Prediction of Pneumonic Oxygenation in a PID-embedded Electro-pneumatic Pressure-Controlled Ventilator Device

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Abstract

Respiratory-type infections of pandemic scale have shown the critical need for suitable ventilator-type for hospitalized patients. While volume and pressure control ventilators are commercial abundance in a clinical setting, the choice of which type is considered a determinant factor in recovery during a large-scale medical emergency. A novel design of the PID architecture with the capacity to mimic the native human lung under the pathological condition of covid-19 type infection is presented. Traction of oxygenation circuit is achieved via electro-pneumatic protocol based on coupled solenoid-energized valve over a computer-controlled electro-pneumatic workstation. Our observations showed the performance of the Pressure-controlled ventilator (PCV) system in terms of peak time, settling time and maximum overshoot yield improved oxygenation throughput. The performance of the lung-mimicking PID-based control mechanism is attributed to smoothing the control of inspiratory pressure and consequently impacting the compliance in the modeled pulmonic vessel.

Keywords
Assisted-Oxygenation, pneumonic airflow, control-loop mechanism, electro-pneumatics.

1. Introduction
The World Health Organization christened the 2019-nCOV pandemic as the single infection with the all-times highest case fatality ratio with mortality of ~4 million and infection cases standing ~ 180 million across all nations of the world as of mid-2021. Over the last fifteen months, the epicenters of coronavirus infection are characterized by overwhelming hospitalization with attendant respiratory complications necessitating the use of a mechanical ventilator as a life-support device. Near-war zone emergencies and fatal breathing conditions are considered as the characteristic feature of nCOV-19 infected patients. With the increasing variants of nCOV-19 in certain parts of the US and Europe and the Indian-Sub continent, the need for ventilators as a life-support device is considered critical in managing patients with coronavirus infection.

A ventilator is a machine that is mechanically designed to deliver breathable air to and from the lungs to provide a breathing mechanism for a patient who is physically unable to breathe enough. A mechanical ventilator is an automated device in which energy is transmitted or transformed (by the ventilator drive mechanism) in a predetermined manner (using a control circuit) to increase or replace the patient's muscles during breathing operation (King 2020). By design, a mechanical ventilator (MV) is an automated machine that is expected to do some or all of the work the body needs to get gas in and out of the lungs. As an alternative mode of ventilation, (MV) can be used in cases of respiratory failure (Higgins and Clarke, 2012). Pneumatic systems are commonly used for manufacturing applications, primarily in a pick and place operation. The main reason for their use is the inexpensive nature of their construction and operation as well as the relatively high actuation force, they have achieved. This makes them very cost-effective with an electric drive for simple positioning tasks (Perez-Nieto et al. 2019, Garg et al. 2020, Larraza et al. 2014), However, the straightforward nature of the pick and place operations that regulate pneumatic systems often dictates the use of equally crude control schemes. Most pneumatic systems operate with on-off or on-off control valves that are coupled to programmable logic controllers via simple limit switches (Alleyne 2000).

1.1 Objectives

This paper aimed to investigate pneumonic oxygenation over a selected range of ventilating parameters in a model clinical ventilator using a computer-activated electro-pneumatic bench. The mimicry of a native pneumonic system was achieved on the PID platform for which compliance during inspiration and expiration can be carefully observed. We utilized an array of the smart solenoid-gated valve to automate the oxygenation process. Thereafter, examinations were carried out on the ventilation performance of the tidal volume, the exhaust time, the exhalation valve using standard delay-timers, which will serve as a blueprint of the control architecture for ventilator users in the medical field.

2. Literature Review

Mechanical ventilation aims to provide patients with limited vital capacity with sufficient oxygen, to treat ventilation failures, to reduce shortness of breath, and to relieve the rest of tired respiratory muscles. The self-inflating resuscitator with a pocket valve mask is a ventilator because the muscle energy of the user acts as a driving mechanism and replaces the muscles of the patient (Electric 2012, Meka 2004).

The dynamics of a breathable ventilation device follow the physiological route of the native lung in humans. This is a partial-pressure-driven system in which partial gradient created by the sequence of O2 inhalation and CO2 exhalation drives the diffusion process. Due to a diseased condition, the ventilator device could be programmed to perform this life-support mechanism under stipulated medical guidance (King et al. 2020) This surrogate lung-performing device could be powered by a pneumatic system which is an established fluid-power architecture in traditional mechanical and industrial machinery (Gregoretti et al. 2013). In the design of ventilators, the choice of pneumatic systems is hinged on the potential to provide a relatively high actuation force in the propulsion of breathable air. An important consideration is the reliability of pneumatic systems for consistent delivery of oxygenation circuits during actuation processes. Recent improvements in pneumatic technology have witnessed the incorporation of electronic control to pneumatic action dynamo (Topçu et al. 2006). This emerging technology is anchored on the versatility of PID architecture in high-precision fluid transport.

The use of mathematical cum physical principles to evaluating air circuits and aerodynamics is an established procedure in medical device technology. In human-bound ventilator systems, the need to employ mathematical strategies as a tool for design and prototyping is cardinal to the development of new models in ventilation technology (Shen et al. 2017, Rahaman et al. 2017 and Staay and. Chatburn 2018). The consideration of the natural ventilation in the physiological lung as a multi-compartmental system is consistent with the philosophies in systems biology of the human lung (Similowski 1991). Some authors have leveraged this narration to develop mathematical models that describe the multi-compartmental dynamics in native lungs to draw inspiration for modeling the operation of ventilator systems for emergency conditions (Lakshmi 2012, Khoo 2018). The versatility of nonlinear mathematics to handling lung compliance in dynamic modeling of biological processes of gaseous exchange was proposed (Crooke 2002). The nonlinear mathematical approach to modeling pneumatically-controlled ventilator devices is consistent with the behaviour of the actuation mechanism in traditional pneumatic systems. The precise control of breathable air circuitry follows the valve-pool model formulated by Richer and fellow has been harnessed to model the actuation of breathable air over a pneumatic propelled ventilation device (Richer 2000).
Since patient-centered medicine is projected as the healthcare of the next generation, some approaches to model respiratory dynamics have been proposed based on the properties of the individual patient (Rees 2006). Likewise, Schranz (2013) developed the approach to predict the patient-specific parameter in a clinical operation of PCV which shows pressure minimization for inspiration for considerable inhalation and exhalation sequence. Crooke et al proposed a one-compartment model based on the Roher-type model designed to capture important variables such as tidal volume, average volume, expiratory pressure, and mean alveolar pressure, Crooke 2003, Acharya and Das

2021 and Naggar 2015 developed simplified mathematical models leveraged on the conceptual framework that delineates the patient-device interaction for PCV in clinical settings.

3. Methods

The symbols used in the system dynamic for the design of the ventilator with 5/2 solenoid valve are, VCV for volume-controlled ventilator, PVC for pressure-controlled ventilator, 1Q1 for Air pressure reservoir, 1Q2 for Nozzle, 1Z1 for Time delay valve, 0Z2 for Air service unit, 1X1 for Single acting cylinder, 1S1 for Pushbutton, K1 for Relay, 1P1 for Mano meter, 1F1 for Flow meter, and 1Y1 for Configured way valve.

3.1 Experimental set up for optimization of oxygenation in PCV

The unit is mounted on the profile plate using the quick release system with two, the single-acting cylinder with trip cam and push-in fitting is mounted on a plastic retainer. This bitable 5/2-way solenoid valve with push-in fitting is screwed to the function plate that is equipped with a P port and silencer and the four electrical connections are equipped with safety connectors as shown in Figure 1. The proximity sensor consists of the sensor in the mounting kit and on the cable, and the cable is equipped with a socket and three jack plugs. The simulation parameters used for the VCV with the 5/2 solenoid valve is presented in Table 1.

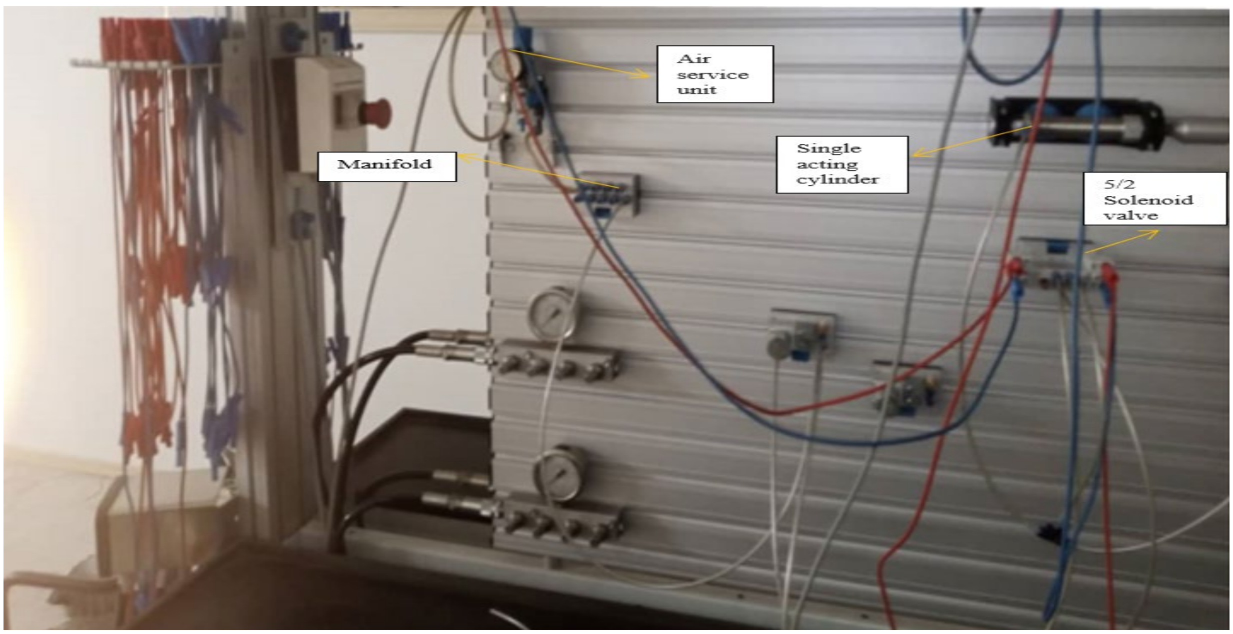

Figure 1. Experimental setup of the Volume and Pressure Controlled Ventilator

Table 1. The simulation parameters values setting of VCV with the 5/2 solenoid valve.

Effective Area (A_{ev}) of the Exhalation Valve. mm^2	Influence of the Tidal Volume. (V_T) mL	Influence of the breathable Time (V_{vo}) sec	Influence of the Tidal Pressure. (P_T) MPa
6	200	10	1
6	600	12	1.2
6	200	14	1.4
6	200	16	1.6

The simulation diagram of the 5/2 solenoid valve is shown in Figure 2. In the initial position cylinder, 1X1 is in the forward end position and the rear cylinder chamber is filled with compressed air. With a pushbutton, the selected switching position is only retained for as long as it is actuated. The pushbutton shown performs the function of a normally open contact. In the case of a normally open contact, the circuit is interrupt in the normal position of the pushbutton that is in the unactuated state. Actuation of the switching stem causes the circuit to be closed and current to flow to the consuming device. Once the switching stem is release, the pushbutton returns to the normal position because of the spring force, thereby interrupting the circuit.

Actuation of pushbutton 1S1 or pushbutton K1 (both in the form of normally open contacts), causes the relay K1 to be energized, the changeover contact K2 (connected in the form of a normally open contact) closes and the solenoid coil 1Y1 of the 5/2-way valve 1V1 is energized. The valve 1V1 reverses and the rear chamber of cylinder 1X1 is exhausted; the spring presses the cylinder into the retracted end position. As soon as the pushbutton 1S1 or K1 (both in the form of normally open contacts), are no longer pressed, the relay K1 is de-energize, the changeover switch K2 (connected in the form of a normally open contact) opens. This causes the coil 1Y1 to be de-energize and the valve 1V1 to be return into the initial position via the return spring. The rear chamber of cylinder 1Y1 is fill with compressed air and the cylinder returns into the forward end position.

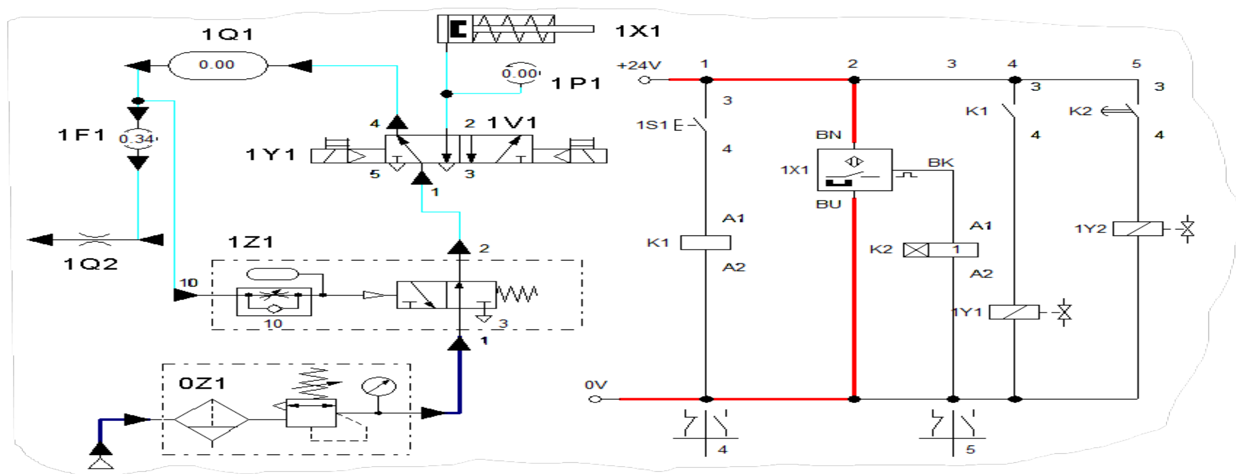

Figure 2. The simulation diagram of the electro-pneumatic simulation of circuit of VCV with a single acting cylinder and 5/2 solenoid valve (PA).

3.2 Experimental set up for the PCV

The modern PCV ventilator is equipped with Actuator, sensors, Valves, On-delay timer and control mechanism as shown in Figure 3. In control mechanism, a single acting cylinder is use to drive the piston mechanism in air-compartment of the system. There are two main parts of lung ventilator. One part is the lung mechanism (Represented by PID) and other is the Electro-pneumatic mechanism.

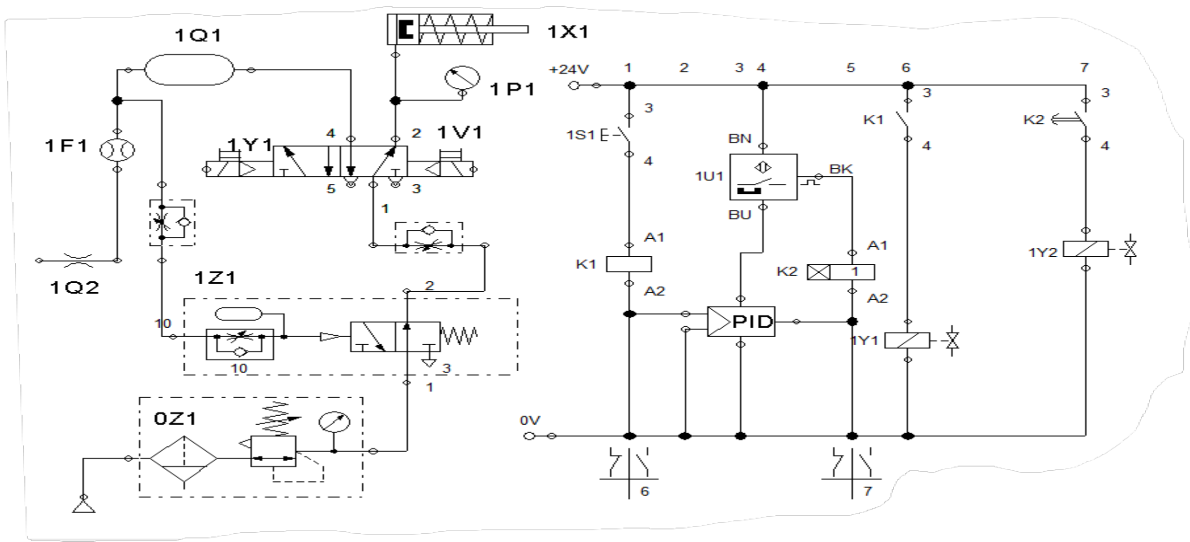

Figure 3**.** The schematic diagram of the electro-pneumatic of circuit of PCV with a single acting cylinder, 5/2-way valves and PID Controller

If the piston is at the left stop Figure 3, ports 1 (compressed air supply) and (work port) 2, as well as port 4 (work port) and port 5 (exhaust port) are connected. If the left solenoid coil energized, the piston moves to the right stop and ports 1 and 4. Also, ports 2 and 3 (exhaust port) are connected (power line, 14 and 12, function during 1 'Actuation. Connection of compressed air supply 1 and working port 4, that is, 2). If the valve must return to the home position, it is not enough to interrupt current to the left solenoid coil, as the right solenoid coil must also be energized. If neither solenoid actuated, the piston, due to friction, remains in its last assumed position (signal control in the power section). This also applies if the two solenoids powered simultaneously, as they then act on each other with the same force. Valve can be switched by manual control in de-energized state.

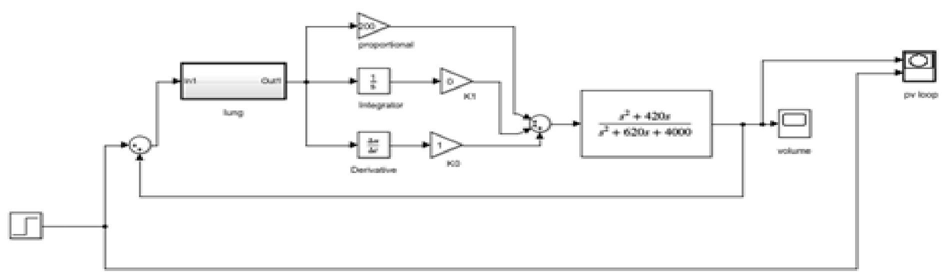

Figure 4. Dynamic model of lung mechanics using Simulink (PID)

The optical proximity sensor with LED and electrical connections assembled on a polymer assembly base. The electrical connection effected by means of safety connectors or via a 3-pin plug socket. The unit mounted on the profile plate via a quick release detent system with blue triple grip nut. The adjustable one-way flow control valve screwed into the function plate, incorporating a straight push-in fitting. The unit slotted into the profile plate via a quick release detent system with a blue, and the model of the lung is shown in Figure 4.

The proposed PID is to find the optimum parameters gain of PID controller considering minimum error between desired and actual airways pressure of the lungs. Initialize the flow rate, volume rate and pressure rate, assign the range of PID controller parameters *(Kp, Ki, Kd),* constant values.

3.3 PID Controller

Proportional-Integral-derivative (PID) controller structure is use to control the artificial ventilation system. Mathematically, it is described as [1]

$$U(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (1)$$

where K_p and K_i and K_d are proportional, integral and derivative gains of the PID controller respectively. Corresponding transfer function is as follows:

$$U(s) = Kp2 + \frac{K_{i2}}{s} + sK_{d2}. \quad (2)$$

The transfer function has expressed the airflow output as a function of pressure input I(s)/P(s) using the transform function in Equation (10). This equation is assume to represent a healthy respiratory system with above stated parameters as well as the total capacity of lungs equal to [2]

$$\frac{I(s)}{P(s)} = \frac{s^2+420s}{s^2+620s+4000} \quad (3)$$

4. Results and Discussion

4.1 Parametric Investigation on Volume Controlled Ventilaor

The Simulation results of electro-pneumatic system of VCV in 10s, 12s, 14s, and 16s, relay using 5/2-way solenoid valves (PA) and single acting cylinder is shown in Figure 5. At 1s the curve stated to fluctuate, we get stable curve at 10 seconds therefore, 10s, 12s, 14s and 16s obtainable. The tidal volume of the ventilator is set to 300 ml, 500 ml, 600 ml and 700 ml, and the simulation results are show in Table 2. It found that with an increase in the tidal volume of the ventilator, the peak pressures increase proportionally, but when the tidal volume is greater than 600 mL, the maximum pressure of the model increases slowly.

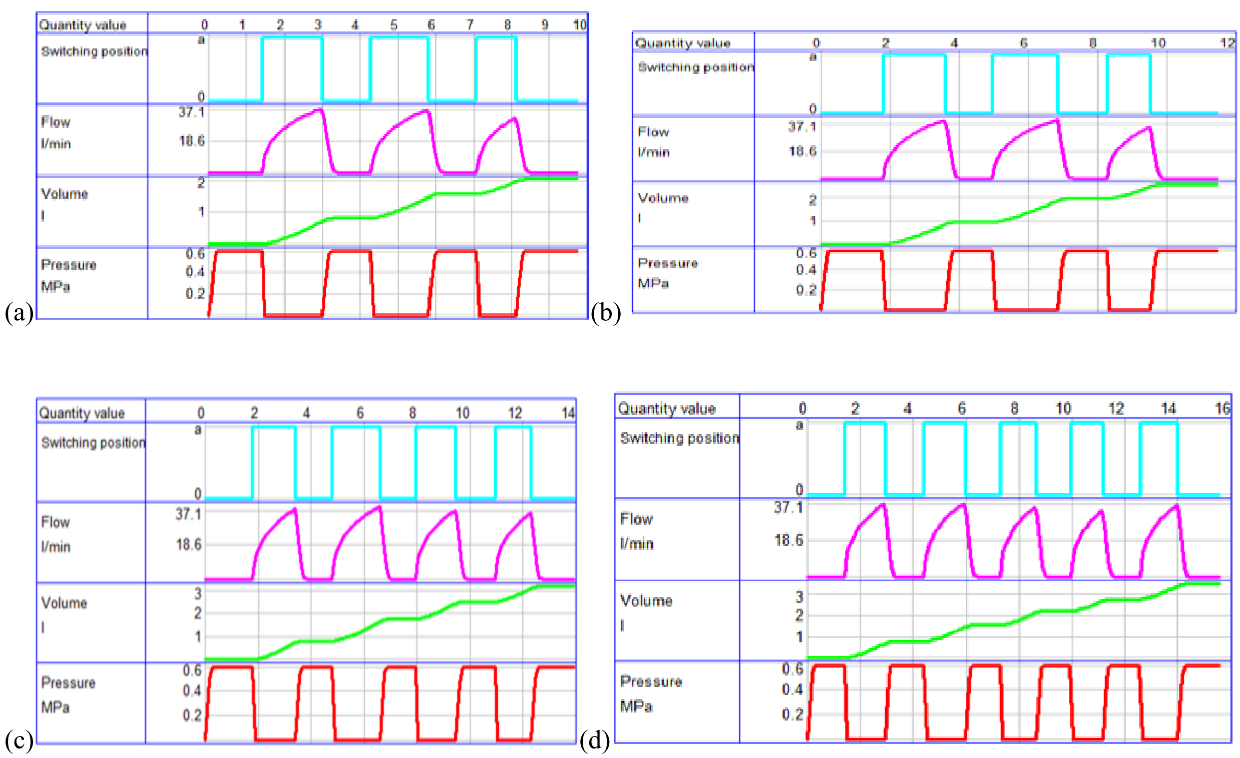

Figure 5. Simulation results of electro-pneumatic system of VCV using 5/2-way solenoid valves, (a) 10s, (b) 12s, (c) 14s, (d) 16s

Table 2. Oxygenation Newly model Volume control ventilator result

Volume (mL)	*Pressure (MPa)*	*Flow Rate (I/min)*	*Time (s)*
300	0.6	4.1	10
500	1	8.1	12
600	2	12	14
700	2.7	16.1	16

Finally, when the ventilator escape time is less than 1.6 s, the maximum lung flow increases with an increase in the discharge time if the discharge time of the ventilator is greater than 1.6 s, the maximum flow rate is constant. With an increase in the effective area of the exhalation valve, the maximum exhaust airflow rate of the lung increasing more and more slowly.

4. 2 Parametric Investigation on Pressure Controlled Ventilator

Simulation result of electro-pneumatic system of PCV in 10s, 12s, 14s and 16s with a single acting cylinder, 5/2 way solenoid valves (VX), on-delay timer and PID controller are shown in Figure 6. For better ventilator response, a PID controller is connected to the system, and the actual airway pressure (Paw) of the ventilator was provided as input to the PID controller. The desired airway pressure is the pulse signal from the reference unit that serves as the input for the PID controller (Figure 6).

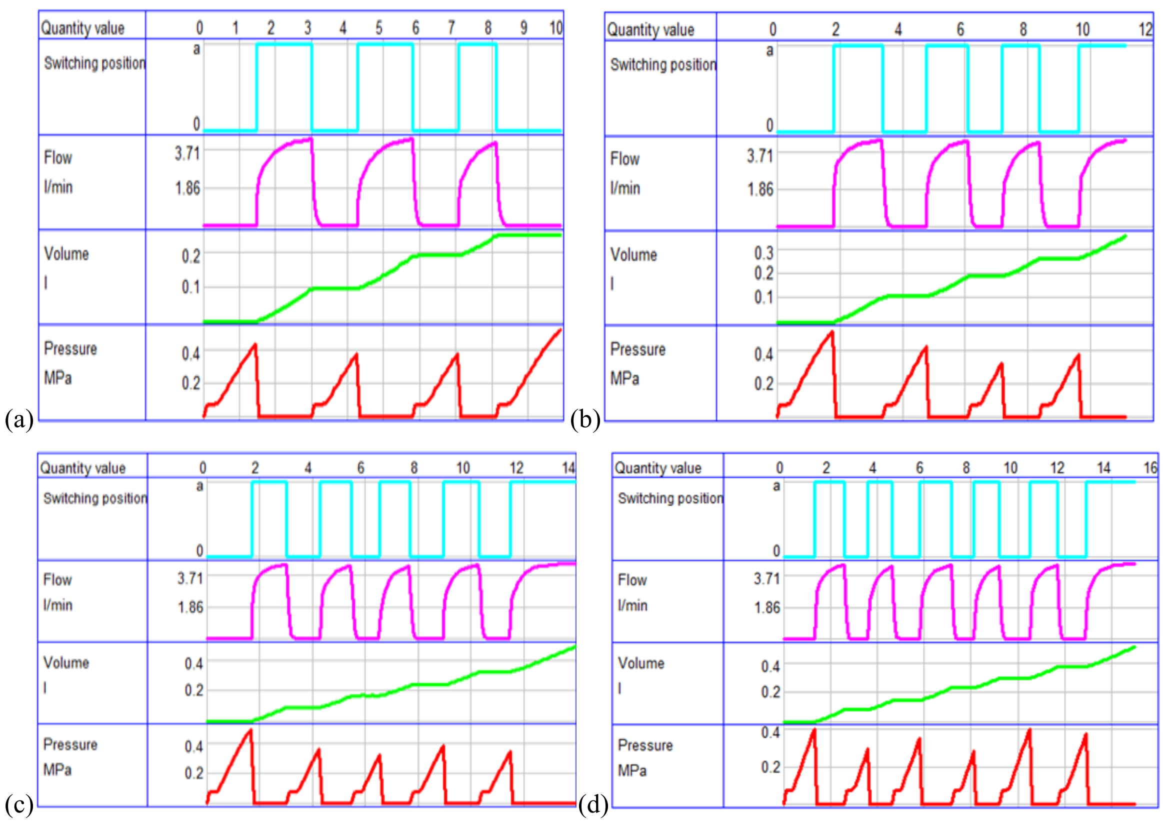

Figure 6. Simulation result of electro-pneumatic system of PCV with 5/2-way solenoid valves, (a) 10s, (b) 12s, (c) 14s, (d) 16s

The principle of PID control consists in performing the proportional (P), integral (I) and differential (D) operations for the deviation of the measured value from the expected value and finally using the linear combination to finally recreate the controlled variable. The structure of a model PID control system is shown in Figure 7.

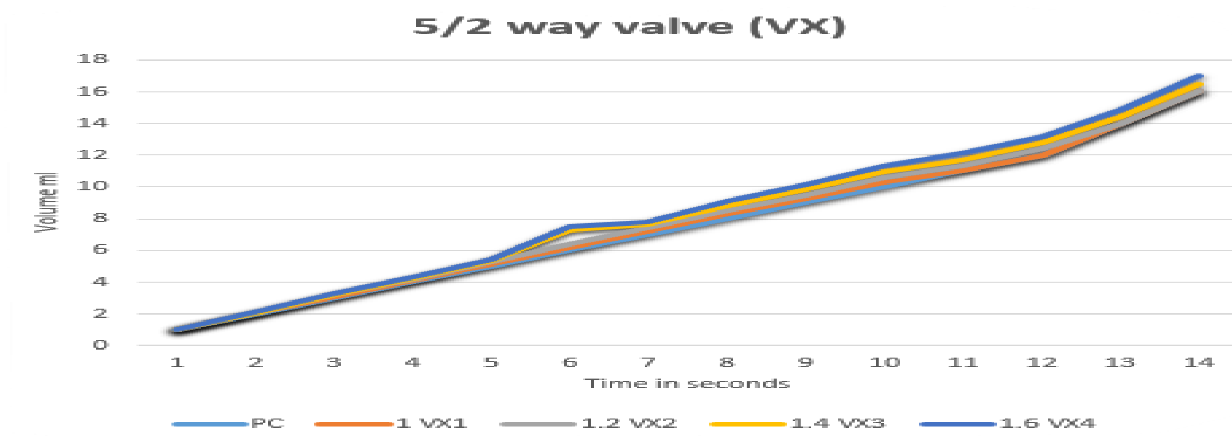

Figure 7. Simulation result of PCV in at different time with the 5/2 way solenoid valves (VX), on-delay timer and PID controller

A simple fast switching valve with PID for Electro-pneumatic position control applications investigated. The result of the developed model is shown in Table 3. In addition, electronic circuits for valve control and PID valve control designed and built as a complete mechatronic system. The compressor pressure level reached 6 bar, it was observed that there was a fluctuation in the pressure movement that dropped below 6 bar, before further increasing to the 6 bar mark after approximately 2 s of operation in Electro-pneumatic PCV model. If the tidal volume is less than 600 ml, the maximum exhaust airflows from the tube and lungs increase proportionally with increasing tidal volume in Electro-pneumatic PCV model. If the tidal volume is greater than 600 ml, the maximum exhaust gas flow of the flexible hose increases faster and faster in Electro-pneumatic PCV model. When the tidal volume is less than 600ml, the maximum flow rate of air extracted from the lung proportionally increases with increasing tidal volume. When the tidal volume is more than 600ml, the maximum the exhaust flow from the lungs increases more and more slowly in Electro-pneumatic PCV model.

Table 3. Result of the Newly developed model (Pressure Control Ventilator)

Volume (mL)	Pressure (MPa)	Flow Rate (l/min)	Time (s)
300	6	4.71	10
500	6	5.00	12
600	6	5.24	14
700	6	5.28	16

The simulated analysis also showed the differences in drop and high pressure but no significant difference in the result obtained. From the actuator analysis. Single-acting cylinder magnetic cushion helps reduce sudden initial system start-up in 1s. This facilitates the slow movement of the actuator to have a good and stable air distribution without the application of an impulsive force that could create a defect or burst the patient's lung

5. Conclusion

The study presented the quantitative evaluation of pneumonic oxygenation in a PID mediated PCV-type life support device. The modelled clinical ventilator employs several valves and sensors along with a processing unit to implement the required control algorithms. We showed that the performance of PCV system in terms of peak time, settling time and maximum overshoot are automatic. The utilization PID control architecture was done to improve response time, enabling patients to inhale gas in a timely manner in each positive pressure inhalation phase, and to have a better experience, which has less pressure shock during exhalation and inhalation, and has higher safety in certain special situations. It was also observed that the maximum pressure of the ventilation device increases slowly when the tidal volumes exceed 600 ml. In addition, influence of evacuation time of the ventilator predicted over high throughput in time regimes of 1 s; 1.2 s; 1.4 s and 1.6 s. showed that the pressure platform in the pipe might not appear if the exhaust time of the ventilator is less than 1.6 s. Meanwhile, decline in pressure fluctuations below 6 bar for intermediate timescale of operation between 1.5s to 16 s. The comparison of response time of the proportional integrated derivative (PID) controller in the PCV model is obtained below the threshold while the electro-pneumatic thus improving oxygenation potential of PCV-type ventilation device.

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