL MEMBRANE OXYGENATOR MODEL

According to the results obtained in section 2, the lungs are not suitable for gas exchange. For this reason, an ECMO will be modeled in this section in order to support the lungs of the person and to obtain the oxygen amount at an adequate level. The mathematical equations given below were used during the ECMO design. The system is modeled by using the components in the normal Simulink library and the components of the Simscape library in a sharing.

### 1. Pump Model

The pump system that cleans the patient's dirty blood is an electromechanical system. It gives an angular speed of 0-500rd / s at its output in response to an input voltage of 0-48V. The corresponding equations are as follows and the scheme of the system with the pump can be seen in figure 26.

$$V_{pump}(t) = L\frac{dI_{pump}(t)}{dt} + RI_{pump}(t) + k_{em}\omega_{pump}(t)$$

$$\tau_{pump}(t) = k_{em}I_{pump}(t)$$

$$J_L\frac{d\omega_{out}(t)}{dt} = N_g\tau_{pump}(t)$$

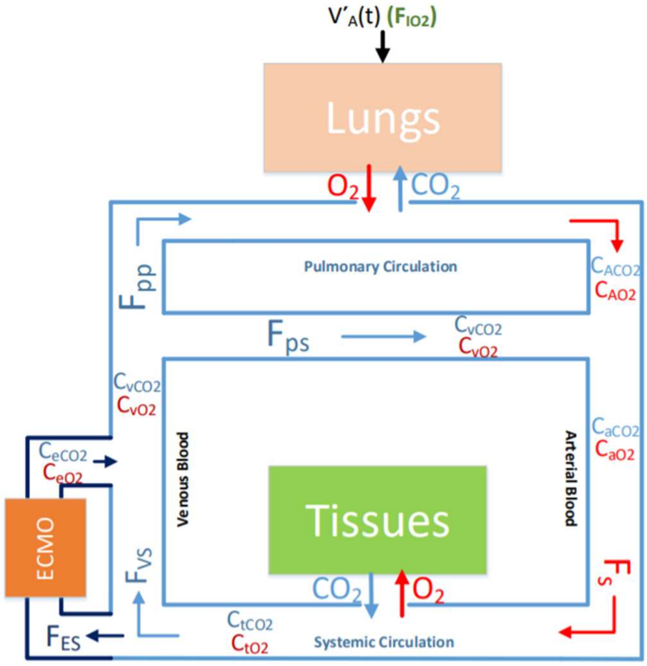


*Figure 26 ECMO Device Included into the System Model*

The Simulink Model of ECMO Device is given in figure 27. The model of ECMO Device was created with the help of Simscape library.

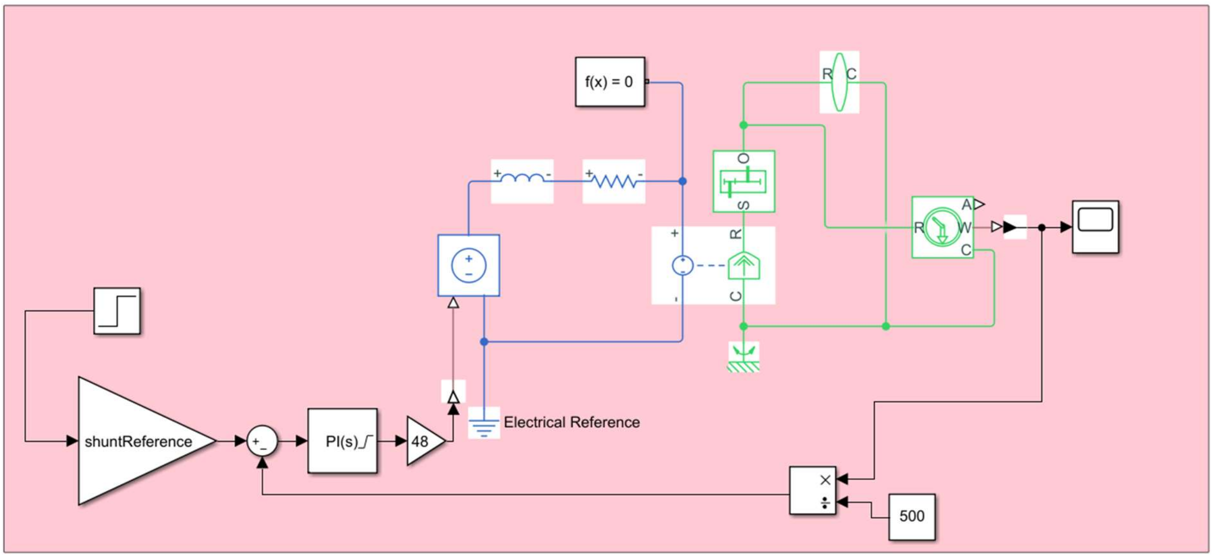


*Figure 27 ECMO Device Simulink Model*

In this context, voltage, resistance, rotational electromechanical converter, gear box and rotational inerter are used in modeling the motor. The main purpose here is to process the incoming voltage through the electrical system and then obtain the angular velocity over the mechanical system. The shunt value was used to define the efficiency of the engine.

$$F_{VS}(t) = (1 - shunt_{ECMO})F_s(t)$$
$$F_{ES}(t) = shunt_{ECMO}\, F_s(t)$$

The mathematical equations given above were used to ensure the input of the values obtained from the pump into the system. The equations are added to the Simulink Model that given before.

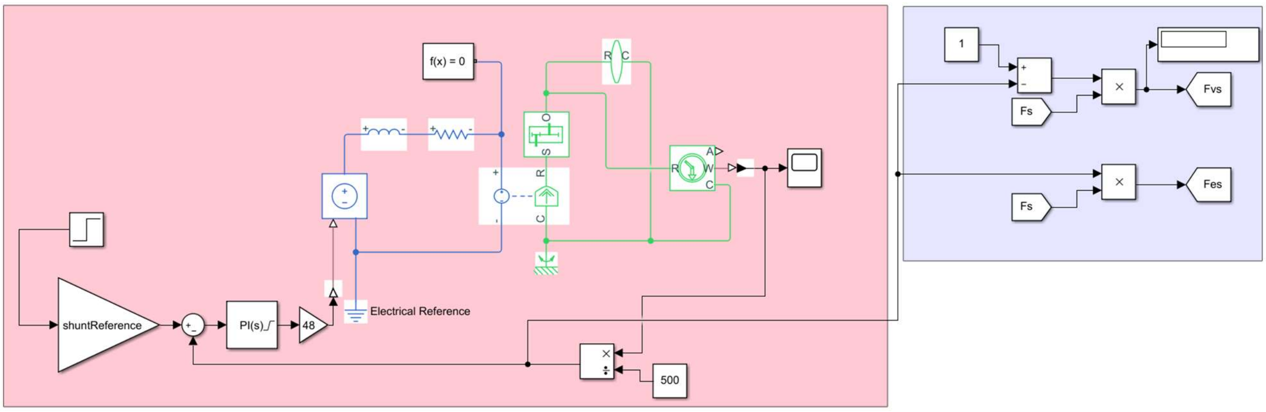


*Figure 28 ECMO Device Simulink Model with Shunt Equations*

a)

The prepared pump system was simulated in Simulink environment. It is examined whether the settling time value is around 4 seconds. It can be seen in the chart given in Figure 29 that the obtained values provide the desired data. The input voltage is set to 48V during the simulation process.

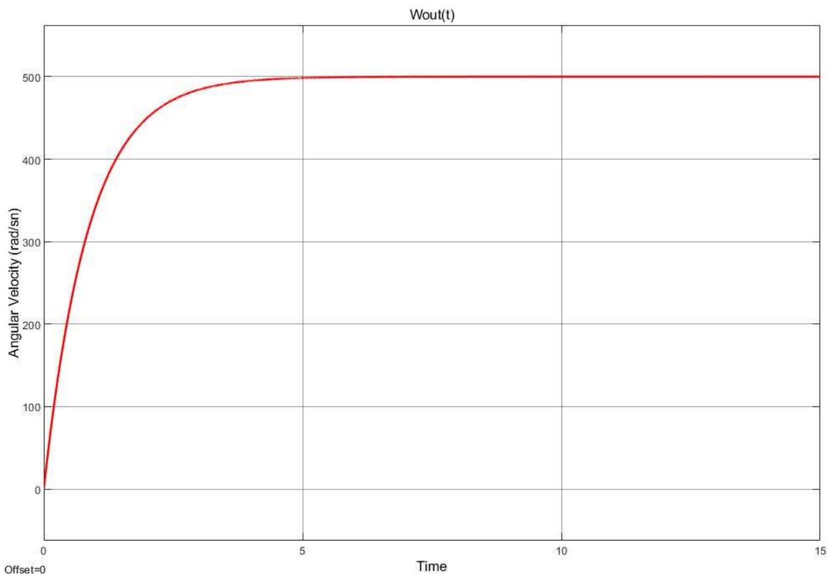


*Figure 29 Angular Velocity Output of Pump*

b)

This section aims to control the Shunt ecmo value. For this purpose, the PI controller structure, whose mathematical equation is given below, is used. The parameters of PI controller are calculated in MATLAB PID Tuning toolbox.

$$C_{PI}(s) = K_P + \frac{K_i}{s} = 52.43 + \frac{7.613}{s}$$

The output of the PI controller is limited in the range 0-48. Unit feedback usage of PI controller can be seen in figure 28. The angular velocity obtained from the outlet is scaled to 500 units. Thus, the value of the previous unit time of shuntecmo was obtained from the output. By taking the difference of the obtained value with the new value, it was entered to the controller and the system was taken under control.

After applying PI Controller, the output angular velocity of pump can be seen in figure 30.

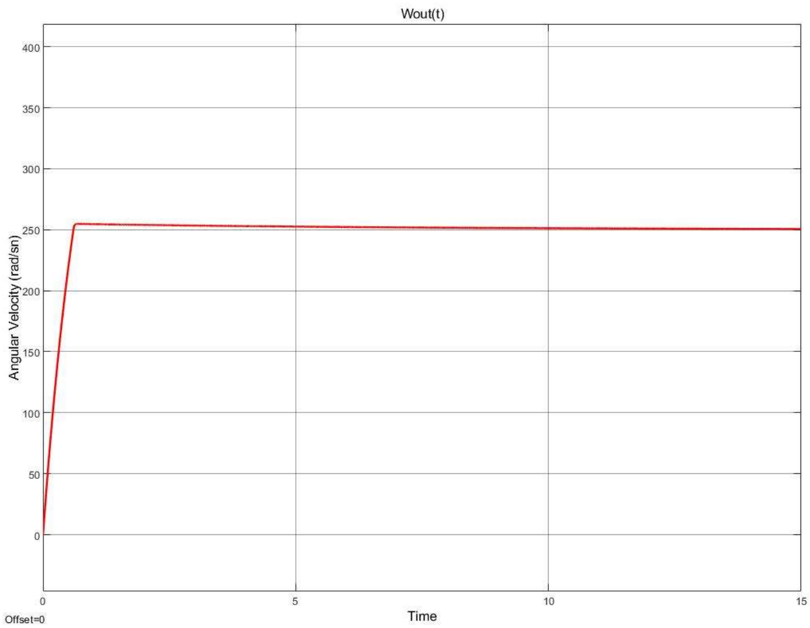


*Figure 30 Angular Velocity Output of Pump (with Controller)*

## 2. Oxygenator Model

The ecmo device acts like an artificial lung. It takes dirty blood, increases oxygen concentration and reduces carbon dioxide concentration. The mathematical model is similar to the lungs and is given below.

$$P_{IEO_2}(t) = (P_{atm} - P_{ws})F_{IEO_2}(t)$$

$$V_{EO_2}\frac{dP_{EO_2}(t)}{dt} = 863F_{ES}(t)[C_{to_2}(t) - C_{eo_2}(t)] + V'_{Ecmo}(t)[P_{IEO_2}(t) - P_{EO_2}(t)]$$

$$V_{ECO_2}\frac{dP_{ECO_2}(t)}{dt} = 863F_{ES}(t)[C_{tco_2}(t) - C_{eco_2}(t)] - V'_{Ecmo}(t)P_{ECO_2}(t)$$

$$C_{eo_2} = C_{sato_2}\frac{\left(P_{EO_2}\dfrac{1+\beta_1 P_{ECO_2}}{K_1(1+\alpha_1 P_{ECO_2})}\right)^{1/h_1}}{1+\left(P_{EO_2}\dfrac{1+\beta_1 P_{ECO_2}}{K_1(1+\alpha_1 P_{ECO_2})}\right)^{1/h_1}}$$

$$C_{eco_2} = C_{satco_2}\frac{\left(P_{ECO_2}\dfrac{1+\beta_2 P_{EO_2}}{K_2(1+\alpha_2 P_{EO_2})}\right)^{1/h_2}}{1+\left(P_{ECO_2}\dfrac{1+\beta_2 P_{EO_2}}{K_2(1+\alpha_2 P_{EO_2})}\right)^{1/h_2}}$$

The Simulink Models of given equations are given in figure 31.

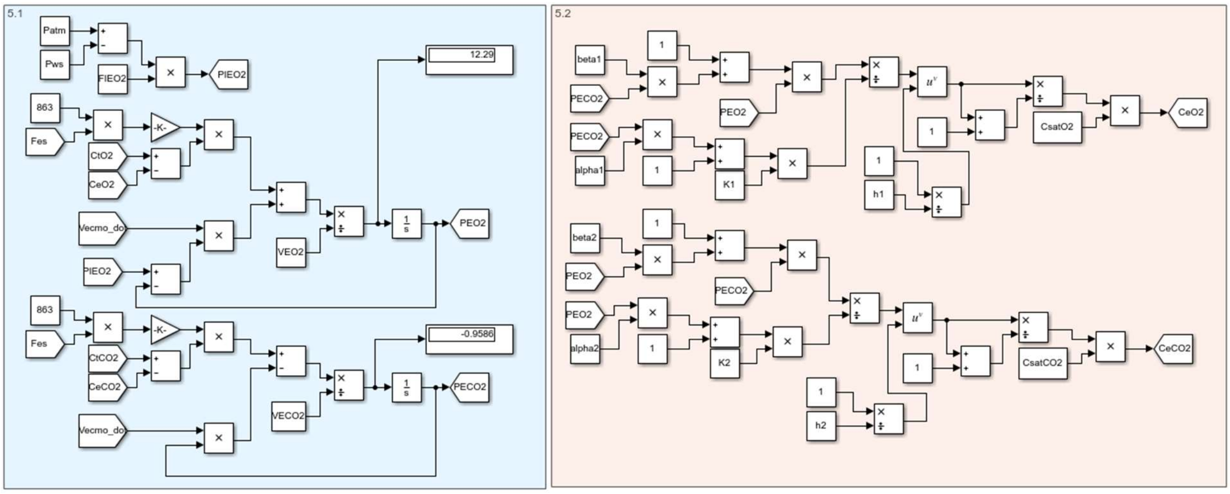

*Figure 31 ECMO Math Model*

Unlike the lung mechanical model, the parameters are characterized under the name ecmo. All parameters in the lung mechanical model are rewritten as sub-indices "e" and "E". Finally, the venous outputs with the ECMO,

$$C_{vO_2} = \frac{F_{ES}(t)\, C_{eO_2}(t) + F_{VS}(t) C_{tO_2}(t)}{F_{ES}(t) + F_{VS}(t)}$$

$$C_{vCO_2} = \frac{F_{ES}(t)\, C_{eCO_2}(t) + F_{VS}(t) C_{tCO_2}(t)}{F_{ES}(t) + F_{VS}(t)}$$

$C_{vO2}$ and $C_{vCO2}$ should be changed into $C_{tO2}$ and $C_{tCO2}$ respectively in Tissue Gas Exchange Model. $V_{ECMO}$'(t) is taken as constant which equals "0.08 L/sec". $F_{IEO2}$ and $shunt_{ECMO}$ are the main parameters to control the device. For treatment arterial oxygen and carbon dioxide value range is given as follow.

$$P_{aO_2} > 80 \text{ mmHg} \;\text{ and }\; P_{aCO_2} < 40 \text{ mmHg}$$

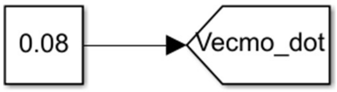


*Figure 32 Vecmo' is a constant*

a)

A substem created for ECMO Device's equations. Input signals are taken as constant blocks from model workspace.

b)

The system was simulated for 10 minutes in the Simulink environment by taking the FIEO2 value as 0.9 and shuntEcmo value as 0.7. It is shown in Figure 33 based on the last 60 seconds of the graph of the outputs of the simulation.

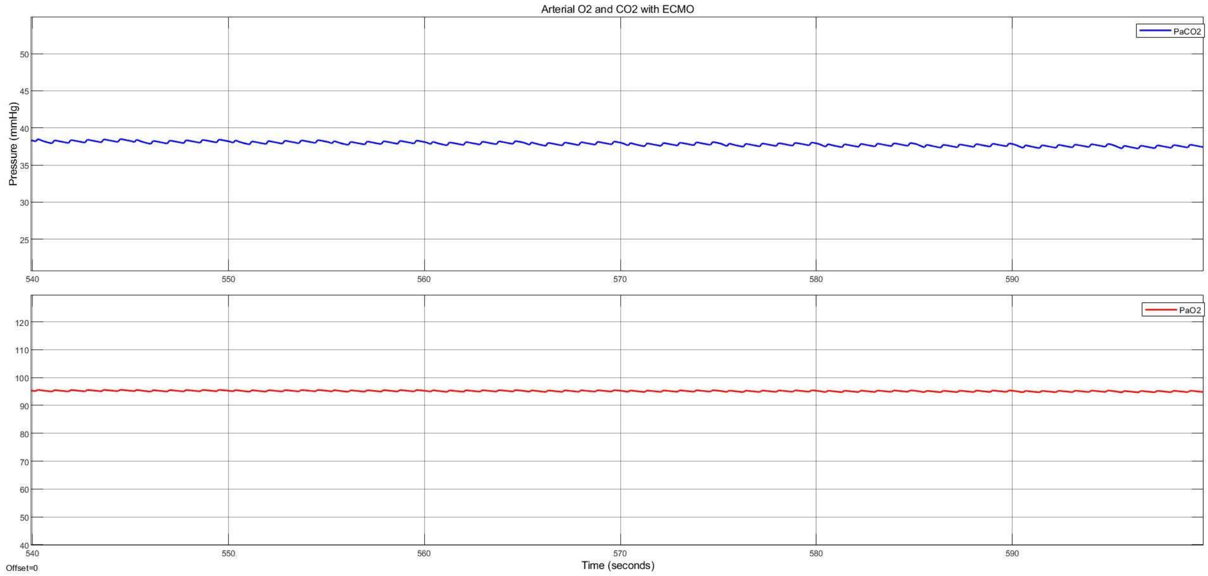


*Figure 33 Partial Pressure of O2 and CO2 (with ECMO)*

As can be seen in figure 33, the oxygen ratio is greater than 80 and the CO2 ratio is less than 40 in arterial ($F_{IEO2}$ = 0.9, $shunt_{ECMO}$ = 0.7). ECMO works properly and treats the patient.

## c)

The system is simulated for different $F_{IEO2}$ and $shunt_{Ecmo}$ values. The values obtained are given in Figure 34 and Figure 35 respectively. $Shunt_{Ecmo}$ and $F_{IEO2}$ values given as input can be seen as a figure text.

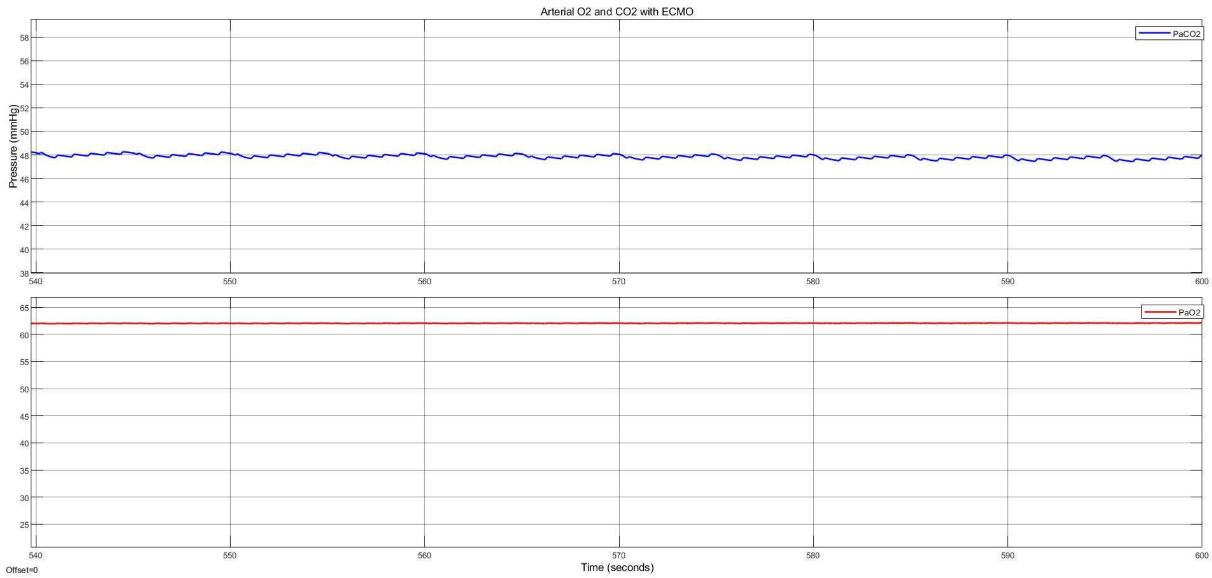


*Figure 34 Partial Pressure of O2 and CO2 (FIEO2=0.1 shuntECMO=0.3)*

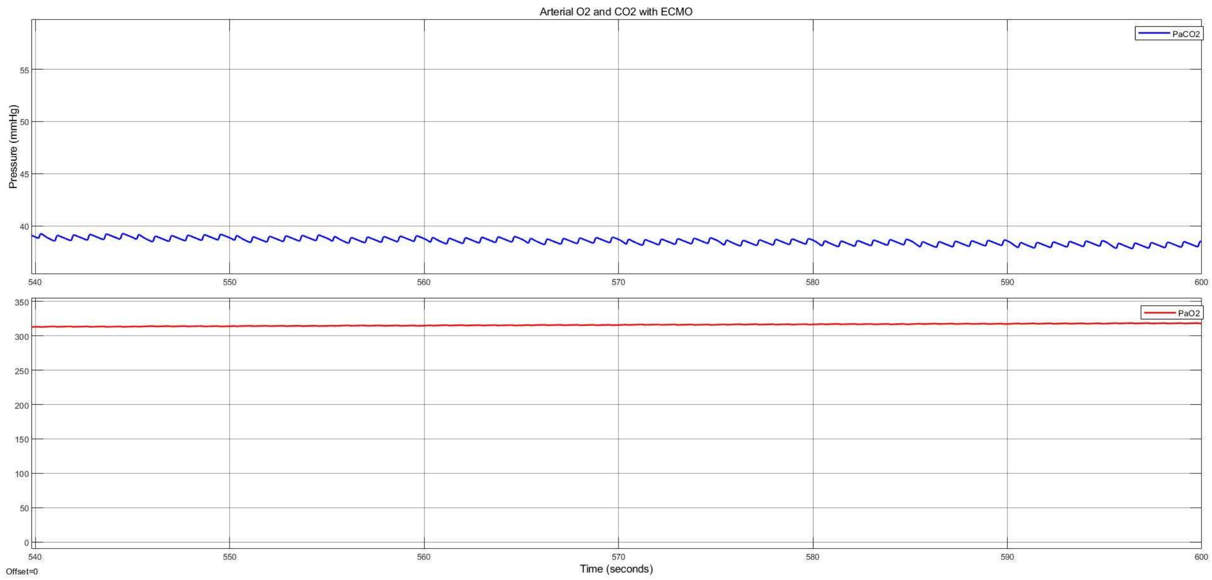


*Figure 35 Partial Pressure of O2 and CO2 (FIEO2=0.5 shuntECMO=1)*

As can be seen, the dominant factor is the shunt parameter. Even if $F_{IEO2}$ is 100%, oxygen and carbon dioxide values in the artery cannot reach the desired value.

### d)

First, the desired $O_2$ value is multiplied by the adjustable constant. Then, it is compared with the $O_2$ value coming from the system and an error is produced. Values between 0-1 are needed because the shunt is wanted to be checked. Therefore, the error rate is scaled with the desired value. Finally, $shunt_{Reference}$ is controlled by inserting PI control with saturation points 0 and 1. The Simulink Model is given below.

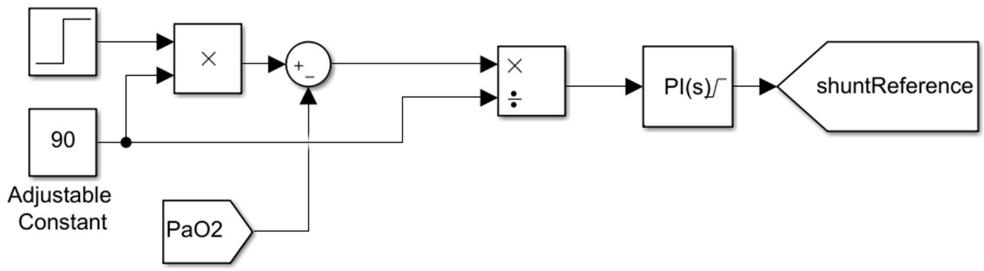


*Figure 36 Simulink Model of ECMO Controller*

The output signals are given in figure 37 and 38.

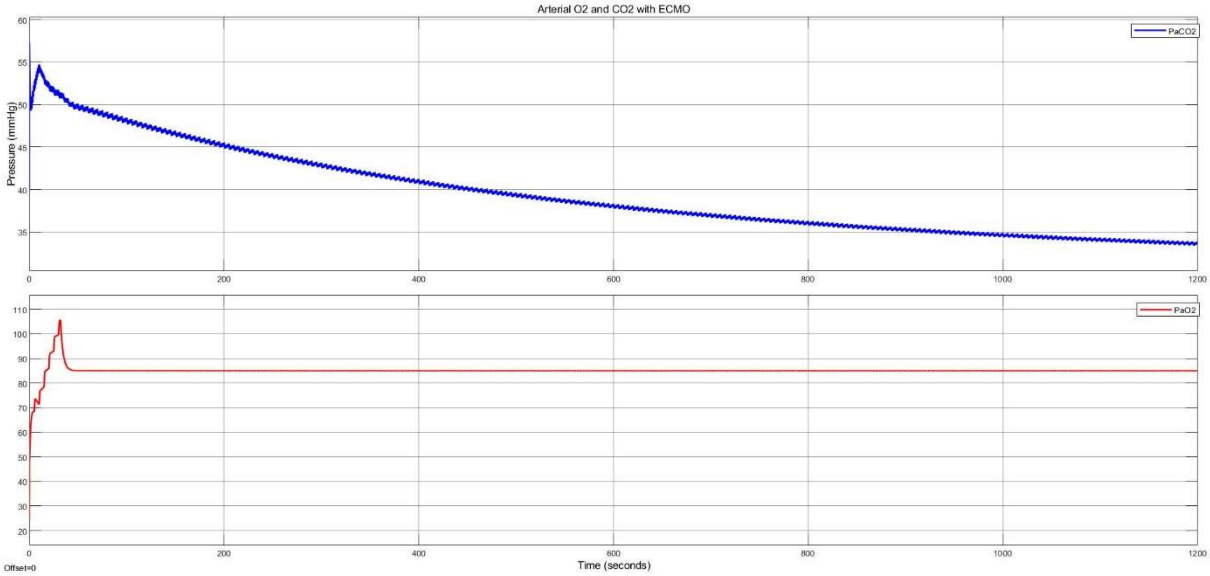


*Figure 37 Partial Pressure of O2 and CO2 (with Controller)*

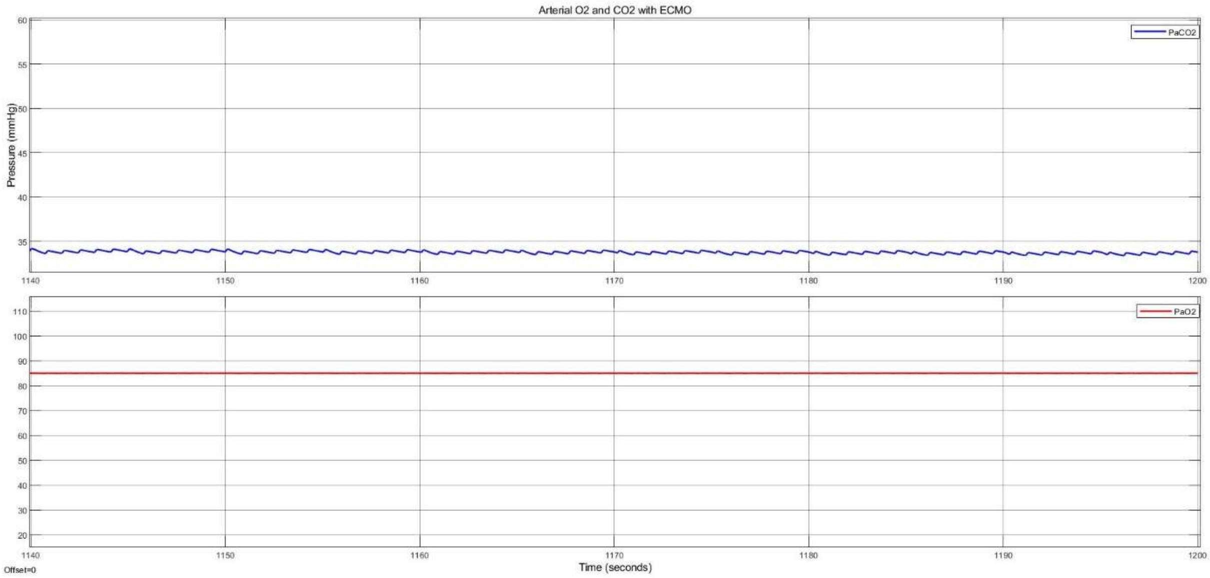


*Figure 38 Partial Pressure of O2 and CO2 (with Controller and Last 60seconds)*

*NOTE : In this report, simulation solver type adjusted to “Fixed-Step” and solver adjusted to “ode4 (Runge-Kutta)”.

*NOTE 2 : In this report, simulation sample time is based on “Tsamp” from model workspace in every simulation.

# CONCLUSION

The scope of this project includes how the lungs work and regulations regarding this working logic. It has been seen that any system existing in real life can be modeled mathematically throughout the project. It has also been seen how effective it is to make all kinds of systems understandable with a single language expression to change or manage them. Namely, lungs are a biological system and we had the opportunity to model and realize this system on Simulink by mathematically modeling it. Then we have seen that this real system can be controlled and changed with various parameters and devices (such as ECMO). In short, if any real-life system can be transferred to the mathematical environment correctly, these systems can be arranged as we want. The biggest advantage of this situation is the opportunity to test the system for different scenarios and risky situations. In addition, since we do not implement the systems in the cost part, it provides us a great benefit.

Another part that needs attention is the place and importance of control systems in our lives. As can be seen in the project, since the systems we created are dynamic systems, keeping the output values the way we want was quite difficult. However, it is necessary to say that by designing both a device and a controller, it can intervene in this situation and make stable changes on the system.

To finish, control systems are part of our lives and can offer effective and creative solutions not only theoretically but also in the face of the troubles in our daily life. In addition, these systems can be simulated before they are built, thus protecting them from many cost items and possible risks.