Technokes Journal
International: Rapid Review: Open Access Journal **Vol. 16, No. 4, December 2023, pp. 232-237 e-ISSN 2407-8964; p-ISSN 1907-7904**

RESEARCH ARTICLE **OPEN ACCESS**

Manuscript received September 28, 2023; revised October 02, 2023; accepted October 12, 2023; date of publication December 25, 2023
Digital Object Identifier (DOI):https://doi.org/10.35882/teknokes.v16i4.635

How to cite: Levana Forra Wakidi, Farid Amrinsani, Alfi Nur Zeha, Riqqah Dewiningrum, and Steyve Nyatte, “Comparison of Pressure Sensor in Flow Analyzer Design for Peep Measurement on Ventilators”, Jurnal Teknokes , vol. 16, no. 4, pp. 232-237, December. 2023.

Comparison of Pressure Sensor in Flow Analyzer Design for Peep Measurement on Ventilators

Levana Forra Wakidi[1], Farid Amrinsani[1], Alfi Nur Zeha[1], Riqqah Dewiningrum[1], and Steyve Nyatte[2]
[1] Departement of Electromedical Engineering, Health Polytechnic Ministry of Health Surabaya, Indonesia
[2] University of Douala, Douala, Cameroon

Corresponding author: Levana Forra Wakidi (e-mail: lep.forra@gmail.com).

ABSTRACT Flow Analyzer allows measurement of flow, pressure, volume, and oxygen concentration delivered to the patient, with PEEP (Positive End Expiratory Pressure) being a crucial parameter in mechanical ventilation. Incorrect PEEP values can elevate the risk of patient mortality. The recommended PEEP range is 5-24 cmH2O, and administration is determined by the patient's clinical condition. This research aims to identify stable and highly accurate pressure sensors by comparing the MPX2010DP and MPX5010DP sensors with pressure readings from a Digital Pressure Meter (DPM). The study involves 5 repetitions of a lung test, each with 11 pressure reading points, within a pressure measurement range of 0-30 cmH2O. The DPM has a resolution of 1 cmH2O, while both pressure sensors have a resolution of 0.01 cmH2O. Results indicated that the MPX2010DP sensor has the smallest error percentage, specifically 0.00%, at a pressure increase of 5 cmH2O and 20 cmH2O. Conversely, the MPX2010DP sensor shows the largest error percentage, 5.16%, when the pressure decreases by 5 cmH2O. The highest standard deviation of 0.52 is observed in the MPX5010DP sensor at a 20 cmH2O pressure increase, while the maximum correction value of 0.54 is found in the MPX5010DP sensor at a 25 cmH2O pressure increase. According to the ANOVA test, there is no significant difference in pressure produced between the MPX2010DP sensor, MPX5010DP sensor, and DPM. The sensors are well-calibrated and provide accurate readings according to calibration tool standards. Therefore, the MPX2010DP and MPX5010DP sensors are deemed accurate for measuring PEEP parameters in ventilators. Based on the obtained data, it can be concluded that the MPX2010DP sensor is more accurate and stable.

INDEX TERMS PEEP, Ventilator, MPX2010DP, MPX5010DP.

I. INTRODUCTION

An outbreak of acute respiratory syndrome occurred in Wuhan, China, in December 2019, caused by the coronavirus SARS-CoV-2. This outbreak is known as coronavirus disease 2019 (COVID-19) [1]–[4]. COVID-19 tends to occur in clusters, spreading rapidly and primarily targeting the patient's respiratory system, leading to the development of acute respiratory distress syndrome (ARDS) without significant involvement of other organs [5], [6]. The pandemic has exacerbated the health service system, resulting in a shortage of healthcare workers and medical equipment, particularly mechanical ventilators Mechanical ventilation plays a crucial role in treating severe cases of COVID-19 with acute respiratory failure, serving to reduce patient mortality [7]–[9]. Mechanical ventilators transfer a specific amount of energy to the patient's respiratory system with each breath, overcoming airway obstructions and expanding the chest wall.

This energy transfer, however, may have consequences. Some of the energy directly affects the lung framework and extracellular matrix, potentially causing damage to the attached endothelial and epithelial cells. Lung elasticity allows the conservation of a small amount of energy in each respiratory cycle, as the lungs return less energy during exhalation compared to the energy absorbed during inspiration. Excessive energy expenditure associated with mechanical ventilation, resulting in heat or inflammation, can potentially cause injury to lung tissue. It is hypothesized that the amount of energy transferred during ventilator use significantly influences the degree of lung injury [10]–[12]. The amount of energy produced by a mechanical ventilator is related to factors such as tidal volume (VT), plateau pressure (PPlat), respiratory rate (RR), and airflow [13].

In cases of lung damage, the amount of air and oxygen delivered to the patient can be increased by using mechanical ventilation through increased inspiratory pressure, which forces oxygen to reach a higher proportion in the alveoli[14]. It has been proven that the use of mechanical ventilation systems can help increase blood oxygen saturation to normal levels that can support life so that mortality can be reduced[15]–[17].

In 2021, Tomy Abuzairi et al. conducted a study entitled "COVENT-Tester: A low-cost, open-source ventilator tester. This research aims to develop an open-source and low-cost ventilator testing device to calibrate medical ventilator output including tidal volume, inspiratory pressure, and oxygen concentration. The study used MPX5010 sensors to monitor pressure on ventilators. However, in this study the measurement results displayed are only in the form of numbers and have not been displayed in the form of graphs[18].

In 2018, Sara Zulfiqar et al. conducted a study entitled "Portable, Low Cost, Closed-Loop Mechanical Ventilation Using Feedback from Optically Isolated Analog Sensors". The research designed a prototype low-cost portable ventilator with breath control feedback lines from two self-calibrated sensors. Users can enter setting data through the Graphical User Interface (GUI) on the touchscreen module and it also displays the signal being controlled. Data from the sensor is optically isolated and converted into PWM signals for precise readings. The system is controlled digitally with various settings so that it can be adjusted to the needs of the patient. Air pumps use DC pistons, with a modified converter as a speed controller, and are PID-tuned so that they can be replaced with similar pumps. Pressure sensors use MPX4250DP for negative and positive pressure parameters such as PEEP and air flow rate sensors use AWM720P1 for breath-rate parameters per minute (BPM)[19].

In 2022, Hannifah Rahmi Fajrin et al. conducted a study entitled "Design of Ventilator with Gas Mixing, Tidal Volume, and Humidifier Parameters". This study aims to design a ventilator using several parameters such as automatic gas mixing, tidal volume, respiratory rate, humidity, and pressure. This study used MPX5700 sensors to measure the pressure applied. As well as testing 5 times using the VT502 gas analyzer calibrator[20].

In 2015, Pu Zhang et al. conducted research entitled "Development of Ventilator Tester Calibration Equipment". This study designed a calibrator device to improve the accuracy of the latest integrated ventilator testing, which involved calibration modules with static parameters (gas flow rate and pressure) and dynamic parameters (tidal volume, airway peak pressure, and positive end-expiratory pressure (PEEP). The study developed a system that can track the results of calibration or verification of ventilator testers with high accuracy and use appropriate software. However, this study did not mention the type of each sensor and did not mention the measurement error value of each parameter[21].

In 2022, Felix Morales et al. conducted a study under the title "Pytu Tester: Raspberry Pi open-source ventilator tester". This study aims to make a Ventilator testing device by measuring flow, pressure, volume, and oxygen concentration. This research uses pressure and flow sensors, namely the FS6122 sensor and the AD620 module to amplify a small signal from the oxygen sensor whose output is analogous to a gain of 1.5 and 1000 times[22].

In 2021, Syed Razwanul Haque et al. conducted a study entitled "Rapidly Developable Low Cost and Power-Efficient Portable Turbine-Based Emergency Ventilator". This research aims to make portable ventilators at low cost using pressure sensors MPX2010[23].

The aims of this research evaluate and compares the performance of the MPX2010DP and MPX5010DP pressure sensors in measuring Positive End Expiratory Pressure (PEEP) during mechanical ventilation. Given the critical role of PEEP in patient safety, the study aims to identify stable and highly accurate pressure sensors. Through multiple lung tests and comparisons with a Digital Pressure Meter (DPM), the accuracy, stability, and reliability of both sensors are assessed. While both sensors provide accurate readings within the specified pressure range, the MPX2010DP sensor exhibits superior accuracy and stability compared to the MPX5010DP sensor. The results suggest that both sensors are well-calibrated and capable of providing accurate readings consistent with calibration tool standards. Overall, this research informs healthcare professionals and device manufacturers about optimal pressure sensor choices, thereby enhancing the quality and safety of mechanical ventilation procedures.

This research provides significant contributions to the field of mechanical ventilation and pressure measurement.

- It systematically compares the performance of the MPX2010DP and MPX5010DP sensors with a Digital Pressure Meter (DPM), offering valuable insights into the accuracy and reliability of pressure sensors commonly utilized in ventilators.
- The study identifies the MPX2010DP sensor as more stable and accurate in measuring PEEP parameters compared to the MPX5010DP sensor.
- Additionally, the ANOVA test results validate that both sensors provide pressure readings consistent with calibration tool standards.
- The research recommends the use of well-calibrated and accurate pressure sensors, particularly the MPX2010DP sensor, for measuring PEEP parameters, thus enhancing the quality and safety of mechanical ventilation.

The significance of this research lies in its potential to inform healthcare professionals and medical device manufacturers about the selection and development of pressure sensors for precise PEEP measurement, thereby improving patient care and safety during mechanical ventilation. These findings are pertinent to clinical practice, device design, and patient care, benefiting healthcare providers and patients in critical care settings.

II. MATERIALS AND TOOLS

This research was conducted as an experimental study. The author researched the creation of the Flow Analyzer modules of Positive End Expiratory Pressure (PEEP) parameters. Materials and methods will be described in the following sections.

A. Data Collection

This research was conducted at the Laboratory of the Department of Electromedical Engineering, Health Polytechnic, Ministry of Health, Surabaya. Data collection is carried out by comparing the pressure produced by the MPX2010DP, MPX2010DP, and DPM pressure sensors as a comparison with the pressure unit used, namely cmH2O.

In FIGURE 1 The data collection method is carried out using an air pump as an air source, which will flow air into the AMBU bag. The main function of the AMBU bag is to provide airflow or oxygen to the lungs of patients who cannot breathe on their own. Then the air from the AMBU bag will flow to the test lung. Test lung or ventilator test lung is used to simulate human lungs and produce breathing patterns and pressures that can be used to test the performance of respiratory equipment. Then the test lung will expand and deflate according to the air pressure given. The air pressure given to the lung test will be read on the DPM and Flow Analyzer.

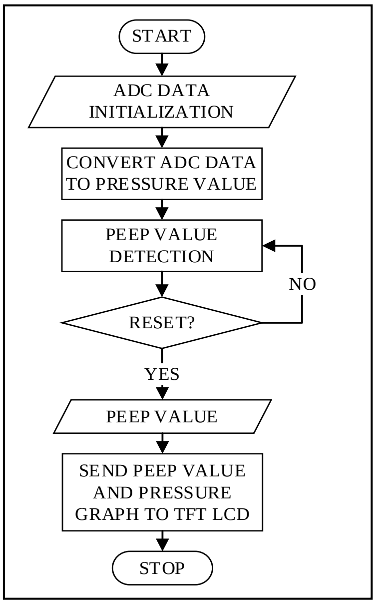

FIGURE2. Flowchart of the Flow Analyzer System with PEEP Parameter

In FIGURE 2 It is a flow chart from the Flow Analyzer, when the flow analyzer is turned on, it starts by initializing the ADC data received from the sensor circuit. The received ADC data will then be converted to cmH2O pressure units. Then the PEEP value will be detected from the converted pressure value. If the reset is pressed, then the detection of the PEEP value will be done again, if the reset is not pressed it will find the PEEP value. The PEEP value as well as the pressure chart will be sent to the TFT LCD for display and the system is completes.

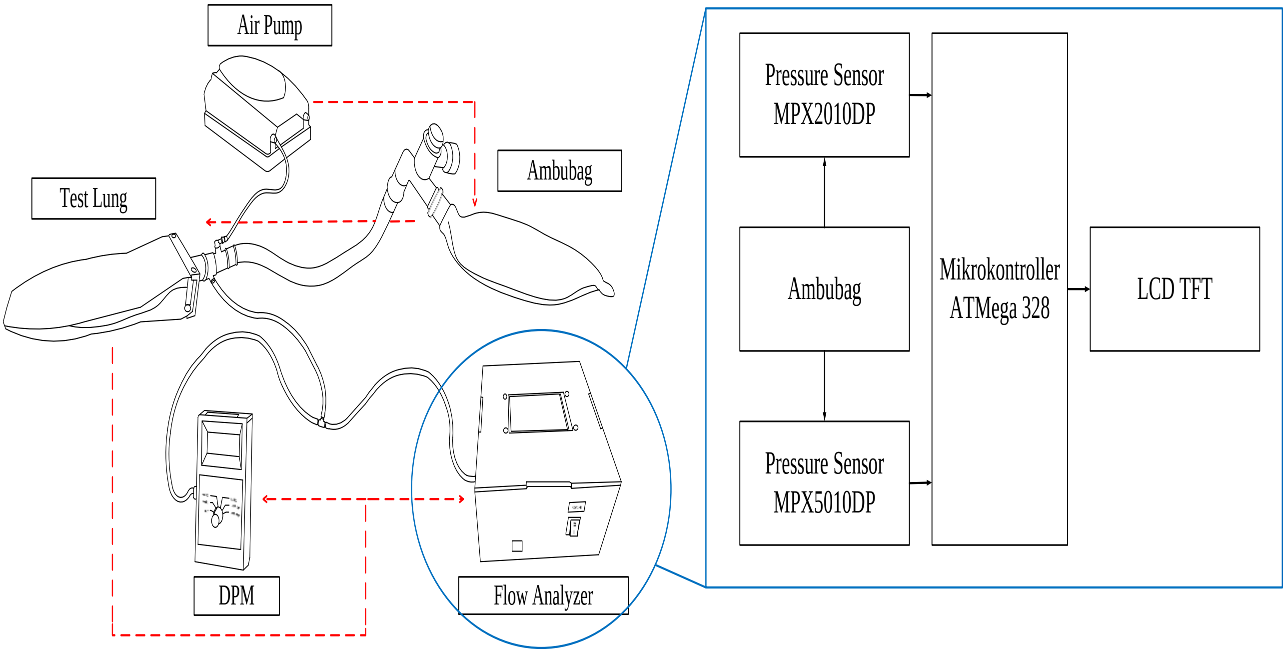

FIGURE 1. System Block Diagram of Flow Analyzer with PEEP Parameter

B. Data Analysis

Measurements on each setting of PEEP and PIP parameters will be carried out as much as 5x. That way, the average of the measurements can be searched using equations (1):

$$X = \frac{X1+X2+\cdots+Xn}{n} \qquad (1)$$

Where X indicates the mean (average) value for n-measurement, X1 indicates the first measurement, X2 shows the second measurement, and Xn indicates the n measurement. Then, the standard deviation (stdev) value that indicates the degree (degree) of data group variation or standard size deviation from the mean can be searched using equation (2):

$$stdev = \sqrt{\frac{\sum_{i=1}^{n}(Xi-X)^2}{n-1}} \qquad (2)$$

Where xi indicates the amount of the desired values, x indicates the average of the measurement results, and n shows the number of measurements. The % Error shows the error of the system. The lower value Error is the difference between the mean of each data. The error value is an error value that can be searched with equations (3):

$$Error\ \% = \frac{Data\ setting - average}{Data\ setting}\ x\ 100\% \qquad (3)$$

Uncertainty Value (UA) indicating lack of definite knowledge of the measured value can be sought by equation (4):

$$UA = \frac{Stdev}{\sqrt{n}} \qquad (4)$$

Where UA indicates the uncertainty value from the total measurement, SD shows the resulted standard deviation, and n shows the amount of measurement.

And correction indicates the value added to compensate for the addition of errors can be searched with equations (5):

$$Correction = Mean - data\ setting \qquad (5)$$

In FIGURE 3 the analog signal data from the MPX2010DP and MPX 5010DP sensors will be transformed into digital data and processed to yield pressure values in cmH2O units. Subsequently, the two sensors will be calibrated using a DPM (Digital Pressure Meter), and the average, error, standard deviation, uncertainty, and correction values will be determined. This data will be subjected to the Anova test to ascertain whether the sensor has been properly calibrated and provides accurate readings in compliance with the standards established by the calibration tool. The sensor will also be calibrated with a standard Flow Analyzer and Ventilator to acquire average, error, standard deviation, uncertainty, and correction values. All obtained data will be analyzed to establish which sensor exhibits superior accuracy and stability.

III. RESULT

In FIGURE 4 it can be seen that in the first experiment the two sensors have a large enough difference when the pressure drops. In the second experiment has a large error when 10 cmH_2O when rising, and 30 cmH_2O to 20 cmH_2O when falling. In the third experiment, almost all points have a difference to DPM but not too high and at 30 cmH_2O has the smallest error value. In the fourth experiment also at almost all points have a difference to DPM but not too high and at 15 cmH_2O when the pressure rises has the smallest error value. In the fifth experiment, the readings of the two sensors when up or down each sensor has a difference to the DPM reading, the largest difference is at 15 cmH_2O pressure when the pressure rises and the smallest at 15 cmH_2O pressure when the pressure drops.

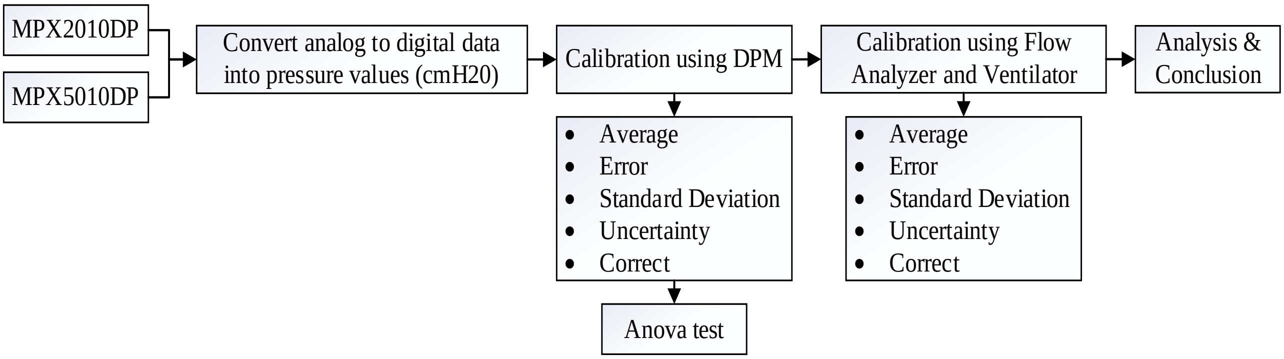

FIGURE 3. **Experimental setup diagram of the Flow Analyzer with PEEP par-ameters.**

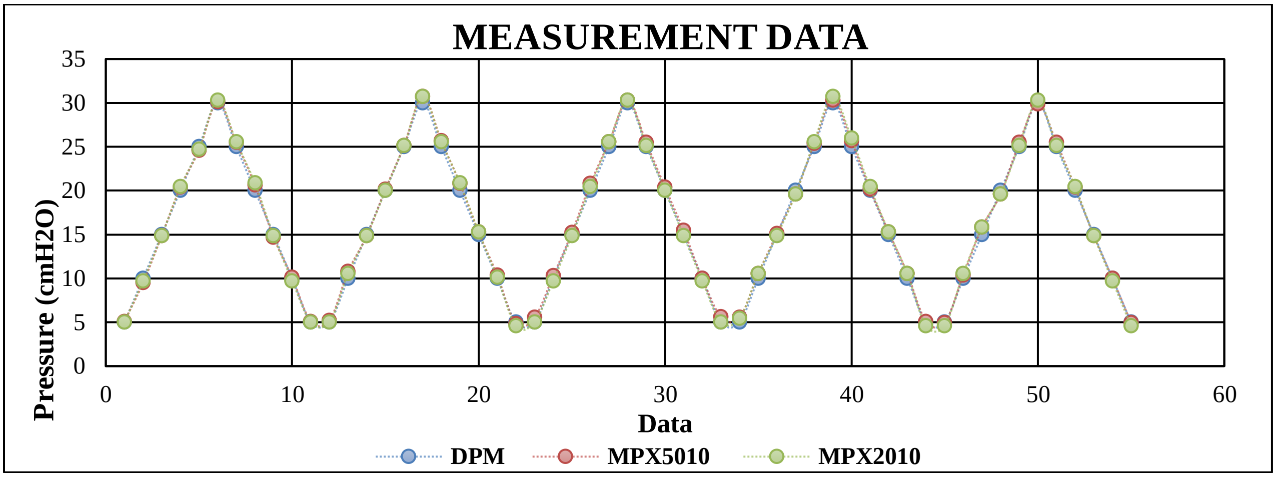

FIGURE 4. Experimental Measurement Data Was Compared with DPM (Digital Pressure Meter) at 11 Pressure Measurement Points Carried Out 5 Time

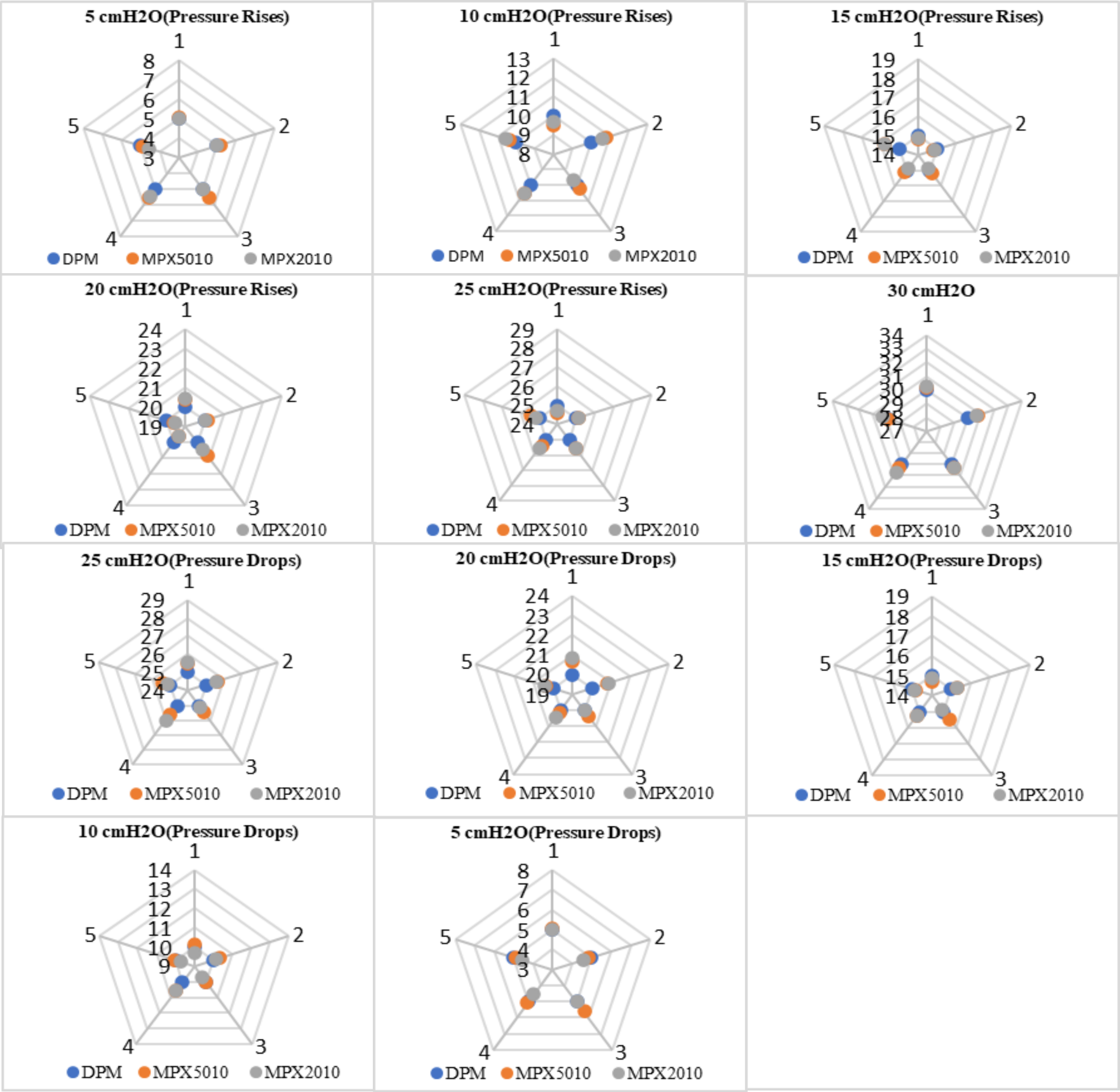

FIGURE 5. Distribution Data Graph of Each Pressure Point on 5 Experiment

In FIGURE 5 it can be seen the distribution of pressure at each point in all experiments, at a pressure of 5 cmH$_2$O when the pressure rises the MPX5010DP sensor has more error than the MPX2010DP sensor. At a pressure of 10 cmH$_2$O when the pressure rises, all sensors have almost the same error value. At a pressure of 15 cmH2O when the pressure rises, the largest error value of both sensors is equally located in the fifth experiment. At a pressure of 20 cmH$_2$O when the pressure rises, the largest error value of the two sensors is equally located in the third experiment but the MPX2010DP sensor error value is smaller than the MPX5010DP sensor.

At a pressure of 25 cmH$_2$O when the pressure rises, the largest error value of the MPX5010DP sensor is located in experiment 5 and the largest error value of the MPX2010DP sensor is located in experiment 4. At a pressure of 30 cmH2O, the largest error value is owned by the MPX2010DP sensor in experiments 2 and 4. At a pressure of 25 cmH2O when the pressure drops, the MPX2010DP sensor has a large enough error, namely in the 4th experiment with an error of 1 cmH$_2$O. At a pressure of 20 cmH$_2$O when the pressure drops, the MPX2010DP sensor has an error of 0 cmH$_2$O in the third experiment and in other experiments has a considerable error and for the MPX5010DP sensor there is an error in all experiments. At a pressure of 15 cmH$_2$O when the pressure drops, the error value is dominated by the MPX5010DP sensor and has the largest error in the third experiment. At a pressure of 10 cmH$_2$O when the pressure drops, both sensors equally have the largest error value in the fourth experiment. At a pressure of 5 cmH$_2$O when the pressure drops, the largest error is owned by the MPX5010DP sensor in the third experiment.

TABLE 1
Data Analysis from MPX2010DP Sensor

Parameter	No	Setting (cmH2O)	MPX2010DP Sensor					
			Mean	Error	Error Percentage	Standard Deviation	Uncertainty	Correction
Pressure	1	5	5.00	0.00	0.00	0.304	0.136	0.00
	2	10	10.23	-0.23	-2.26	0.471	0.211	0.23
	3	15	15.05	-0.05	-0.33	0.425	0.190	0.05
	4	20	20.00	0.00	0.00	0.430	0.192	0.00
	5	25	25.23	-0.23	-0.90	0.360	0.161	0.23
	6	30	30.45	-0.45	-1.51	0.236	0.105	0.45
	7	25	25.48	-0.48	-1.94	0.360	0.161	0.48
	8	20	20.52	-0.52	-2.58	0.360	0.161	0.52
	9	15	15.03	-0.03	-0.19	0.230	0.103	0.03
	10	10	9.97	0.03	0.32	0.385	0.172	-0.03
	11	5	4.74	0.26	5.16	0.236	0.105	-0.26

In TABLE 1 it can be seen in the table above that the average pressure has a different value from the reading on the DPM, where the MPX2010DP sensor obtained the largest error value of 5.160% at a pressure of 5 cmH$_2$O at the time of pressure drop while the smallest error value was obtained, namely 0.000% when the pressure was 5 and 20 cmH$_2$O when the pressure increase. Then, the largest standard deviation value is 0.471 at a pressure of 10 cmH$_2$O when increasing pressure and the lowest value is 0.23 at a pressure of 15 cmH$_2$O when decreasing pressure. The largest uncertainty value is 0.211 at 10 cmH$_2$O pressure when increasing pressure and the smallest value is 0.103 at 15 cmH$_2$O pressure when decreasing pressure. The largest correction value is 0.516 at a pressure of 20 cmH$_2$O when decreasing pressure while the smallest value is 0.0 at pressures 5 and 20 cmH$_2$O when increasing pressure.

In TABLE 2 it can be seen that the MPX5010DP sensor obtained the largest error value of 5.00% at a pressure of 5 cmH2O at the time of pressure increase while the smallest error value is 0.54% at a pressure of 20 cmH2O when the pressure increase. Then, the largest standard deviation value is 0.529 at a pressure of 20 cmH2O when increasing pressure and the lowest value is 0.099 at a pressure of 25 cmH2O when decreasing pressure. The largest uncertainty value (UA) is 0.237 at a pressure of 20 cmH2O when increasing pressure and the smallest value is 0.044 at a pressure of 25 cmH2O when decreasing pressure. The largest correction value is 0.542 at a pressure of 25 cmH2O when decreasing pressure while the smallest value is 0.108 at a pressure of 20 cmH2O when increasing pressure and 15 cmH2O when decreasing pressure.

TABLE 2
Data Analysis from MPX5010DP Sensor

Parameter	No	Setting (cmH2O)	MPX5010DP Sensor					
			Mean	Error	Error Percentage	Standard Deviation	Uncertainty	Correction
Pressure	1	5	5.25	-0.25	-5.00	0.272	0.122	0.25
	2	10	10.30	-0.30	-2.96	0.492	0.220	0.30
	3	15	15.16	-0.16	-1.09	0.393	0.176	0.16
	4	20	20.11	-0.11	-0.54	0.529	0.237	0.11
	5	25	25.23	-0.23	-0.91	0.388	0.173	0.23
	6	30	30.27	-0.27	-0.91	0.321	0.144	0.27
	7	25	25.54	-0.54	-2.17	0.099	0.044	0.54
	8	20	20.47	-0.47	-2.34	0.269	0.120	0.47
	9	15	15.11	-0.11	-0.72	0.332	0.149	0.11
	10	10	10.21	-0.21	-2.06	0.238	0.106	0.21
	11	5	5.11	-0.11	-2.20	0.306	0.137	0.11

TABLE 3
The Result of ANOVA Analysis

Anova: Single Factor

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	11	181.692	16.51745	73.66885
Column 2	11	182.754	16.614	71.43998
Column 3	11	180	16.36364	70.45455

ANOVA Alpha : 0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.350764	2	0.175382	0.002441	0.997562	3.31583
Within Groups	2155.634	30	71.85446			
Total	2155.984	32				

Based on TABLE 3, the results of the ANOVA analysis indicate that there is no significant difference in the pressure generated between the MPX2010DP sensor, MPX5010DP sensor, and DPM. This conclusion is drawn because the calculated F-value (0.002441) is less than the critical F-value (3.31583), and the P-value (0.997562) is greater than the specified significance level of 0.05. Therefore, the null hypothesis (H0) is accepted, suggesting that there is no significant difference between the sensors. It can be inferred that the sensor has been properly calibrated and provides accurate readings in accordance with the standards set by the calibration tool. Consequently, both the MPX2010DP sensor and MPX5010DP sensor are considered accurate in measuring the PEEP parameter on the ventilator.

IV. DISCUSSION

Based on the data collected from five experiments, the average error value of the MPX2010DP sensor is -0.15 cmH2O, while the error value of the MPX5010DP sensor is -0.25 cmH2O. Additionally, the average standard deviation for the MPX2010DP sensor is 0.34 cmH2O, and for the MPX5010DP sensor, it is 0.33 cmH2O. Both sensors have an average uncertainty of 0.15 cmH2O. Given these findings, it can be concluded that the MPX2010DP sensor performs better than the MPX5010DP sensor due to its smaller average error value, despite having almost identical standard deviation and uncertainty values.

In previous studies that utilized the MPX5010DP sensor, only numerical results were presented without accompanying graphs. However, in this research, data results and graphs were displayed on the GUI, similar to previous studies, but with the use of two pressure sensors: MPX2010DP and MPX5010DP. The aim was to compare and test the stability and accuracy of both sensors in the Flow Analyzer design.

It's important to note that the comparison tool used was the DPM, with a resolution of 1 cmH2O, while the readings from the MPX2010DP and MPX5010DP sensors have a resolution of 0.01 cmH2O. This difference in resolution significantly impacts the accuracy and precision of the measurements. This research facilitates the identification of the advantages and disadvantages of each sensor, aiding in the selection of the pressure sensor for the flow analyzer design. This selection greatly influences the accuracy and precision of pressure measurements made on the ventilator. Ultimately, this enables the development of a cost-effective flow analyzer with a user-friendly display for easier monitoring of measurements.

V. CONCLUSION

The purpose of the comparison between the two sensors was to determine the most stable and accurate pressure sensor for measuring PEEP in the Flow Analyzer design. Based on the research conducted, it was found that the MPX2010DP sensor is the most stable and accurate, but the MPX5010DP sensor has a lower cost because it does not require additional circuits. For further development, a standard Flow Analyzer tool should be used as a comparison, which is connected directly to the ventilator. Additionally, a DPM with a smaller resolution can be used to obtain highly accurate and precise measurement data. The comparison tool used should have a resolution of 0.01 cmH2O, which matches the resolution of both sensors. Using a comparison tool with a lower resolution can significantly affect the accuracy and precision of the measurements. For further development, an Internet of Things (IoT) system can be used to add other parameters such as flow, air temperature, and oxygen levels.

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