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Mathematical Modelling of an Automatic Bag Mask Valve Emergency Ventilator

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Abstract - *Recently COVID-19 pandemic has arisen the need for a rapidly manufacturable low cost emergency ventilator to cope up with the surge of patients in affected countries worldwide. As a viable solution to bridge the gap between low end manual ventilation and high end ICU ventilators, researchers all over the world have evaluated the* ***Automated Bag Valve Mask (ABVM)*** *ventilator design to be used for ICU triage. Moreover, even in a non-pandemic scenario, there has always been a scarcity of high end ventilators due to their high cost and dependence on compressed air supply, trained operators, etc. In order to augment the design process of these ABVM's and to enhance the understanding of the dynamic interaction of the patient-ventilator system, this paper investigates different approaches to capture the lung mechanics using electro-mechanical models. In the first section of this paper a mechanical model for respiration has been subjected to thermodynamic analysis to ascertain the required ventilator power, restrictive losses, compliance etc. This is important from the aspect of ventilator component selection. The second section is dedicated to the development of an equivalent electric circuit for human respiratory system in conjunction with an ABVM ventilator. The selection of circuit components is performed by drawing analogies with the governing equation models of the processes under investigation. The derived ventilator power resulted from the thermodynamic model was found to be close to values present in the published literature. The response of the equivalent electric for different modes of ventilation, namely PC, VC were analysed and found to be satisfactory.*

Key Words: Mechanical Ventilator, Bag Valve Mask (BVM), RC Device, Thermodynamics, Equivalent Circuit, Respiration System.

1. INTRODUCTION

An unparalleled life-preserving electro-mechanical ventilator results in ensured delivery of regulated quality and quantity of air to the patients suffering from lung dyspnea, hence guarding their lives. There are multiple medical conditions such as Amyotrophic lateral sclerosis (ALS), coma or loss of consciousness, brain injury, collapsed lung, chronic obstructive pulmonary disease (COPD), drug overdose, etc. where ventilators are irreplaceable factors of the treatment process. According to a report by the World Health Organisation (WHO), the deaths due to lung diseases in India were on the rise accounting for 11 per cent of the total deaths. As many as 142.09 in every one lakh, died of one form of lung disease or the other, giving India the dubious distinction of ranking first in lung disease deaths in the world. One of the prominent causes of such deaths related to respiratory systems occurred in 3rd world countries, are results of shortfall of ventilators being expensive and unaffordable for necessitous people. As well as the requirement of trained staff for operating such bulky and complex devices in small hospitals becomes an impediment. To address this shortfall attempts have been made world-wide to bridge the gap with rapidly manufacturable low cost ventilators [1, 2]. One such ventilator design is that of an automate AMBU bag device namely Automatic Bag Mask Valve Emergency Ventilator [3]. Due to the current COVID-19 situation a lot of research groups, medical device manufacturers, have put their confidence in the ABVM design to meet the challenge of a massive surge of patients expected to be requiring ventilatory care. RMVS [4]

This paper focuses on the need for a human-ventilator model essential to design such low cost ABVM ventilators. Though human respiratory modelling has been discussed in literature [5, 6], there is no combined human-ventilator model, especially for a novel ABVM ventilator. Moreover, these models [7] only focus on the electrical analogies. In our investigation a diverse approach has been taken, where apart from equivalent electrical circuits, a thermodynamic analysis of a mechanical respiration model is presented. Furthermore, both the ventilator as well as the patient respiratory system have been modelled in a combined fashion. Such a combined model is envisaged to be be effective in the design process, primarily when new methods of administrating ventilation are under investigation. The model response and further modifications have been discussed in subsequent sections of the paper.

The ABVM-Human Respiratory System Model presented in this work has been used to design a low cost ventilator developed in collaboration with Gyrodrive Machineries (P) Ltd. India and PGIMER Chandigarh. The developed design has been patented [8] and is under regulatory certification process.

2. THERMODYNAMIC MODEL OF RESPIRATION

In this section the human respiration system of an intubated patient shown in Fig.1a has been modelled considering basic analogy of a spring loaded piston-cylinder assembly and a pipe as shown in Fig 1b. The spring loaded piston cylinder structure functions quite alike human lungs which are part of the lower respiratory system as described in Fig 1a.

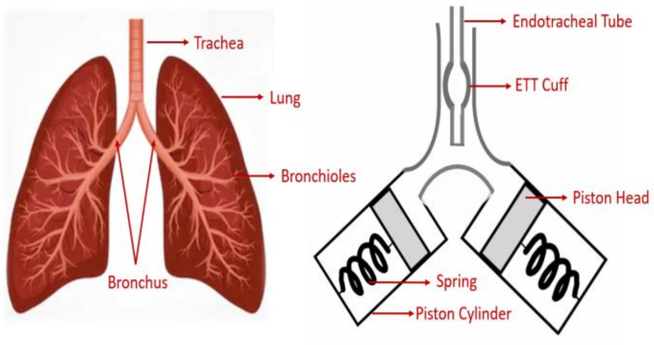

Fig 1: (a) Human respiratory system. (b) Mechanical equivalent model for an intubated patient

The human lung provides a volume to receive air, is sponge like in physiology and has special cell called Alveoli responsible for gas transport. The lung structure is elastic in nature, thus having a net compliance similar to a stretched membrane or spring. The discussed model illustrates human respiration through mechanical components as explained in the Fig 1b. The lung compliance is modelled using a spring element whereas the viscous losses incurred in the trachea, bronchioles etc. have been modelled as a pipe with equivalent diameter and length. The respiratory system of an intubated patient, i.e. of a patient connected to a ventilator, consumes some amount of power for the respiration process. In the inspiration phase the ventilator has to develop a positive pressure to overcome the lung compliance as well as the pressure drop experienced by virtue of the viscous losses in the endotracheal tubing and lung bronchi etc.

In Fig. 2 a, b a simplified model of the thermodynamic system has been shown. The volume of gas in the system comprises of the air inside the BVM piston depicting the BVM bag and the dead volume of the breathing circuit, while the spring loaded piston is in relaxed state in the beginning of the inspiration process. Fig 2b shows the transport of this volume, coloured yellow, from BVM to the spring loaded piston during inspiration. The two state points are shown in Fig. 3 on a PV diagram.

Assuming the total system volume involved in the inhalation process to be V1 = 750 ml at the beginning of BVM piston compression and Pressure P1 = 101325 Pa, we get the total system mass using Equation 1

$$m = \frac{PV}{RT} \tag{1}$$

Where R = 287 J/Kg-K and T = 311.15 K considering ambient conditions. For calculating the pressure of state point 2 we make use of the lung compliance C, which is equal to 50ml per 98 Pa i.e. for 650 ml [4], this amounts to a pressure

$$P_2 = 101325 + 1274 = 102599\ Pa.$$

Moreover temperature on start of the process is considered equal to the temperature at the end of the process, i.e. the process is assumed to be an Isothermal process. Mass of the gas inside the lungs is considered equal to the mass of gas inside the BVM and the breathing circuit. Considering that the spring is uncompressed when the volume in the lungs is zero, once the specified tidal volume is delivered to the lungs, the spring is compressed amounting to a pressure increase. Since mass m is constant and process is isothermal we get the volume of inside the lungs as

$$V_2 = 650ml = 0.00065\ m^3$$

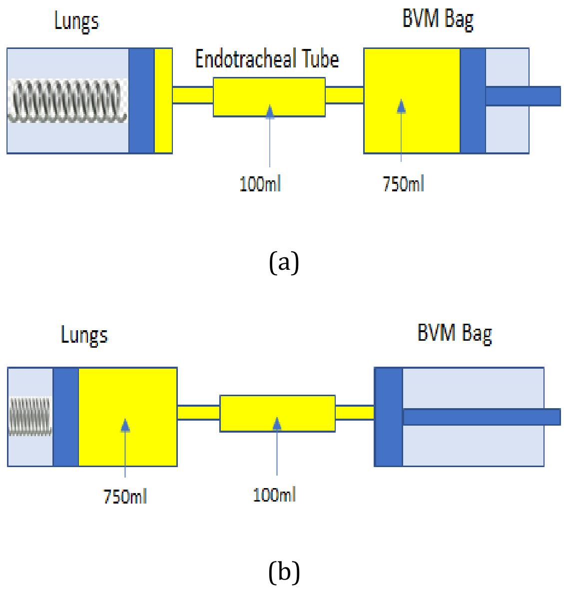

Fig 2: Thermodynamic system description of human respiratory system with BVM device.

For an isothermal compression, work done on the system is calculated using the following:

$$W_{if} = mRT \ln \frac{V_f}{V_i} \tag{2}$$

Calculating mass for initial state points P_1 and V_1 using Equation 1, we get system mass as

$$\boldsymbol{m = 8.509 \times 10^{-4}\ kg}$$

Now, aging using Equation 2 we get the work done on the system as follows:

$$W_{if} = 8.509 \times 10^{-4} \times 287 \times 311.15 \times ln(\frac{650}{750})$$

$$\boldsymbol{W_{if} = -10.8735\ J}$$

Time required for inhalation and exhalation is considered as 5 seconds. For an inspiratory to expiratory ratio, i.e. I: E ratio of 1:2, Inhalation Time is taken as 1.7 seconds and Exhalation Time is taken as 3.3 seconds. Therefore, since power,

$$P = \frac{W_{if}}{t_{in}} \tag{1}$$

We get the average power for this phase of respiration without considering any viscous losses as,

$$\boldsymbol{P = 6.3961\ W}$$

The value of Power required for lungs during inhalation is around 5 to 7 Watts, from this comparison the value of power we have calculated is approximately accurate and hence study of analogy of lungs and piston-cylinder is successful.

The process can be visualised on a PV diagram as shown in Fig. 3. The area under the PV curve is equal to the work done on the system in this process. This curve is for a reversible isothermal process. For a more realistic calculation we have to incorporate the viscous losses incurred in the endotracheal tube, lung bronchi etc. The losses in the tubing can be modelled using the Hagen-Poiseuilli law [10]. Moreover, we have to consider the efficiency of the ventilator actuation system, motors and other electrical-electronic to come up with the actual power requirement of the ABMV device.

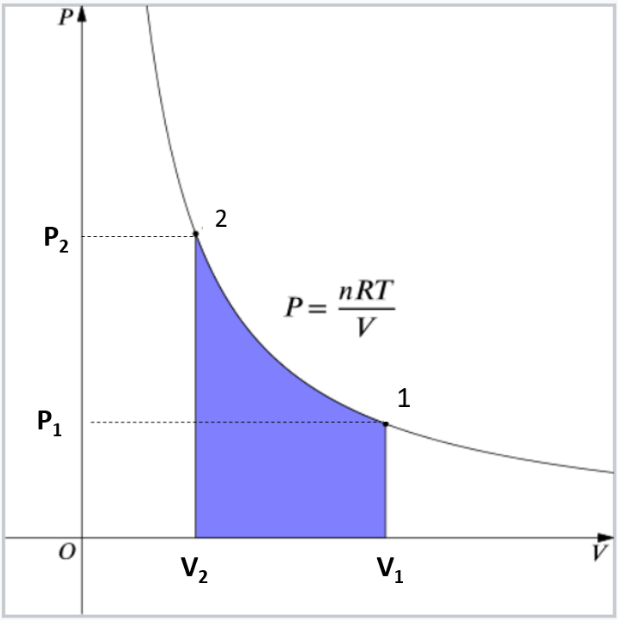

Fig 3: PV Diagram for an Isothermal process

3. VENTILATOR ELECTRICAL ANALOGUE

Creating and simulating an electrical equivalent assembly of the proposed device virtually, is one of the most efficient and feasible way to have a look at the human respiration patterns in normal people and the ones suffering from any of the respiratory disorders. These lung mechanics waveforms help us understand the quantities such as volume, pressure of the air being inhaled and exhaled by a person. Fig 4 shows the lung mechanics of an intubated patient for various modes of ventilation. It is expected that the equivalent electric model shall have similar response for the respective input pressure-volume waveform. For the same purpose of creating such assembly one should be aware of the various basic electrical & electronic components as well as parameters & terminologies associated with them which are taken into consideration while electrical equivalent circuit designing.

Model schematic can be built and simulated using any of the software tools used primarily for electronic design automation purposes e.g. Proteus Design Suite, Altium or any open source platform. The circuit described in this section is designed using one such open source platform EsayEDA.

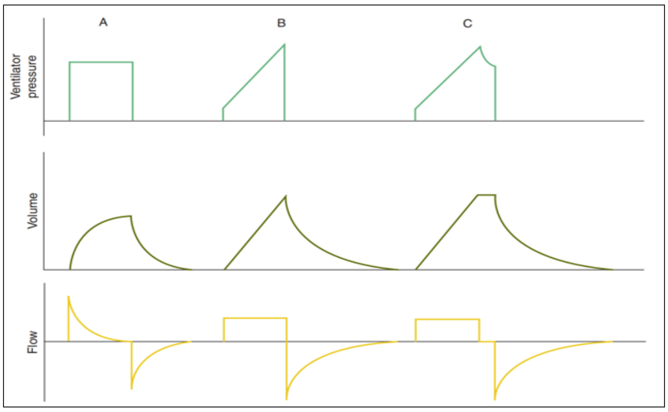

Fig 4: Human Respiration Mechanics for Different Modes of Ventilation A. Pressure Control B. Flow Control C. Volume Control

3.1 Electric-Mechanical Analogy

Considering and understanding the equivalence between electrical and mechanical terms is the key term that needs to be taken into account while designing the circuit. As discussed earlier in the thermodynamics analysis section lungs act as a spring loaded piston cylinder assembly. An equivalent electric element to represent it is a capacitor. Similarly, representing the patient-ventilator interaction in the form of an equivalent electric circuit, it is important to identify components which bear similar behavior in an analogous manner. This can be done if the basic underlying differential equations of two processes are similar in form. If the equations are similar, then it can be assumed that the solution of these shall also be similar. In this section we shall try to find this similarity by equating the governing differential equations of the process under observation.

The flow of air in the patient-ventilator circuit can be well represented by the Navier-Stokes equation as,

$$\rho\frac{\partial v}{\partial t} + (v.\nabla)v = -\nabla P + \mu\nabla^2 v + \rho g \tag{4}$$

Equation 4 is a partial differential equation with no analytical solution. For converting Equation 4 in a usable form we make use of the fact that in the given process some of the terms of are not significant relative to other. This conclusion is arrived at by conducting an order of magnitude analysis described in many fluid mechanics books [10]. Conducting this analysis and comparing terms with a simple RC circuit we arrive at Table.1 where the electro-mechanical elements are juxtaposed. Using these set of electronic and electrical components we come up with an equivalent electric model as shown in Fig. 5.

Table - 1: Electrical analogues of physical parameters

Physical Parameter	Electric Analog
Pressure	Voltage
Volume	Charge
Flow Rate	Current
Compliance	Capacitance
Orifice Restrictor	Resistance

The EEM shown in Fig. 5 is composed of three salient sections depicted by the dotted lines. The automated BVM section comprising of a pulse voltage source V_4 and Diode D_4 represent the automated BVM bag and the non-return fish mouth valve.

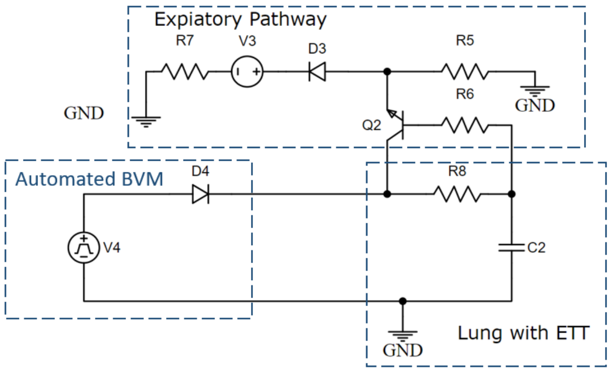

Fig 5: Equivalent electrical circuit for patient ventilator interaction

Next section, namely Lung with ETT comprises of a resistor R_8 and capacitor C_2 connected in series which mimics the human respiratory system. The expiratory pathway section comprises of a transistor Q_2, Diode D_3, Voltage source V_3 and resistors R_7, R_5, R_6. This section captures the features of the expiratory breathing circuit with PEEP settings. The voltage source V_3 can be set analogous to the end expiratory pressure, whereas the transistor Q_2, Diode D_3 combination provide the expiratory pathway exactly at the end of inspiration phase.

4. RESULTS

A square voltage pulse was specified for the voltage source V4 with a duty cycle analogous to the I: E ratio of pressure control ventilation as shown in Fig 6. The simulation was conducted in EasyEDA simulation suit.

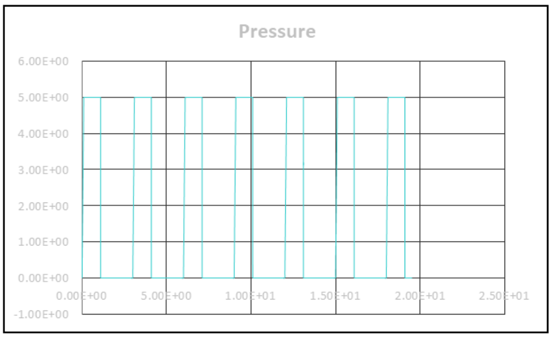

Fig 6*:* Input Pressure Profile for the Equivalent electrical circuit for patient ventilator interaction

Fig 7 shows the waveform response in the form of capacitor charging voltage. This is equivalent to the static pressure inside the lungs dynamically changing in the breathing process. The RC value was selected intentionally to match the inspiration and expiration time for the process.

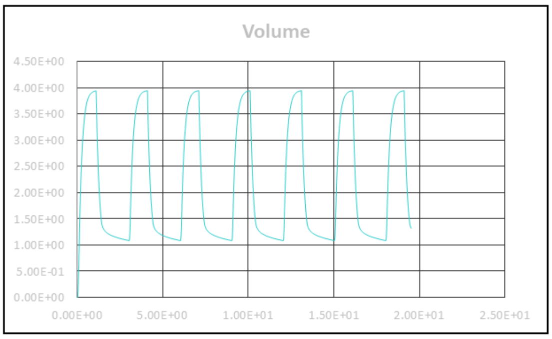

Fig 7*:* Output Capacitor Charging Profile for the Equivalent electrical circuit for patient ventilator interaction

Fig 8 shows the current waveform in the series RC circuit which is equivalent to the flow rate in the respiratory tract of the patient. It can be seen that the direction of current changes it direction as we go from inspiration to expiration process. A small voltage offset in Fig 7 depicts the positive end expiratory pressure by virtue of the PEEP settings set using the expiratory circuit settings. The capacitor dynamic voltage is equivalent to the stored charge in the capacitor which in turn relates to the tidal volume of a human respiratory system. The model can also be non-dimensionalised for getting an exact match with the ideal lung mechanics observed in different modes of ventilation process.

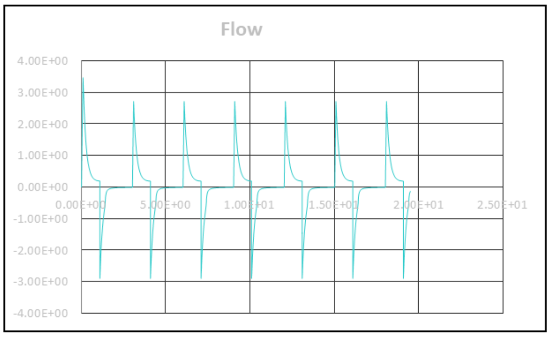

Fig 8: Output Current Profile for the Equivalent electrical circuit for patient ventilator interaction

In the present model both the human lungs and associated respiratory pathways have been lumped into a single RC combination. We can further modify the model by incorporating different RC circuits for individual lung. This can be helpful while simulating different lung ailments like obstructive lung disease etc. where the disease may be more prevalent in one of the lungs.

Fig 9: Prototype of Low Cost Respiration Control Device

Further modification can be made to the respiration model by using nonlinear transfer functions for the resistance and capacitance. Also advance model fitting techniques can be used by using techniques like neural networks and genetic algorithms if classified data of a large sample of ventilator data pertaining the human lung mechanics is made available.

5. CONCLUSIONS

A low cost ventilator as shown in Fig. 9 was designed keeping the present COVID-19 pandemic in perspective. For ascertain the design specifications of the device, a model based on human ventilator interaction was devices using electro-mechanical analogies. The thermodynamic modeling of the human respiration system considering an isothermal process resulted in work and power input requirement, which is 6 Watts, were found to be close to the values present in known literature.

An equivalent electrical model was formulated using a simple RC circuit for modeling the human lung and other equivalent electrical elements for non-return valves, PEEP valves etc. The developed model was subjected to a square input voltage wave-form which was analogous to the settings used in the pressure control mode of ventilation. The response of the model in the form of capacitor charging voltage and capacitor current was representative of air tidal volume and air flow rate respectively. These results were compared with the standard wave-forms normally see in a lung mechanics display and were found to be satisfactorily close.

The developed patient-ventilator model can be used to further improvise the ABMV design. Though the lung model is primitive in nature, it can be used to mimic various lung conditions with some alterations. Other modes of ventilation like Volume Control, Synchronous Intermediate Mandatory Ventilation etc. can also be simulated used the RC Device model.

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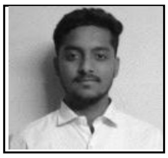

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