

# Dual Inlets Design of an Air Purifying Respirator to Study Inhalation Pressure Drop Reduction and Heart Rate Prediction

Y.C. Su, C.C. Li, and Y.C. Chang

**Abstract**—In this paper, computational fluid dynamics (CFD) method is used to research and compare the inhalation pressure drop reduction and heart rate prediction for APR\_C and APR\_A. APR\_A was improved according to the dual inlets of APR\_C, which does not feature a one-way inhalation valve.

The results indicate that the inhalation pressure drop of APR\_C (22.2 Pa, 85 L/min) is 82.3% lower than that of APR\_A (125.4 Pa). Consider the case of APR mounted with canister A and B, the inhalation pressure drop of APR\_C mounted with dual canister B (206.4 Pa, 85 L/min) is 61.2% lower than that of APR\_A mounted with canister B (531.5 Pa).

Using Li's prediction equation of inhalation pressure drop and heart rate, under high exercise condition of  $P = 120$  W, the predicted  $Hr/Hr_{max}$  for APR\_C mounted with dual canister B is 74.3%, which is 8.6% lower than the experimental value of APR\_A mounted with canister A (82.9%).

In addition, the  $Hr/Hr_{max}$  is lower than the anaerobic threshold ( $Hr/Hr_{max} = 80\%$ ), thereby preventing fatigue in users resulting from anaerobic respiration. The results verified that the dual inlets design substantially reduce inhalation pressure drop while decelerating users' heart rate.

**Index Terms**—CFD, Dual Inlets, Inhalation Pressure Drop, Hr/H.

## I. INTRODUCTION

Wearing high-performance gas masks can guarantee the safety of people working in threatening chemical, biological, radiological, and nuclear (CBRN) environments. Air purifying respirator (APR), which provides wearers with an excessively high inhalation resistance, because multi-pleated filter layers and activated carbon layers are installed inside CBRN canisters. These layers can filter particles and adsorb toxic gases, and the characteristics of the porous media contribute to the high inhalation resistance of these canisters. According to the National Institute for Occupational Safety and Health (NIOSH) federal respiratory regulations 42 Code of CFR Part 84 criteria for CBRN canister-mounted APR, when inhalation rate is 85

L/min, the maximal pressure drop should be 65 mmH<sub>2</sub>O [1], which is approximately 638 Pa. Respiratory resistance influences the human body in three aspects: it (a) increases respiratory muscle fatigue, (b) intensifies the burden on the heart, and (c) exacerbates the effects of deadspace. Hence, the respiratory physiological functions of workers who wear gas masks in various exercise conditions are worth exploring. Relevant respiratory physiological parameters included minute ventilation rate ( $V_E$ ), heart rate (Hr), oxygen uptake rate ( $VO_2$ ), and inhalation resistance (R). Oxygen uptake rate and exercise power level were positively correlated [2]. Therefore, oxygen uptake rate is an indicator of physical activity levels. Maximal oxygen uptake rate refers to the maximal amount of oxygen a person inhales per min and is closely related to cardiorespiratory endurance. Thus, maximal oxygen uptake was considered the optimal indicator of cardiorespiratory endurance. People who exhibit an  $Hr/Hr_{max}$  of below 80% are performing aerobic exercises. When a person's  $Hr/Hr_{max}$  reaches 80%, this state is known as heart rate threshold. When most of the muscles of the body undergo anaerobic respiration and a substantial amount of lactic acid accumulates, this state is referred to as anaerobic threshold, which is an essential indicator in exercise physiology.

The purpose of this study is to investigate the improved APR (APR\_A mounted canister A) which workers often use (Fig. 1). When the flow rate was 85 L/min, the APR\_A mounted with canister A yielded an inhalation pressure drop of 822.6 Pa which exceeded the NIOSH 42 CFR part 84 criteria.

Li [3] had been used CFD and flow visualization experiments to revise a commercially available CBRN canister (canister A). Without changing the porous media and filtering performance, the modified canister (canister B, Fig. 1) with honeycomb passageway design reduced 40% pressure drop than the canister A at inhalation rate 85 L/min. Subsequently, Li [4] adopted respiratory physiology experiment to observe the physiology parameters of 13 subjects who used a air purifying respirator (APR\_A) that were mounted with four types of CBRN canisters under six exercise powers (0-150 W) were analyzed. The results showed that  $Hr/Hr_{max}$  of APR\_A mounted with canister A reached 81.92%, which exceeded 80% of the heart rate threshold. According to the results, Li [4] developed a prediction equation of inhalation pressure drop and heart rate in different exercise powers.

The evolution of current protective mask such as AVON's M50 gas mask (Fig. 2) are adopted dual inhalation inlets design. Due to inhalation flow rates equal sharing in dual canisters, the inhalation pressure drop at least be reduced by about half due to

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the quadratic P-Q curve. In addition, the unidirectional valve of nose cup within APR\_A can avoid mist generation on eyepiece when user exhaled but it increases pressure drop within respirator. To reduce the overall inhalation pressure drop, the removal of unidirectional valve on nose cup and the passageway design within respirator could be considered.

In this study, we expect to design the dual inlets and without unidirectional valves of nose cup for APR\_A in order to reduce the inhalation pressure drop and improve heart rate increasing of users. The paper assumes that the removal of the unidirectional valve on nose cup does not make the eyepiece fogging.

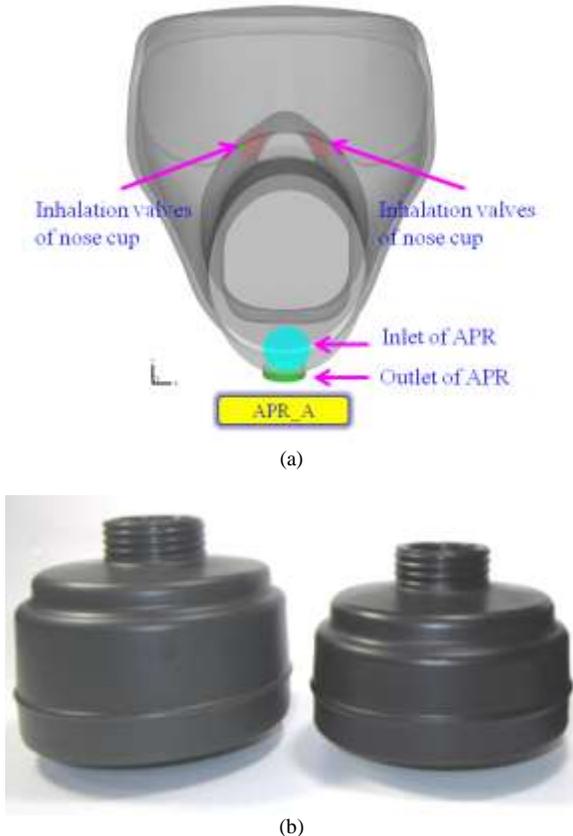


Fig. 1 (A)APR\_A; (B)Canister A (Left Picture), And Canister B (Right Picture).



Fig. 2 M50 APR.

## II. PROBLEM

### A. Pressure drop measure

AMCA wind tunnels are employed to measure the inhalation pressure drop of APR\_A mounted canister A-B and analyze the P-Q curve.

In common air purifying respirator and canisters, the mean inhalation flow rate varies from 15 L/min at rest to 135 L/min for intense exercise[5].

### B. Governing equations

The governing equations herein include the continuity and momentum equations, both of which obey the conservation principle,

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i - \frac{\partial}{\partial x_j}(\rho \overline{u'_i u'_j}) + S_i \quad (2)$$

where  $\rho$  is the gas density;  $u_i$  is the velocity component in the  $i$  direction. The momentum (2) are steady, 3-D Reynolds-averaged Navier-Stoke's equations;  $p$  is the pressure;  $\tau_{ij}$  is the viscosity shear stress tensor;  $g_i$  is the acceleration due to gravity in the  $i$  direction;  $\rho \overline{u'_i u'_j}$  is the Reynolds stress term, related to the mean flow by the Boussinesq hypothesis when the flow is not laminar, and  $S_i$  is a source term that describes the pressure gradient. The inlet Reynolds number ranges from 950 to 8,600, so this study adopts a modified low-Reynolds number  $k-\epsilon$  turbulent model [6].

### C. Boundary conditions

The mask inlet maintains a steady volumetric flow rate in all simulations. Since the inlet area is fixed, the calculated mean velocity is specified by the inlet boundary. A flow rate of 30 L/min, which is regarded as the mean inhalation flow rate of normal adults in light motion, serves as the reference value for subsequent simulations. The reference pressure is fixed at the inlet, with a value of 101,325 Pa. The outlet boundary condition is the pressure outlet boundary. The no-slip condition is assumed for all solid walls.

### D. Numerical method

This study uses the FLUENT 12.1.2 flow solver, which is based on the finite volume method. The integral form of the governing equations is discretized using an unstructured tetrahedral grid. The convection term is discretized with the first-order upwind scheme and the viscosity term is discretized with a second-order central differential scheme. The SIMPLE algorithm [7] is the solution algorithm for pressure-velocity coupling, and related discretization algebraic equations are solved using the TDMA method.

### E. Grid configuration and research matrix

An unstructured tetrahedral mesh with a complex structure and self-adaptive characteristics is adopted. Local grids for the inlet, outlet, valve, and the canister are refined to accurately capture the flow patterns. The domain is yielding a grid number of approximately 1,810,000 grids for the prototype (Fig. 3). All

the results presented in this study are grid insensitive. The residual convergence threshold in all cases is less than  $1 \times 10^{-4}$ .

Table I and Fig. 4 presents the research matrix. Grid distributions for the APR\_B and APR\_C were generated based on APR\_A. APR\_B was designed as that was single inlet without valves of nose cup, and APR\_C was designed as that was dual inlets without valves of nose cup.

TABLE. I  
RESEARCH MATRIX

Item	Valves of nose cup	Air inlet
APR_A	With	Single inlet
APR_B	W/O	Single inlet
APR_C	W/O	Dual inlets

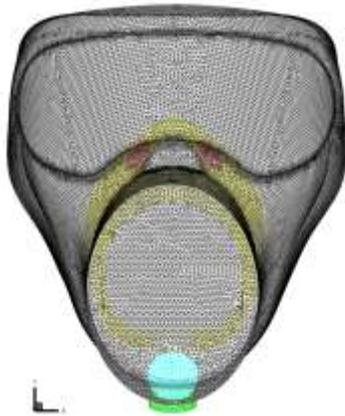


Fig. 3 Mesh System Of APR\_A

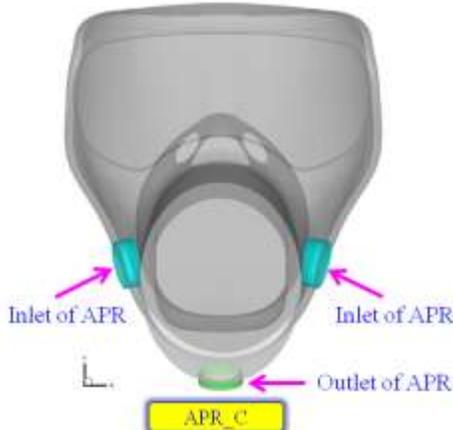
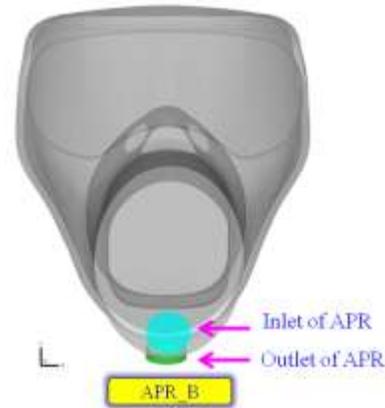


Fig. 4. Research Matrix

### III. RESULTS AND DISCUSSION

#### A. Determination for the porous medium parameters of the canister

Pressure drop of the canister is mainly contributed by the characteristics of porous medium. The macroscopic property of the porous media is commonly the quadratic equation of pressure-velocity [8].

$$\Delta p = a_1 V_s + a_2 V_s^2 \quad (3)$$

where  $a_1$  is the viscous term coefficient,  $a_2$  is the inertia term coefficient and  $V_s$  is the superficial velocity. Under different flow rate condition, the pressure drop for the canisters are measured. Besides, quadratic curve fitting are adopted to calculate the pressure-velocity equation for the canisters. The relationship of pressure-velocity for canister A is displayed below:

$$\Delta p = 144.13V + 12.86V^2 \quad (4)$$

To take into account pressure drops occurring in the porous media, it may be expressed as

$$\nabla p = \frac{\mu}{\alpha} + C \left( \frac{1}{2} \rho V |V| \right) \quad (5)$$

where  $\alpha$  is the porous media permeability and  $C$  is an inertial resistance factor, while the general frame of the momentum sink term to be introduced in the (2). By comparison of (4) and (5) we obtain

The canister A:

$$\frac{1}{\alpha} = 9.24 \times 10^7 m^{-2} \quad C = 240.87 m^{-1}$$

Using the same method, the relationship of pressure-velocity for canister B is displayed below:

$$\Delta p = 90.15V + 5.86V^2 \quad (6)$$

The canister B:

$$\frac{1}{\alpha} = 5.78 \times 10^7 m^{-2} \quad C = 106.26 m^{-1}$$

Finally, the coefficients for the porous media are substituted into the full model. There is very good agreement in the comparison between the calculation result and experiment. As shown in Fig. 5, the porous media coefficients for the canisters have been accurately solved.

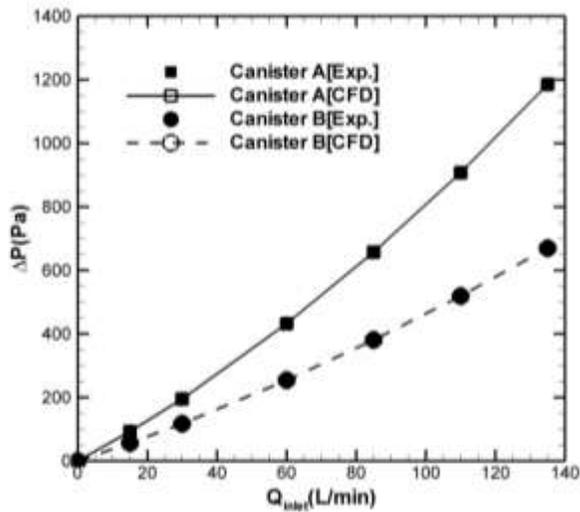


Fig. 5 Canisters Experiment And Calculation Result Of CFD.

**B. Inhalation pressure drop test**

Fig. 6 shows the pressure drop of APR\_A (without canister) in experimental test and CFD results of APR\_A-C at inhalation rate of 0-135 L/min. The maximum differences between experimental data and simulated results are only 6%. It shows that the simulated pressure drops are very close to the experimental values. The pressure drop of APR\_A is about 125.4 Pa, which is 44.7% higher than the 69.3 Pa values of APR\_B at flow rate of 85 L/min. The results reveal the design of unidirectional valve on nose cup to cause high inhalation pressure drops in APR\_A. Subsequently, the pressure drop of APR\_C with dual inlets is 22.2 Pa which is 68% lower than the 69.3 Pa values of APR\_B at 85 L/min. The results reveal the design of dual inlets to cause the high reduction of pressure drop due to the inhalation flow rates equal sharing in dual inlets. The pressure drop of APR\_C is 82.3% lower than the values of APR\_A.

Fig. 7 shows the inhalation pressure drops of APR\_A-C mounted with the canister A-B respectively. The pressure drop test of M50 APR mounted with canisters is also presented in Fig. 7. The pressure drop of APR\_A mounted canister A is about 822.6 Pa at flow rates of 85 L/min. It exceeds NIOSH for CBRN canister-mounted APR of 65 mmH<sub>2</sub>O (638 Pa) standard. The pressure drop of APR\_C mounted with dual canisters B is approximately 206.4 Pa, which is 61.2% lower than the 531.5 Pa values of APR\_A mounted with canister B at flow rate of 85 L/min. According to the above results, the design of dual inlets and the removal of unidirectional valve on nose cup can significantly reduce the inhalation pressure drop of APR. In addition the pressure drop of APR\_C mounted with dual canisters B compare with the M50 APR mounted with canisters, the pressure drop is 33% lower than the 307.7 Pa values for the M50 APR mounted with canisters. However, the size of canister B must be reduced to facilitate placement over the cheeks. The size reduction will increase the inhalation pressure drop.

Figs. 8-10 show the pressure contour of APR\_A-C mounted canister B. Obviously the dual inlets design for APR\_C can significantly reduce the inhalation pressure drop. Secondly the elimination of unidirectional valve on nose cup also reduce the pressure drop. However the removal of unidirectional valve on

nose cup must integrate passageway design within respirator to avoid eyepiece fogging.

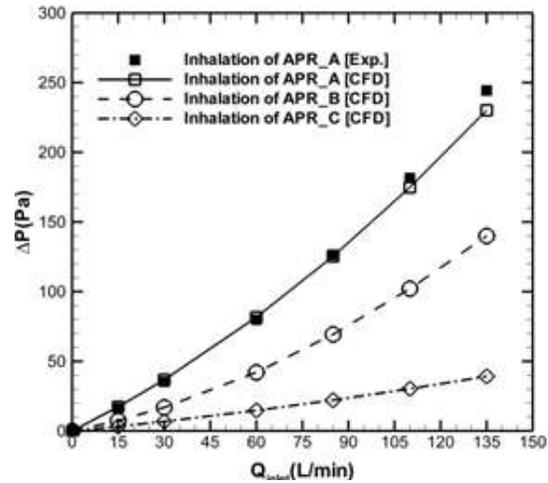


Fig. 6 P-Q Relationships For Various Models (W/O Canister).

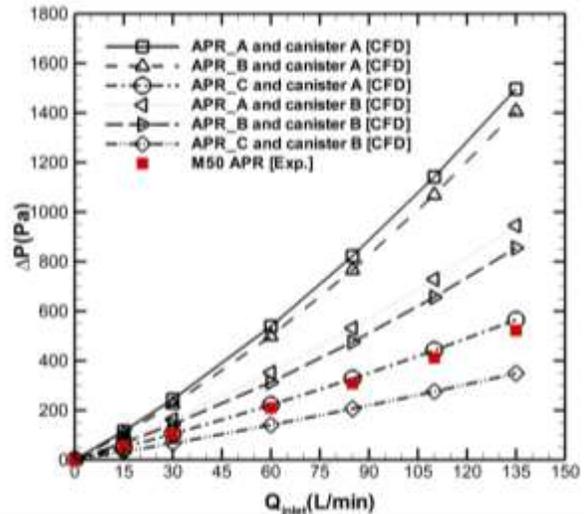


Fig. 7 P-Q Relationships For Various Models (With Canister) And M50 APR.

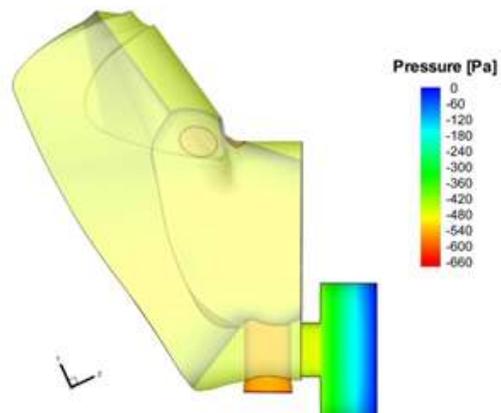


Fig. 8 The Pressure Contour Of APR\_A Mounted With Canister B Distribution At 85 L/Min.

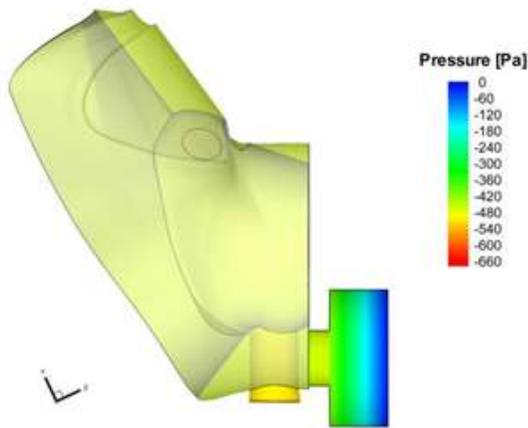


Fig. 9 The Pressure Contour Of APR\_B Mounted With Canister B Distribution At 85 L/Min.

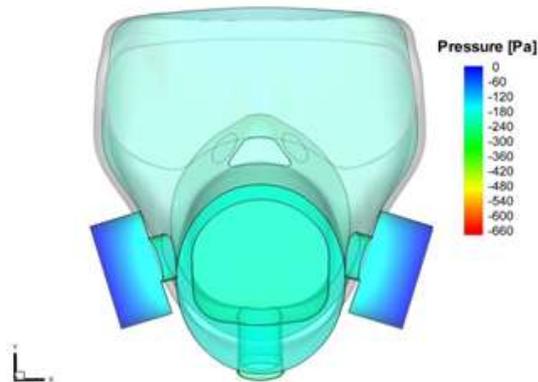


Fig. 10 The Pressure Contour Of APR\_C Mounted With Dual Canister B Distribution At 85 L/Min.

### C. Heart rate prediction

Li had been adopted respiratory physiology experiment to observe the physiology parameters of 13 subjects who used a air purifying respirator (APR\_A) that were mounted with four types of CBRN canisters under six exercise powers (0-150 W) were analyzed. The results showed that  $Hr/Hr_{max}$  of APR\_A mounted with canister A reached 82.9%, which exceeded 80% of the heart rate threshold. According to the results, Li developed a prediction equation of inhalation pressure drop and heart rate in different exercise powers.

Fig. 11 shows the relationship between average inhalation pressure drop and  $Hr/Hr_{max}$  for different APR mounted canister. The differences between experiment and prediction for subjects wearing APR\_A mounted FERNEZ canister were only 3% shown in Fig.11. According to the results of Fig. 11, the inhalation pressure drop of APR mounted canister is higher, the higher the user's heart rate. The results present that the  $Hr/Hr_{max}$  of APR\_A mounted canister A is over 80%, the  $Hr/Hr_{max}$  of the other models are under 80% at  $P=120W$ . Under the exercise condition of  $P = 120W$ , the predicted  $Hr/Hr_{max}$  for APR\_C mounted with dual canister B was 74.3%, which is 8.6% lower than the experimental value of APR\_A mounted with canister A (82.9%). Therefore, the dual inlets design not only significantly reduces the intake pressure drop also reduces the user's heart rate.

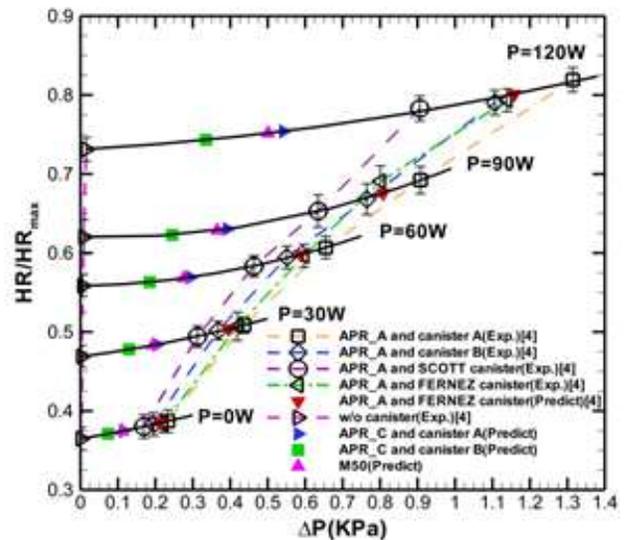


Fig. 11  $Hr/Hr_{max}$ -Pressure Drop Relationships For APR\_C And M50 APR[4]

### IV. CONCLUSION

APR\_A was improved according to the dual inlets of APR\_C, which does not feature a unidirectional inhalation valve. The simulation results indicated that the inhalation pressure drop of APR\_C (22.2 Pa, 85L/min) is 82.3% lower than that of APR\_A (125.4 Pa). The inhalation pressure drop of APR\_C mounted with dual canister B (206.4 Pa) is 61.2% and 33% lower than that of APR\_A mounted with canister B (531.5 Pa) and the M50 APR (307.7 Pa), respectively.

Using Li's prediction equation of inhalation pressure drop and heart rate, under the exercise condition of  $P = 120W$ , the predicted  $Hr/Hr_{max}$  for APR\_C mounted with dual canister B was 74.3%, which is 8.6% lower than the experimental value of APR\_A mounted with canister A (82.9%). In addition, the  $Hr/Hr_{max}$  was lower than the anaerobic threshold ( $Hr/Hr_{max} = 80\%$ ), thereby preventing fatigue in users resulting from anaerobic respiration. The aforementioned results verified that the dual inlets design substantially reduce inhalation pressure drop while decelerating users' heart rate.

The inhalation pressure drop of APR\_C mounted with dual canister B is lower than that of M50 APR mounted with canisters; however, when canister B is worn over the cheeks, problems related to large size and human factors arise. When the canister decreases in size, air flow velocity increases, elevating inhalation pressure drop. In addition, decreased size influences the breakthrough time of toxic gases. Future studies will be conducted to design an optimal dual inlets canister by comprehensively analyzing the inhalation pressure drop, human factors, and toxic gas breakthrough time following size decrease in canister B.

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