DESIGN OF AN AUTONOMOUS BILEVEL VENTILATOR FOR FULL TERM AND PRETERM NEONATES

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ABSTRACT

The team chose the design and simulation of "Autonomous Bilevel Ventilator" as its final year project. Knowledge of Fluid Mechanics, Control Systems, Measurement, Instrumentation and Biomedical is integrated to provide a solution to the existing medical problem in economically developing nations. Bubble CPAP (Continuous positive airway pressure) is treatment to provide respiratory support to full term and preterm neonates across the globe. However, the project focuses on super babies that require a dual pressure treatment (BiPAP), costing at least four figures amount. The team pursues to design an autonomous, simpler, cheaper, effective, and minimum human intervention requiring **NIPPV** set up that could be replaced as a cheaper solution to other autonomous bilevel machines. An intelligent oxygen blending system design is presented which could be used for any ventilator, thus saving hundreds of dollars on market-based oxygen blenders.

ACKNOWLEDGMENTS

First, we are very thankful to our Creator and Sustainer Allah Almighty, The Most Beneficent, The Most Merciful, WHO helped us through each step of this project. Indeed, nothing is possible without His divine decree. We owe a great debt of gratitude to our parents who has always lent us their valuable support through all the ups and downs of our life. We are thankful to our project supervisor Dr. Najam ul Qadir for being a great supervisor and for helping and supporting us through all the phases of this project. Sir, we appreciate your patience and believe that you are the perfect embodiment of an honest and inspiring teacher. We are also profoundly grateful to our advisors Dr. Jawad Aslam and Dr. Sana Waheed, Dr Waqas Khalid and Dr Zaib Ali for their generous support and guidance. Our Principal Dr. Javaid Iqbal as well as HOD Dr. Emad-ud-Din are also be thanked for all the support we got from the school and department.

ORIGINALITY REPORT

DESIGN OF AN AUTONOMOUS BILEVEL VENTILATOR FOR FULL TERM AND PRETERM NEONATES

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ABBREVIATIONS

NIV	Noninvasive ventilation
NIPPV	Noninvasive positive pressure ventilation
CPAP	Continuous positive airway pressure
BiPAP	Bilevel Positive airways pressure
IPAP	Inspiratory positive airway pressure
EPAP	Expiratory positive airway pressure
PMOSFET	P-Channel MOSFET

NOMENCLATURE

τ	Time Constant
t	Response Time
C	Capacitance
R	Resistance
K_p	Proportional Gain (in PID control)
K_i	Integral Gain
K_d	Derivative Gain
P_{Air}	Air Inflow Pressure

CHAPTER 1: INTRODUCTION

1.1. Motivation

Pneumonia can be regarded as one of the primary causes of illness and death in children in developing countries [1– 2]. It is reason for 28.5% of deaths in children under age 5 and equals two third of deaths due to Acute Respiratory Tract Infection (ARI). In Pakistan, over **250,000 child deaths** annually are ascribed to ARI, and death rate is particularly elevated in the rural areas of Pakistan where the occurrence of ARI is stated to be **30-35%** [3]. The three major reasons for the overwhelmingly high mortality rate attributed to ARI are (a) poor accessibility of patients towards the hospitals, (b) extreme lack of trained health-care staff, and (c) unavailability of pediatric ventilators.

This proposal focuses on the third major reason from amongst the three ones. The price of a neonatal bilevel ventilator in Pakistan is **2 million PKR** which cannot be at all afforded by most public sector hospitals of Pakistan given the amount of total funding invested in these hospitals by the Pakistani Government. In this context, this research proposes a much cheaper, yet easily reproducible prototype of a neonatal ventilator for use in the substandard public sector hospitals of Pakistan.

1.2. Problem Statement:

Several factors distinguish the market for medical devices in rural third world settings. First, these centers have less income from patients. Hence their budgets for medical equipment are much smaller. In addition, items like electricity are often highly variable and equipment-servicing options can be limited. Also, operators will frequently have less discipline specific training. For example, nurses would have to operate respiratory equipment due to a lack of Respiratory Therapists. In view of these challenges, the strategy will be to help the most people for the least cost. This is accomplished through designing simpler and stronger devices for a fraction of the cost that adequately serve most of the population.

1.3. Objective:

To propose a BiPAP ventilator design for delivering an economical and autonomous respiratory support for preterm and full-term neonates. The design should be simple and autonomous requiring less human intervention.

CHAPTER 2: LITERATURE REVIEW

2.1. Definition of Ventilator

“A ventilator is a kind of device that helps or assumes control over the breathing interaction, siphoning air into the lungs. Individuals who stay in intensive care units (ICU) may require the help of a ventilator. This incorporates individuals with extreme COVID-19 symptoms.”

Before COVID-19 turned into a pandemic, a requirement for ventilation was quite possibly the most well-known reasons trusted Source individuals got treatment in ICUs. From that point forward, the interest in ventilators has expanded.

2.2. Requirement of Ventilator

Individuals require ventilation if they are encountering respiratory disappointment. At the point when this happens, an individual cannot get sufficient oxygen and will be unable to remove carbon dioxide very well by the same time. It tends to be a perilous condition. There are many injuries and conditions that can cause respiratory failure such as heart diseases, lung diseases, pneumonia etc.

A few Patients with COVID-19 have extreme trouble breathing or foster ARDS. In any case, this just happens in individuals who become fundamentally not well Trusted Source, which represents around 5% Trusted Source of all affirmed COVID-19 cases. Likewise, specialists additionally use ventilators for individuals who go through a medical procedure and are not able to inhale all alone because of anesthesia.

2.3. Mechanical ventilation

Mechanical ventilation is a treatment to assist an individual with breathing when they experience that it is difficult or cannot inhale all alone. A mechanical ventilator drives the air to stream into the victim's lungs to assist them with breathing shown [4]:

Figure 1. Patient On Mechanical Ventilator

It can be:

- Invasive ventilation with a cylinder embedded through the tubing injected into the patient's trachea proceeded in the ICU in the clinic.
- Noninvasive ventilation can be utilized at home by individuals or infants with respiratory distress.

2.4. Different Types of mechanical ventilation

The two main types of mechanical ventilation are [4].

- ***Negative- pressure ventilation:*** chest is expanded and contracted alternatively by pumping air into the lungs.
- ***Positive -pressure ventilation*** pushes the air into the lungs.

2.4.1. Negative-pressure ventilation:

Mostly utilized in early ventilators. Nowadays, negative pressure ventilation is very uncommon.

- ***Iron lung:*** Consists of a metal cylinder which wrapped around the patient completely till the neck.
- ***Chest cuirass:*** small shell fastens around the patient's chest to generate required negative pressure.

2.4.2. Positive-pressure ventilation:

In this ventilation air is blown into patient's lungs via cylinder. They might be invasive or noninvasive.

It has following types:

- ***Endotracheal intubation*:** The tube is injected into the patient's airway (trachea) orally or through nose.

  Tracheostomy: The tube is injected via a cavity made into the airway.

2.4.3. Noninvasive ventilation:

Noninvasive mechanical ventilators are offered with different type of masks and can be used at home. It has 3 types:

- ***Continuous positive airway pressure (CPAP):*** provides steady and continuous value of air pressure.
- ***Auto titrating (adjustable) positive airway pressure (APAP):*** automatically adjusts the air pressure matching to the patient's breathing pattern.
- ***Bilevel positive airway pressure (BiPAP):*** A distinct pressure is delivered for exhalation (EPAP) and inspiration (IPAP).

2.5. Working Modes of Positive-pressure ventilation:

Nowadays hospitals have moved on from negative ventilation and most commonly provide positive pressure support. Positive-pressure ventilators pump the air into the patient's airway. According to the preset value of pressure, volume, or time (depending upon ventilator's mode), patient switches from inspiration to expiration in each breath. Positive-pressure machines can be [4]:

- ***Volume-controlled:*** Expiration is switched on after a preset Tidal Volume (VT) is achieved during inspiration. It is not controlled via airway pressure.
- ***Pressure-controlled:*** Expiration is switched on after a preset pressure is delivered to the airways during inspiration.
- ***Dual control:*** It blends the gains of both volume control and pressure control. They provide option for both volume and pressure control either "within a breath" or "breath to breath".
- ***Time Controlled:*** Inspiration stops after the preset inspiratory time elapses.

2.6. BiPAP vs CPAP performance Comparison for Infants:

It is a respiratory technology used worldwide with premature neonates. It is simple and effective; the water column providing the backpressure both sets and indicates the delivered backpressure. Results are comparable to traditional ventilator CPAP. However, for infants suffering more severe respiratory distress, this is inadequate. Nasal Intermittent Positive Pressure therapy with a steady baseline and cyclic peaks is required to adequately recruit and stabilize the alveoli. As the next level of non-invasive treatment, NIPPV is less invasive than intubation and mechanical ventilation, but provides greater support than CPAP. In the States this is often done with a ventilator or other expensive technology. In many places around the world, however, there are not the funds, resources, and expertise to offer this. So, patients beyond the reaches of CPAP die.

To study which type of treatment is more effective, 78 full term newborns in **NICU** hospital who got admitted for neonatal distress were cured with nCPAP and nBIPAP ventilation [5]. The results concluded that a soon BiPAP ventilation on RDS is the more effective NIV because it enhances CO_2 removal and lowers FiO_2 requirement in contrast to nCPAP.

2.7. Problems with Existing BiPAP ventilators:

Current treatment modalities of NIPPV include BiPAP machines and ventilators. These machines offer great flexibility in ranges of settings and can provide excellent patient care. However large power requirements, expensive equipment costs, expensive
repair and shipping options and the high level of skills required by the user largely limit these devices to developed countries.

Table 1. Comparison of BiPAP and NIPPV equipment prices

Equipment	Function	Cost	Power Requirement
Respironics BiPAP autoSV Advanced - System One	BiPAP machine	$3,145.00	100-240 VAC
ResMed S9 VPAP ™ S Bilevel w/H5i ™	BiPAP machine	$1,726.00	100-240 VAC
DeVilbiss IntelliPAP Bilevel S with Heated Humidifier	BiPAP machine	$ 1,025.00	100-240 VAC
Fisher & Paykel ICON Auto CPAP Machine with Built-In Heated Humidifier and ThermoSmart Heated Hose	CPAP machine	$509.00	100-240 VAC
HEYER iTernIS BASE, intensive care ventilator	Ventilator	$7633.00	100-240 VAC

CHAPTER 3: METHODOLOGY

The aim was to develop a moderate cost Bilevel supported autonomous microcontroller-based ventilator. Initially we are presenting simulation-based procedures on modern engineering software like **Simulink** and **Proteus** while taking approximation of some parameters. Some parameters will be added from practical testing of components and after that it will pass through the testing phase followed by large scale manufacturing.

3.1 Analysis of Parameters

Selecting right values for right parameters is critical for ventilators especially for infants. After detailed literature review, parameters for analysis were chosen with their appropriate and practically achievable values:

Table 3. Analysis of Parameters

Parameter	Value/Range
Flow rate (preterm infants)	5-10L/min
Flow rate(neonates)	3-5L/min
IPAP (weight<1500g)	16-28 cm H_2O
IPAP (weight>1500g)	20-30 cm H_2O
EPAP	4-6 cm H_2O
Breath Rate	30-40/min
Inspiratory time	0.3-0.5 sec
Response Time	In Milliseconds

3.2. Materials

All materials are selected to provide the required magnitudes of parameters, while checking for their suitability for medical grade applications. Most of them are already used in special respiratory circuits.

VSO miniature proportional valve is a thermally compensated valve. A 2-way direct acting solenoid valve will be used as well. Differential Pressure Sensor **MPXV4006** is **0** to **612 cm H_2O** gauge pressure range high sensitivity sensor. **AR91** series pressure regulator is also specific for low flowrates. Plastic in-line valves and Centrifugal Blowers are very cost-efficient. **OOM204** is a high-quality oxygen sensor specific for respiratory applications.

Figure 2. Materials Required

3.3. Complete Respiratory Circuit

The configuration consists of a unique oxygen blending system, bubble biphasic system, additional pneumatic valves for flow adjustments plus safety valves as shown:

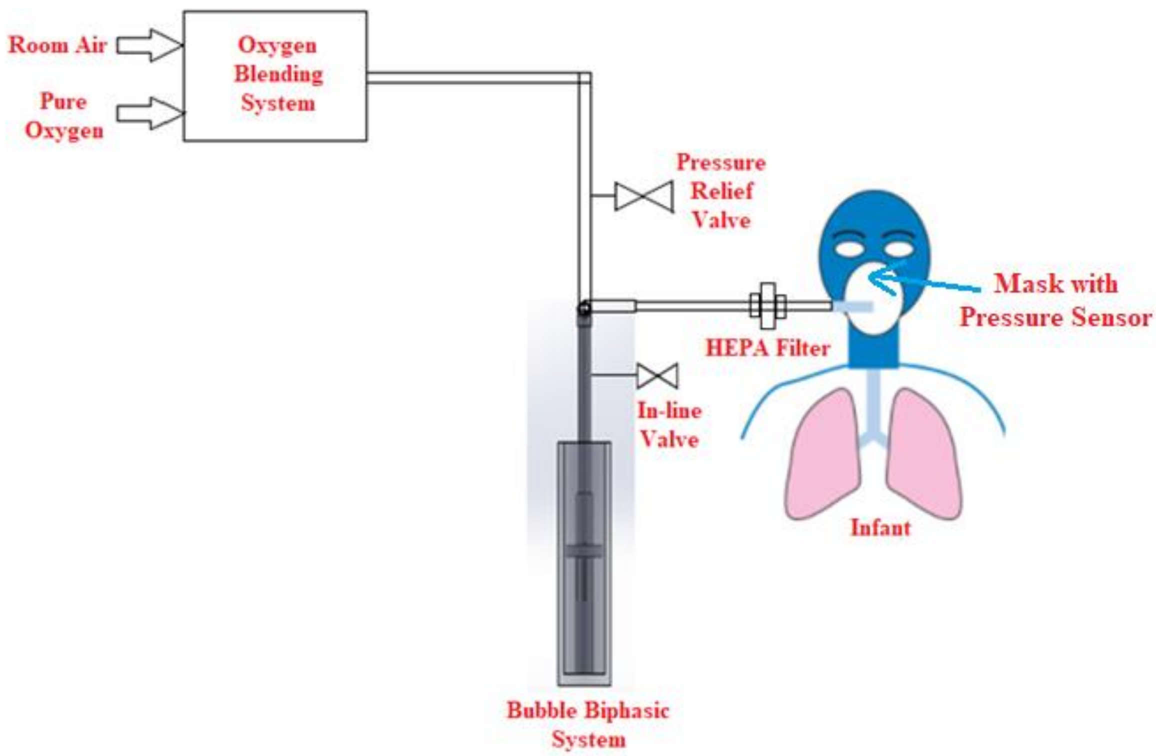

Figure 3. Complete Respiratory Circuit

3.3.1. Bubble Biphasic System

The aim was to provide 20cm H2O IPAP and 5 cmH2O EPAP for this design. This was done by utilizing the principle of hydrostatic pressure. Air must defeat the hydrostatic pressure corresponding to length of submerged depth of liquid in the tube. One proximal and one distal hole open sequentially thereby changing effective submerged depth after one breathing phase. So simply each time pressure delivered to the baby equals depth of corresponding hole from top surface of water in cm.

The Figures of the bubble biphasic system of our ventilator are attached:

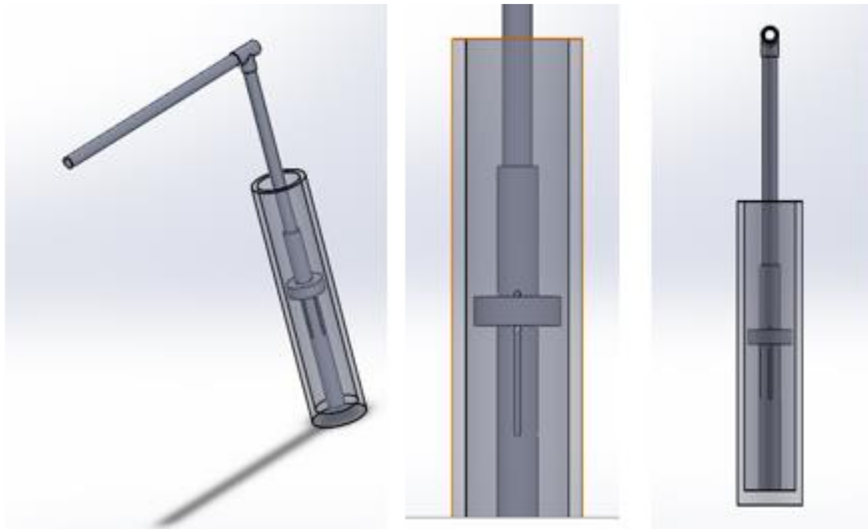

Figure 4. a) Isometric View b) Right side View

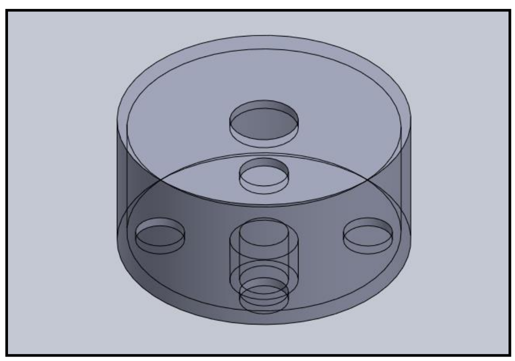

Figure 5. Isometric transparent view of cup component of the pneumatic system

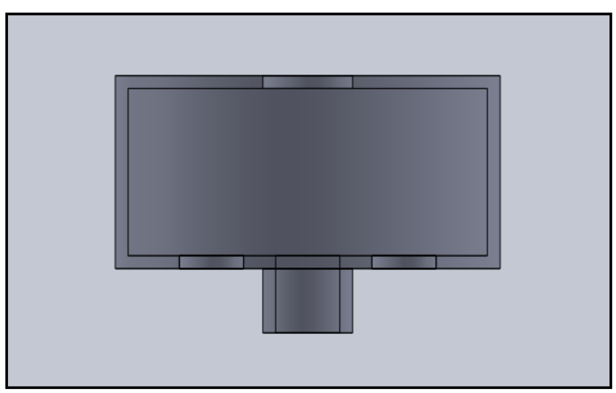

Figure 6. Side view of the cup of the pneumatic system

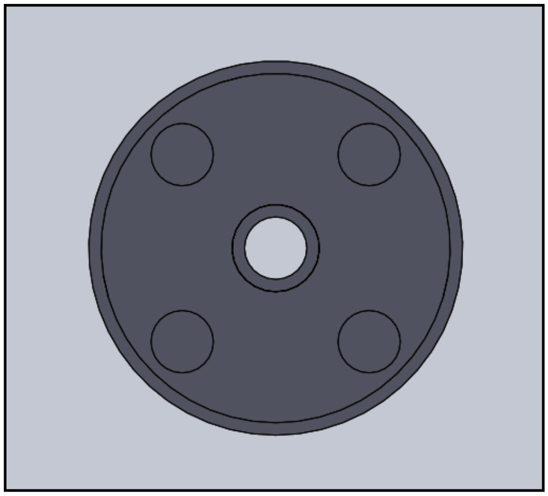

Figure 7. Top and Bottom view of the cup of the pneumatic system

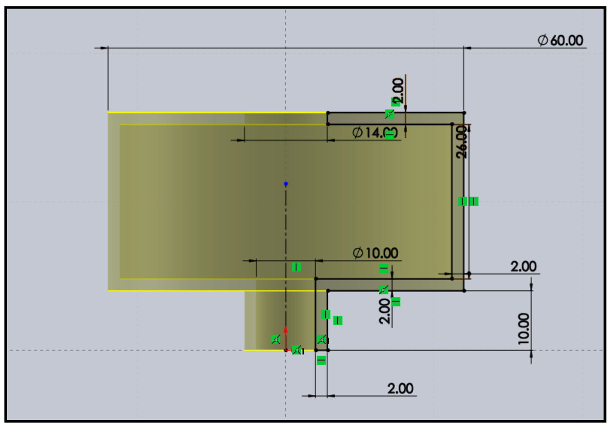

Figure 8. Sketch of the cup of the pneumatic system and the necessary dimensions

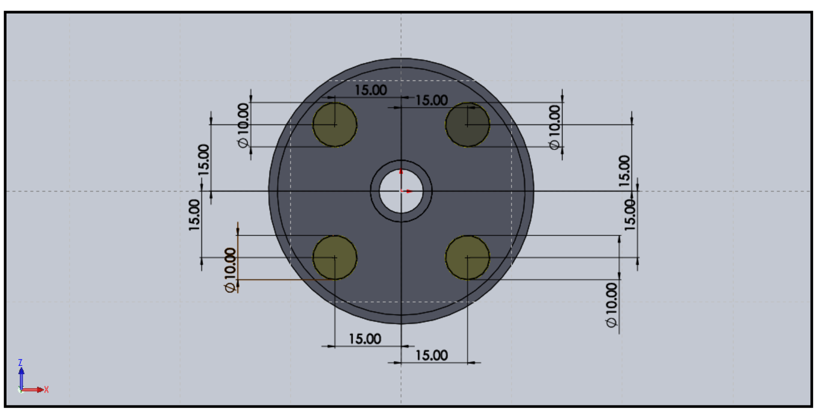

Figure 9. Dimensions of the holes of the cup

3.3.2. Pneumatic Valves

Pressure Relief valve is a safety valve that will release all the extra pressure if in any case pressure delivered to infant goes above 40cm H2O, to prevent infant lungs. An inline check valve installed will assist in decreasing flowrate from the maximum value, thereby decreasing breathing frequency. Check valves are simplest to use of all directional valves [6]. HEPA filter will be necessary since we are using room air.

3.4. Oxygen Blending System

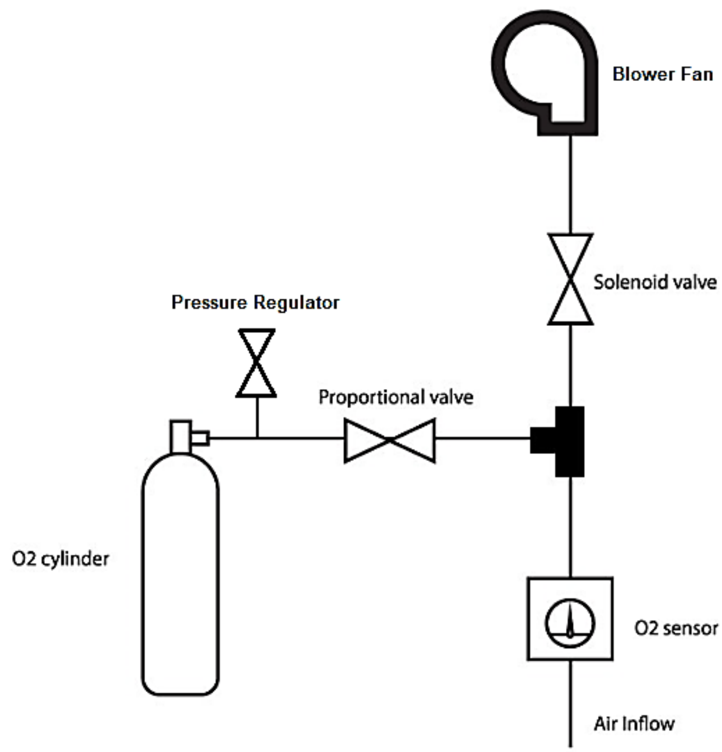

Figure 10. Oxygen Blending System

It is a replacement for commercial oxygen blender. Here, a pressure regulator is initially required since our working pressure limit is **14.7-15.3** psi while oxygen is generally delivered from cylinder at **50psi**.A blower fan directs room air into tubing. Oxygen is delivered from cylinder at **1L/min** while air from blower will be delivered at **2L/min**. CFD analysis performed in the later section of reports predicts output flowrate to be near **3.1L/min**. Opening of proportional valve decides the proportion of oxygen in the air (already containing **21%** oxygen) available to the patient (FiO_2). Valves are closed during exhalation to conserve pure oxygen. O_2 sensor is required for closed loop control of **FiO_2** by the patient.

3.4.1 Flowchart-Oxygen Blending System

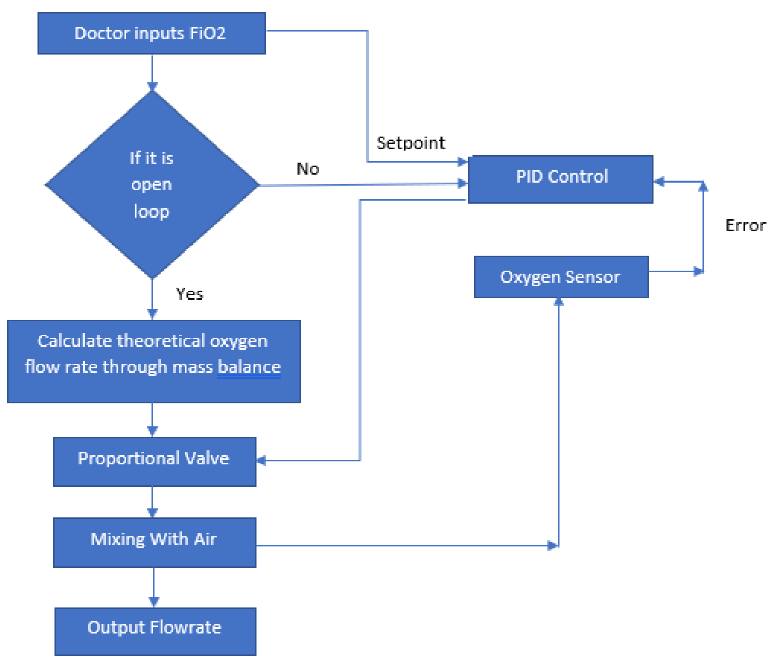

Figure 11. Flowchart-Oxygen Blending System

3.4.2. Open Loop Simulation-Proteus

In this case doctor sets **FiO_2** via potentiometer. Voltmeter shows reading proportionally to it, while blower fan rotates at constant rpm all the time. After 90% potentiometer input LED also glows as in the figure. According to mass balance:

$$FiO_2 = \frac{\dot{m}_{oxygen} + 0.21\,\dot{m}_{air}}{\dot{m}_{oxygen} + \dot{m}_{air}} * 100$$

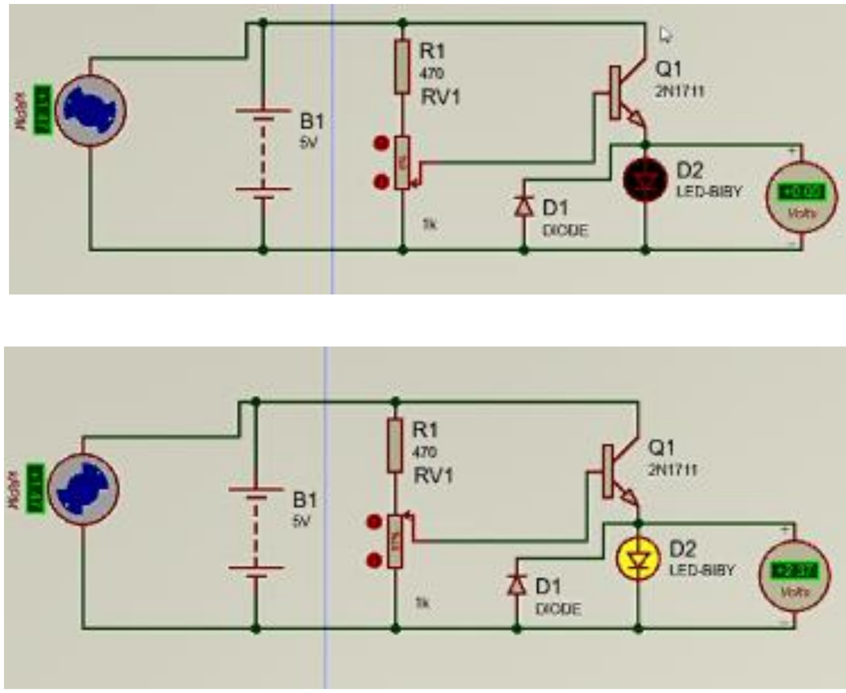

Figure 12. Open Loop Simulation-Proteus

3.4.3. Closed Loop Simulation-Proteus

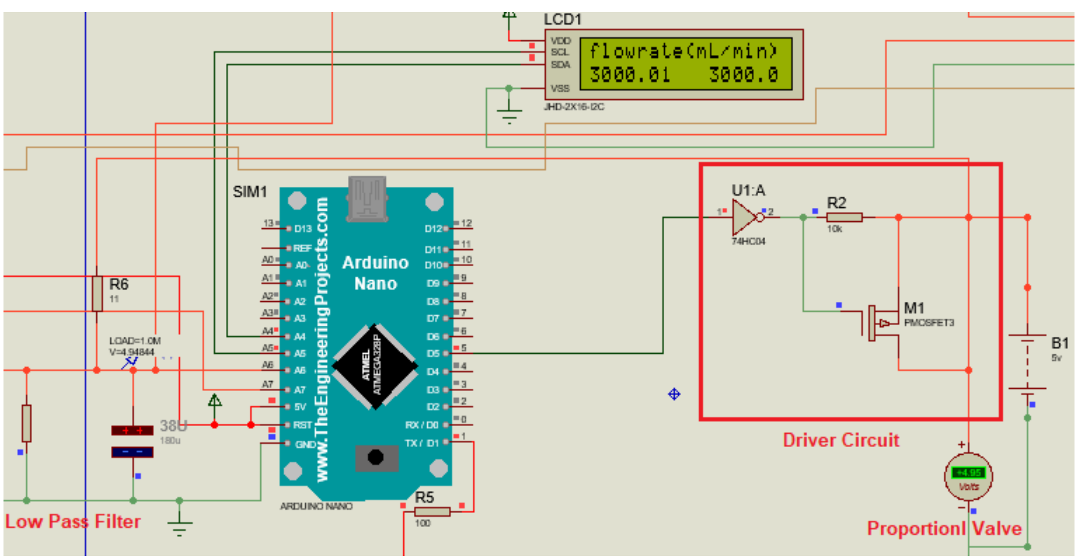

Figure 13. Closed Loop Simulation-Proteus

Driver circuit consists of **PMOSFETS** (due to high voltage and current requirements of proportional valves), **7404 logic inverter** (to make valves close initially) and discharge resistance between gate and source to make gate discharge once gate signal is turned off.

It works based on closed loop feedback system in which feedback is sent again as input after passing through a **low pass filter**. A setpoint for flowrate is set and the control system tries to achieve that. **PID** tuning diminishes overshoot. Microcontroller used for simulation purpose was **Arduino Nano**.

For initial parametric results we considered 50% opening of valve and studied system stability without applying any PID control while for final results methodology described in the next section was implemented.

3.4.3. Flow Chart for Closed Loop Simulation-Proteus

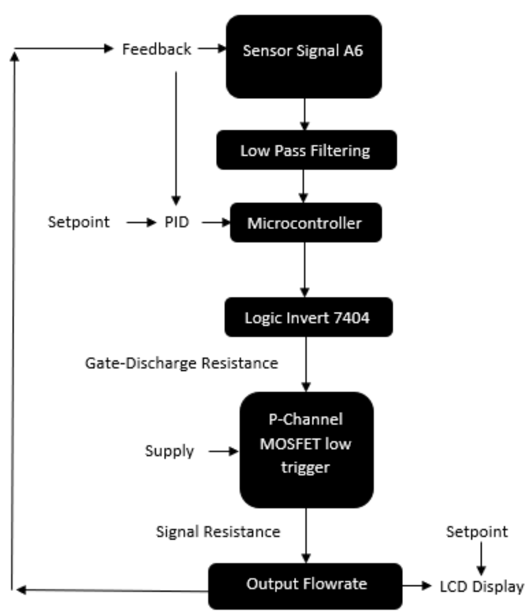

Figure 14. Flow Chart for Closed Loop Simulation-Proteus

3.5. Initial Parametric Results and Design Validation Study

Following MATLAB code was used for system transfer function and design validation study. It utilizes voltage response graph from Proteus for half opening of valve at 2.5V (5V operating voltage). Then it checks for system stability by finding system poles by utilizing the following MATLAB Code:

3.6. Lung Model-Simulink

```
[D,S,R] = xlsread('data.csv');
tv = D(:,1);
vi = D(:,2);
vi(1) = 0;
vo = D(:,2);
[ti,ia,ic] = uniquetol(tv, 4.8E-7);                 % Get Unique Times
vi = vi(ia);                                        % Corresponding Input Voltages
vo = vo(ia);                                        % Corresponding Output Voltages
Ts = mean(diff(ti));                                % Sampling Interval (sec)
ti = [(0 : 5E-7 : 1E-6)'; ti+1.5E-6];               % Pad All Vectors With 3 Initial Time Samples
vi = [zeros(3,1); vi];                              % Pad All Vectors With 3 Initial Time Samples
vo = [zeros(3,1); vo];                              % Pad All Vectors With 3 Initial Time Samples
Fs = 1/Ts;                                          % Sampling Frequency (Hz)
Fn = Fs/2;                                          % Nyquist Frequency
L = numel(ti);                                      % Vector LEngth
FTvi = fft(vi)/L;                                   % Input Fourier Transform
FTvo = fft(vo)/L;                                   % Output Fourier Transform
FTtf = FTvo./FTvi;                                  % Transfer Function Fourier Transform
Fv = linspace(0,1,fix(L/2)+1)*Fn;                   % Frequency Vector
Iv = 1:numel(Fv);                                   % Index Vector                          % Transfer Function
figure(1)
plot(ti, vi,    ti, vo)                             % Plot Input & Output
xlabel('Time (sec)')
ylabel('Amplitude (V)')
grid
dataobj = iddata(vo,vi,Ts);                         % Prepare Data For Identification
tfobj = tfest(dataobj, 3, 2);                       % Create Transfer Function Object
NumTF = tfobj.Numerator;                            % Transfer Function Numerator
DenTF = tfobj.Denominator;                          % Transfer Function Numerator
TF = tf(tfobj)
sys = tf(tfobj);% Transfer Function
P = abs(pole(sys))
B = isstable(sys)
C = pidtune(TF,'PI');
pidTuner(TF,C)
```

Figure 15. MATLAB code for Initial Results and Design Validation Study

Michael C [7] and Noman Q. Al-Naggar [8] assumed multiple compartments for lung and developed its equivalent electric model as shown:

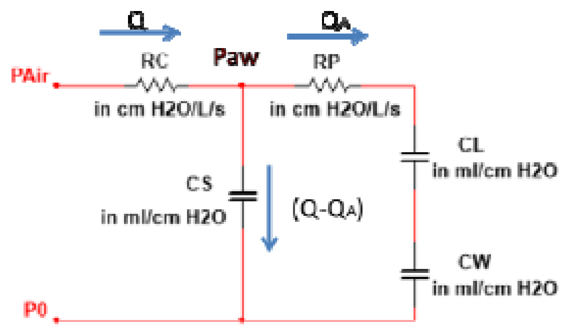

Figure 16. Equivalent electrical model of lung.

From Kirchhoff's voltage law (KVL) and Kirchhoff's current law (KCL), these differential equations can be obtained [7,8]:

$$\frac{d^2P(t)}{dt^2}+\frac{1}{R_pC_T}\cdot\frac{dP(t)}{dt}=R_C\frac{d^2Q(t)}{dt^2}+\left(\frac{1}{C_S}+\frac{R_C}{R_PC_T}\right)\frac{dQ(t)}{dt}+\frac{1}{R_PC_SC_T}Q(t)$$

From Laplace transformation, the derived transfer function is:

$$\frac{Q(s)}{P(s)}=\frac{s^2[1+\left(\frac{1}{sR_PC_T}\right)]}{R_Cs^2+\left(\frac{1}{C_S}+\frac{R_C}{R_PC_T}\right)s+\frac{1}{R_PC_SC_T}}$$

Here, resistors are analogous to Airway Restriction, capacitors denote compliances that represent alveoli and chest wall capacities. The airflow is equal to the current (I) of the circuit, and the $\mathbf{P_{Air}}$ becomes the voltage source (V). Considering pressure signal's input, the flow (F), volume (V) and pressure (P) signals can be simulated as the following waveforms which sort of serves as output screen for ventilator.

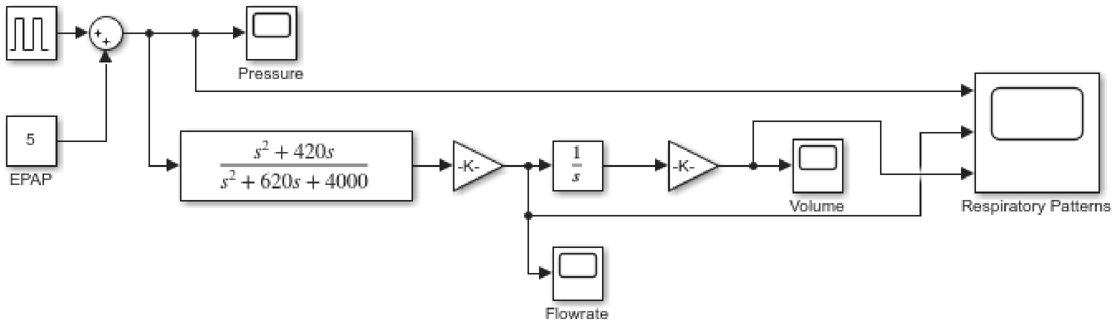

Figure 17. Lung Model-Simulink

So, this model can be considered analogous to the graphical user interface of actual machine. Here we have adjusted gains accordingly for the variables corresponding to a typical **1 kg** birth weight of infant, since these properties are weight dependent.

3.7. Simulink Model of Proportional Valve

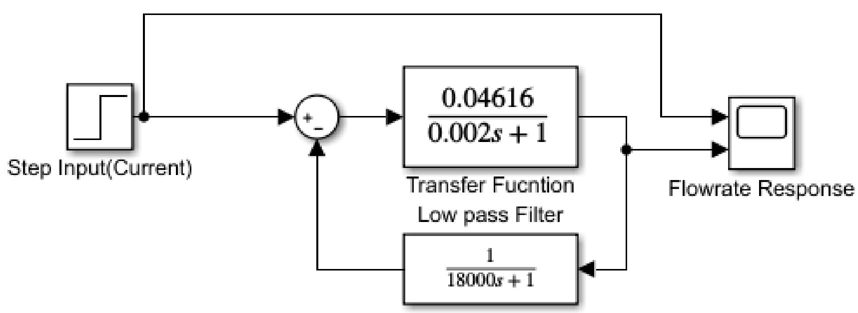

Figure 18. Simulink Model of Proportional Valve

A first order proportional valve model was simulated in Simulink using following characteristics of valve from its datasheet [9]:

- Response Time (Assumed Steady state response time) t = 10ms
- Time constant, τ = 10/5 = 2ms
- Constant Gain = 0.04616 (65mA corresponds to 3L/min)
- For low pass filter, C = 180uF, R = 10^4ohm, RC = 18,000

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Voltage Response of Valve for 50% opening:

For initial parametric results and design validation study, we considered **50%** step input opening of proportional valve. For **5V** valve, it should be near **2.5V**. Following graph is obtained in MATLAB analogous to voltage response of valve from proteus.

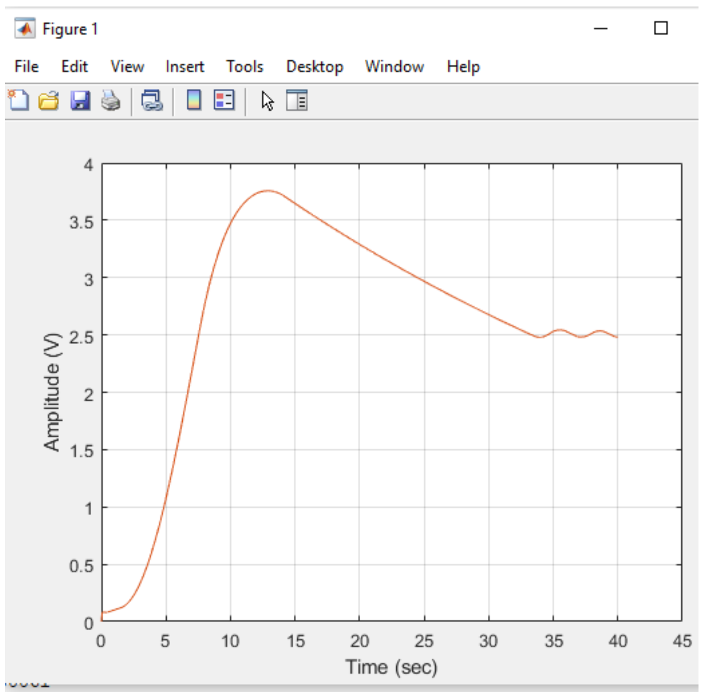

Figure 19. Voltage Response of 50% Valve opening

4.2. Auto PID tuning in Simulink:

Step plot reference tracking graph is obtained in which it tries to follow a particular reference. Simulink Auto tuner was used. After autotuning it can be observed that overshoot is reduced to **0%** with **40ms** settling time Practically these PID tuning parameters will be applied to the system depending on the characteristics of proportional valve to adjust the required flowrate values.

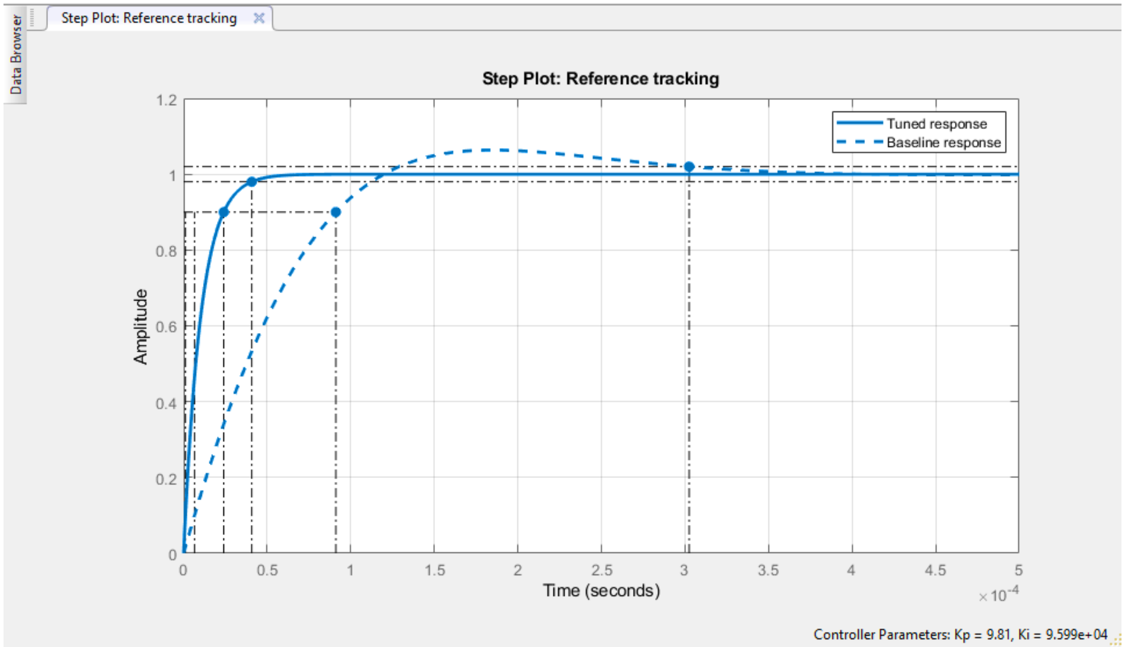

Figure 20. Step plot reference tracking

We can observe baseline as well as tuned response. In case of ventilators response time in milli seconds is mostly dealt with. Value of Derivative constant (k_d) was zero hence it became a **PI** controller. These values were the basis for our initial parametric results and design validation study. Since the settling time was already in milliseconds after autotuning, we tried to decrease the overshoot to 0% on the expense of responsiveness of controller.

Table 2. Controller Parameters and Characteristics

Controller Parameters

	Tuned	Baseline
Kp	9.8096	1.6069
Ki	95991.1682	28728.0863
Kd	n/a	n/a
Tf	n/a	n/a

Performance and Robustness

	Tuned	Baseline
Rise time	2.29e-05 seconds	8.45e-05 seconds
Settling time	4.07e-05 seconds	0.000302 seconds
Overshoot	0 %	6.37 %
Peak	1	1.06
Gain margin	Inf dB @ NaN rad/s	Inf dB @ NaN rad/s
Phase margin	90 deg @ 9.6e+04 rad/s	74 deg @ 1.92e+04 ra...
Closed-loop stability	Stable	Stable

All poles lied on left half plane and system is declared stable.

```
TF =

  From input "u1" to output "y1":
     9790 s^2 + 5463 s + 4210
  ------------------------------
  s^3 + 9786 s^2 + 5461 s + 4208

Continuous-time transfer function.


P =

   1.0e+03 *

  -9.7855 + 0.0000i
  -0.0003 + 0.0006i
  -0.0003 - 0.0006i


B =

  logical

   1
```

Figure 21. Output Transfer Function and System Poles

4.3. Simulink Output-Proportional Valve

This is the output of Simulink model of proportional valve We observe that when step input of **0 to 65mA** is given, valve takes time equal to its response time **(10ms)** to achieve flowrate of **3L/min** [9].

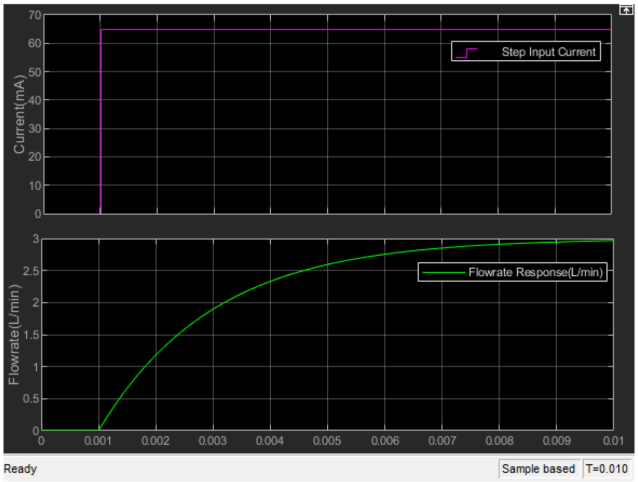

Figure 22. Simulink Output-Proportional Valve

4.4. Simulink Output-Lung Model

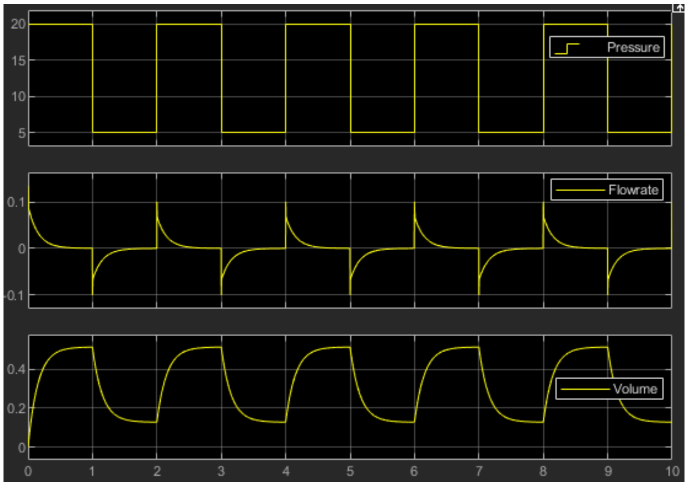

Figure 23. Simulink Output-Lung Model

This is the output of Simulink lung model. **2** pressure levels of **20 cmH_2O** and **5 cmH_2O** are achieved. Flow rate of expiration is **0.1L/min**. Tidal Volume is about **0.4mL**. Practically there will be some fluctuations in pressure levels due to bubbling forces.

4.5. Oxygen Blender-Ansys Simulation

On the left side we have oxygen mass flowrate inlet with value of **0.0238g/s**. On top side we have air mass flow rate inlet with value of **0.0408g/s**. In these conditions flow came out to be **laminar**. Initially air will be present inside the system. Diameters are considered same as proportional valve diameters, provided from valve datasheet [9]. Mesh was designed to have a blend of less computational power and good accuracy.

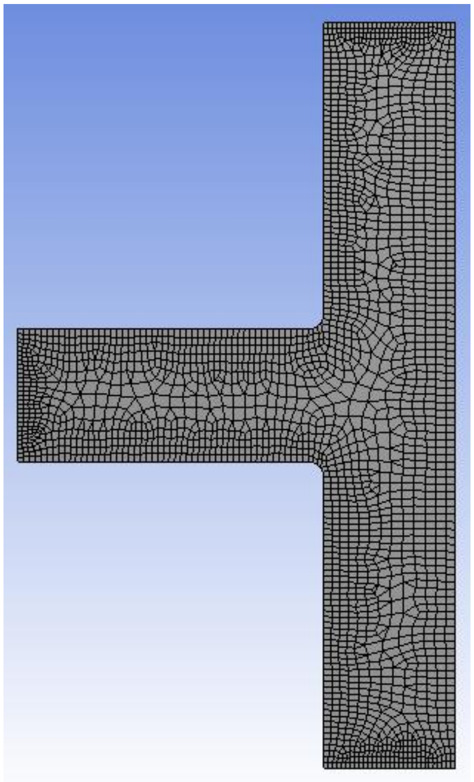

Figure 24. Mesh for CFD

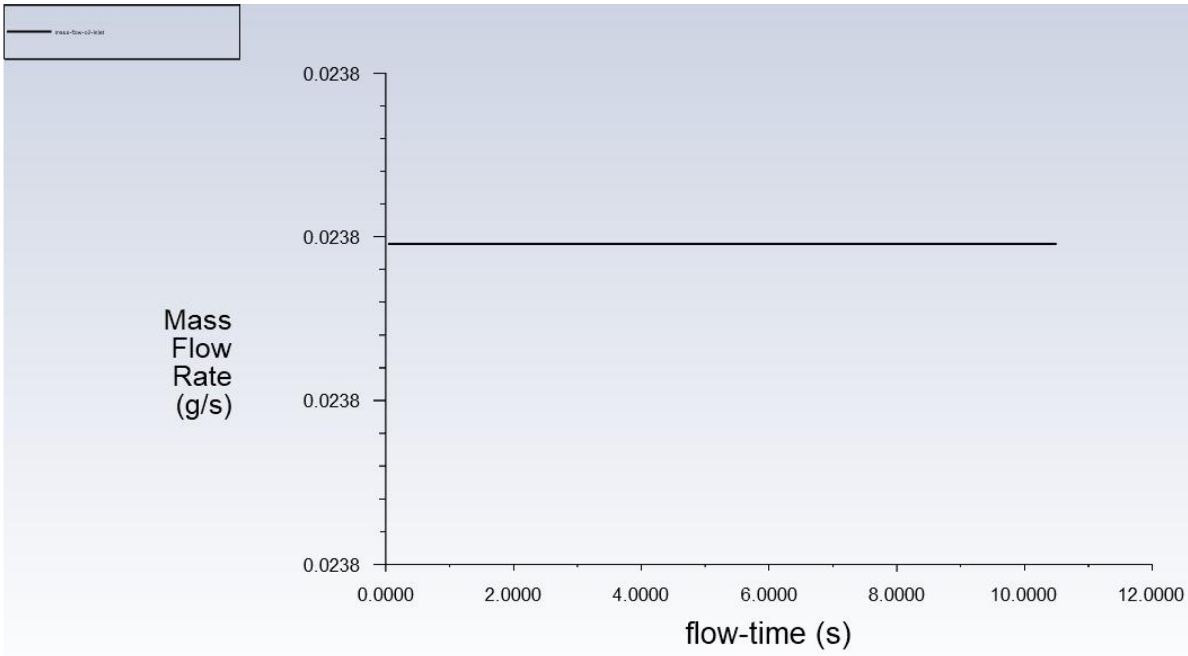

Figure 25. Mass Flowrate Oxygen Inlet

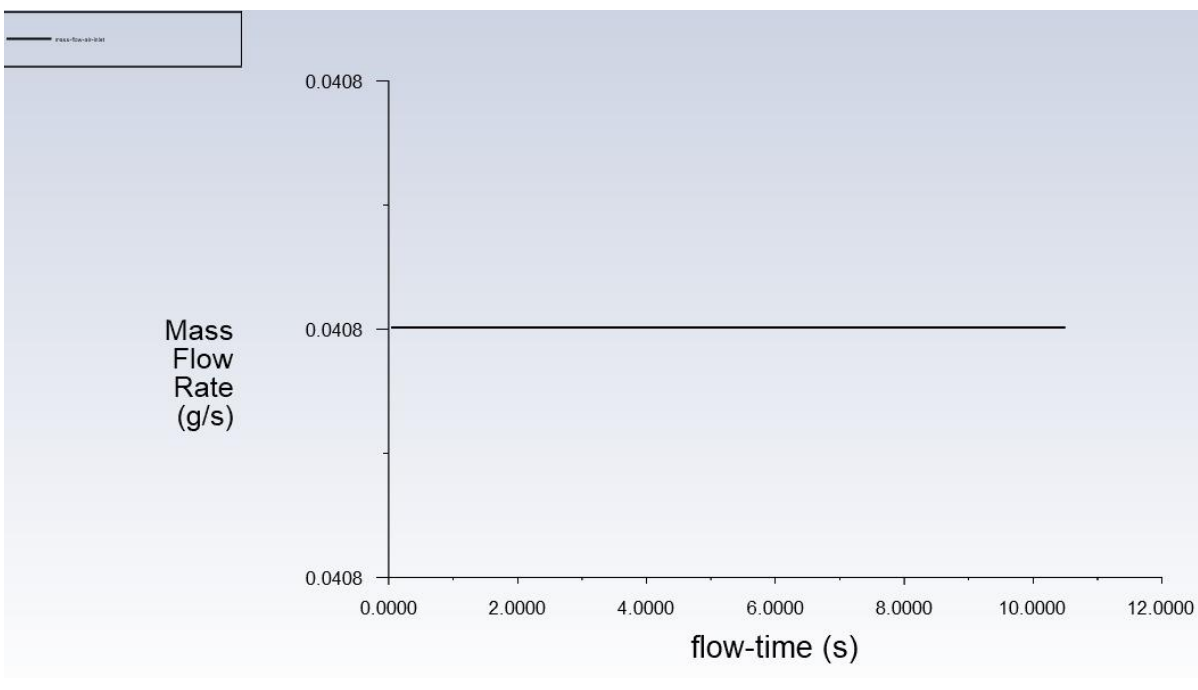

Figure 26. Mass Flowrate Air Inlet

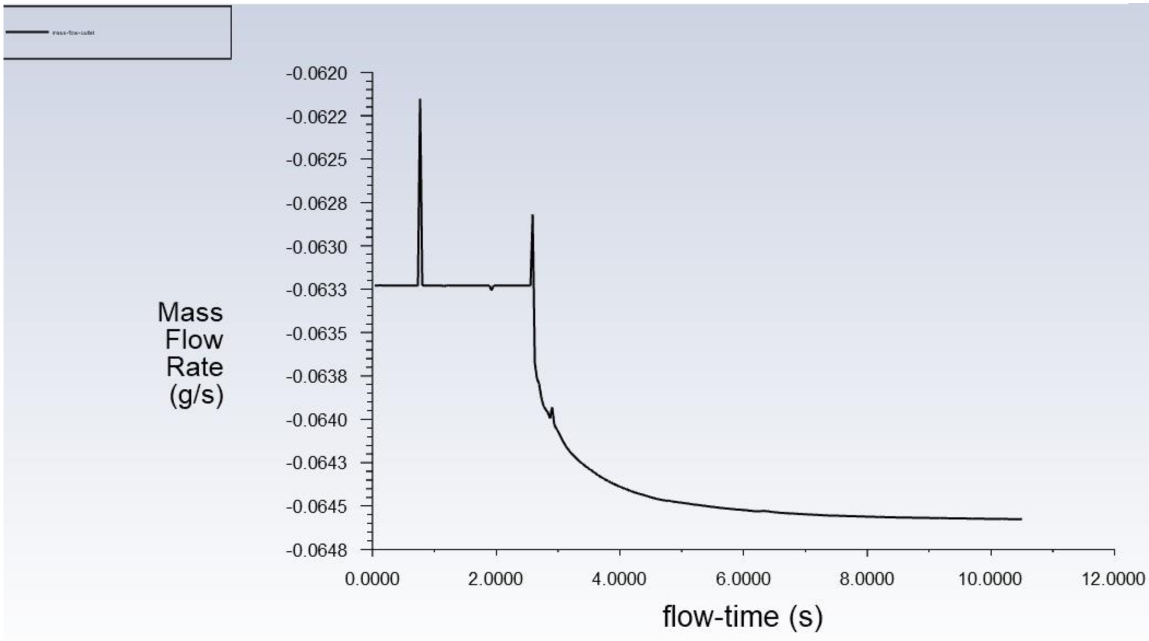

Figure 27. Mass Flowrate at Outlet

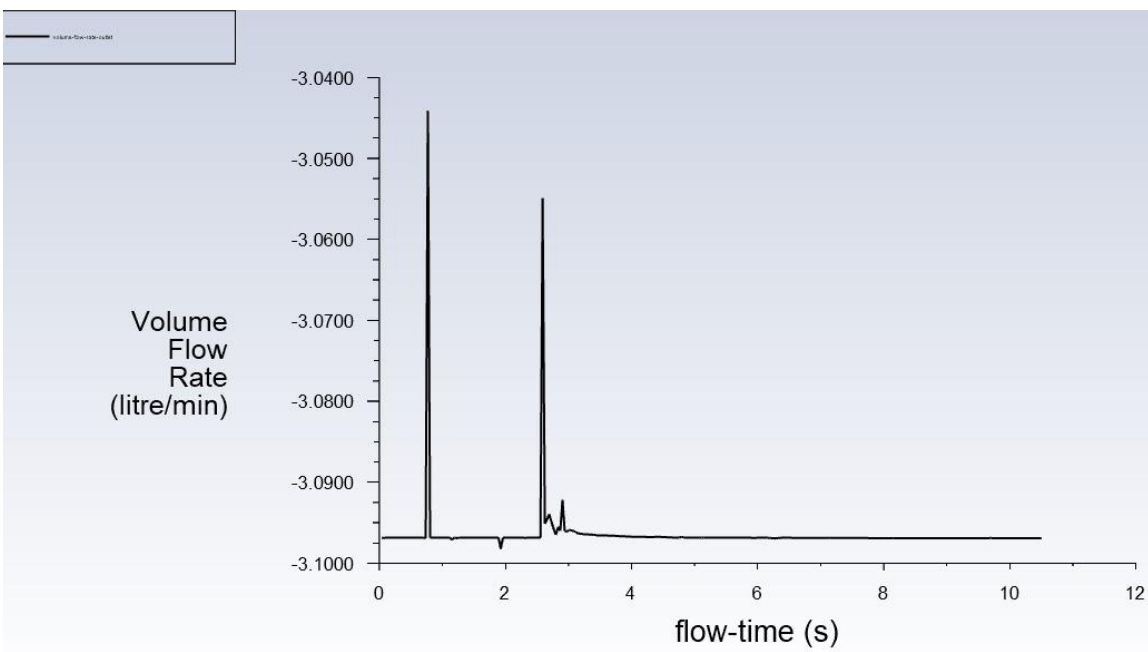

Figure 28. Volume Flowrate at Outlet

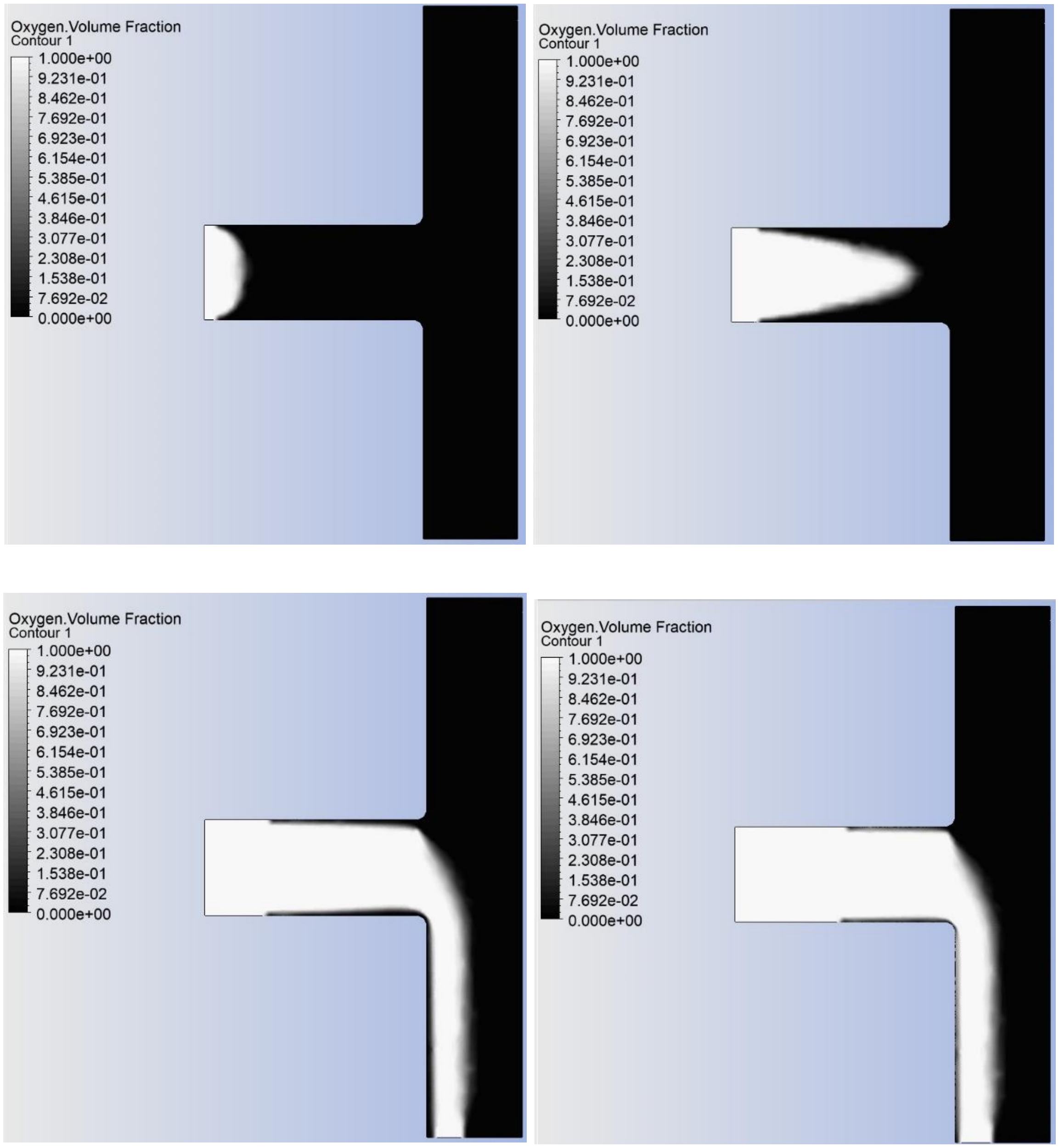

Figure 29. Oxygen Volume Fraction Contour at t=2,4,6, and 10.5 seconds

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Achieved Target:

The proposed simulated BiPAP ventilator design aims to deliver an economical and autonomous respiratory support for preterm and full-term neonates. It incorporates an in-built oxygen Blending System saving the cost of market Oxygen Blender costing at least **$500 USD**. Mass production will result in its production around Rs **50,000**.

5.2. Bill of Materials:

Table 3. Bill of Materials

Component	Price
BiPAP Tubing	Rs.1800
BiPAP Mask	Rs.1500
Oxygen Sensor	Rs.11,000
VSO Proportional Valve MPXV4006	Rs.12,000
2-way Solenoid Valve	Rs.1300
Miniature Pressure Regulator	Rs.7000
Arduino Due	Rs.2500
Check Valve	Rs.300
Centrifugal Blower	Rs.400
HEPA Filter	Rs.10,000
Bubble Biphasic System	Rs.4000
Total	**Rs.51,800**

5.3. Novelty of Design

- Simple Design
- Low-cost Bubble Biphasic System
- Utilization of Bubble Exhaust energy during expiration
- Inbuilt Oxygen Blending System
- Safety Valves
- Medical Grade Material
- Oxygen Blending system can be used with any other ventilator.

5.4. Recommendations:

5.4.1. Recommended Microcontrollers for manufactured prototype:

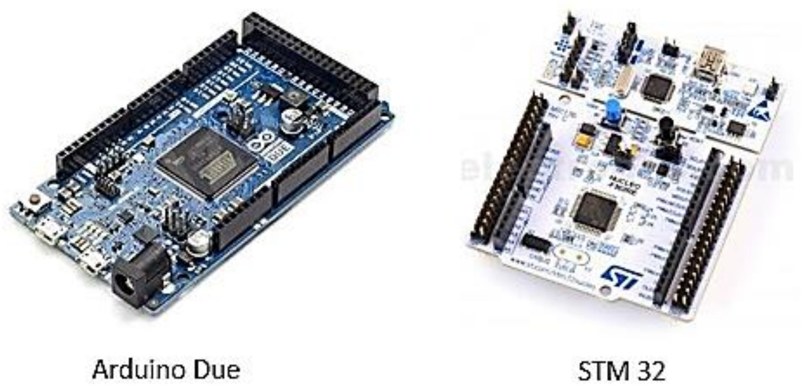

Figure 30. Recommended Microcontrollers

5.4.2. Recommendations for Manufacturability of Bubble Biphasic System:

The complex part geometry of the inverted basket must be produced at a low cost with fine tolerances for the clearance between the inverted basket and cylindrical shell. Thus, an injection molded design utilizing the widely available and low-cost PVC would be the best choice. Small metal insets can be embedded to achieve the appropriate weight.

First design case would be the production of parts in two symmetrical halves fitted together with pins and grooves or a snap-fit. The pieces can be permanently fastened with adhesive or reversibly fastened with silicone O-rings. As a design alternative to the production of two halve which are fastened together, the device can be produced as single pieces with two sliding pin mounted cams to hollow out the middle.

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APPENDIX I: PROTEUS CODE FOR CLOSED LOOP SIMULATION OF OXYGEN BLENDER

```
#include "DFRobot_LCD.h"
#define setpoint A7
#define valve1 5
#define valve2 3
double set_val, pressure, amp, setpoint2, Input2;
  const int colorR = 255;
  const int colorG = 0;
  const int colorB = 0;
#include <PID_v1.h>
#define PIN_INPUT A6
#define PIN_OUTPUT 5
double Setpoint, Input, Output;
double Kp=0.89, Ki=1.3, Kd=0.02;
PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, DIRECT);
DFRobot_LCD lcd(16,2);
int de =0;
int diff=0;
int OLD=0;
int PM=0;
int timest= 10;
int PWM=0;
void setup() {
   pinMode(valve2,OUTPUT);
digitalWrite(valve2,LOW);
   lcd.init();
```

```
  lcd.setRGB(colorR, colorG, colorB);//If the module is a monochrome screen, you need to
shield it
  lcd.print("flowrate(mL/min)")
 Input = analogRead(PIN_INPUT);
 Setpoint = analogRead(setpoint);
 myPID.SetMode(AUTOMATIC);
Serial.begin(9600);
}
void loop() {
Setpoint = analogRead(setpoint);
 Input = analogRead(PIN_INPUT);
 myPID.Compute();
 analogWrite(PIN_OUTPUT, Output);
  lcd.setCursor(0, 1);
setpoint2 = Setpoint*3*1.41443;
lcd.print(setpoint2);
  lcd.setCursor(10, 1);
  Input2=Input*3*1.41443;
  lcd.print(Input2);
}
```