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Evaluation of Air-supply Units of Powered Air-Purifying Respirators

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Abstract. The authors are developing a low-cost, high-performance Powered Air-Purifying Respirator (PAPR), "Distancing-Free Mask", as an alternative to "lockdown" due to a pandemic caused by COVID-19 or a new airborne virus. An air supply unit was developed for the next prototype of the "Distancing-Free Mask". The air supply unit developed consists of an airtight chamber formed of styrene board in the front of a light work helmet, a Pomp installed in the chamber, and a HEPA filter embedded in the front of the air supply unit. "The evaluation device for differential pressure dependence of flow rates of air supply and exhaust units of Powered Air-Purifying Respirator (PAPR)". (Hereinafter abbreviated as "The evaluation device for differential pressure dependence of flow rates") was developed. This device is used to measure the differential pressure dependence of flow rates of the air supply unit.

"The evaluation device for differential pressure dependence of flow rates" was used to evaluate the differential pressure dependence of flow rates for the developed Air supply unit and a commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit).

Based on the measured differential pressure dependence of flow rates of the developed air supply unit, the air supply flow rate was formulated as a function of the pump applied voltage $\boldsymbol{V}$ [V] and the differential pressure $\boldsymbol{\Delta P}$ [Pa] between the inside and outside of the unit, and regression equations were obtained using the least-squares method. The RMS value of the difference $\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$ between the actual flow rate $\boldsymbol{Q}_{\mathbf{measured}}$ [L/min] and the estimated flow rate $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] obtained from the regression equation was 2.97 [L/min] in the range 320 > Flow_rate $\boldsymbol{Q}$ > 50 [L/min]. Within this measurement range, the relative standard uncertainty of this regression equation was estimated to be 7.3 %.

Based on the measured differential pressure dependence of flow rates of the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit), the air supply flow rate was formulated as a function of the differential pressure inside and outside the unit, $\boldsymbol{\Delta P}$ [Pa], and regression equations were obtained for the two modes (High power mode and Low power mode) using the least-squares method. The RMS value of the difference $\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$ between the actual flow rate $\boldsymbol{Q}_{\mathbf{measured}}$ [L/min] and the estimated flow rate $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] obtained from the regression equation was 0.58 [L/min] in High power mode and 1.71 [L/min] in Low power mode in the range 500 > Differential pressure $\boldsymbol{\Delta P}$ > 50 [Pa]. Within this measurement range, the relative standard uncertainty of this regression equation was estimated to be 6.8 % in High power mode and 6.8 % in Low power mode.

1. Introduction

COVID-19, which raged around the world for more than three years, forced us to take measures against infectious diseases such as new lifestyles (social distance, mandatory wearing of masks, hand washing, and etc.) and the acquisition of mass immunity through vaccination [1, 2]. However, due to the emergence of new COVID-19 mutant strains and other factors, pandemics have occurred many times around the world, and each time a "lockdown" situation has continued to be implemented, imposing significant economic losses and restriction of freedom for individuals, companies, and society [3-7]. Even in the current situation, we can expect to continue to face a situation where we may need to "lockdown" due to another pandemic caused by a new COVID-19 mutant or a new airborne virus at any time.

In this current situation, the authors have proposed an alternative that has less economic damage, restriction of freedom of activity, and other disadvantages to individuals, companies, and society compared to "lockdown" is the construction of a social system using a "Distancing- Free Mask", a low-cost high-performance PAPR, and a PAPR wearing rate network management system. These two measures are countermeasures against airborne and droplet transmission routes [8, 9]. As prototype PAPR devices, we have developed a very low-cost model [10] with performance equivalent to that of high-end medical PAPR, and a high-function model [11] equipped with sensors (CO2 sensor, differential pressure sensor) and a controller.

In creating the "Distancing-Free Mask" a "Breathing air simulator" was developed as an option for the "Permeation Flow Rate Evaluator" and the device [12]. "Permeation Flow Rate Evaluator" is a device for measuring the relationship between the transmission flow rate and differential pressure of filters, such as the non-woven fabric filters used in face masks for general use and medical use, commercially available unprocessed non-woven fabric filters, and HEPA filters used in the air supply unit [13] and exhaust unit [14] of the "Distancing-Free Mask" [15]. "Breathing air simulator" is a device that is connected to the "Permeation Flow Rate Evaluator" to supply and exhaust air to the "Permeation Flow Rate Evaluator".

In this study, we used “The evaluation device for differential pressure dependence of flow rates” to evaluate the differential pressure dependence of flow rates for the developed Air supply unit and the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit). "The evaluation device for differential pressure dependence of flow rates" can measure individually the differential pressure dependence of flow rates of the air supply and exhaust units of the PAPR prototype as well as the non-woven filter itself. In addition, the characteristics of the PAPR can be measured with the air supply and exhaust units combined. Measuring the differential pressure dependence of the flow rates of the air supply and exhaust units separately is an important indicator of performance in creating a "Distancing- Free Mask".

To evaluate the differential pressure dependence of flow rates, we measured the differential pressure and voltage dependence of the flow rates of an air supply unit and the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit). From the measurement results, we attempted to develop a regression equation.

2. Measuring device and air supply unit

Figure 1 shows a schematic diagram of "The evaluation device for differential pressure dependence of flow rates". Figure 2 shows a schematic diagram of the connection between the developed Air supply unit and the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit).

"The evaluation device for differential pressure dependence of flow rates" can measure individually the differential pressure dependence of flow rates of the intake and exhaust units of the PAPR prototype as well as the non-woven filter itself. In addition, the characteristics of the PAPR can be measured with the air supply and exhaust units combined.

"The evaluation device for differential pressure dependence of flow rates", air from the air supply unit enters the pressure buffer, passes through Flow_meter 1 (model: SFM3000-200-C, manufacture: Sensirion) and Flow_meter 2 (model: SFM3000-200-C, manufacture: Sensirion) connected in parallel and is discharged from the exhaust pump.

The volume of the pressure buffer in "The evaluation device for differential pressure dependence of flow rates" was about 1.6 [L], which is the same as the volume in the hood of the PAPR to be developed.

This device is equipped with a Flow_meter 1 and Flow_meter 2 in parallel that measure the flow rate of air delivered from the pressure buffer. Flow_meter 1 and Flow_meter 2 (model: SFM-3000-200-C, manufacturer: Sensirion) with capacity of ± 200 [L/minPa], update time of 0.5 [ms], span accuracy of ±1.5 [% m.v.] in typical, offset accuracy of ± 0.05 [L/min] in typical, is used to measure the flow rate.

For the direction of air flow (flow rate $\boldsymbol{Q_1}$, $\boldsymbol{Q_2}$) in "The evaluation device for differential pressure dependence of flow rates", the direction of the red and blue arrows in Fig. 1 is positive.

"The evaluation device for differential pressure dependence of flow rates" can supply and exhaust air by connecting pipes from "Breathing air simulator". [12]

The differential pressure in the pressure buffer relative to the outside air is measured by a differential pressure sensor (Model: SDP816-500 Pa, manufacture: Sensirion). The differential pressure can be changed by operating a pump on top of the device. A differential pressure sensor (model: SPD-816-500Pa, manufacturer: Sensirion) with capacity of ± 500 [Pa], update time of 5 [ms], span accuracy of ±3 [% m.v.], offset accuracy of ±0.1 [Pa], is used to measure the differential pressure. The differential pressure $\boldsymbol{\Delta P}$ is positive when the pressure inside the pressure buffer is negative with respect to atmospheric pressure, since the inside of the pressure buffer is used as the reference.

The differential pressure sensor and Flow-meter are controlled by an Arduino; the sensor values measured by the Arduino are sent to a PC and displayed on the measurement software.

"The evaluation device for differential pressure dependence of flow rates" is used to evaluate the differential pressure dependence of flow rates of the measured object (Non-woven filter, intake and exhaust units of PAPR prototype machine) by measuring the flow rate $\boldsymbol{Q}$ and differential pressure $\boldsymbol{\Delta P}$ with a flow meter and a differential pressure sensor.

The side and top views of the Air supply unit are shown in Figure 3.

The air supply unit is made of a part of a light work helmet (commercial price: 8 USD) cut off as a base. In addition, polystyrene board (Color: white, Thick: 5 [mm]) is used as a structural material. The air-supply unit consists of an airtight chamber made of styrene board at the front of the helmet and a Pomp installed inside the chamber.

A non-woven filter is embedded in the front of the Air-supply unit. External air is introduced through the filter into the airtight chamber, which is filled with purified air. The purified air is supplied through an opening above the wearer's forehead by a Pomp installed in the airtight chamber.

The non-woven filter on the air supply side was cut from a HEPA filter for an air purifier (model: PMMS-DCHF, manufacturer: IrisOyama Ltd.). The expanded surface area of the air intake filter is approximately 7.0×10^2 [cm^2]. The exhaust side filter is a thin non-woven filter (Total surface area: approximately 25 [cm^2]), placed in front of the left and right ears.

Pomp (model: San Ace B76 109BD12HC2, manufacturer: Sanyo Denki Corp.) has a rated output of DC 12 [V], 0.37 [A], maximum static pressure of 150 [Pa], maximum airflow of 360 [L/min], and an operating voltage range of 10.2 [V] to 13.8 [V]. The battery shown in Fig. 3 is not used in this experiment, but the Power supply unit is used as the power source as shown in Fig. 1.

The 3M consists of a main unit (Waist unit) consisting of a battery, HEPA filter, and pump, and a tube that delivers purified air. The 3M has two output modes: High power mode and Low power mode.

To measure the differential pressure dependence of flow rates, the Air supply unit and 3M are equipped with a pipe through which air from the pump passes, a polystyrene board to connect the Pipe to the Air supply unit, and a Plate (an aluminum plate with φ80 [mm] holes) to connect the Pipe to the device.

Figure 4 shows a captured image of the measurement software. The software displays time series of differential pressure, flow rate of Flow_meter 1, and flow rate of Flow_meter 2, and their average values. The measurement interval is fixed at 10 [ms] units. The number of measurements (number of samplings) can be adjusted in increments of one using Adjustment button of the number of measurements, $\boldsymbol{N}$. Therefore, the measurement time is $\boldsymbol{N} \times 10$ [ms]. After the measurement is completed, the screen displays a time series of differential pressure and flow rates of Flow_meter 1 and Flow_meter 2 and their average values.

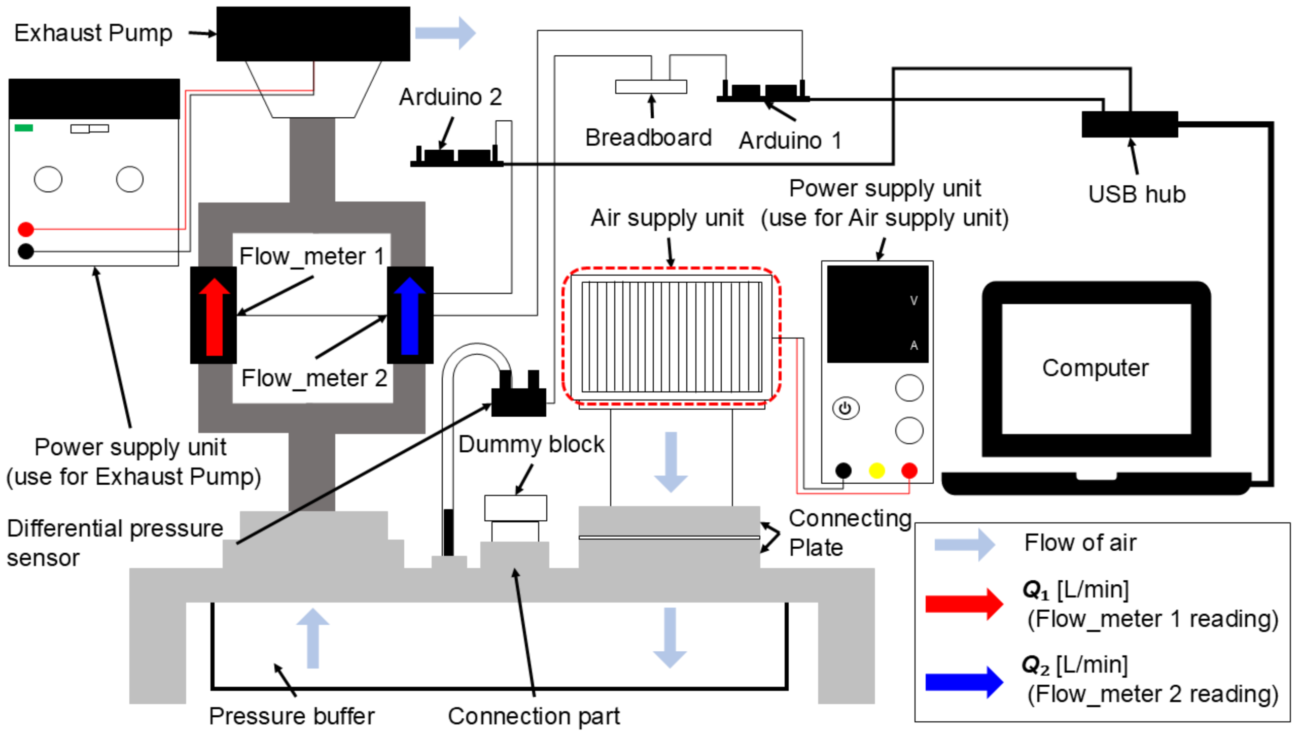


Fig. 1. A schematic diagram of "The evaluation device for differential pressure dependence of flow rates".

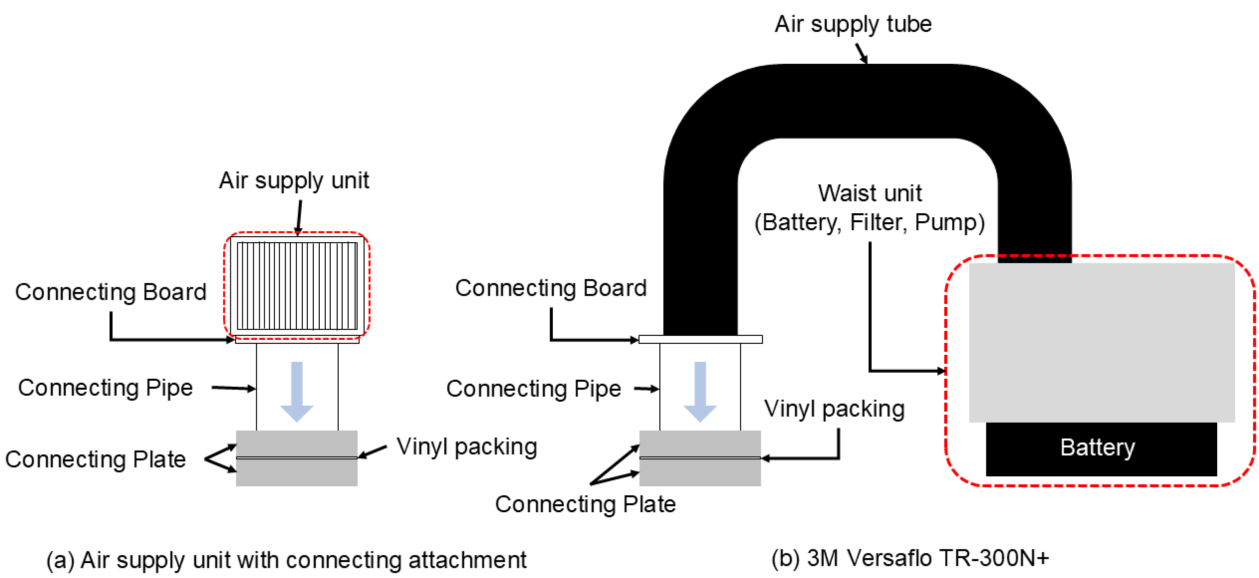
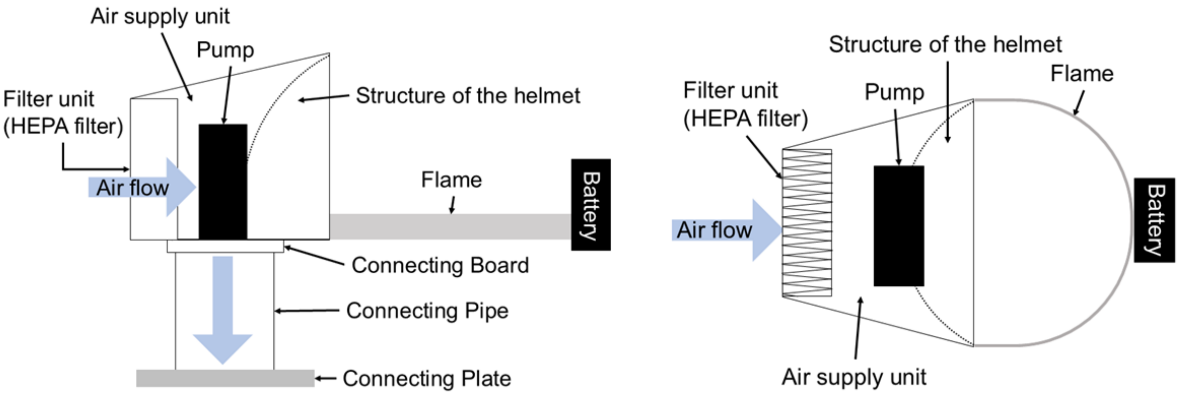


Fig. 2. A schematic diagram of connection of Air supply unit and 3M



(a) Side view of Air supply unit with connecting attachment (b) Top view of Air supply unit

Fig. 3. Side view and Top view of Air supply unit

Fig. 4. A captured image of the measurement software

3. Evaluation of differential pressure dependence of flow rates in air supply units

Using "The evaluation device for differential pressure dependence of flow rates", the differential pressure dependence of flow rates was evaluated for the developed Air supply unit and a commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit).

3.1 Experimental equipment

The experiment was conducted using the experimental equipment shown in Fig. 1. The hole for connecting the air pipe from the "Breathing air simulator" should be blocked with a special dummy block.

3.2 Experimental method

The measurement procedure is described below.

・Attach the Air supply unit or 3M to the equipment.

・While watching the differential pressure displayed in real time on the measurement software, change the fan output so that it approaches the target differential pressure value $\boldsymbol{\Delta P_t}$.

・While changing the fan output, measure the measured value $\boldsymbol{Q_1}$ [L/min] of Flow_meter 1, the measured value $\boldsymbol{Q_2}$ [L/min] of Flow_meter 2, and the differential pressure $\boldsymbol{\Delta P}$ [Pa] inside and outside the pressure buffer.

・The differential pressure $\boldsymbol{\Delta P}$ [Pa], flow rate $\boldsymbol{Q_1}$ [L/min], and flow rate $\boldsymbol{Q_2}$ [L/min] measurements were averaged over a sampling interval of 10 [ms] and 1000 sampling points.

・The measurement voltage of the Air supply unit is set from 10.5 [V] up to 13 [V] in 0.5 [V] increments.

・The measurement range of the Air supply unit was set to the maximum differential pressure when the exhaust port of the exhaust pump was closed, and the differential pressure was gradually lowered by opening the exhaust port of the exhaust pump until $\boldsymbol{\Delta P_t}$ = 0 [Pa].

・The measurement range of 3M is from $\boldsymbol{\Delta P_t}$ = 480 [Pa] to $\boldsymbol{\Delta P_t}$ = 400 [Pa] in decrements of 40 [Pa]. From $\boldsymbol{\Delta P_t}$ = 400 [Pa], the measurement is made in increments of 50 [Pa] down to $\boldsymbol{\Delta P_t}$ = 50 [Pa]. From $\boldsymbol{\Delta P_t}$ = 50 [Pa], measure in 25 [Pa] increments until $\boldsymbol{\Delta P_t}$ = 0 [Pa].

3.3 Experimental results

Let Flow_rate $\boldsymbol{Q}$ be Flow_rate $\boldsymbol{Q} = \boldsymbol{Q_1} + \boldsymbol{Q_2}$.

Figure 5 shows the relationship between differential pressure and flow rate at each voltage of the Air supply unit.

Figure 6 shows the relationship between differential pressure and flow rate in each mode of 3M.

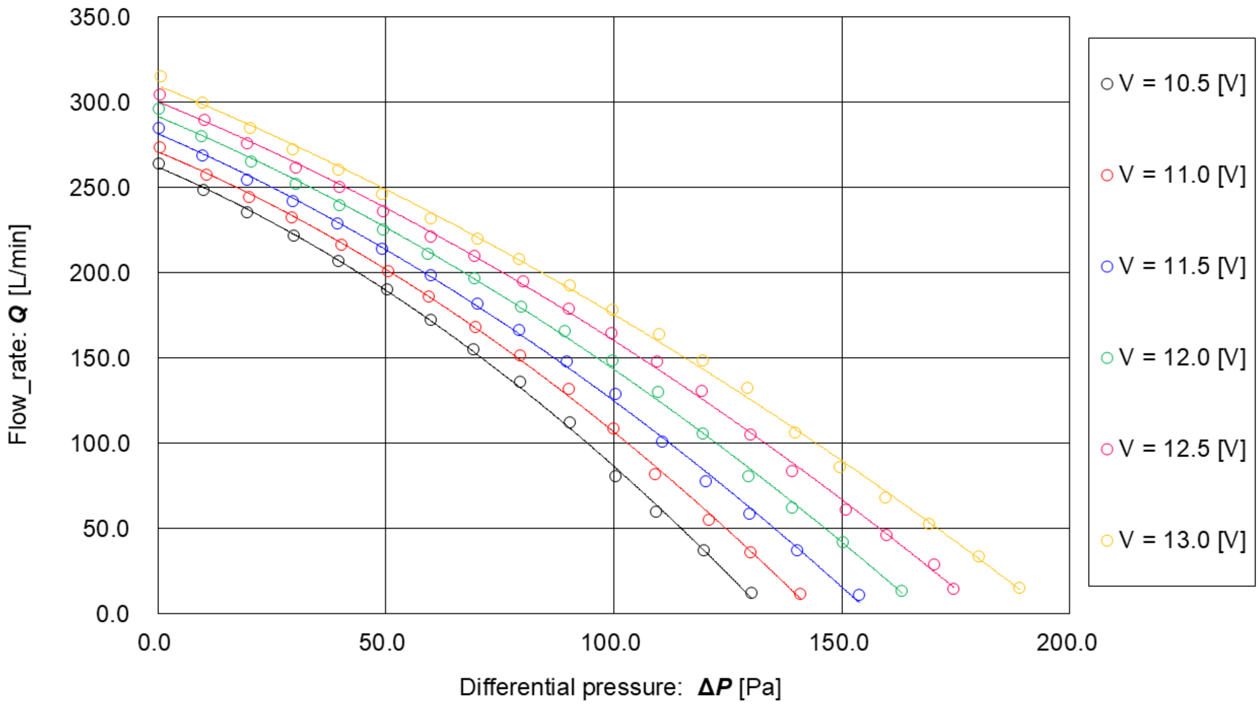


Fig. 5. Result of the relationship between differential pressure and flow rate for Air supply unit

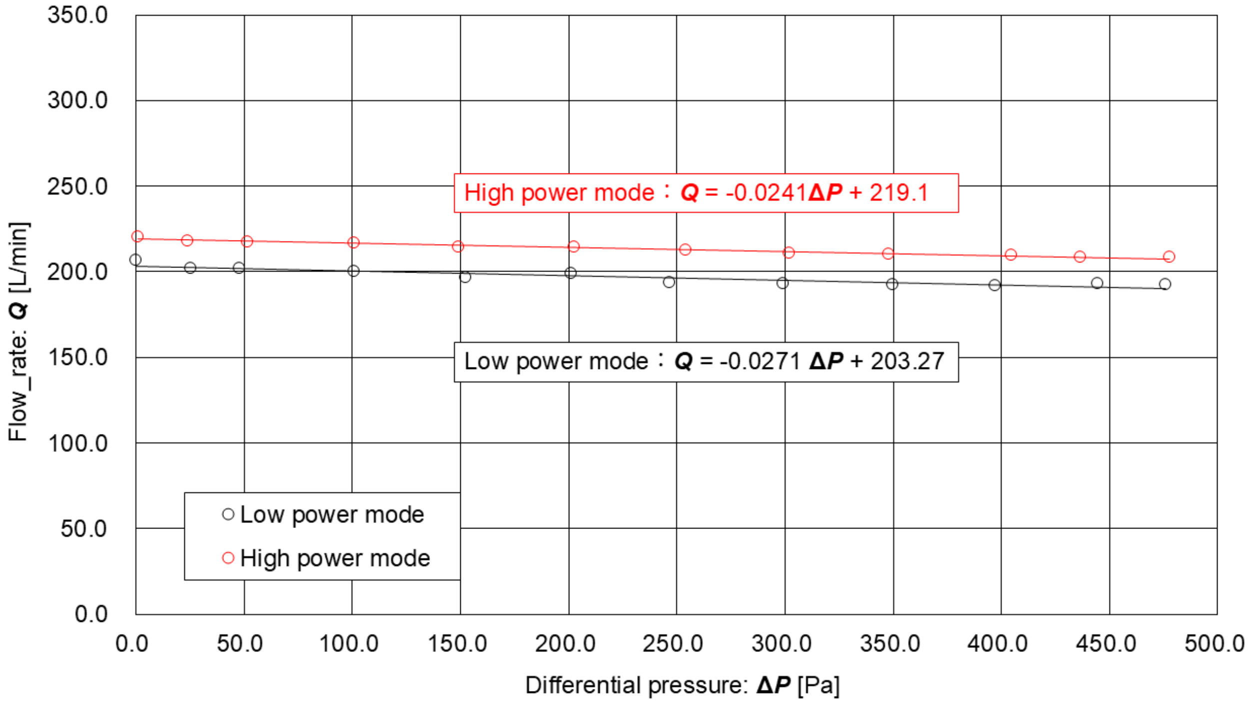


Fig. 6. Result of the relationship between differential pressure and flow rate for 3M

The regression equation for the differential pressure dependence of flow rates was obtained from the measured differential pressure, flow rate, and voltage for the Air supply unit using the method of least squares. This regression equation expresses the differential pressure dependence of the flow rate through the filter.

The regression equation is given by the following equation, where the voltage $\boldsymbol{V}$ [V] is X and the differential pressure $\boldsymbol{\Delta P}$ [Pa] is Y.

$$\boldsymbol{Q} = a_1X^2Y^2 + a_2XY^2 + a_3Y^2 + a_4X^2Y + a_5XY + a_6Y + a_7X^2 + a_8X + a_9$$

The coefficients $a_1 \sim a_9$ [L/min] of this regression equation are shown in Table 1.

Table. 1. Coefficients of regression equation

a_1	a_2	a_3
-0.000223324	0.006697	-0.05183
a_4	a_5	a_6
0.003729	-0.06837	-0.83329
a_7	a_8	a_9 [L/min]
-0.27277	25.67116	22.41659

From Figure 6, the regression equation of the differential pressure dependence of flow rates for 3M is $\boldsymbol{Q} = -0.0241\Delta\boldsymbol{P} + 219.1$ in High power mode and $\boldsymbol{Q} = -0.0271\Delta\boldsymbol{P} + 203.27$ in Low power mode.

$\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] and [$\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$] / [$\boldsymbol{Q}_{\mathbf{measured}}$] was calculated using $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] as the estimated flow rate obtained by this equation and $\boldsymbol{Q}_{\mathbf{measured}}$ [L/min] as the flow rate measured by the Flow_meter 1 and Flow_meter 2.

The flow mean $\boldsymbol{\mu}$, standard deviation $\boldsymbol{\sigma}$ and RMS value of $\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] and [$\boldsymbol{Q}_{\mathbf{measured}}$ - $\boldsymbol{Q}_{\mathbf{estimated}}$] / [$\boldsymbol{Q}_{\mathbf{measured}}$] for the Air supply unit and 3M, respectively, in the range 320 > Flow_rate $\boldsymbol{Q}$ > 50 [L/min] in Air supply unit and 500 > Differential pressure $\boldsymbol{\Delta P}$ > 50 [Pa] in 3M are given in Table 2.

Table. 2. The flow mean μ, standard deviation σ and RMS value of $Q_{measured} - Q_{estimated}$ [L/min] and $[Q_{measured} - Q_{estimated}] / [Q_{measured}]$.

	$Q_{measured} - Q_{estimated}$ [L/min]			$[Q_{measured} - Q_{estimated}] / [Q_{measured}]$		
	μ [L/min]	σ [L/min]	RMS value [L/min]	μ	σ	RMS value
Air supply unit	-0.15	2.97	2.97	-0.005	0.027	0.028
3M (High)	-0.11	0.57	0.58	-0.0019	0.0086	0.0088
3M (Low)	-0.37	1.67	1.71	-0.00053	0.0027	0.0028

4. Discussion

4.1 Uncertainty in estimating the differential pressure dependence of flow rate

According to the datasheet, the accuracy of the flow meter is as follows,
[1] Span accuracy is ±1.5 [% m.v.] in typical
[2] Offset accuracy is ± 0.05 [L/min]. This is 0.5 % when the flow rate is 10 [L/min]
A standard uncertainty of flow rate measurement using the flow meter is estimated as follows,
$(1.5^2 + 0.5^2) \times 0.5 = 1.6$ % of the measured value, which is equal to or larger than 10 [L/min].
According to the datasheet, the accuracy of the flow meter is as follows,
[1] Span accuracy is ±3 [% m.v.]
[2] Offset accuracy is ± 0.1 [Pa]. This is 1 % when the flow rate is 10 [Pa]
A standard uncertainty of flow rate measurement using the Flow_meter is estimated as follows,
$(3^2 + 1^2) \times 0.5 = 3.2$ [%] of the measured value, which is equal to or larger than 10 [Pa].

4.2 Uncertainty evaluation of regression equation for differential pressure dependence of flow rates in air supply units

・The relative standard uncertainty of Flow_meter 1 (model: SFM-3000-200C, manufacturer: Sensirion) is 4.8 %.
・The RMS value of $[Q_{measured} - Q_{estimated}] / [Q_{measured}]$ for the air supply unit in the range of 320 > Flow_rate Q > 50 [L/min] is 0.028 from Table 2.
・The RMS value of $[Q_{measured} - Q_{estimated}] / [Q_{measured}]$ for 3M in the range of 500 > Differential pressure ΔP > 50 [Pa] is 0.0088 in high power mode and 0.0028 in low power mode from Table 2.
・Therefore, the relative standard uncertainty of the regression equation for the differential pressure dependence of flow rates of the Air supply unit can be estimated as follows.

$$\text{Air supply unit: } \sqrt{0.028^2 + 0.048^2 + 0.048^2} = 7.3\ \%$$
$$\text{3M (High power mode): } \sqrt{0.0088^2 + 0.048^2 + 0.048^2} = 6.8\ \%$$
$$\text{3M (low power mode): } \sqrt{0.0028^2 + 0.048^2 + 0.048^2} = 6.8\ \%$$

5. Conclusion

The authors are developing a high-performance, inexpensive, and comfortable Powered Air-Purifying Respirator (PAPR) as an alternative to lockdown, with the aim of building a society that does not require lockdown.

"The evaluation device for differential pressure dependence of flow rates" was used to evaluate the differential pressure dependence of flow rates for the developed Air supply unit and the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit).

In the developed Air supply unit, the RMS value of the difference $Q_{measured} - Q_{estimated}$ between the actual flow rate $Q_{measured}$ [L/min] and the estimated flow rate $Q_{estimated}$ [L/min] obtained from the regression equation of differential pressure dependence of flow rates was 2.97 [L/min] in the range

320 > Flow_rate $\boldsymbol{Q}$ > 50 [L/min]. Within this measurement range, the relative standard uncertainty of this regression equation was estimated to be 7.3 %.

In the commercially-available PAPR (model: Versaflo TR-300+, manufacturer: 3M) air supply unit (Waist unit), the RMS value of the difference $\boldsymbol{Q}_{\mathbf{measured}} - \boldsymbol{Q}_{\mathbf{estimated}}$ between the actual flow rate $\boldsymbol{Q}_{\mathbf{measured}}$ [L/min] and the estimated flow rate $\boldsymbol{Q}_{\mathbf{estimated}}$ [L/min] obtained from the regression equation of differential pressure dependence of flow rates for the two modes (High power mode and Low power mode) was 0.58 [L/min] in High power mode and 1.71 [L/min] in Low power mode in the range 500 > Differential pressure $\boldsymbol{\Delta P}$ > 50 [Pa]. Within this measurement range, the relative standard uncertainty of this regression equation was estimated to be 6.8 % in High power mode and 6.8 % in Low power mode.

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