MATLAB/Simulink Medical CO2 Insufflator Model with a Pressure PID Controller

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Abstract— **– *Laparoscopic minimally invasive surgery (MIS) requires the use of medical carbon dioxide (CO2) insufflator to expand the peritoneal cavity. This is aiming to provide a better and easier view for surgeons during the surgery. Such a device requires a precise pressure and flow control. Since 2017, the Food & Drug Administration (FDA), the medical devices regulation authority in USA, has adopted the use of in-silico model (computational model and simulation) to accelerate and facilitate the costly long-time process of getting FDA approval as well as other medical device regulation authorities. In this paper, MATLAB/Simulink medical CO2 insufflator model has been developed. This Simscape computational model includes sensors (flow, pressure, temperature etc.) and actuators (solenoid valve, reducing valves, safety valves etc.). Also, a pressure Proportional Integral Derivative (PID) controller model has been created to drive precisely and accurately proportional pressure regulator (PPR) in the proposed pneumatic model. Also, a non-linear abdominal model has been made to test the functionality of the whole system. Finally, promising results have been accomplished due to the integration of all models into a final model and its simulation.***

Keywords— CO_2 insufflator; pneumatic system; PPR; in-silico model; MATLAB/Simulink and PID controller.

I. INTRODUCTION

A pneumoperitoneum is a gas-filled space within the peritoneal cavity. Insufflators are used to produce and maintain such condition [1]. Insufflators are medical devices used in laparoscopic surgeries regulating the pressure and flow of a gas supply from a high- pressure medical gas tanks (e.g. CO_2, N_2O) aiming to inflate the peritoneal cavity. This leads a huge working space. Consequently, this can help to provide more room for the insertion of instruments as well as allowing a surgeon to visualize easily the internal organs. Female tubal ligation is considered as one of the most popular used of laparoscopy. Another popular is the diagnosis and the treatment of infertility and cancer. Moreover, laparoscopic procedures include a variety of surgical operations such as cholecystectomy (removal of the gallbladder). This helps to avoid open surgical techniques [2][3]. The advantages of laparoscopic techniques include small abdominal incision, minimal postoperative pain, short hospital stay as well as faster recovery [2][3].

Prior to the start of a gas insufflation into the abdominal cavity, a surgeon inserts a needle, which allows the injection of medical grade CO_2 (or N_2O as an alternative) under a precise pressure and flow control into the peritoneal cavity as shown in Figure 1 [4]. After the creation of the pneumoperitoneum, a further enlargement of the needle puncture is made through the use of a sharp-pointed instrument, such as trocar, within a sleeve or even a cannula [5]. Such enlargement is necessary to allow the accommodation of the laparoscope simultaneously with the prevention of any gas leak [5]. The insufflation pressure is preserved via a connection of insufflation tube to the trocar sleeve equipped with a gas inlet.

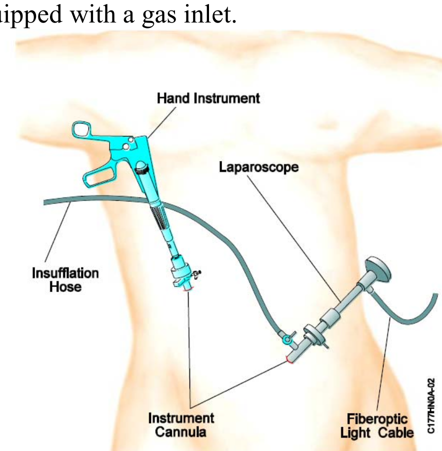

Fig. 1. The insertion of insufflation needle and primary trocar into the inferior portion of the umbilicus [4]

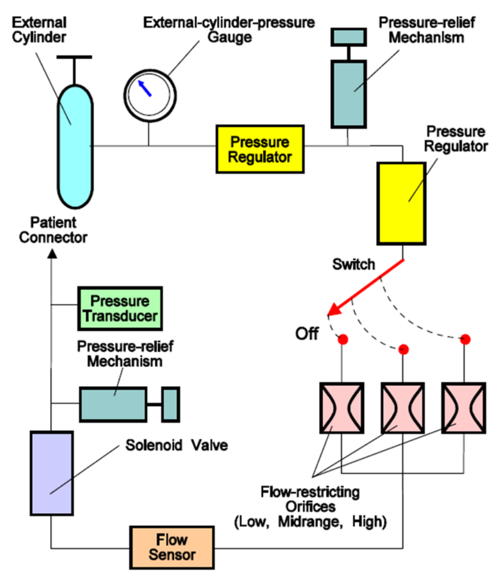

Fig. 2. Typical electronic insufflators

Laparoscopic insufflator can be classified into two types: pneumatic and electronic [6]. In the pneumatic type, the gas is

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flowed continuously into the peritoneal cavity until the abdominal pressure reaches the set value. Whereas, the electronic insufflator firstly inserts the gas during the insufflation phase, and then it measures the pressure in the measurement phase under a zero flow condition. Figure 2 shows a block diagram of a typical example of the electronic insufflator.

In complex surgical procedures, the use of electronic insufflators is preferable due to their capability to deliver high flows. However, pneumatic insufflators are more convenient in the diagnostic surgical cases, where flow lower than 4 L/min is needed [7].

Today's rapid growth of technology calls for many types of actuators and control system for controlling and operating insufflators. In medical insufflators two sources are important for the working of the instrument which are electric and pneumatics.

To obtain the regulated air pressure from the pneumatic air reservoirs, a pneumatic pressure regulator is used. This pressure regulator is a mechanical component which can be used to set a desired pressure by manually adjusting the control knob. It works fine for single value of pressure but in case of variable operation we need something that can change the pressure output dynamically, in this case a proportional pressure regulator (PPR) is used. PPR is a closed loop control system which utilizes PID algorithm to control the pressure control knob. For a PID controller it is very important to finely tune the system to obtain optimum stable system. The manual trial and error-based system for tuning requires many iterations with the system being not optimum [8]. Therefore, MATLAB/Simulink can be used to solve this optimization by simulating the whole system. The values of PID controller can be obtained in the simulation process. These values can be used on the actual hardware implementation.

Furthermore, the Model-Based Design with MATLAB/Simulink can be used to accelerate the delivery of certified medical insufflator hence shorten development time while improving quality and satisfying the certification requirements of the FDA and German regulatory authorities.

The literature reviews and the system design are explained in Section II and III respectively. Results are analyzed and discussed in Section IV. Finally, Section V offers a brief conclusion.

II. Background

World of Medicine (WOM) is a German company specialized in the endoscopic field. Firstly, WOM created a MATLAB/Simulink model-based design to facilitate the production of certified medical insufflators and pumps. In the project, WOM's team had worked with System Identification Toolbox and used measured input-output data to create a nonlinear mathematical of the abdominal cavity.

Then, the WOM team has connected the abdominal model with a Simscape plant model in Simulink environment. The plant model is made up of flow and pressure sensors, actuators (solenoid valves, reducing valves, relief valves...etc.) and other hardware components.

Next, the team had created a control model using two cascaded proportional integral (PI) controllers, one for flow and one for pressure. Another Simulink tools had also been used in this paper including the Simulink Check, Stateflow, and finally Simulink Coder [9].

III. System Design

The real motivation beyond this work is an attempt to shorten development time of insufflators while improving quality and satisfying the certification requirements of the FDA and German regulatory authorities in a short time. By Using Model-Based Design with MATLAB/Simulink, we can model and simulate control designs, generate code for real-time rapid control prototyping hardware, and generate optimized code for production embedded processors.

In this paper, we have used modeling and computational simulation, particularly MATLAB/Simulink, of a medical CO_2 insufflator to find the optimized solution prior to the development of a real physical prototype.

Figure 3 shows the CO_2 insufflator Simulink/Simscape model.

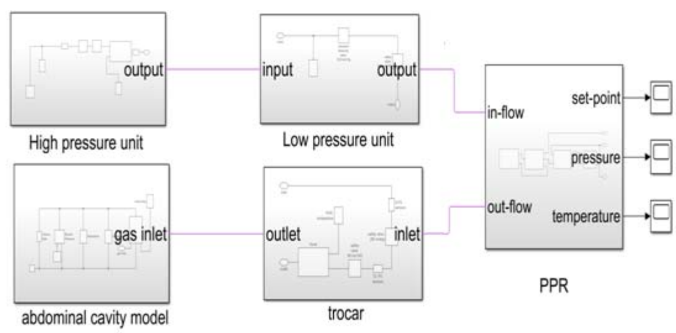

Fig. 3. CO2 insufflator MATLAB/Simulink model

The system consists of 5 blocks: The high-pressure unit (HPU), the low-pressure Unit (LPU), the proportional pressure regulator (PPR), the trocar subsystem and the abdominal model.

1- High-pressure unit (HPU)

Figure 4 shows the HPU Simscape block diagram using Simscape.

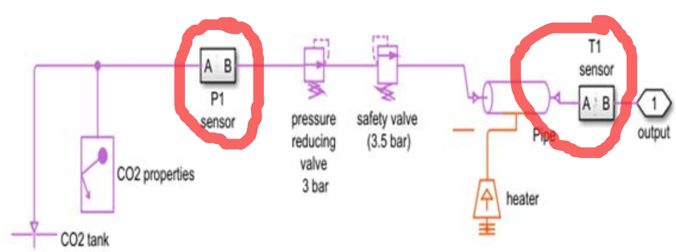

Fig. 4. HPU Simscape block diagram

The first component is a medical CO_2 gas cylinder. The pressurized CO2 gas in the cylinder has the following characteristics: a liquid form, pressure (around 50 bar), temperature (around -2 °C). The liquid form of CO2 is converted into a gas at room temperature. (The pressure in the CO_2 cylinders drops to zero only when the last liquid converts to gas. Thus, the CO_2 gas cylinder is represented in the HPU block diagram by a reservoir (G), which gives a constant pressure. The second component in HPU is the gas properties component "CO_2 Prosperities". It is used to specify the characteristics of CO_2 gas. In this component, the selected type of CO_2 gas is defined as a perfect gas and not the real one, since this reduces the entered parameters of this component. The next component is a P1 sensor, which is a pressure sensor used to monitor the pressure of the reservoir G. Then, the first pressure reducing valve (3 bar) is used to reduce the pressure from 50 Bar to 3 Bar. The type of this pressure reducing valve is a real one and its parameters are taken from a data sheet of a real physical pressure reducing valve. After the pressure reducing valve, a safety pressure relief valve (3.5 bar) has been used for safety. A constant temperature source is used as a heater to rise the CO_2 temperature from the room temperature into 37 °C prior to enter the abdominal cavity. This helps to minimize the patient's pain after the surgical procedure [10][11]. The temperature is monitored via a temperature sensor T1 to ensure the proper work of the heater.

2- *Low-pressure unit (LPU)*

Figure 5 shows the LPU Simscape block diagram.

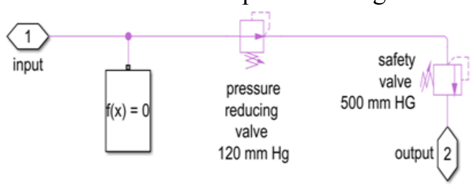

Fig. 5. LPU Simscape block diagram

This block is made up of: a pressure reducing valve and safety valve. The pressure reducing valve decreases the pressure from 3 bar to around 0.16 bar (120 mmHg). The safety valve's operating pressure is around 0.26 bar (200 mmHg).

3- *Proportional pressure regulator (PPR)*

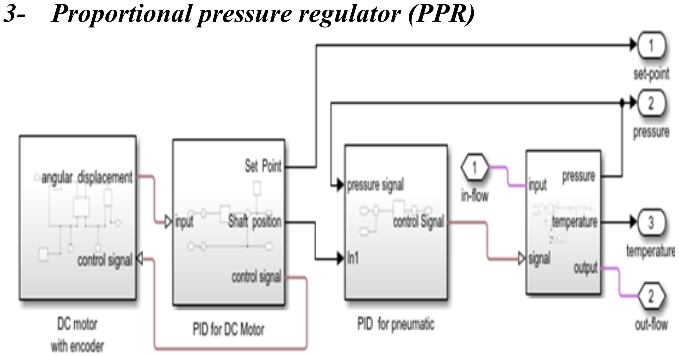

Fig. 6. PPR Simscape block diagram

In the PPR block, there are two proportional integral derivative (PID) controllers to reach the desired output pressure. The process of manual tuning of such PID controllers is cumbersome, and consumes a lot of time. PPR is completely modeled in MATLAB/Simulink to simulate it before manufacturing. It can give an idea about the whole system and most importantly setting the control parameter of each PID loop. Figure 6 shows the model of PPR in MATLAB/Simulink, which consists of: a DC motor with its encoder, Motor PID controller, and a PID controller for a mechanical pressure control valve. The DC motor is used to rotate the knob of a mechanical pressure control valve. Three parameters of this block visualized in the scopes are: pressure, temperature and out-flow.

a) *PPR DC Motor with its PID controller Simscape Sub-block*

Figure 7 shows the PPR DC motor Simscape sub-block diagram using MATLAB/Simulink.

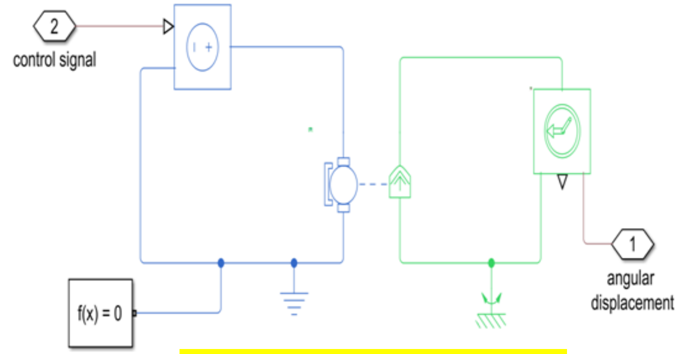

Fig. 7. PPR-DC motor Simscape sub-block diagram

This sub-block consists of: a DC motor block along with a voltage source, and an ideal rotation sensor component. Ideal rotation sensor component aims to measure the output angular velocity of the DC motor. The output angular velocity is used as a feedback signal in the closed loop control system. The output of PPR DC motor PID controller, as shown in figure 8, is then used as an input to the voltage regulator, which accordingly controls the DC motor.

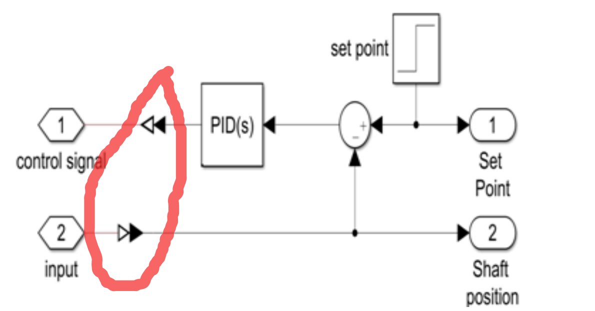

Fig.8. PPR-DC motor PID controller Simscape sub-block diagram

Figure 8 shows the pneumatic Simscape sub-block diagram. This sub-block has a PID controller for a closed loop control of DC motor. It consists of a physical signal (PS) to Simulink signal (S) PS-to-S converter, which converts a physical output signal of an ideal rotational signal into a Simulink signal. Also the set point (reference) signal is displayed in a scope.

b) *Pneumatic Simscape sub-block*

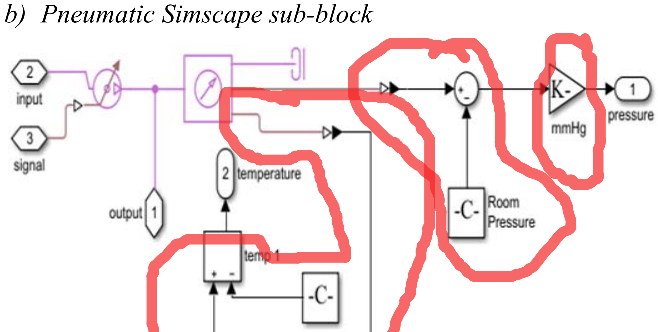

Fig. 9. Pneumatic Simscape sub-block diagram

In Figure 9, multiple components have been used to model the physical pneumatic circuit imported from the new 2019

Simulink/Simscape pneumatic library version. Such components were unavailable in previous versions of Simulink/Simscape components libraries. The controlled pressure block functions as a mechanical pressure regulator valve controlled via a PID controller. Pressure and temperature sensors are used for measuring the output pressure and temperature of CO_2 gas. This is required for the closed loop feedback circuit.

c) PID controller for the pressure regulator

Figure 10 shows the pressure regulator's PID controller Simscape sub-block diagram.

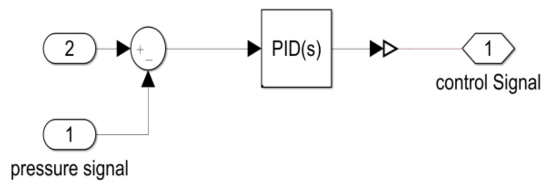

Fig. 9. Pressure regulator's PID controller Simscape sub-block diagram

This sub-block consists of a 2nd PID controller for controlling the output of the pressure regulator. The input signal of this controller comes from the DC motor sub-block after converting the pressure value into a Pascal (set point). The output of the PID controller is then fed into a S-to-PS converter for converting the Simulink signal into a physical signal.

d) Trocar

Figure 11 shows the trocar sub-block Simscape diagram.

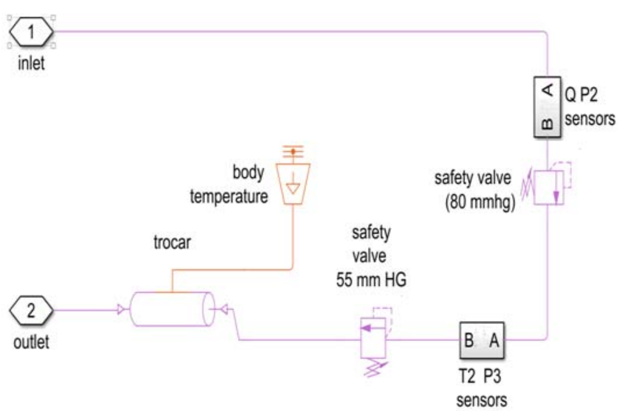

Fig. 10. Trocar Simscape sub-block diagram

This sub-block is made up of 4 sensors: two pressure sensors, one flow sensor, and one temperature sensor. These sensors measure the pressure, the volumetric flow, and the temperature of the CO2 gas before entering the abdominal cavity. The trocar is represented via a pipe, which is impacted by the patient's body temperature. Finally, two safety valves are used to ensure the safety of the patient from an overpressure.

e) Abdominal cavity Simscape sub-block diagram

Figure 12 shows abdominal cavity Simscape sub-block diagram. The Translational Mechanical Converter (G) converts the CO2 gas pressure into a translational motion. By setting the Interface cross-sectional area to a unity type, the displacement of the mechanical translational network represents the delivered volume of CO_2 gas. Also, the force represents the gaseous pressure in the abdominal cavity. Moreover, the spring's constant is considered as an abdominal elastance. Finally, the damper's coefficient represents the abdominal resistance.

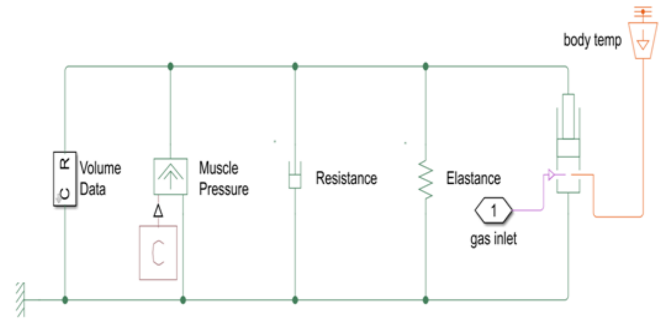

Fig. 11. Abdominal cavity Simscape sub-block diagram

IV. Results

A. PPR Results

The figure 13 denotes the response of PID controller before the use of Simulink auto-tuning tool. It shows the curve's fluctuations before attaining the desired pressure value i.e. the reference value. Such fluctuations will cause a strain on the hardware of the system. And in the extreme cases, this could lead to a complete hardware failure. Therefore, it is necessary to get the optimum values prior to the development of a physical prototype.

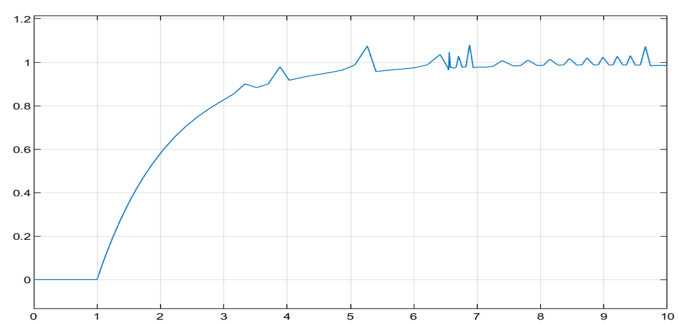

Fig. 12. Simulink PPR PID controller manual tuning

In Simulink, there is a very useful tool for automatic tuning of a PID controller, known as a PID auto-tuner. The auto-tuner is automatically calculating the weights of proportional value, integral value and derivative value of a PID controller to reach an optimized response/output as shown in figure 14. Using MATLAB/Simulink model consequently helps to avoid damage to the components of the real physical system due to the bad tuning problem as shown in Figure 13.

Using an auto-tuner helps to tune the system automatically for a minimum response time without excessive fluctuations. In case of PID controller, to get a minimum possible response time could affect the smoothness of trajectory response. Thus, a compromise must be done between the curve's smoothness response, and the minimum response time. Auto-tuner tool in MATLAB/Simulink gives the designer the flexibility to set both the parameters as per the need of system.

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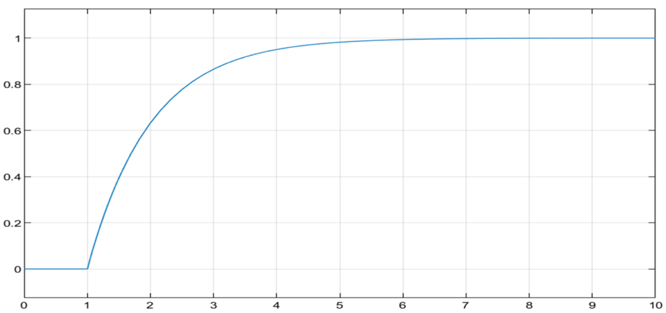

Fig. 13. PPR output after the use of auto-tuner tool

B. Pressure results

The pressure inside the medical CO2 cylinder is around 50 bar unless it's empty. Figure 15 shows the pressure sensor reading values of HPU's P1 sensor inside the CO2 cylinder. Figure 16 shows the pressure sensor reading values of LPU's P2 sensor. LPU-P2 sensor measures the pressure after the PPR unit. The surgeon sets the abdominal pressure reference value. For example, in the figure 16 the set point of PPR is 15 mmHg. This means that the pressure had dropped from 88 mmHg to 15 mmHg before entering the abdominal cavity.

Fig. 14. HPU's P1 pressure sensor readings

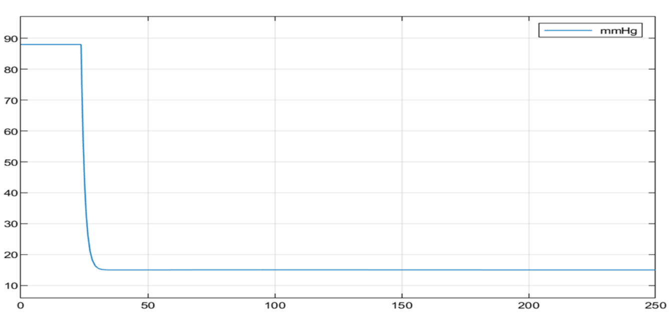

Fig. 15. LPU's P2 pressure sensor readings

C. Temperature

Figure 17 shows the T1 temperature sensor reading values at the point exactly after the temperature source's usage. Also, this figure shows the temperature sensor T2 reading values of the CO_2 gas, which becomes approximately 37 °C prior to the entrance of the abdominal cavity.

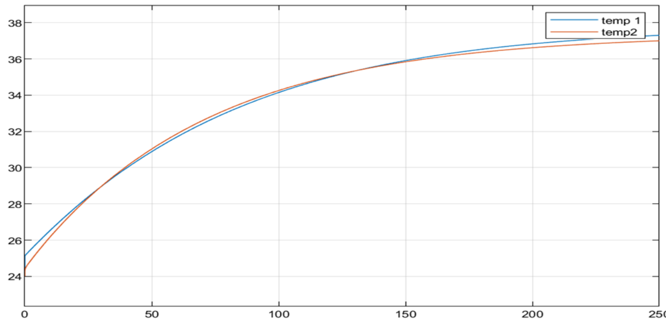

Fig. 16. T1 and T2 sensors reading

D. Flow

Figure 18 shows the flow sensor reading values of the CO2 gas. This graph shows that the flow becomes constant after certain time as expected.

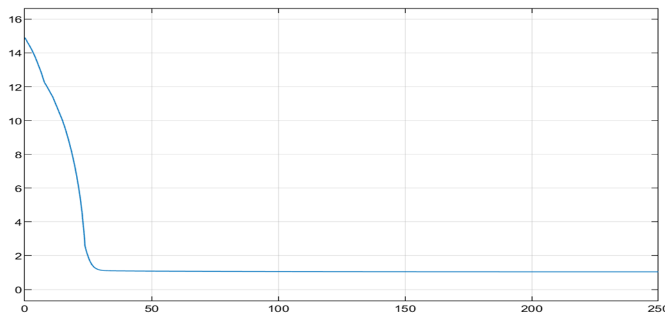

Fig. 17. CO_2 gas flow sensor readings

E. CO2 volume

Figure 19 shows the delivered CO_2 gas volume in the abdominal cavity in liters. This graph shows that the volume had reached a 1.2-liter constant value. The missing elements of the abdominal model in this work are the abdominal orifices leakage and the abdominal blood absorption of CO_2 gas.

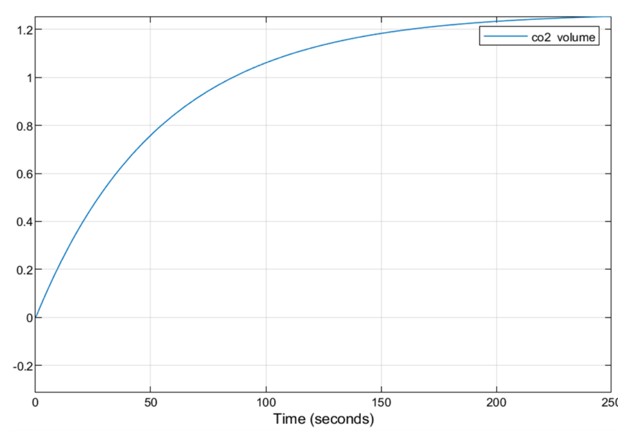

Fig. 18. CO_2 volume in the abdominal cavity

V. Conclusion

A MATLAB/Simulink medical CO2 insufflator with PID controllers for DC motor and PPR valve has been created.

Also, a MATLAB/Simulink nonlinear abdominal model has been made up. An integration of both models has performed to automatically tuning the PID controller for the acquisition of best optimized parameters, and additionally to test the functionality of the whole system. Further advantages of this work are firstly the performance of the previous mentioned tasks computationally without the need to jeopardize the physical real components of the system, and secondly to reduce the time from the early idea of design to reach a final physical endpoint product.

Acknowledgment

The authors would like to acknowledge at Ingenious Medical for the sponsorship of this project. In addition, they would like to thanks Eng. Hassan Wehbi, Development Manager at Ingenious Medical for his help and his inputs of this project.

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