



# Optimizing operating parameters of a honeycomb zeolite rotor concentrator for processing TFT-LCD volatile organic compounds with competitive adsorption characteristics

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## ABSTRACT

In this study, we attempted to enhance the removal efficiency of a honeycomb zeolite rotor concentrator (HZRC), operated at optimal parameters, for processing TFT-LCD volatile organic compounds (VOCs) with competitive adsorption characteristics. The results indicated that when the HZRC processed a VOCs stream of mixed compounds, compounds with a high boiling point take precedence in the adsorption process. In addition, existing compounds with a low boiling point adsorbed onto the HZRC were also displaced by the high-boiling-point compounds. In order to achieve optimal operating parameters for high VOCs removal efficiency, results suggested controlling the inlet velocity to <math><1.5\text{ m/s}</math>, reducing the concentration ratio to 8 times, increasing the desorption temperature to 200–225 °C, and setting the rotation speed to 6.5 rpm.

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## 1. Introduction

With the rapid development of high-technology manufacturing industries, increasing amounts of air pollutants are being generated annually. Such pollutants include volatile organic compounds (VOCs), which are commonly emitted by semiconductor and optoelectronic manufacturers. The emission of these VOCs shows specific characteristics such as high-flow rates, low concentrations and a complex composition, the latest generally consisting of a mixture of acetone, isopropyl alcohol (IPA), propylene glycol monomethyl ether (PGME) and propylene glycol monomethyl ether acetate (PGMEA) [1]. One of the most often used devices for VOCs abatement is the honeycomb zeolite rotor concentrator (HZRC). A standard HZRC system comprises the following three main components: the HZRC, an incinerator, and airflow ducts. Moreover, the HZRC has also been summarized as being efficient in treating VOCs with a wide range of concentrations and characteristics [2–4].

The removal efficiency of an HZRC is influenced by parameters such as the process flow rate, rotation speed, thermal response, and the type of zeolite used to coat the concentrator [5–7]. Several studies have estimated the non-dimensional number between the efficiency and optimal rotation speed of the rotor, with a specific

set of operating and design parameters [8,9]. Combining the HZRC with an oxidation process is more economical and efficient, and yielded fewer secondary emissions [2,10,11] compared to single-oxidation processes such as regenerative thermal oxidizer (RTO), regenerative catalytic oxidizer (RCO), and catalytic thermal oxidizer (CTO) processes.

In the authors' previous study [12], we examined the effects of various inlet flow conditions and operating parameters on the characteristics of adsorption and desorption of VOCs emitted from semiconductor manufacturers, in terms of their removal efficiencies by a HZRC. Those results provided information for field applications to semiconductor industries to obtain optimal operating conditions of the concentrator for both efficient VOC controls and energy savings. Both field scale [3,10,13–15] and lab-based assessments [2,7,8,12] have been performed for such an HZRC system, and this system can achieve 90% VOCs removal efficiency over a long period of stable operation. However, the current field efficiencies of HZRCs applied to thin film transistor liquid crystal display (TFT-LCD) industries are not as efficient as those used in the semiconductor and other chemical industries.

VOCs pollutants produced from the manufacturing processes of LCD panels have characteristics of high-flow rate with a variety of VOCs emitted at low concentrations, which are similar as those generated by semiconductor industries. The flow rate and concentrations of the VOCs exhausts are dependent on the display area of an LCD panel, and increase for larger display areas. This results in

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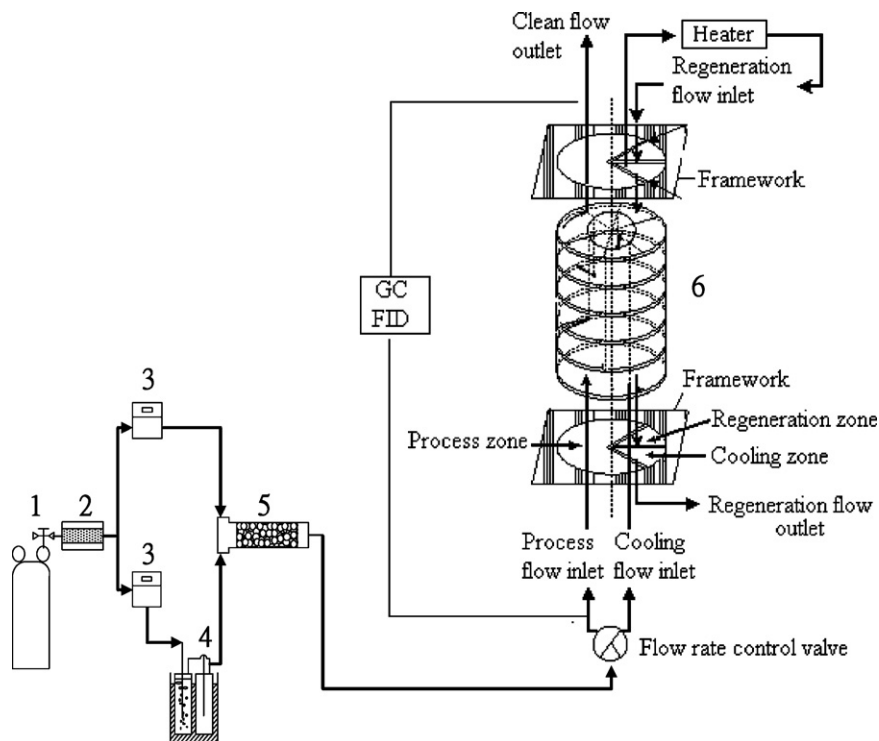


Fig. 1. Simplified flow diagram of the honeycomb zeolite rotor concentrator (HZRC) test facility. (1. Air cylinder and control valve; 2. humidity and high-efficiency particulate air filter; 3. mass flow control; 4. VOCs vapor generator and thermostatic water bath; 5. mixing chamber; 6. HZRC.)

the concentrations and flow rate of VOCs from TFT-LCD industries surpassing those generated by semiconductor industries by several times. However, with the greater concentration of high-boiling-point compounds (such as PGME and PGMEA) in the VOCs emitted from TFT-LCD industries, the competitive adsorption between these VOCs on an HZRC also leads to a decline in efficiency. The aforementioned factors and situations have not been studied in the previous literature.

Thus, this study provides information on field applications to TFT-LCD and other optoelectronic industries, to obtain corresponding optimal operating conditions of HZRCs. In this study, enhancement of removal efficiency of a HZRC in optoelectronic industries is mainly attempted. First, the static and competitive adsorption of high- and low-boiling-point VOCs on the HZRC is discussed. Dynamic process results of laboratory tests on the removal efficiencies of major VOCs in TFT-LCD industries, including acetone, IPA, PGME, and PGMEA, by an HZRC module are also addressed.

## 2. Experimental

The HZRC was constructed using honeycomb ceramic fibers, coated with a hydrophobic ZSM-5-type zeolite, and the manufacturing process of HZRC followed that described by Kuma [16]. Subsequently, the element was formed into a honeycomb-shaped laminate, with several small channels from one end of the surface to the other.

To start this experiment, a brief introduction of HZRC adopted this time has to be brought. The HZRC surface area was  $160 \text{ m}^2/\text{g}$  with total pore volume of  $0.167 \text{ cm}^3/\text{g}$  and average pore diameter of  $41.9 \text{ \AA}$ , the above-mentioned characteristics being measured by  $\text{N}_2$  adsorption-desorption at  $-196^\circ\text{C}$  in a Micromeritics ASAP 2020 system. The Si/Al ratio of HZRC was 13.70, as analyzed by an energy dispersive spectrometer analyzer (Hitachi S-47001). For both kinds of measurements, pieces of HZRC were employed.

Fig. 1 presents a simplified flow diagram of the dynamic HZRC test facility. The framework divides the cross-surface of HZRC which faces to flow-direction into three zones; process (adsorption), regeneration and cooling. The area ratio of each zone of the zeolite concentrator in the mentioned order is 10:1:1, and the dynamic HZRC is rotated through these three procedures in a row.

Carrier flow in Fig. 1 was produced from an air cylinder. After passing through the high-efficiency particulate air filter (HEPA), the concentrations of VOCs in the flow were generated from the VOCs impingers, which were immersed on thermostated water-tank at  $25^\circ\text{C}$ . The flow was separated into process flow and cooling flow, which respectively passed through the process and cooling zones of the HZRC. The concentration ratio was determined by the process flow rate divided by the cooling flow rate. In addition, this was regulated by a flow rate control valve. The clean cooling flow, exiting from the HZRC, was recycled, heated and became as the regeneration flow. Then the regeneration flow would enter HZRC system again from the other entrance, and the high temperature of the regeneration flow caused desorption of the VOCs and activated the process zone. The height and diameter of HZRC on the dynamic test were 0.30 and 0.32 m, respectively; those parameters of the HZRC in the static adsorption column, which was the only adsorption zone without the cooling and regeneration procedure, were 0.32 and 0.05 m, respectively.

The concentration of the VOCs was measured by gas chromatography/flame ionization detector (GC/FID) (Shimadza GC14B) to determine the efficiency of the zeolite concentrator. The removal efficiency was defined as  $\eta = (C_{\text{inlet}} - C_{\text{outlet}}) / C_{\text{inlet}} \times 100\%$ , where  $C_{\text{inlet}}$  and  $C_{\text{outlet}}$  were the concentrations of inlet and outlet VOCs respectively. Samples were injected into the GC/FID for analysis. A Shimadza C-R6A integrator was used to calculate VOCs concentrations. A J&W DB-WAX column was used in the GC analysis. All VOC reagents were purchased from Acro Organics, and the properties of these adsorbates are listed in Table 1.

**Table 1**  
Properties of volatile organic compounds adsorbates

Property	Compound			
	Acetone	IPA <sup>a</sup>	PGME <sup>b</sup>	PGMEA <sup>c</sup>
Formula	C <sub>3</sub> H <sub>6</sub> O	C <sub>3</sub> H <sub>8</sub> O	C <sub>4</sub> H <sub>10</sub> O <sub>2</sub>	C <sub>6</sub> H <sub>12</sub> O <sub>3</sub>
Molecular weight	58.08	60.10	90.12	132.16
Vapor pressure (mbar) measured at 25 °C	304.0	57.9	15.5	4.9
Boiling point (°C)	57	82	120	146

<sup>a</sup> Isopropyl alcohol.

<sup>b</sup> Propylene glycol monomethyl ether.

<sup>c</sup> Propylene glycol monomethyl ether acetate.

### 3. Results and discussion

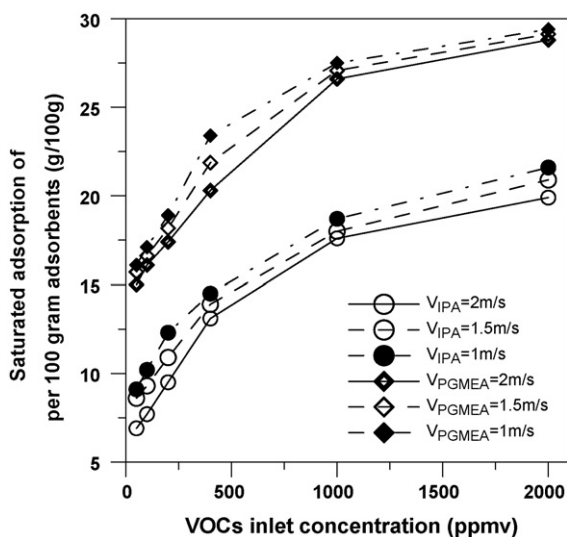
#### 3.1. Static adsorption

Under inlet linear velocities of 1, 1.5, and 2 m/s, single-substance adsorption experiments were individually conducted using an HZRC for both IPA and PGMEA. The results are the average data of three repeated experiments, and their standard deviation was around 3% in terms of the VOCs removal efficiency.

As illustrated in Fig. 2, all saturated adsorption amounts can be calculated by the adsorption isotherms, and the saturated adsorption can be estimated when the outlet concentration is equal to inlet concentration.

The saturated adsorption of IPA by the HZRC was between 6.9 wt.% and 12.3 wt.%, when the inlet concentration ranged from 50 to 200 ppmv. When the inlet concentration reached 2000 ppmv, the adsorption rose to around 19.9–21.6 wt.%. The saturated adsorption of PGMEA, on the other hand, reached around 26.6–27.6 wt.% when the inlet concentration was 1000 ppmv. The experimental results indicated that the saturated adsorption of an HZRC for IPA and PGMEA increased as VOC concentration increased. In other words, by the adsorption isotherms we can conclude that the higher inlet concentration is more amount can be adsorbed. The saturated adsorption of adsorbent is as the function of the concentration of adsorbate through adsorption isotherms.

The saturated adsorption performance of PGMEA is better than that of IPA by approximately 50% in terms of efficiency. Such



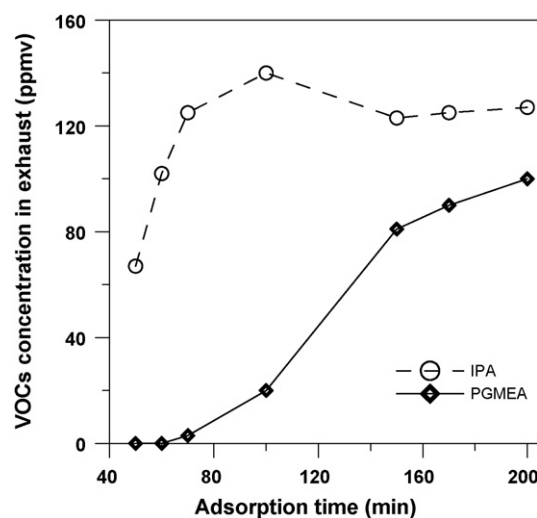
**Fig. 2.** Effects of inlet concentration and inlet linear velocity on the saturated adsorption of a honeycomb zeolite rotor concentrator for isopropyl alcohol (IPA) and propylene glycol monomethyl ether acetate (PGMEA).

enhancement can be related to the higher boiling point and the greater molecule weight of PGMEA than those of IPA [17–19]. In addition, the ZSM-5 zeolite of high Si/Al ratio coated on the HZRC has the hydrophobic and non-polar characterization, and therefore the HZRC has the affinity for the non-polar PGMEA more than the polar IPA. [20,21].

The experimental results also indicated that the saturated adsorption of an HZRC for IPA and PGMEA decreased as linear velocity increased; the effect of the superficial velocity on the saturated adsorption was small and lower than that of the inlet concentration. Such a result indicates that the adsorption amounts in the HZRC for both IPA and PGMEA were less subject to the influence of superficial velocity. This was because the mass transfer zone of HZRC in this study was enough to process the linear velocity between 1 and 2 m/s, which were the common linear velocities on the physical operation. Therefore, processing much higher flow rate of VOCs exhaust needs deeper mass transfer zone to enhance the removal efficiency.

Fig. 3 illustrates the competitive adsorption of IPA and PGMEA on the HZRC, with an inlet flow containing a mixture of these compounds. Both compounds had the same inlet concentration of 100 ppmv and the linear velocity of 2 m/s. In the initial adsorption period, IPA was the main compound in the exhaust stream. 100 min later, few concentration of PGMEA appears in the exhaust stream. The concentrations of IPA and PGMEA in the exhaust stream increased with adsorption time. The emission concentration of IPA increased faster than that of PGMEA, and was also higher than the inlet concentration until the end of the adsorption phase. The above phenomenon was due to the competitive adsorption of PGMEA, which displaced IPA during the adsorption phase of the HZRC. There were not sufficient adsorption sites for IPA to be adsorbed, hence it was emitted in the exhaust stream without effective adsorption. Clause et al. (1998) and Simonot-Grange and Garrot (2001) [22] also indicated that the breakthrough order of lower boiling-point VOC is earlier than that of higher boiling-point VOC on the process of multi-VOCs adsorption, and the outlet concentration of lower boiling-point VOC get beyond the inlet concentration. Simultaneously, the lower boiling-point VOC was displaced by the higher boiling-point one from zeolite.

In order to understand the behavior of IPA, which was displaced by PGMEA on the HZRC during the competitive adsorption process,



**Fig. 3.** Individual concentrations of the exhaust from a honeycomb zeolite rotor concentrator processing an inlet flow with mixed isopropyl alcohol (IPA) and propylene glycol monomethyl ether acetate (PGMEA).

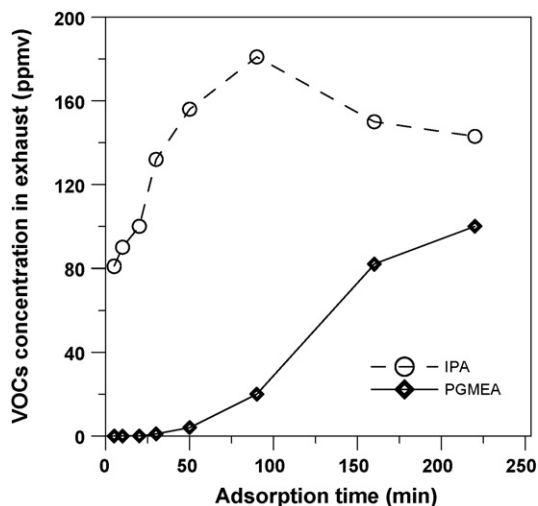


Fig. 4. Individual concentrations of the exhaust from a honeycomb zeolite rotor concentrator of an isopropyl alcohol (IPA)-saturated adsorption process with an inlet flow of mixed IPA and propylene glycol monomethyl ether acetate (PGMEA).

further experiments were conducted. IPA and PGMEA at 100 ppmv were individually adsorbed until saturated on the HZRC. Subsequently, a mixed stream of both compounds was induced in the system, with both inlet concentrations at 100 ppmv and the linear velocity of 2 m/s. Analyzing the emission concentrations of the compounds verified that PGMEA, instead of IPA, was competitively adsorbed onto the HZRC.

Fig. 4 shows the emission concentrations of the compounds after the mixed stream of IPA and PGMEA passing through the HZRC. Prior to this, the HZRC had previously adsorbed IPA to saturation. Under this scenario, the emission exhaust had a higher concentration of IPA, which indicates that the HZRC could not effectively process IPA. In addition, the emission IPA concentration exceeded the inlet concentration of 100 ppmv after 20 min. The emission IPA concentration peaked at around 180 ppmv, and was maintained at around 140 ppmv to the end of the experimental period. The above phenomena indicate that PGMEA not only took precedence in the adsorption process on the HZRC, but was also displacing existing IPA, which had previously been adsorbed onto the HZRC.

In addition, PGMEA was completely adsorbed by the HZRC during the initial adsorption process. It was not until approximately 100 min later that a gradual increase in the PGMEA concentration was detected in the emission exhaust. At around 220 min later, the HZRC showed signs of saturated adsorption of PGMEA, as the outlet concentration of PGMEA at that moment was the same as the inlet concentration. Such results indicate that a great amount of existing IPA, which had been adsorbed onto the HZRC, was displaced by PGMEA similarly to the results from Fig. 3. Furthermore, the saturated adsorption of IPA alone was 7.1 wt.%/g HZRC. However, the saturated adsorption of HZRC increased to 17.4 wt.% after processing the mixed stream of IPA and PGMEA. These results further support the above-described findings. The saturated adsorption here was estimated from whatever adsorbed in the adsorbent, including those originally adsorbed plus those adsorbed in the second time.

Next, prior to the introduction of the mixed stream of IPA and PGMEA, the HZRC adsorbed 100 ppmv of PGMEA to saturation. The results from the analysis of the emission VOCs concentrations are illustrated in Fig. 5. Initially, the emission concentrations of IPA and PGMEA were both zero, when the mixed stream passed through the HZRC. However, the emission concentrations of IPA and PGMEA soon rapidly rose, and both approached the inlet concentrations of

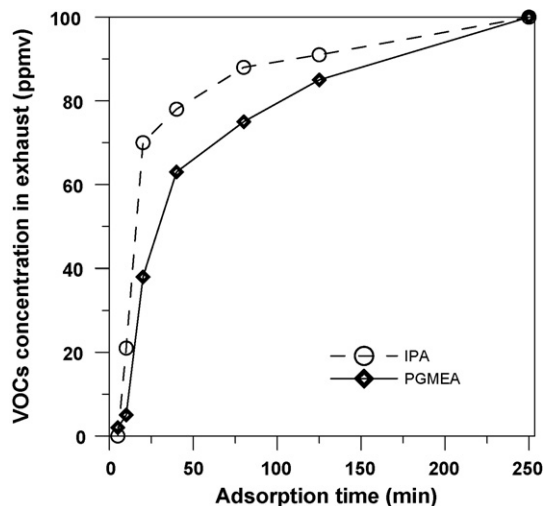


Fig. 5. Individual concentrations of the exhaust from a honeycomb zeolite rotor concentrator of propylene glycol monomethyl ether acetate (PGMEA)-saturated adsorption process with an inlet flow of mixed isopropyl alcohol (IPA) and PGMEA.

100 ppmv. However, the adsorption breakthrough curve of IPA did not have the peak, which indicated that the emission concentration of IPA did not cap the inlet concentration.

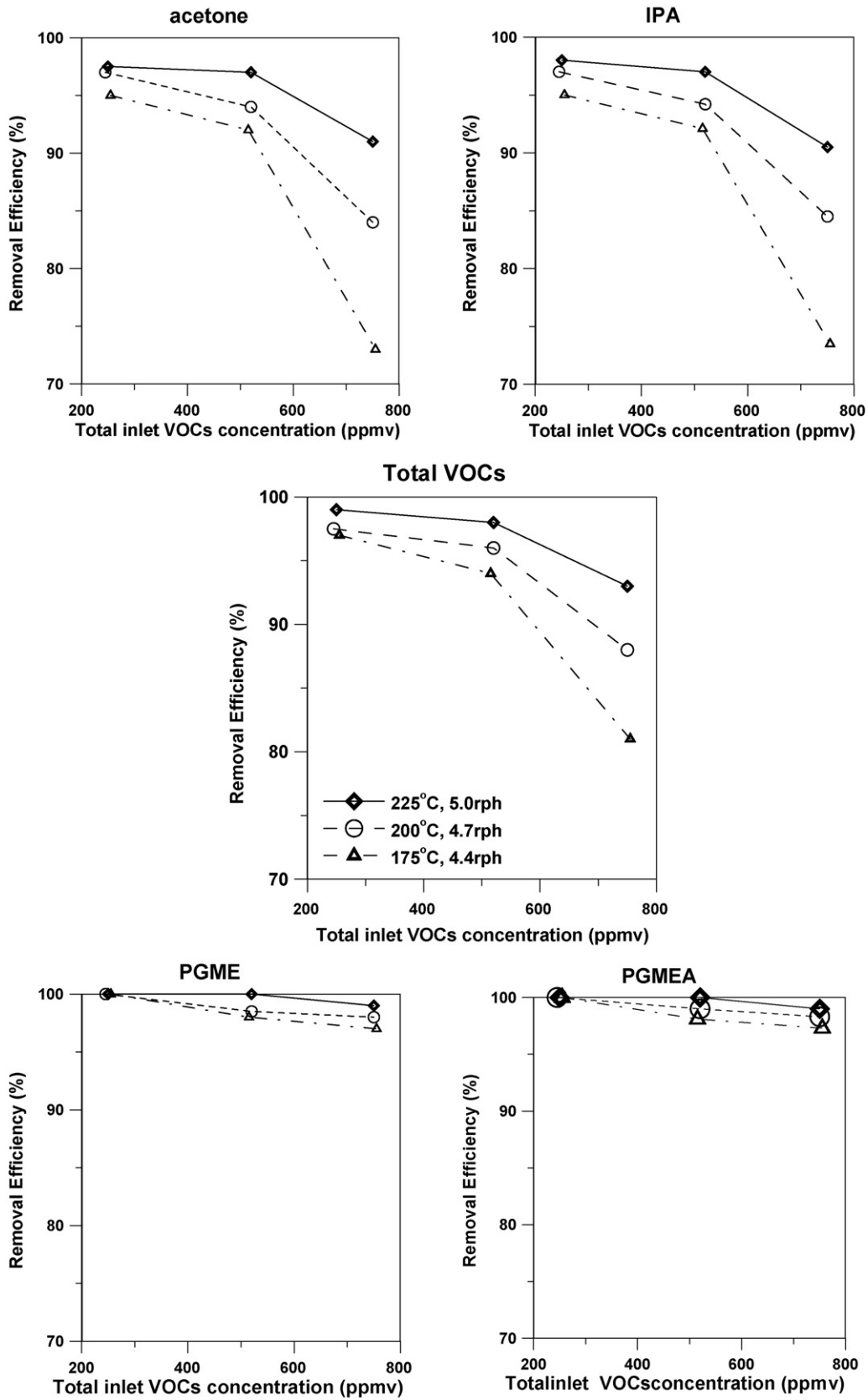
The result significantly differs from those in Figs. 3 and 4. This is because the IPA in the mixed stream could not displace the adsorbed PGMEA from the HZRC, and the PGMEA in the mixed stream had advantage to be adsorbed on the residual adsorption site of the HZRC. IPA could not be adsorbed on the HZRC effectively, and broke through immediately at exhaust. In the experiments of Figs. 3 and 4, PGMEA displaced the adsorbed IPA from the HZRC, and this displaced IPA contributed to the emission concentration exceeding the inlet concentration. However, there was not any or maybe few IPA adsorbed on the HZRC in the experiment of Fig. 5, and the displaced IPA could be negligible. Therefore, the emission concentration of IPA did not exceed the inlet concentration. The saturated adsorption times for IPA and PGMEA were more or less the same.

In addition, the higher IPA concentration level in the emission exhaust indicates a lower processing efficiency of IPA by the HZRC, which had previously adsorbed PGMEA to saturation. The saturated adsorption of PGMEA alone was 16.4 wt.%/g HZRC. However, the saturated adsorption of HZRC increased to 21.1 wt.% after processing the mixed stream of IPA and PGMEA, the enhanced saturated adsorption being attributed to the higher total charging concentrations (PGMEA + IPA).

The above experimental results verified that under the same conditions, the existing IPA adsorbed on the HZRC was displaced by PGMEA, causing competitive adsorption. This was due to PGMEA having a higher boiling point and molecular weight. One thing worth mentioning is that VOCs exhausts emitted from wafer and TFT-LCD manufacturing plants consist of a high ratio of IPA or other lower/mid-boiling-point VOCs. As such, under physical operations, if the PGMEA cannot be completely desorbed and thus occupies adsorption sites on the HZRC, the removal efficiency for lower/mid-boiling-point VOCs could be seriously affected. This would cause the overall removal efficiency of the HZRC to decline.

### 3.2. Dynamic adsorption

In order to obtain optimum operating parameters for the HZRC to achieve high VOCs removal efficiencies and avoid the inhibition of competitive adsorption, adsorption/desorption experiments with multiple VOCs were conducted. To simulate the characteris-



**Fig. 6.** Effect of the desorption temperature and rotation speed of a honeycomb zeolite rotor concentrator of 400 mm thickness processing a volatile organic compounds flow at a linear velocity of 1.5 m/s on its removal efficiency. (The acronyms of IPA, PGME and PGMEA indicate isopropyl alcohol, propylene glycol monomethyl ether and propylene glycol monomethyl ether acetate, respectively.)

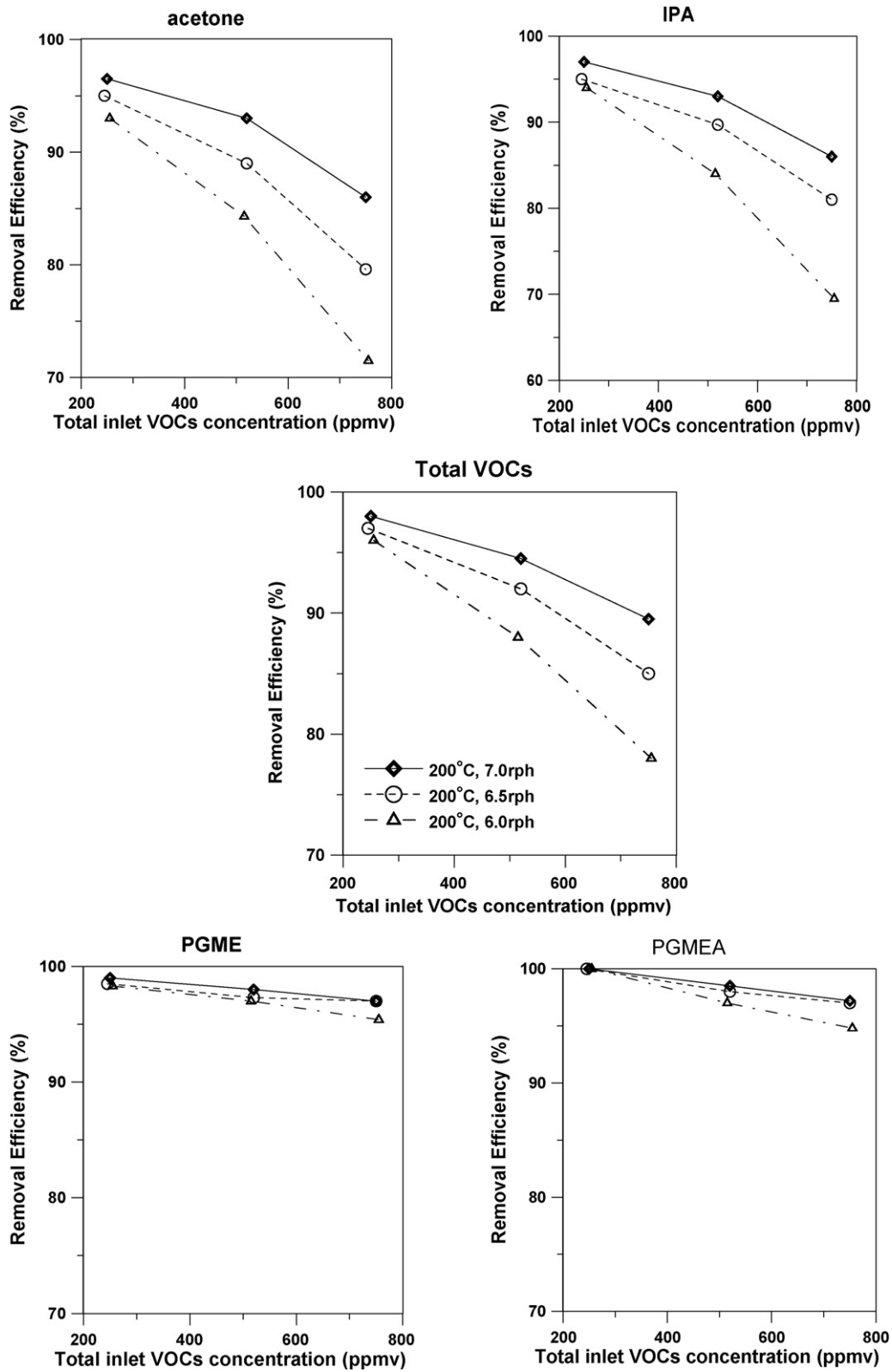


Fig. 7. Effect of the rotation speed of a honeycomb zeolite rotor concentrator of 400 mm thickness processing a volatile organic compounds flow at a linear velocity of 2.0 m/s on its removal efficiency. (The acronyms of IPA, PGME and PGMEA indicate isopropyl alcohol, propylene glycol monomethyl ether and propylene glycol monomethyl ether acetate, respectively.)

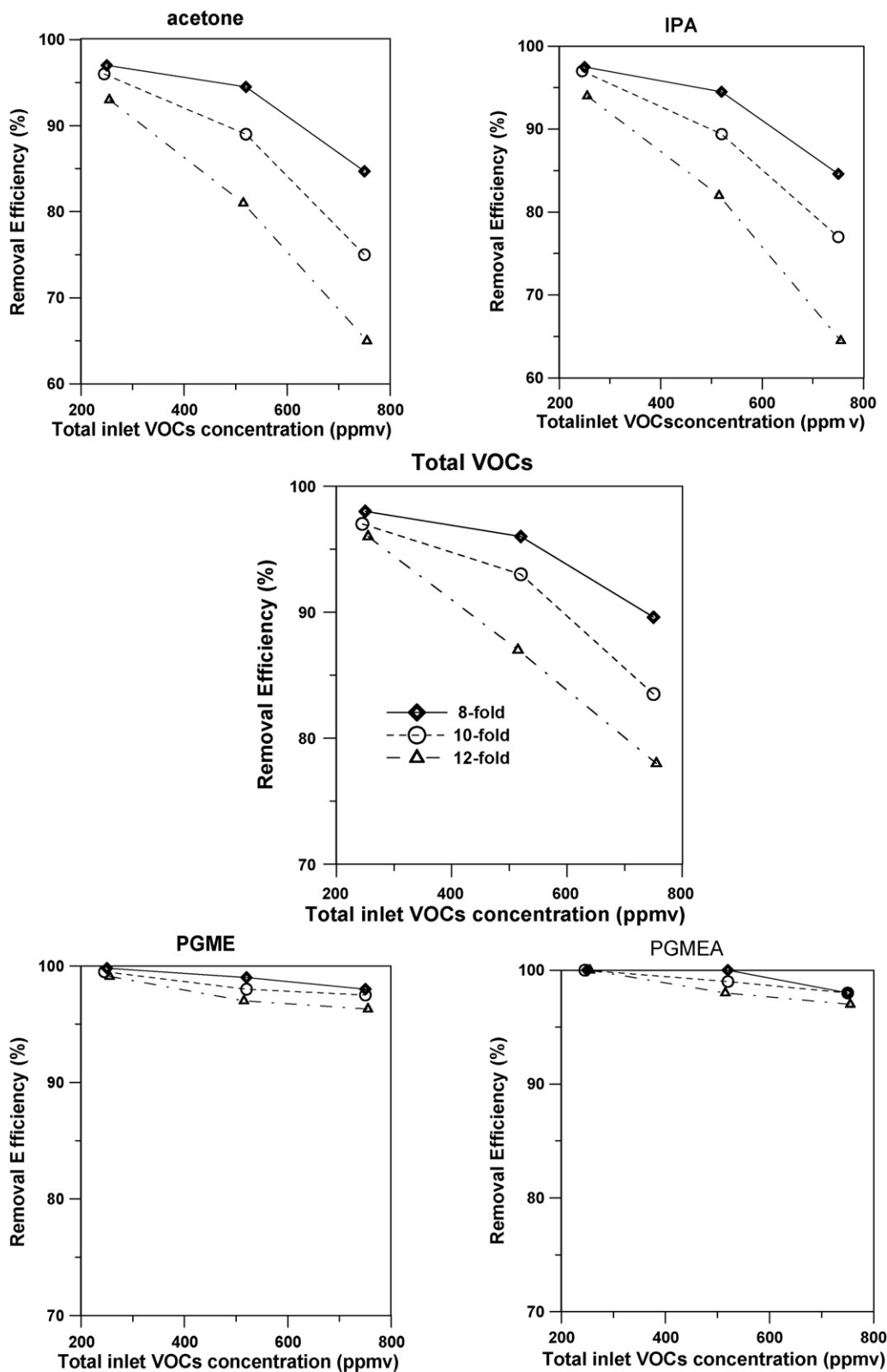


Fig. 8. Effect of the concentration ratio of a honeycomb zeolite rotor concentrator of 400 mm thickness processing a volatile organic compounds flow at a linear velocity of 2.0 m/s on its removal efficiency. (The acronyms of IPA, PGME and PGMEA indicate isopropyl alcohol, propylene glycol monomethyl ether and propylene glycol monomethyl ether acetate, respectively.)

tics of VOCs exhausts produced by TFT-LCD manufacturers, multiple VOCs with compounds and molar ratios of IPA (35%), acetone (25%), PGMEA (20%), and PGME (20%) were created for the experiments. The temperature and relative humidity of the inlet stream were 25 °C and 50%, respectively. The operating parameters of interest included the inlet concentration, the concentration ratio, the linear velocity of the inlet stream, and the desorption temperature. The test conditions consisted of inlet concentrations of 250, 500, and 750 ppmv; concentration ratios of 8-, 10-, and 12-fold; linear velocities of 1.5 and 2.0 m/s; and desorption temperatures of 175, 200, and 225 °C. The tested concentrations are typical for the TFT-LCD industry, and the ratio of process flow rate to cooling flow rate determines the concentration ratio.

The results from Fig. 6 indicate that the VOC removal efficiency of the HZRC declined as the inlet concentration increased. However, increasing the desorption temperature enhanced all of VOCs desorbed, especially for VOCs with a high boiling point which needed higher temperature to be desorbed more efficiently. In addition, increasing the speed of rotation assisted a faster rotation of the part of HZRC from an adsorption to a desorption zone, and prevented the part of HZRC on adsorption zone from adsorption breakthroughs. Currently, the environmental regulations of Taiwan require semiconductor manufacturers to achieve  $\geq 90\%$  VOCs removal efficiency. Optoelectronics manufacturers, on the other hand, are required to achieve  $\geq 85\%$  under the corresponding regulations. Therefore, setting the desorption temperature to 200 °C and the rotation speed to 4.7 rpm enabled the inlet VOC stream of 750 ppmv to achieve a 90% removal efficiency. This not only meets the regulation requirements, but at the same time maintained an appropriate rotation speed to economize operational expenses. In addition, the desorption temperature of an onsite operating HZRC can be increased by adjusting the second heat exchanger. As such, no additional energy is consumed. Although increasing the desorption temperature to 225 °C would further improve the VOCs removal efficiency, however, long-term operation under such conditions would deteriorate the air-tight silica applied between the HZRC and its framework, resulting in leakage of the process VOCs stream.

The total removal efficiency of the HZRC declined when the total inlet concentration of the VOCs stream was increased. However, the rate at which the efficiency declined for each individual VOCs differed. Among the tested compounds, the removal efficiency of acetone showed the greatest decline, followed in order by IPA, PGME, and PGMEA. One thing to note is that the declines in the removal efficiency for both PGME and PGMEA were not as significant. Among the selected VOCs, PGMEA was the most efficiently adsorbed onto the HZRC. This was followed by PGME, IPA, and then acetone. As for desorption, the order was reversed, as acetone was the most efficient compound desorbed. Such behavior must be probably related with the molecular weight and boiling point of each compound. In other words, VOCs with a greater molecular weight and a higher boiling point have better removal efficiencies. Both the competitive adsorption and adsorption replacement further enhance the removal efficiency of high-boiling-point VOCs. The above phenomena conform to the results of Clause et al. [17] and Rook et al. [18], who found that high-boiling-point VOCs substituted lower boiling-point VOCs adsorbed on zeolite and activated carbon, respectively.

When the linear velocity of an inlet VOCs stream was increased to 2 m/s (as illustrated in Fig. 7), with a desorption temperature of 200 °C, the rotation speed of the HZRC had to be increased to 6.5 rpm in order to achieve 90% removal efficiency for VOCs with an inlet concentration of 750 ppmv. Processing the VOCs exhaust with a greater linear velocity in the HZRC accelerated saturation of the adsorption zone. This caused the VOCs removal efficiency to decline. Therefore, by increasing the rotation speed of the HZRC,

which led to a faster transition from the adsorption to the desorption zone, an early adsorption zone breakthrough and decline in VOCs removal efficiency could be prevented.

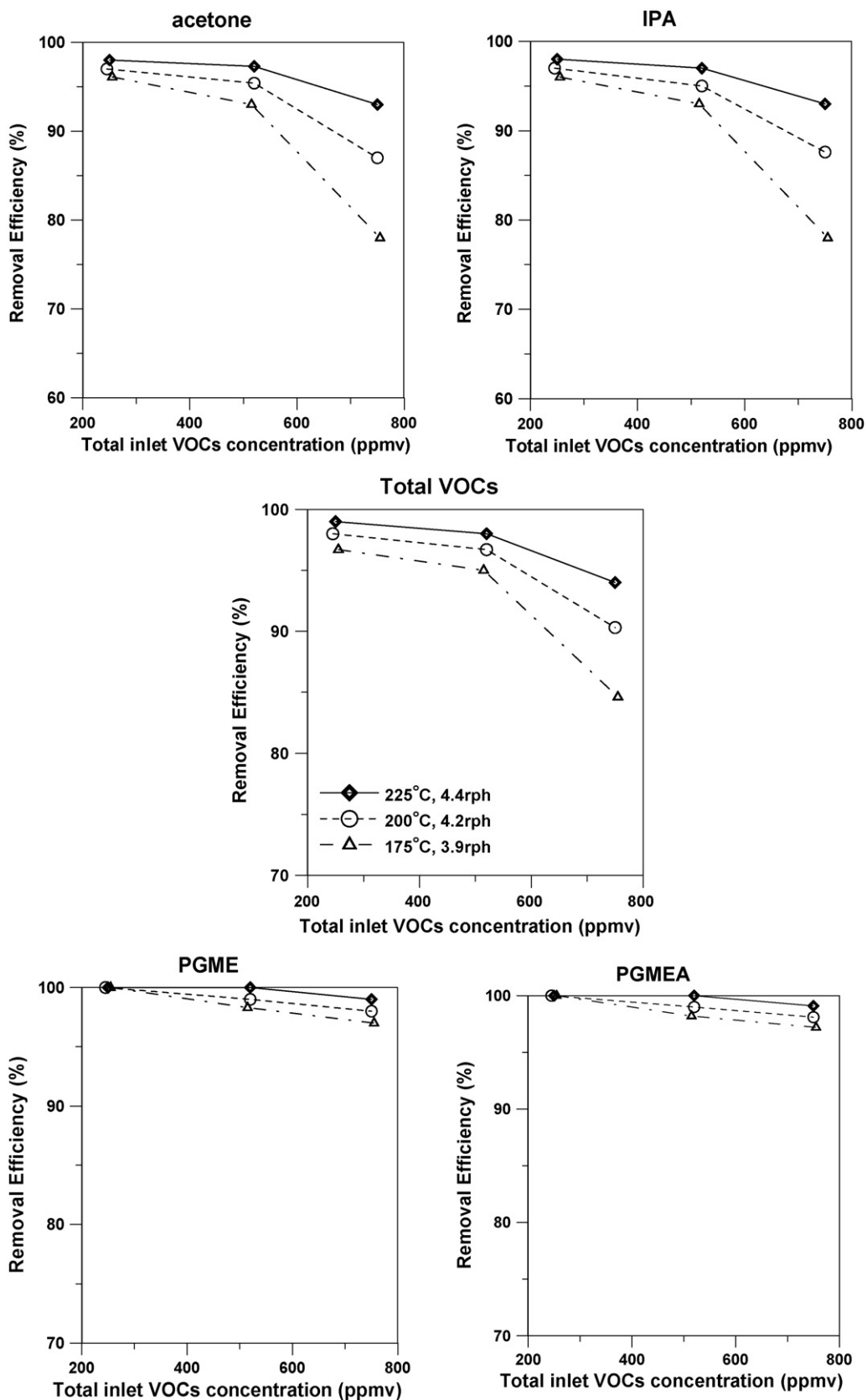
Fig. 8 shows the VOCs removal efficiencies obtained from a range of concentration ratios through these experiments. It was found that the total efficiency of the HZRC increased as the concentration ratio decreased. As above indicate, the concentration ratio is defined as the VOCs inlet flow of the adsorption zone divided by the VOCs inlet flow of the cooling zone, which also circulates to the desorption zone. Hence, a decrease in the concentration ratio represents a decline in the flow rate of the adsorption zone and an increase in the flow rate of the cooling zone (desorption zone). By adjusting the concentration ratio to 8, the adsorption zone of the HZRC was able to process the VOCs inlet stream of 750 ppmv and achieve a 90% VOCs removal efficiency. A lower concentration ratio increased the VOCs removal efficiency in the adsorption and desorption zones. However, physical onsite application of such an approach can lead to an increase in the inlet flow rate of the backend incinerator, causing greater fuel consumption. Therefore, considering the removal efficiency and resource consumption, adjustments to the concentration ratio should be performed according to actual conditions. Take the characteristics of the VOCs exhausts from TFT-LCD manufacturers for example. Controlling the concentration ratio to 10 not only fulfills the industry requirements of Taiwan's environmental regulations, but also economizes the operating costs of the backend incinerator.

The flow rate and concentration level of VOCs streams emitted by the TFT-LCD industry are greater than those from the semiconductor industry. If altering the operating parameters of the HZRC cannot further enhance the VOCs removal efficiency, the specification of the HZRC should be designed and planned before being installed at a TFT-LCD manufacturing site. Fig. 9 shows the effects of the thickness of the HZRC on the VOCs removal efficiency. The difference in total VOC removal efficiencies between the 400- and 450-mm HZRC was slight when processing a VOC stream of <200 ppmv in concentration. However, if the concentration level exceeds 200 ppmv, the difference in removal efficiency begins to become more evident. In addition, under such conditions, the total VOCs removal efficiency of the 450-mm HZRC was significantly enhanced. Regarding each individual VOC, the removal efficiencies of acetone and IPA were substantially improved on the thicker HZRC. Such differences in performance were not significant for PGME and PGMEA.

In an HZRC of thinner thickness, IPA and acetone would not have sufficient adsorption sites, as both compounds were displaced by the competitive adsorption of PGMEA and PGME. This caused IPA and acetone to be emitted along with the VOCs exhaust, leading to a decline in the VOCs removal efficiency of the HZRC. However, by increasing the thickness of the HZRC, the mass transfer zone for processing VOCs exhaust extends the adsorption zone. This means that the displaced IPA and acetone can be adsorbed in the mass transfer zone of adsorption, which will improve the VOCs removal efficiency. According to the above phenomenon, the front end of the adsorption zone accumulates a greater amount of high-boiling-point compounds, such as PGMEA and PGME, whereas the rear end of the adsorption zone consists of a greater amount of low/mid-boiling-point compounds, such as IPA and acetone. When the HZRC transits from adsorption to desorption, the rear end of the adsorption zone becomes the entry of the desorption zone. Therefore, given the characteristics of low/mid-boiling-point compounds and a larger amount of desorption energy at the entry of the desorption zone, both IPA and acetone can achieve greater desorption under such conditions.

In the case the thickness of the HZRC is increased, if the desorption energy is insufficient, the energy will further significantly





**Fig. 9.** Effect of the desorption temperature and rotation speed of a honeycomb zeolite rotor concentrator of 450 mm thickness processing a volatile organic compounds flow at a linear velocity of 1.5 m/s on its removal efficiency. (The acronyms of IPA, PGME and PGMEA indicate isopropyl alcohol, propylene glycol monomethyl ether and propylene glycol monomethyl ether acetate, respectively.)

decline at the rear of the mass transfer zone of desorption. As such, PGMEA, PGME, and other high-boiling-point compounds cannot achieve effective desorption, causing the overall VOCs removal efficiency of the HZRC to decline. Therefore, it is important to supply sufficient desorption energy, if the thickness of the HZRC is increased to ensure the effective desorption of VOCs.

The desorption energy can be improved by increasing the desorption flow and temperature. However, it is unfavorable to purposely increase desorption temperature, as it can smolder the HZRC, causing an unexpected system shutdown. In addition, increasing desorption temperature can also cause VOCs leakage due to oxidation of the silica packing. Adjusting desorption flow rate can avoid the aforementioned drawbacks, but will increase fuel costs.

#### 4. Conclusions

As the HZRC processes a VOCs stream of mixed compounds, high-boiling-point compounds (such as propylene glycol monomethyl ether and propylene glycol monomethyl ether acetate) take precedence in the adsorption process. In addition, existing low-boiling-point compounds (such as isopropyl alcohol and acetone) adsorbed onto the HZRC are also displaced by the high-boiling-point compounds. The ratio of IPA and acetone in VOC streams emitted by TFT-LCD industries commonly exceed 60%. As such, the competitive adsorption and unsatisfactory desorption of high-boiling-point compounds will result in adsorption deficiencies of low-boiling-point compounds. This will cause a decline in the total VOC removal efficiency of the HZRC.

The VOCs exhausts emitted by TFT-LCD manufacturers have the characteristics of higher ratios of high-boiling-point compounds, VOCs concentrations, and flow rate. To accommodate such characteristics, the optimal parameters for high-efficiency VOCs removal are suggested to be an inlet velocity of <1.5 m/s, a concentration ratio of 8 times, a desorption temperature of 200–225 °C, and a rotation speed of 6.5 rpm.

Alternatively, by installing a thicker HZRC and simultaneously increasing the desorption energy, which includes the desorption temperature and flow rate, these parameters can also enhance the total VOC removal efficiency to exceed 90% and even 95%.

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