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Valve control system on a venturi to control FiO_2 a portable ventilator with fuzzy logic method based on microcontroller

Hadi Pranoto[1], Arief Marwanto[1], Suryani Alifah[1], Lukman Abdul Fatah[2]
[1]Master of Electrical Engineering Department, Faculty of Industrial Technology, Universitas Islam Sultan Agung (UNISSULA), Semarang, Indonesia
[2]CV. Bartec Utama Mandiri, Medical Equipment Industry, Semarang, Indonesia

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ABSTRACT

The results of several studies for portable ventilators state that it is difficult to regulate oxygen levels of fraction of inspired oxygen (FiO_2) that are in accordance with what is needed directly during the implementation of oxygen therapy. Some portable ventilators cannot set the FiO_2, so the ventilators work with a fixed FiO_2. To overcome this problem, medical oxygen with a level of 100% is lowered by mixing with free air with an oxygen content of about 40%. Mixing is carried out using a venturi with a large/wide hole that can be adjusted using a slated disk rotated by a direct current motor. The rotation control method uses Mamdani's fuzzy logic. The results of clinically lab-scale testing show that the fuzzy logic control system is able to control the average error pressure of 10.3%, better when compared to the on-off control method, which is 14.5%. The fuzzy logic method is able to increase the accuracy of FiO_2 on a portable ventilator.

Corresponding Author:

Arief Marwanto
Master of Electrical Engineering Study Program, Sultan Agung Islamic University (UNISSULA)
Semarang Indonesia
Email: arief@unissula.ac.id

1. INTRODUCTION

A mechanical ventilator is a positive or negative pressure breathing apparatus that produces controlled air flow in the patient's airway so that it is able to maintain ventilation and oxygen delivery for a long time. The mechanical breathing apparatus acts as a substitute for the function of the chest pump that is experiencing fatigue or failure [1]–[3]. There are many techniques and models of tools that can be used in oxygen therapy (O_2) which each have advantages and disadvantages. The selection of techniques and tools to be used is largely determined by the condition of the patient who will be given oxygen (O_2) therapy [4].

The techniques and tools that will be used in the administration of oxygen (O_2) therapy should meet the following criteria [2], [5]–[11],

– Able to regulate the concentration or fraction of oxygen (FiO_2) of inspiring air.
– Does not cause the accumulation of carbon dioxide (CO_2).
– Resistance to minimal breathing.
– Economical and efficient in the use of oxygen (O_2).

Due to the importance of oxygen therapy for several treatment therapies, the lack of availability and high availability of ventilators that can regulate oxygen levels in the air [12]. This study is designed an accurate and stability control of the oxygen concentration value or Fraction of Inspired Oxygen (FiO_2) that can be applied to a portable mechanical ventilator at a relatively low price. The ventilator can be used in public medical services other than in the ICU room of a large hospital.

2. METHOD

The architectural design in this study was designed in several parts, namely; oxygen level, oxygen mixing system, Maxtec Max-250 sensor as oxygen content detector, microcontroller data processing, fuzzy logic control system control, and display. The object taken in this study was the oxygen level in the breathing circuit of a ventilator. The analog signal from the oxygen sensor enters the analog to digital converter (ADC) microcontroller to convert the signal from the analog signal into a digital signal and the data will enter the Fuzzy logic oxygen level control software. The result of the control system will regulate the variable magnitude of the opening which will regulate the amount of air entering the mixing venturi [13], to obtain the oxygen concentration in accordance with the settings, then the processing results will be displayed in an LCD.

The prototype of the system in this study was designed using Arduino Mega as the main microcontroller. Figure 1 has shown the diagram of the equipment block as a whole [14]. Figure 2 has shown the process of air mixing due to pressure differences. The process of mixing oxygen can be carried out using the principle of continuity and Bernoulli's equation [14], [15]. Figure 3 have shown Bernaulli's principle [13].

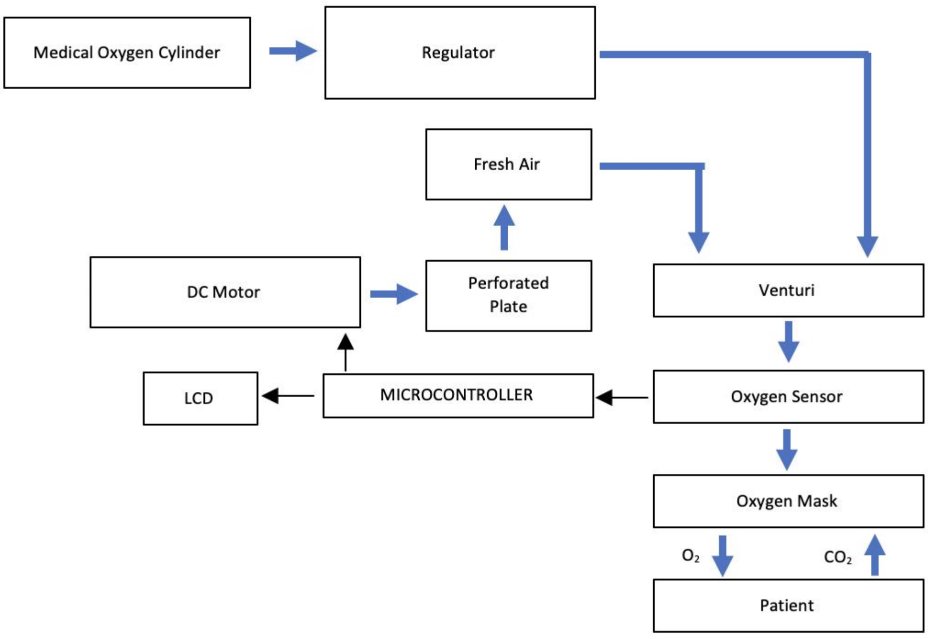


Figure 1. Ventilator oxygen concentration control system model

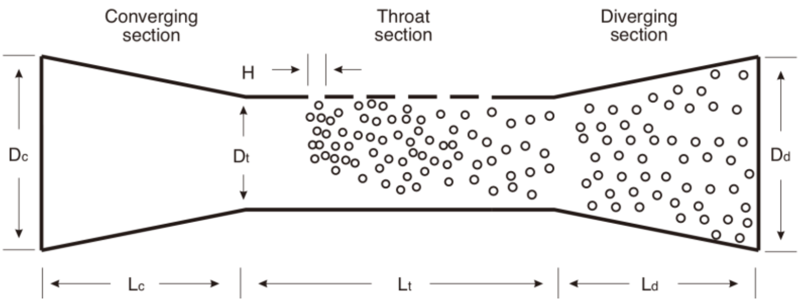


Figure 2. The process of air mixing due to pressure differences

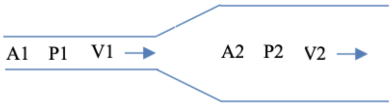


Figure 3. Bernoulli principle [13]

Information,

P1: Pressure 1	A1: Cross-sectional area 1	P3: Free air pressure
V1: Volume 1	P2: Pressure 2	
A2: Cross-sectional area 2	V2: Volume 2	

the number of times that come in and the time that comes out is the same [16], [17].

$$Q = \frac{Volume}{time} \quad (1)$$

The volume of fluid passing through the cross section of the pipe in a certain interval of time (ΔT) can be expressed as the product of the cross-sectional area of the pipe (A) multiplied by the distance the fluid travels (Δx) [16], [17]. Where (ΔT/Δt) there is a substitution of the velocity of the fluid V. Therefore, we can calculate the volumetric flow rate of the fluid simply by measuring the velocity of the fluid. Speed measurements can be achieved by applying the concepts discussed above to pipes with varying cross sections as shown in Figure 2. By making a venturi that has a hole that can be adjusted in area, we can adjust the amount of space air that will enter and mix so that the oxygen concentration could be controlled. Figure 4 has shown a space air hole area regulating system design. A fuzzy-controlled direct current motor will rotate the scuffed disk [18]–[20]. The amount of air entering depends on the rotation of the disk.

$$Q = \frac{A\,x\,\Delta x}{\Delta t} = \mathrm{AV} \quad (2)$$

$$\Delta P = P_1 - P_2 = \frac{1}{2}\rho(V_2^2 - V_1^2) \quad (3)$$

$$\rho A_1 V_1 \Delta t = \rho A_2 V_2 \Delta t \quad (4)$$

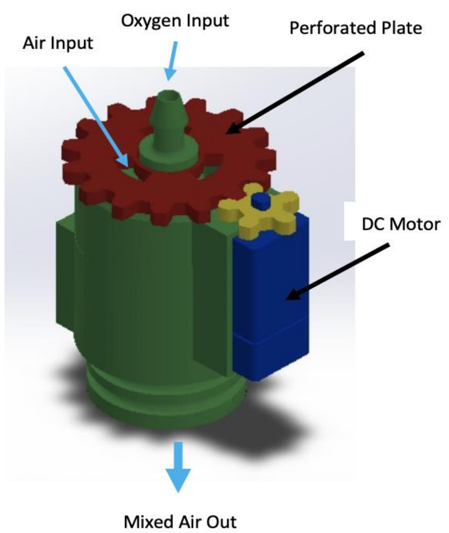
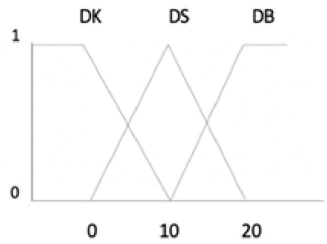


Figure 4. Space air hole area regulating system

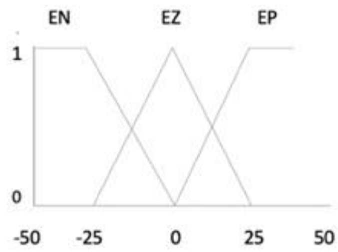
2.1. Fuzzy logic method and defuzzification

The Fuzzy logic method used in this study is Mamdani. Mamdani is also referred to as the MAX-MIN method [21], [22]. To find out the output through 4 steps: First, forming membership function of Fuzzy sets; Second, applying the implications of Mamdani functions (rules) using the Min Implications function; Third, Mamdani's rule preparation can use 3 composition rules, namely: max, additive, or; Fourth, affirming (defuzzied) the result of the composition set, needs to be interpreted into a crisp value as the final result.

The fuzzy control system is designed with two input variables (Error and delta error) as well as one output variable (Aperture time). The input error variable is the specified oxygen level minus the measured oxygen level. The delta error input variable is the difference between the current error and the previous error. Figure 5(a) has shown error vaiable membership function and Figure 5(b) has shown delta error membership function. Figure 6 as shown the output variable of aperture time is the length of the rotating chamber air gap disk with membership function.



(a)



(b)

Figure 5. Fuzzy membership function. (a) Error variable and (b) Delta error variable

Note:
EN: Negative error; EZ: Error zero; EP: Positive error; EN: Negatif error; Zero error; EP: Positif error

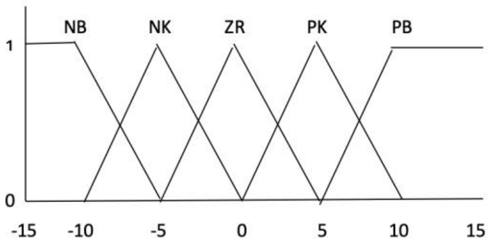


Figure 6. Rotating old variable membership function

2.2. Inference model

In the functional form, the degree of membership is expressed as a certain mathematical function. Degree of membership of each element requires calculation. Mamdani fuzzy inference system operation: First is to determine a set of fuzzy rules. The input membership function is used as fuzzification. secondly, fuzzy operations are performed by combining inputs that are fuzzified according to fuzzy rules to form fuzzy operations. The mathematical function that is usually used is the trapezoidal function. Following is error variable membership function.

$$\mu_{EN}(X) = \begin{cases} 1 & ;\ x \leq -25 \\ \frac{-x}{25} & ;-25 < x < 0 \\ 0 & ;x \geq 0 \end{cases} \tag{5}$$

$$\mu_{EZ}(X) = \begin{cases} 0 & ;\ x\ \leq -25\ or\ x \geq 25 \\ \frac{x+25}{25} & ;-25 < x < 0 \\ \frac{25-x}{10025} & ;0 < x < 25 \\ 1 & ;x = 0 \end{cases} \tag{6}$$

$$\mu_{EP} = \begin{cases} 0 & ;\ x\ \leq 0\ or\ x \geq 50 \\ \frac{25-x}{25} & ;\ 0 < x < 25 \\ \frac{25-x}{25} & ;\ 25 < x < 50 \\ 1 & ;\ x = 25 \end{cases} \tag{7}$$

Variable delta error membership function,

$$\mu_{DK}(X) = \begin{cases} 1 & ; x = 0 \\ \frac{10-x}{10} & ; 0 < x < 10 \\ 0 & ; x \geq 10 \end{cases} \quad (8)$$

$$\mu_{DS}(X) = \begin{cases} 0 & ; x \leq 0 \; or \; x \geq 20 \\ \frac{x}{10} & ; 0 < x < 10 \\ \frac{10-x}{10} & ; 10 < x < 20 \\ 1 & ; x = 10 \end{cases} \quad (9)$$

$$\mu_{DB}(X) = \begin{cases} 0 & ; x \leq 10 \\ \frac{10-x}{10} & ; 10 < x < 20 \\ 1 & ; x \geq 20 \end{cases} \quad (10)$$

The fuzzy processing stage is based on a set of logical rules in the form of an IF-THEN statement, where the IF part is called the "antecedent" and the THEN part is called the "consequence" [23]. This research fuzzy control system has 9 rules. Table 1 has shown the fuzzy base role mode created for the control system.

Table 1. The fuzzy base role mode

Rule		Error		ΔError		Output
1	IF	EP	AND	DK	THEN	PB
2	IF	EP	AND	DS	THEN	PB
3	IF	EP	AND	DB	THEN	PK
7	IF	EN	AND	DK	THEN	NB
8	IF	EN	AND	DS	THEN	NB
9	IF	EN	AND	DB	THEN	NK

2.3. Defuzzification

The next stage is defuzzification which converts the fuzzy output to crisp according to the predetermined affiliate function [24]. If the oxygen level has not reached the specified one, the controlling system will rotate the splattered disk in such a way that it can be achieved. The input of the defuzzification process is a fuzzy set obtained from the composition of fuzzy rules, while the resulting output is a firm real number. So that if given a fuzzy set in a certain range, a certain firm value can be taken as a value to rotate the motor clockwise or counterclockwise with the duration of the DC motor flame. The longer the motor rotates, the larger the opening of the free air valve. The defuzzification used is the centroid method (Composite moment), a crisp solution obtained by taking the center point of the fuzzy area [25].

Examples of Defuzzification processes,
Error = 20 and delta error 17,

$$\mu_{EP}(20) = \frac{20}{25} = 0.8$$

$$\mu_{DK}(17) = \frac{17-10}{10} = 0.7$$

$$\mu_{DB}(17) = \frac{20-17}{20-10} = 0.2$$

Rule1: If **EP** and **DK** then **PB**

$$\alpha - Predicate_1 = \mu_{EP}(20) \cap \mu_{DK}(17)$$

$$\alpha - Predicate_1 = \min\,(\mu_{EP}(20);\ \mu_{DK}(17))$$

$$\alpha - Predicate_1 = \min(0.8; 0.7)$$

$$\alpha - Predicate_1 = 0.7$$

Rule2: If **EP** and **DB** the **PK**

$$\alpha - Predicate_2 = \mu_{EP}(20) \cap \mu_{DB}(17)$$

$$\alpha - Predicate_2 = \min\,(\mu_{EP}(20);\ \mu_{Dk}(17))$$

$$\alpha - Predicate_2 = \min(0.2; 0.7)$$

$$\alpha - Predicate_2 = 0.2$$

the next stage is used the maximum method, which is to take the maximum values from the minimum values in the previous stage. Figure 7 has shown compositional result area.

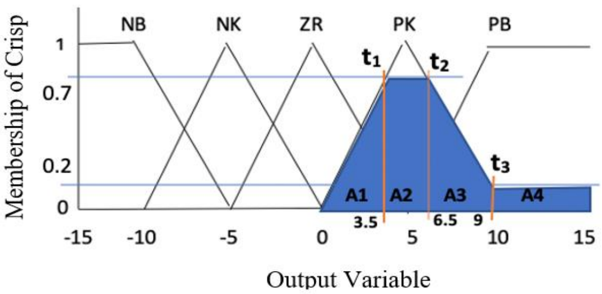


Figure 7. Compositional result area

Looking for the value of t_1:

$$\frac{t1-0}{5-0} = 0.7$$

Then it can be calculated t_1 = 3.5. In the same way t_2 and t_3 can be calculated, that is, t_2 = 6.5 and t_3 9. Membership curve $\mu_1(z)$,

$$\mu(Z) = \begin{cases} 0 & ;\ x \leq 0 \\ \frac{z}{3.5} & ;0 < x < 3.5 \\ 0.7 & ;x \geq 3.5 \end{cases}$$

Calculating the moment M_1,

$$M_1 = \int_0^{3.5} \frac{z}{3.5}\, z\, dz = 4.08$$

Calculating the area of A1,

$$A_1 = \int_0^{3.5} \frac{z}{23.5}\, dz = 1.75$$

In the same way we can calculate M_2, M_3, M_4, A_2, A_3 and A_4,
M2 = 10.5; M3 = 42.39; M4 = 14.4; A2 = 2.1; A3 = 7.68; A4 = 1.2.

Centroid Defuzzification:

$$Z^* = \frac{\int \mu(z)z\,dz}{\int \mu(z)\,dz} = \frac{M_1+M_2+M_3+M_4}{A_1+A_2+A_3+A_4} \quad (11)$$

$$Z^* = \frac{4.08+10.5+42.39+14.4}{1.75+2.1+7.68+1.2} = 5.6$$

3. RESULTS AND DISCUSSION

FiO_2 testing is carried out at the Testing and Calibration of Clinical Laboratory, Semarang. The test equipment used is a Fluke brand ventilator calibration device with the Mobile VT type. The test uses a breathing circuit and artificial lungs (test lung) to simulate the actual patient. The first test was carried out using an on-off control system. System control is carried out without a reverse value as feedback. Testing is performed repeatedly with different set values of points. It starts with a set of 40% to 100% points with an interval of 5%. Measurements with a calibration tool are carried out 5 times. The result of the average value of the oxygen level is read on the calibration tool compared to the value on the set of points. After testing, the results listed in Table 2 are obtained. The difference between the specified value (set of points) and the average value read on the measuring instrument is compared. The difference in values that occur (errors) for each set of points is made on average, which is 14.5%.

The next step is ventilator testing using the Fuzzy Logic method. System control is carried out by entering values that read as feedback. Testing is performed repeatedly with different set values of points. It starts with a set of points 20% to 100% with an interval of 5%. Measurements with a calibration tool are carried out 5 times. The result of the average value of the oxygen level is read on the calibration tool compared to the value on the set of points. After testing, the results listed in Table 1 are obtained. Figure 8 has shown the venturi regulates oxygen levels design. Table 2 has shown F_iO_2 on-off control test result and Table 3 has shown fuzzy methode.

Table 2. Test results on-off method

No	Set Point	Measured Value (%)					Ave-rage	Error
1	40	35.2	34.1	36.3	46.2	50.6	40.5	1.2
2	45	44.7	44	47.3	38.5	38.5	42.6	5.3
3	50	59.4	55	62.7	46.2	59.4	56.5	13.1
4	55	64.9	66	59.4	62.7	51.7	60.9	10.8
5	60	66	59.4	70.4	58.3	73.7	65.6	9.3
6	65	73.7	60.5	77	81.4	75.9	73.7	13.4
7	70	67.1	69.3	82.5	75.9	74.8	73.9	5.6
8	75	77	88	83.6	86.9	90.2	85.1	13.5
9	80	83.8	99	85.8	80.3	84.7	86.7	8.4
10	85	94.5	97.9	90.2	90.3	90.2	92.6	9.0
11	90	99.3	96.8	98.4	96.8	96.8	97.6	8.5
12	95	98.3	98.6	98.4	93	90.4	95.7	0.8
13	100	95.9	98.4	99.4	98.6	94.5	97.4	2.6
							Average	14.5%

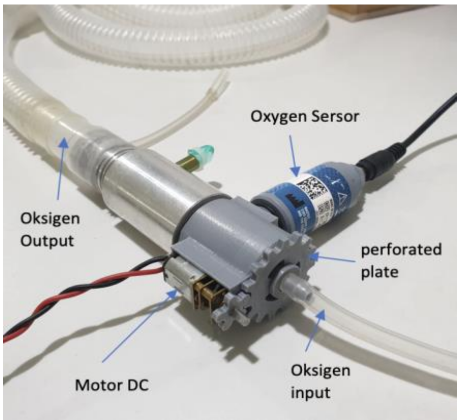


Figure 8. Venturi regulates oxygen levels

Table 3. Test result fuzzy method

No	Set Point	Measured Value (%)					Ave-rage	Error
1	40	42.9	42.9	42.6	38.6	41.4	41.7	4.2
2	45	46.4	44.5	47.5	42.6	46.4	45.5	1.1
3	50	53.4	48.9	48.5	51.3	53.3	51.1	2.2
4	55	50.5	52.3	57.5	54.3	56.3	54.2	1.5
5	60	58.5	58.3	58.6	63.5	63.2	60.4	0.7
6	65	64.5	66.4	67.5	66.7	66.6	66.3	2.1
7	70	69.4	72.4	74.3	73.5	69.5	71.8	2.6
8	75	77.5	68.4	74.6	74.5	78.5	74.7	0.4
9	80	80.8	78.8	79.6	82.4	85.3	81.4	1.7
10	85	86.3	87.6	86.4	84.5	87.4	86.4	1.7
11	90	93.5	89.5	92.2	88.9	93.4	91.5	1.7
12	95	98.3	94.5	93.6	96.4	98.9	96.3	1.4
13	100	100	99.5	100	97.5	95.9	98.6	1.4
							Average	2.1%

Figure 9 has shown the deviation that occurs in the on-off control system. The number of errors/deviations that occur is randomly valued between 0.8% and 13.6%. Figure 10 has shown that the deviation that occurs is relatively smaller, namely in the fuzzy control system. The number of errors/deviations that occur is randomly valued between 0.8% and 13.6%. The number of errors/deviations that occur is randomly valued between 0.4% and 4.2%.

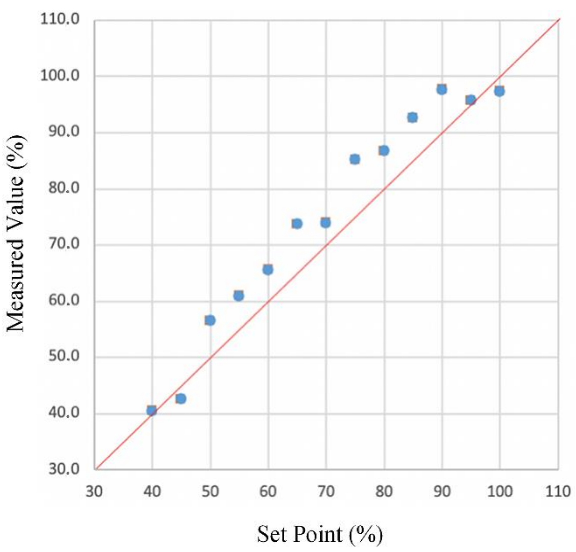


Figure 9. Test results on-off method

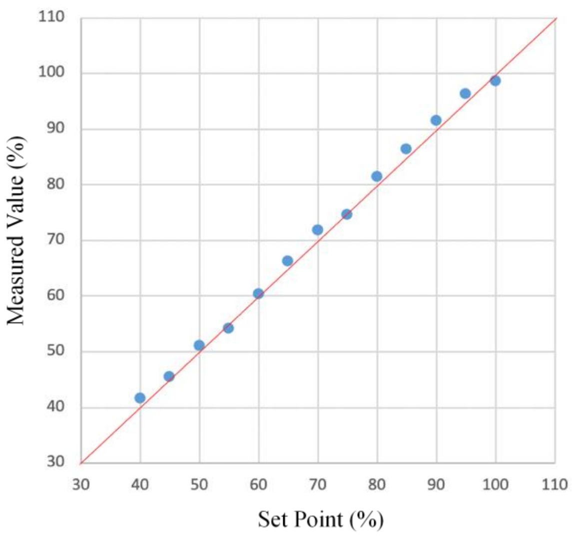


Figure 10. Test result fuzzy method

4. CONCLUSION

The arrangement of the size of the venturi hole so that free air can enter can be used to regulate the oxygen concentration on a ventilator. The Fuzzy method control system is very well applied in a ventilator to control the stability of FiO_2 oxygen levels that have been predetermined at a certain amount by the user. The error for FiO_2 control is 2.1% with a minimum set point of 40%. The manufacture of portable mechanical ventilators that can be regulated by FIO_2 can be done domestically relatively easily and cheaply, so that they can be used en masse in emergency hospitals when there is a pandemic of diseases that attack the health of the human respiratory system.

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BIOGRAPHIES OF AUTHORS

Hadi Pranoto is currently a leader at CV. Bartec Utama Mandiri, a manufacturer of Medical Devices. He graduated from the Faculty of Mechanical Engineering, University of Indonesia. He taught as a Lecturer who teach Cooling System Engineering Courses and Pumps & Compressor Courses from 1999 to 2004, and served as Head of the Laboratory of Mechanical Engineering Department at the Academy of Technology Semarang. In 1996, he became one of the research teams at the Institute for the Study of Energy, University of Indonesia for refrigerator testing. In 2018 he resumed his Master's Degree in Electrical Engineering at Sultan Agung University. Currently focusing on the production and development of medical devices by collaborating with other companies, and also with universities to produce innovative medical device products. He can be contacted at email: pranotohadi354@gmail.com.

Arief Marwanto is lecturer in Master of Electrical Engineering Department, Faculty of Industrial Technology Universitas Islam Sultan Agung (UNISSULA), Semarang, Indonesia. He graduated from the faculty of Engineering, major in Electrical Engineering at Muhammadiyah University of Jogjakarta. His master and Ph.D degree has obtained from Universiti Teknologi Malaysia major in Electrical and Electronic Engineering Department. He was published more than 100 academic papers in reputable conferences end journals. His interest research in renewable energy, biomedical engineering, IoT, telematics and embedded technolgy. He can be contacted at email: arief@unissula.ac.id

Suryani Alifah is lecturer in Master of Electrical Department, Faculty of Industrial Technology. Universitas Islam Sultal Agung (UNISSULA), Semarang. She received the Degree and Master of Engineering in Electrical Engineering from Institut Teknologi Bandung (ITB), Indonesia in 1993 and 2005 repectively. She obtained her Ph.D in Electrical Engineering from Universiti Teknologi Malaysia in 2012. She was published more than 75 academic papers in reputable conferences and journals. Her main researchs interest area are Radio over Fiber Communication System and Internet of Things. She can be contacted at email: suryani.alifah@unissula.ac.id

Lukman Abdul Fatah is lecturer in Institut Digital Ekonomi LPKIA, Bandung, Indonesia. He graduated from Bandung Institute of Technology, majoring in Physics, FMIPA Department. In 2010 he continued his Masters at Yappan Jakarta, graduating with a master of public adminstration degree. In 2018 he took another Master's Degree in Electrical Engineering at Sultan Agung University, Semarang. Currently the fields being occupied are Sensor System & PC Interfacing, Electronic Circuit Designer Measuring, Controlling and Automation System Designer, Equipment Microcontroller Based Designer, CNC Machining, Robotic and Drone Designer. He can be contacted at email: lukman.a.f@gmail.com