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# Effect of efficient supply of pure $O_2$ concentrated by PSA-type $O_2$ separator on improvement of indoor air quality

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**Abstract**−To minimize the cost and loss rate of energy artificial room ventilation system, the $O_2$ separator was suggested for the flow of the excessive ventilation amount between indoor and outdoor because the pure $O_2$ separated and concentrated by the $O_2$ separator can be supplied with the ventilation amount minimized. How the $O_2$ separator applies to ventilation and its operation characteristics were investigated by controlling under various conditions as well as the operation conditions optimized required for indoor air quality such as the concentration of $CO_2$ and $O_2$. Consequently, it was known that the $O_2$ concentration was increased; however, the increase of the $CO_2$ concentration was suppressed by the sufficient supply of $O_2$ concentrated from the storage tank into the room despite the two persons' breathing in the room having an inner volume of about 56 $m^3$. Consequently, it was concluded that the supply system of the concentrated $O_2$ which was stored into the tank after the production with the $O_2$ separator can be applied to the room ventilation system for the improvement of the indoor air quality.

Keywords: Indoor Air Quality, Room Ventilation System, Zeolite-based Adsorbent, $O_2$ Separator, Supply, PSA-type

## INTRODUCTION

Indoor air is usually polluted by various gases and particulates generated by human respiration, fuel combustion, air-suspended dust, bacterial virus, odor/fragrance, tobacco smoke, and so on [1-4]. The $CO_2$ mainly derives from the human breath which also originates from consumption of $O_2$ (about 5%) in the air [5]. Therefore, the concentration of $CO_2$ continuously increases with the concomitant reduction of $O_2$ in the indoor air under the improper room ventilation condition. However, fluctuation of the $CO_2$ concentration is hardly more than 1.0% in indoor air, which does not adversely affect human health. On the other hand, the hygienic deterioration of the indoor air with generation of heat and $H_2O$ caused by the human respiration is synergistic with odor, dust and bacterial virus. Although $CO_2$ from human respiration is not highly detrimental to human health, the $CO_2$ concentration is listed as an index of indoor air pollution [6-12]. Therefore, the amount and concentration of $CO_2$ is now indexed for quantitative definition of ventilation efficiency, and the ventilation method is roughly classified into the natural and mechanical (artificial) ones. The ventilation method is classified to the natural and mechanical (artificial) and the characteristics of each ventilation method are as in the following. The natural ventilation method is carried out by the differential interior-exterior temperature and driving force of the wind through an opening, and its operation characteristics are the low energy cost, the difficult artificial control and the ventilation amount required for the indoor air quality due to using natural power. The various pollutants are diffused into other points of the room from an indoor point in which the harmful gases and dust are generated and then other risks can be dotted in the dangerous working area handling the hazardous substances. Moreover, in the natural ventilation method, the polluted air generated indoors is discharged to outdoor through the opening, and a variety of the environmental problems should be considered. Therefore, to improve and compensate for the defect of the inefficient natural ventilation, artificial ventilation should be considered for the indoor air quality required for the breath/health of human being. In the artificial ventilation method, the operation rate of the ventilation system can be increased with high the concentration of $CO_2$ generated by the body activity and other energy consumption in indoor air. As a defect of the artificial ventilation system, a large amount of the ventilation air which is unnecessary and uncontrolled in detail can flow into the indoor room and be discharged outdoors. And then the operation/energy cost and energy loss rate are increased because the excessive amount of the ventilation air flows between inflow and indoor and the indoor-outdoor temperature differential required for the air conditioning and heating is reduced. When seen from this viewpoint, the minimization of ventilation amount required for indoor air quality is necessary for the reduction of the cost and loss rate of energy [13,14].

In this study, to investigate the applicability of the $O_2$ separator combined with the room ventilation system to minimize the outdoor-air volume and amount of ventilation and the cost and loss rate of energy in the ventilation system, a PSA-type $O_2$ separator with

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‡This article is dedicated to Prof. Seong Ihl Woo on the occasion of his retirement from KAIST.

zeolite-based adsorbent was used and optimized for the efficient ventilation. Furthermore, a storage tank was installed for the efficient supply of $O_2$ concentrated by the $O_2$ separator. The zeolite-based adsorbent was selected for the PSA-type separator to apply to the room ventilation system and then the operation conditions of the $O_2$ separator required for the indoor air quality such as the concentration of $CO_2$ and $O_2$ were optimized.

## EXPERIMENTAL

### 1. Characterization of Zeolite-Based Adsorbent for PSA-Type $O_2$ Separator

Zeolite-based adsorbents made of pellet-type extrudate were packed into two beds for the adsorption and desorption of the adsorbate, and their performance was tested in the PSA-type $O_2$ separation system. The adsorbent particle size ranged within 0.5-1.0 μm and the physico-chemical properties of the various zeolite-based adsorbents, such as composition and surface morphology, were characterized via X-ray diffraction, SEM/EDX, and isothermal $N_2$ adsorption-desorption analysis method.

### 2. Construction and Operation of PSA-Type $O_2$ Separator in Room Ventilation System

Fig. 1 schematically shows the diagram of the $O_2$ separator (60 cm (W)×60 cm (L)×150 cm (H)) used in the room ventilation system along with $CO_2$ adsorption module. The $O_2$ separator consisted of four adsorbent-packed beds parallel to it. The $O_2$ separator was operated by filtering the air inflow for moisture and dust removal and then taken into the adsorbent-packed bed. Then the $O_2$ was separated and concentrated for discharge. In the $O_2$ separation/concentration process, the filtered air was supplied into the adsorbent bed pack of 2 kg mass at 60 L/min flow rate and the internal pressure of the bed was thus automatically controlled by the discharged oxygen outflow in the range of 2-12 L/min.

A storage tank was made of high quality aluminum for efficient supply of the concentrated $O_2$ from the $O_2$ separator at a desired flow rate. The aluminum storage tank consisted of four tanks of 22 L capacity each with total volume of about 88 L and each tank could be individually operated, if need be. The concentrated $O_2$

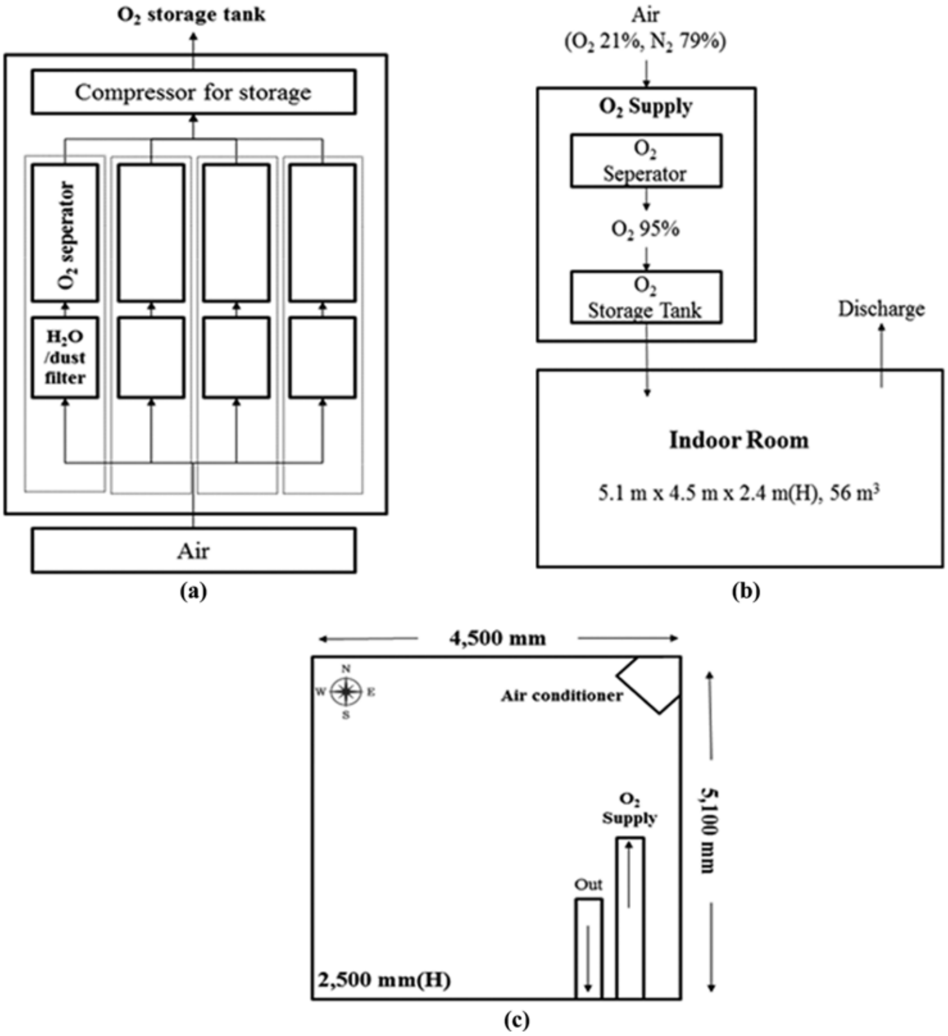


**Fig. 1. Schematic diagram of the room ventilation system combined with $O_2$ separator for the improvement of the indoor air quality.**
((a) $O_2$ separator, (b) ventilation system with $O_2$ separator and $CO_2$ adsorption module, (c) specification of indoor room for the ventilation system)

from the $O_2$ separator was introduced into the aluminum storage tank at 6-8 $kg_f/cm^2$, which was monitored by the digital pressure gauge. The concentrated $O_2$ from the storage tank was discharged at the flow rate controlled by MFC (mass flow controller, Linetech Co. Ltd.) for supply into the room.

The volume of the room was 56 $m^3$ with 5.1 m (W)×4.5 m (L)× 2.4 m (H) and its temperature was controlled and maintained by an air conditioner.

The $O_2$ supply unit consisted of the $O_2$ separator and the outdoor storage tank from which the concentrated $O_2$ was supplied into the room. For each step involving inflow and discharge of $O_2$, the flow rate and concentration of $O_2$ were quantitatively controlled and monitored by MFC and $O_2$ analyzer (Omega Instruments, Model: s3520), respectively.

## RESULTS AND DISCUSSION

### 1. Characterization of the Zeolite-Based Adsorbent for PSA-Type $O_2$ Separator

The composition of the various adsorbents for the PSA-type $O_2$ separator was characterized by EDS analysis and listed in Table 1. With the exception of the organic elements such as C, H and O, the main components of the adsorbent were Na, Al and Si and their composition was different. Regardless of the kind of the adsorbent, the Si content was high and was in the range of about 40-45 at%. However, the Al content of adsorbent A, C and E of about 35-37 at% was higher than that of adsorbent B and D of about 29 at%. The Na content of adsorbent A, B, C and D was about 19-25 at%, but that of the adsorbent E was relatively low, about 8.0 at%. Especially, the Ca element was not detected in the adsorbents of the adsorbents of A, B, C and D but was detected in the only adsorbent E and its content was about 12.8 at%. It was shown that the Si/Al ratio according to the content of Si and Al has the order of A>C>D>E>B. This content variation of the inorganic components has a distinct influence on the structural characteristics and textural properties such as a surface area of the various adsorbent.

Table 2 shows the textural properties of the various adsorbents corresponding to the structural characteristics such as the pore size and surface area with the isothermal $N_2$-adsorption method. It was shown that the adsorbent A has the lowest surface area among the adsorbents, and this result matches the isothermal $N_2$ adsorption-desorption curves of adsorbent A shown in Fig. 3. In the case of adsorbent E, the surface area of the mesopore area was larger than other adsorbents because the crystal structure of the adsorbent E is composed of the Ca component having an ionic radius larger than Na as compared of other adsorbents. The BET surface area of the adsorbent E was the highest among the various adsorbents, and it was estimated that the performance of the adsorbent E would be relatively favorable as compared with other adsorbents.

Fig. 2 shows the isothermal $N_2$ adsorption-desorption curves of the various adsorbents used for the $O_2$ separator. As shown, it was known that the $N_2$ adsorption-desorption isotherms of the adsorbents belonged to reversible type IV with a clear H4 hysteresis loop which is typical of mesoporous materials of irregular structure according to IUPAC (International Union of Pure and Applied Chemistry) classification. We estimated that they have a considerable amount of the small mesopores because the widely opened knees and the slight hysteresis loops were presented in the range of 0.4-0.5. Regarding adsorbent A, the capillary condensation showing type V with H4 hysteresis loop with the increase in relative pressure happened [15-18]. It was shown that the adsorbent B has a relatively large mesopores as compared to other adsorbents. The adsorption volume of the adsorbent E was the highest among the variety of the adsorbents, and then the surface area was also the highest among the adsorbents. From the next section, the adsorbent E which may be favorable for the PSA system due to the superior surface area and pore and so on will be applied to the $O_2$ separator.

**Table 1. EDS analysis of the various zeolite-based adsorbents**

| Element | A | B | C | D | E |
|---|---|---|---|---|---|
| Na K | 19.4 | 21.4 | 25.5 | 25.9 | 8.0 |
| Al K | 32.3 | 37.7 | 29.4 | 29.5 | 35.8 |
| Si K | 49.9 | 40.9 | 45.1 | 44.6 | 43.4 |
| Ca K | -- | -- | -- | -- | 12.8 |
| Si/Al ratio | 1.54 | 1.08 | 1.53 | 1.51 | 1.21 |

**Table 2. Textural properties of the various adsorbents for $O_2$ separator**

| Sample | A | B | C | D | E |
|---|---|---|---|---|---|
| $S_{BET}$ ($m^2/g$) | 19.2 | 539.1 | 668.9 | 754.3 | 832.5 |
| $S_{micro}$ ($m^2/g$) | 9.7 | 489.6 | 616 | 711.9 | 726.3 |
| $S_{meso}$ ($m^2/g$) | 11.6 | 53.9 | 52.5 | 25.1 | 86.2 |
| $V_{total}$ ($cm^3/g$) | 0.102 | 1.512 | 0.295 | 0.421 | 0.819 |
| $V_{micro}$ ($cm^3/g$) | 0.004 | 0.186 | 0.23 | 0.264 | 0.313 |
| $V_{meso}$ ($cm^3/g$) | 0.101 | 1.322 | 0.103 | 0.117 | 1.53 |
| $D_{Avg.}$ (nm) | 1.29 | 3.09 | 2.19 | 2.02 | 4.08 |

### 2. Operation of the PSA-Type $O_2$ Separator with Zeolite-Based Adsorbent

To investigate the $O_2$ separation efficiency, the concentration

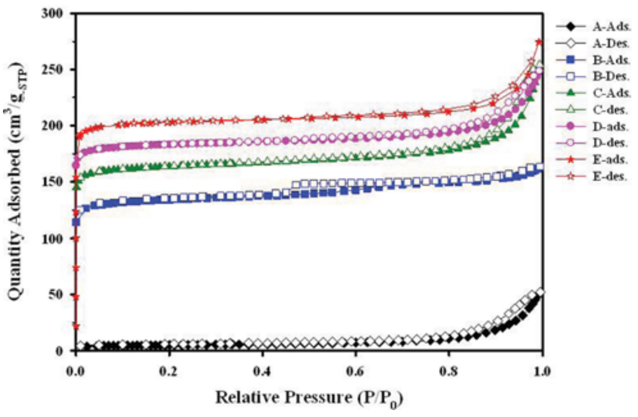


**Fig. 2. Isothermal $N_2$ adsorption-desorption curves of the various zeolite-based adsorbents.**

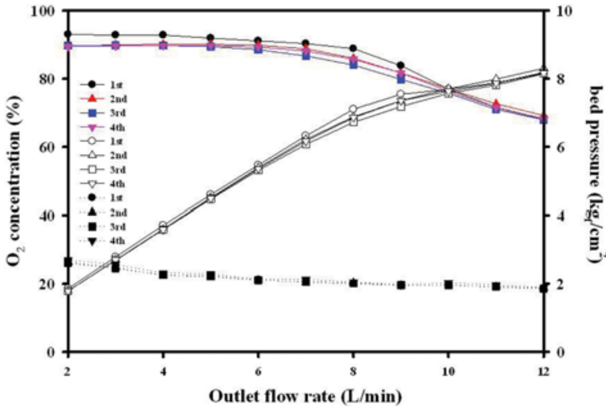


**Fig. 3. The concentration and flow rate of $O_2$ from each adsorbent beds and the internal pressure of the adsorbent bed with the outlet flow rate.**

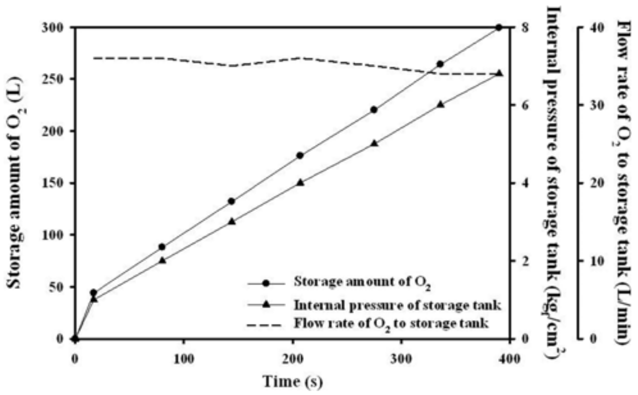


**Fig. 4. The outlet amount of $O_2$ produced from the $O_2$ separator and the internal pressure of the tank for the $O_2$ storage.**

and the flow rate of $O_2$ were monitored in the PSA-type $O_2$ separator using four adsorbent-packed beds. Fig. 3 shows the concentration and flow rate of $O_2$ from each adsorbent bed and the internal pressure of the adsorbent bed with the outlet flow rate as a result of the $O_2$ separation efficiency in the PSA system using the four adsorbent-packed beds with adsorbent E for the $O_2$ separation. Regardless of the type of the packed bed, the $O_2$ concentration as an $O_2$ separation efficiency was reduced according to the characteristics of the PSA system because the internal pressure of adsorbent bed was gradually decreased with increasing the outlet flow rate. In addition, the flow rate of $O_2$ was increased despite the decrease of the $O_2$ concentration as the outlet flow rate of the adsorbent-packed bed increased. The concentration of $O_2$ was not dramatically decreased as the outlet flow rate increased from 2 up to 12 L/min in spite of the high increasing rate because the decreasing rate of the $O_2$ concentration was relatively lower than that of the $O_2$ flow rate as an amount of the pure $O_2$ separated by the adsorbent bed. However, with increasing the outlet flow rate from 2 up to 8 L/min, the $O_2$ concentration was decreased in the range of about 89 and 93% with the low decreasing rate. However, as the outlet flow rate increased from 8 up to 12 L/min, the $O_2$ concentration was dramatically decreased. These results may be due to the fact that the internal pressure of the adsorbent bed which is significantly dependent on the $O_2$ concentration was over the minimum levels required for the sufficient $O_2$ separation in the outlet flow rate range of below 8 L/min. Therefore, the outlet flow rate of the absorbent bed was optimized at about 8 L/min for the supply $O_2$ having the sufficient concentration and flow rate.

Fig. 4 shows the outlet amount of $O_2$ produced from the $O_2$ separator and the internal pressure of the tank for the $O_2$ storage. In this case, the flow rate and concentration of $O_2$ produced from $O_2$ separator using four adsorbent-packed beds were, respectively, in the range of 34-36 L/min and 88-90%. In addition, the volume of the storage tank was about 20 L. The internal pressure of storage tank and the $O_2$ amount was increased with the time stream after the operation of the $O_2$ separator and reached about 280 L and 7 $kg_f/cm^2$ after 3.5 h, respectively. This result may be due to the fact that the feeding amount and concentration of $O_2$ supplied from the $O_2$ separator into the storage tank was about 3 L/min and 90%, respectively. It was estimated that this storage amount of $O_2$ could be applied to the design of the indoor ventilation system with the storage and supplying of $O_2$ having about 2 L/min and 90%, respectively.

Fig. 5 shows the internal pressure and the outlet flow rate of the storage tank with the storage and supply of $O_2$ after the supply of

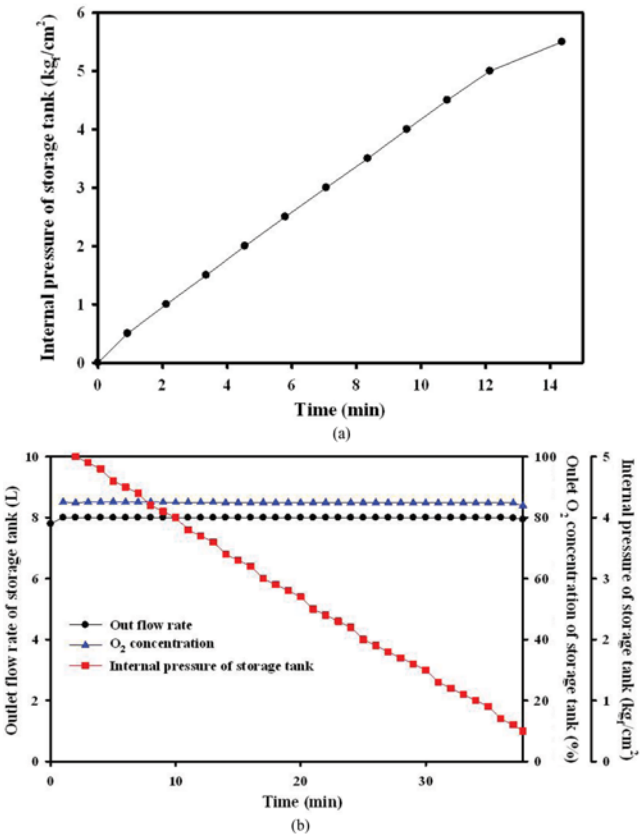


**Fig. 5. The internal pressure and the outlet flow rate of the storage tank ((a) The internal pressure of the storage tank with feeding $O_2$, (b) the internal pressure was proportionally decreased by the $O_2$ supply from the storage tank and reached from about 5.5 to 0.5 $kg_f/cm^2$).**

$O_2$ produced and stored from the $O_2$ separator. As shown in Fig. 5(a), the internal pressure of the storage tank with feeding $O_2$ from the $O_2$ separator to the storage tank was proportionally increased by the $O_2$ accumulation with the time steam and reached up to about 5.5 $kg_f/cm^2$ after about 14.7 min. During the supply of $O_2$ from tank after the $O_2$ storage, the flow rate and concentration of $O_2$ were about 8 L/min and 85%, respectively. As shown in Fig. 5(b), the internal pressure was proportionally decreased by the $O_2$ supply from the storage tank and reached from about 5.5 to 0.5 $kg_f/cm^2$. In addition, although the $O_2$ was discharged from the storage tank and the internal pressure was decreased to 0.5 $kg_f/cm^2$, the outlet flow rate and concentration of $O_2$ were continuously maintained. From these results, it was thought that this system composed of $O_2$ separator and storage tank could be applied to the $O_2$ supply to improve the indoor air quality.

### 3. Application of PSA-Type $O_2$ Separator in Room Ventilation System

To confirm the reference of the indoor concentration of $O_2$ and $CO_2$ without the $O_2$ supply from outside, the indoor concentration of $O_2$ and $CO_2$ was monitored in the room occupying two persons' breathing. Fig. 6 shows the indoor concentration of $O_2$ and $CO_2$ without the $O_2$ supply in the room with the people's breathing. The inner volume of room was about 56 $m^3$ and two persons occupied the room. Before their breathing, the initial concentration of $O_2$ and $CO_2$ was about 20.5% and 1,063 ppm, respectively. After the two persons' breathing room, they were monitored during about 60 min without the $O_2$ supply. As a result, the $CO_2$ concentration was maintained during about 10 min and proportionally increased according with the passage of time after 10 min. After about 60 min with two persons' breathing, the $CO_2$ concentration reached up to 1,630 ppm. On the other hand, the $O_2$ concentration was maintained during 10 min and gradually decreased after 10 min. After 60 min with two persons' breathing, the indoor $O_2$ concentration was about 20.3%. It was thought that $O_2$ was consumed and its concentration decreased as well as $CO_2$ was generated and its concentration increased by the two persons' breathing Also, it led to both a decrease of the $O_2$ concentration and the increase of $CO_2$ concentration.

In this section, the effect of the supply of the high purity $O_2$ concentrated by the $O_2$ separator and stored by the storage tank on the indoor air quality of room was tested to investigate the applicability to the room ventilation of the $O_2$ supply system. Fig. 7 shows the indoor concentration of $O_2$ and $CO_2$ after the supply of high purity $O_2$ from the storage tank after the concentration by the $O_2$ separator. The concentration of $O_2$ and $CO_2$ was respectively monitored after the supply of $O_2$ from the storage tank in the room with the inner volume of 56 $m^3$ and occupied by two persons. The flow rate of $O_2$ supply was varied from 20 to 30 L/min and the $O_2$ concentration was fixed at about 88%. In the case of the $O_2$ flow rate of 20 L/min, the initial concentration of $O_2$ and $CO_2$ were, respectively, about 20.6% and 1,144 ppm and were monitored during about 27 min after the $O_2$ supply to indoor room from the storage tank in two persons' breathing room. As a result, the $CO_2$ concentration was slightly increased up to 1,195 ppm after 12 min and was almost maintained during about 14 min. On the other hand, the $O_2$ concentration was gradually increased and reached up to about 20.7%. These results may be caused by the fact that the increase of the $CO_2$ concentration was inhibited and the indoor $O_2$ concentration increased by the artificial supply of high purity $O_2$ from the outside storage tank as compared with the case without $O_2$ supply, although $O_2$ was consumed and $CO_2$ was generated by the two persons' breathing. In case of the $O_2$ flow rate of 30 L/min, the $CO_2$ concentration was maintained in the narrow range of 992 and 1,034 ppm and the $O_2$ concentration was proportionally and dramatically increased from about 20.6 up to 21.2% after 27 min with the time stream despite the two persons' breathing. As compared with the case of the $O_2$ flow rate of 20 L/min, the increasing rate of $O_2$ concentration was increased and the increasing rate of $O_2$ concentration was suppressed despite the two persons' breathing. It was thought that these results were caused by the fact that the $O_2$ amount supplied from the storage tank is more than that consumed by the two persons and it leads to the continuance of the $CO_2$ concentration and the dramatic increase of the $O_2$ concentration. Consequently, it was estimated that the $O_2$ supply system, which is composed of the $O_2$ separator and storage tank, could be applied to the indoor ventilation process to improve the room condition such as the concentration of $O_2$ improved and $CO_2$ suppressed.

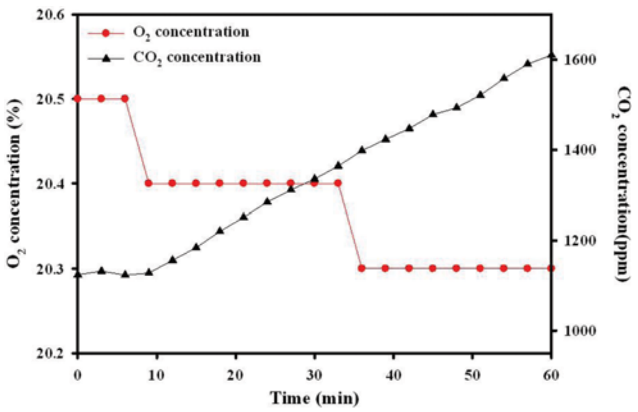


**Fig. 6. The indoor concentration of $O_2$ and $CO_2$ without the $O_2$ supply in room.**

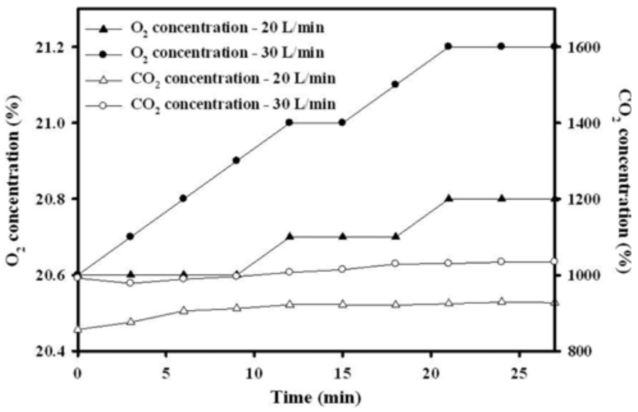


**Fig. 7. The indoor concentration of $O_2$ and $CO_2$ after the supply of $O_2$ from the storage tank.**

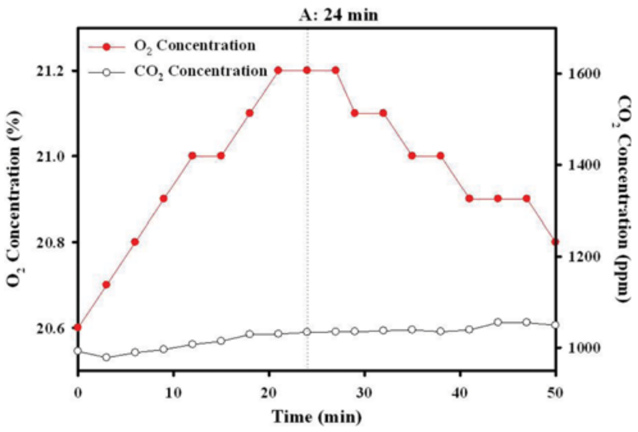


**Fig. 8. The indoor concentration of $O_2$ and $CO_2$ monitored depending on whether or not the $O_2$ supply into the room.**

Fig. 8 shows the indoor concentration of $O_2$ and $CO_2$ monitored depending on whether or not the $O_2$ supply into the room. $O_2$ with the flow rate of about 10 L/min and the concentration of about 88% was supplied into the room with the two persons' breathing until 24 min after the $O_2$ supply; however, the $O_2$ supply was stopped in spite of the two persons' breathing after 24 min. In the process with $O_2$ supply, the $O_2$ concentration was dramatically increased from about 20.6 up to 21.2% and then the $CO_2$ concentration was slightly increased from 1,007 up to 1,020 ppm, however; almost maintained with the low increasing rate. In this case, the $O_2$ concentration was dramatically increased and the $CO_2$ concentration was almost maintained by the sufficient supply of the high purity $O_2$ although $O_2$ was consumed and $CO_2$ was generated by the 2 people's breathing. On the other hand, after the interruption of the $O_2$ supply, the $CO_2$ concentration was slightly raised from about 1,034 up to 1,055 ppm; however, the $O_2$ concentration was rapidly reduced from 21.2 to 20.8% after 26 min. This result may be attributed to the fact that the $O_2$ consumption was increased with the high decreasing rate due to the two persons' breathing. It was estimated that the indoor air quality such as the concentration of $O_2$ and $CO_2$ is influenced and is able to be improved by a sufficient $O_2$ supply.

## CONCLUSION

The applicability of PSA-type $O_2$ separator into the ventilation system to minimize the amount of the outdoor-air volume and amount of ventilation and the cost and loss of energy was investigated to apply to the supply of outdoor $O_2$ into the room ventilation system. Also, a zeolite-based adsorbent used for the PSA-type $O_2$ separator and the storage tank of $O_2$, which was concentrated by the $O_2$ separator, was combined with the ventilation system for the efficient $O_2$ supply. Among the various zeolite-based adsorbents, the performance of the adsorbent E was the most favorable for the PSA-type $O_2$ separator because the BET surface area of the adsorbent E was the highest due to the structural characteristics with the content of the inorganic components. After the storage of $O_2$ into the tank, concentrated $O_2$ was supplied into the room for the improvement of the concentration of $O_2$ and $CO_2$ as an indoor air quality. From the various results, it was known that the $O_2$ concentration was increased; however, the increase of the $CO_2$ concentration was suppressed by the sufficient supply of concentrated $O_2$ from the storage tank into the room despite the two persons' breathing in the room having an inner volume of about 56 $m^3$. Consequently, it was concluded that the supply system of the concentrated $O_2$ which was stored into the tank after the production with the $O_2$ separator can be applied to the room ventilation system for the improvement of the indoor air quality.

## ACKNOWLEDGEMENTS

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