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Cushioning the Pressure Vibration of a Zeolite Concentrator System Using a Decoupled Balancing Duct System

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A honeycomb Zeolite Rotor Concentrator (HZRC) is the main air pollution control device utilized by many semiconductor and optoelectronics manufacturers. Various plant exhaust streams are collected and then transferred to the HZRC for decontamination. In a conventional HZRC, the exhaust fan movement and the switching between different air ducts can cause significant duct pressure variations resulting in production interruption. The minimization of pressure fluctuations to ensure continuous operation of production lines while maintaining a high volatile organic compounds (VOCs) removal efficiency is essential for exhaust treatment in these high technology manufactures. The article introduces a decoupled balancing duct system (DBDS) for controlling the airflows to achieve a balanced pressure in the HZRC system by adding a flow rate control device to the VOCs loaded stream bypass duct of a conventional system. Performance comparisons of HZRC with DBDS and other air flow control systems used by the wafer manufacturers in Hsinchu Science Park, Taiwan are presented. DBDS system had been proved effectively to stabilize the pressure in the airflow ducts, and thus avoided pressure fluctuations; it helped to achieve a high VOCs removal efficiency while ensuring the stability of the HZRC. © 2007 American Institute of Chemical Engineers Environ Prog, 26: 188–196, 2007

Keywords: pressure fluctuation, semiconductor and optoelectronics manufacturing, air pollution control devices, volatile organic compounds (VOCs), adsorption, rotor concentrator

INTRODUCTION

With the development of high technology manufacturing industries, large amounts of air pollutants are being generated each year. The pollutants include volatile organic compounds (VOCs) commonly emitted by the semiconductor and the optoelectronics manufacturers. These VOCs have distinct characteristics such as high flow rates and low concentrations [1]. Honeycomb zeolite rotor concentrator (HZRC) is one of the most popular VOC abatement devices. A standard HZRC system comprises three main components: the zeolite rotor, incinerator, and the airflow

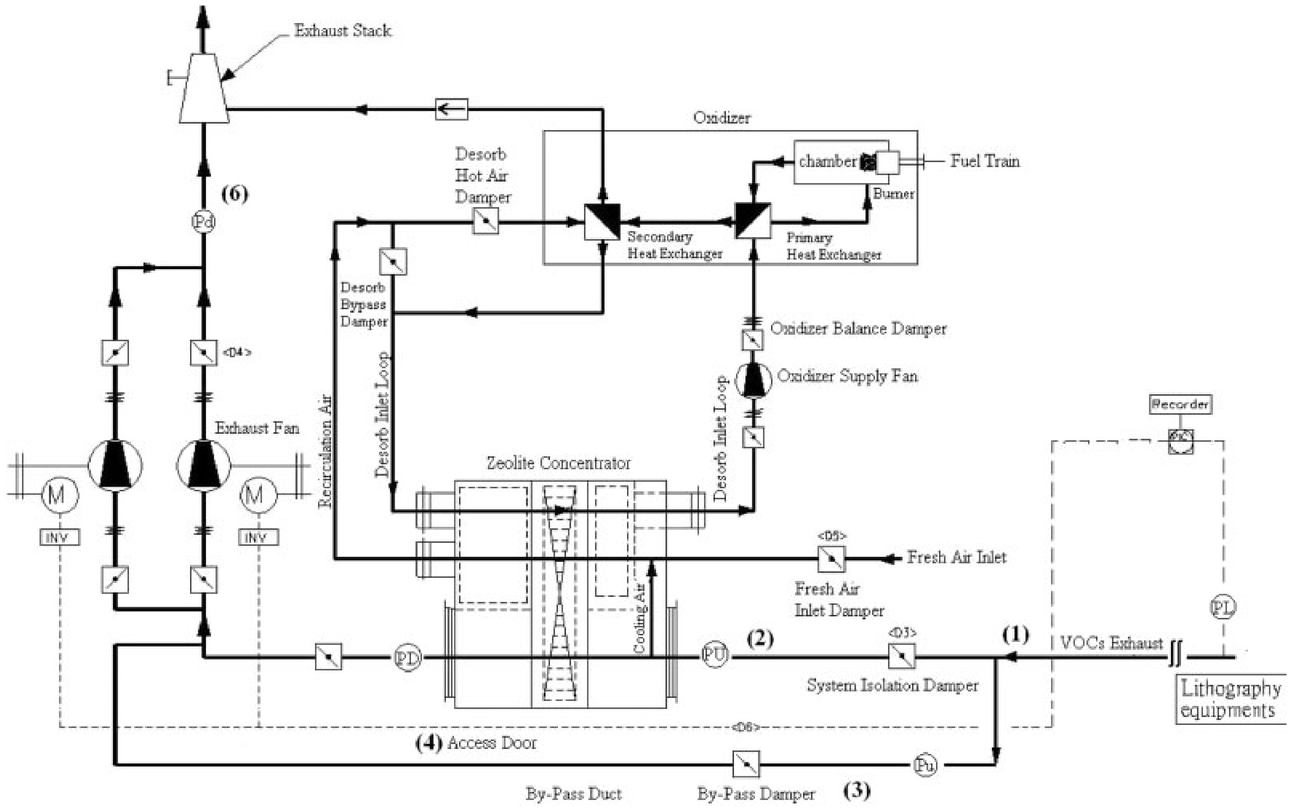

Figure 1. The process flow diagram and duct design of System A.

ducts. The rotor is made of a honeycomb ceramic fiber structure coated with zeolite.

When the rotor is operated continuously in a rotational procedure of adsorption, desorption, and cooling, the VOCs in the exhaust are induced into the adsorption zone for adsorptive purification via the primary duct. Upon completion of this process, the VOCs are adsorbed on the zeolite rotor and the purified exhaust is released into the atmosphere. As the rotor continues to cycle, the process continues to the desorption phase. During this stage, a high temperature clean airflow (180$\sim$220°C) flows into the system to desorb the VOCs. This stream of high temperature air is formed from the cooling air circulating through the heat exchanger, which is installed between the cooling zone and the backend incinerator. The ratio of desorption (cooling) airflow rate to the VOCs process rate is $\sim$1/10 or less. Therefore, the concentration of VOCs is increase considerably in the desorbed stream.

Following desorption, the released VOCs are transferred to the thermal incinerator for combustion to form water and carbon dioxide (CO_2) at 700°C or higher. Because the flow rate of VOCs fed to the combustion unit is relatively low, the incinerator setup and operating costs can be reduced, even though the main cost is to heat the stream to 700°C. The cooling zone normalizes the highly-heated zeolite rotor with a constant stream of air current at ambient temperature. Before cycling into the adsorption zone again, the zeolite rotor relies on the cooling process to increase the VOCs adsorption efficiency for the next adsorption phase. Meanwhile, the cooling airflow forms a highly-heated airflow through the heat exchanger as mentioned previously, and subsequently desorbs VOCs on the rotor. Both actual [2–5] and lab-based assessments [6–9] are performed for such an HZRC system. This system has maintained 90% VOCs removal efficiency for a long period of stable operation.

In a typical situation, the VOCs containing exhaust streams from all plant operations are collected and transferred to the HZRC system for decontamination. The VOCs exhaust treatment operation requires the support of an exhaust fan system to prevent pressure drops. When the system cycles between purification and bypass modes, improper switching operations will cause significant pressure variations in the HZRC and the transfer duct systems that adversely affect airflow stability during the manufacturing process resulting in production interruptions. Minimizing the pressure fluctuations because of the switching in the HZRC system ensures continuous operation of the production lines while maintaining a high VOCs removal efficiency, which is essential for exhaust treatment in high technology manufacturing.

This study proposes a decoupled balancing duct system (DBDS) that overcomes the high pressure variation problem of a conventional HZRC. The proposed system adds a flow area changing device to the bypass duct. This study deployed four different

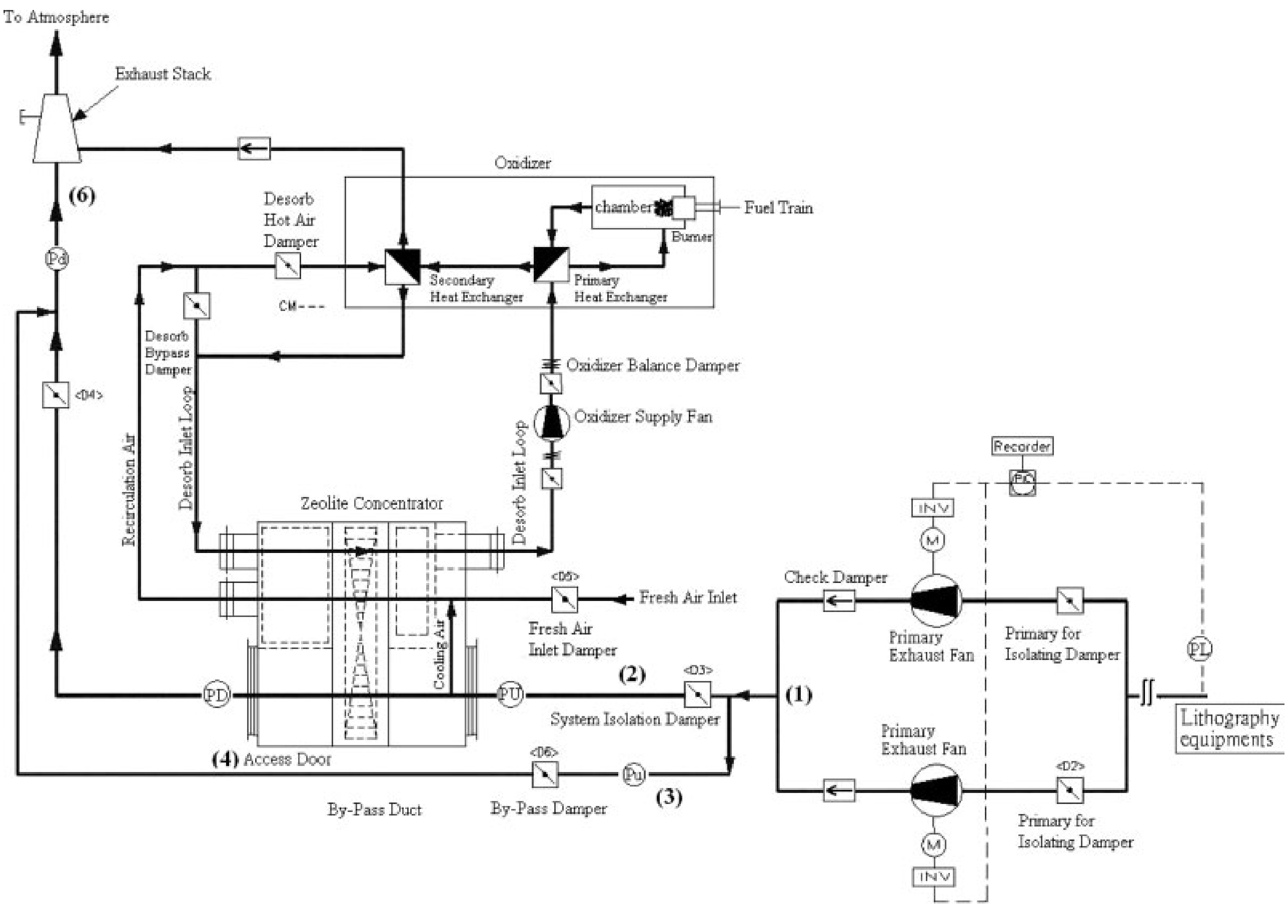

Figure 2. The process flow diagram and duct design of System B.

air flow control systems and then evaluated their performance in the wafer manufacturing plant in Hsinchu Science Park, Taiwan. The different systems have been compared, and the contribution of the DBDS is assessed throughout this study. The design principles and observations of DBDS are also discussed.

EXPERIMENTAL

This study evaluated four different experimental air flow control models for operation and analysis. Those of the systems A, B, and C are considered as standard designs. Figure 1 illustrates the blueprint of System A, in which an exhaust fan system is installed at the downstream position of the zeolite concentrator. The purpose of this design is to enable the zeolite concentrator to operate at negative pressure. On the other hand, System B is to enable the zeolite concentrator to operate at positive pressure. In System B the exhaust fan system is installed at the upstream position of the zeolite concentrator, as shown in Figure 2. System C combines the exhaust fan system layout from A and B. As illustrated in Figure 3, an exhaust fan system is installed at both the upstream and downstream positions of the zeolite concentrator. This arrangement enables the zeolite concentrator to operate in pressure dependent conditions, i.e., either negative or positive. All three systems include a bypass duct and an isolating damper installed at the side of the primary duct. The layouts of system A, B, and C are commonly found in exhaust abatement devices for purification mode or bypass mode switching operations.

Similar to System C, System D includes exhaust fan systems installed at both the upstream and downstream positions of the zeolite concentrator, as illustrated in Figure 4. Meanwhile, the system also includes a bypass duct installed alongside the primary duct with a modification to the damper. The key innovation that distinguishes the proposed system D from other systems is the utilization of a flow area changing device to replace the standard isolating damper. This device balances the duct pressure by automatically adjusting the size of its opening. The opening allows full inlet of airflow when the exhaust flows downstream, but partially closes to limit reverse airflow. This system, known as decoupled balancing duct system (DBDS), achieves pressure independence in a conventional honeycomb Zeolite Rotor Concentrator (HZRC) system. However it allows volatile organic compounds (VOCs) loaded stream directly to the atmosphere, lowering the overall VOCs removal efficiency.

The five static pressure gauges are employed to measure the pressure variations in all four experiment control system operating in actual production environments. The pressure measurements are performed

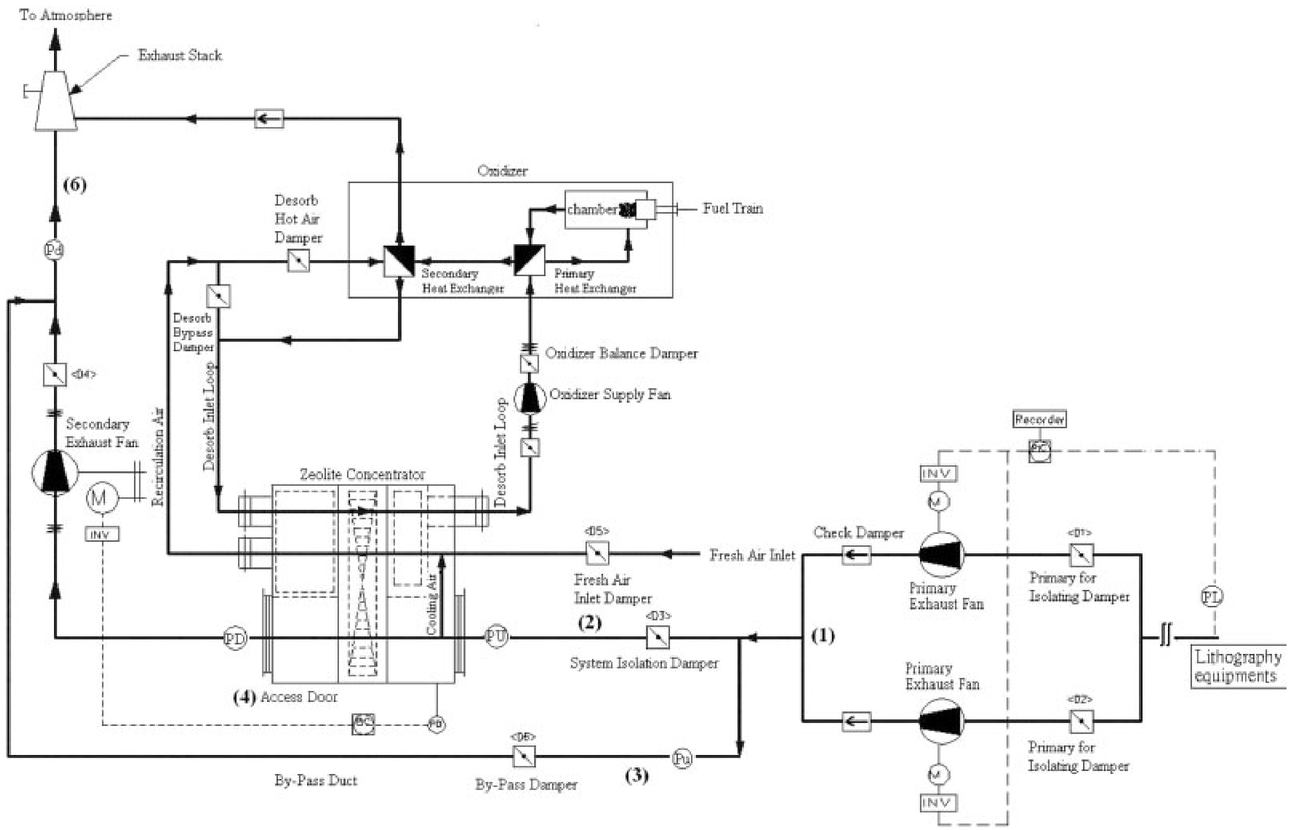

Figure 3. The process flow diagram and duct design of System C.

at the upstream (P_u) and downstream (P_d) locations of the bypass duct, also at the entry (P_U) and the exit (P_D) of the zeolite concentrator, and at the location neighbored on the lithography equipments (P_L). GC/FID (China Gas Chromatograph 9800, Taiwan) is used to analyze the concentration of the preprocessed and the postprocessed VOCs (as THCs). The analyzer column in the GC/FID is a carbon wax model 2 m long. The analytical results are used to comparatively demonstrate the VOCs removal efficiency of the HZRC system with the different pressure variation. The standard deviation of the repeated experiment was around 5% in terms of the VOCs removal efficiency. In addition, the pressure deviation was also obtained from the average results of the several test runs.

RESULTS AND DISCUSSIONS

Pressure Stability Comparisons

The HZRC operation includes purification (normal) and bypass modes. The purification mode processes the exhaust through the zeolite concentrator under normal conditions; the bypass mode bypasses the purification process by diverting the exhaust through the bypass duct to the other backup air pollution control device (APCD), while the HZRC has a breakdown in need of maintenance. Sudden pressure fluctuations often occur when the HZRC system switches from the bypass to the purification mode, affecting system pressure stability. Opening and closing of access doors during maintenance and exhaust fan system failures can also cause notable pressure variations in the HZRC system. Table 1 lists the pressure variations caused by all four experiment systems for comparison, and the pressure, labeled as P_L on the Figure 1–4, measured by the pressure gauge installed at the location neighbored on the lithography equipments.

Systems A and B are operated under negative and positive pressures, respectively. Switching from the purification mode to the bypass mode causes sudden system pressure variation. The pressure variation ranges from +0.05 to −0.6 mbar and can cause the frequency transformer to malfunction. The desired airflow capacity of the exhaust fan system is then affected resulting in increased system pressure fluctuation. If the pressure variation exceeds the system limits, the pressure in the airflow ducts, from the fabrications through to the HZRC system becomes unbalanced, at which time the production would be interrupted reducing the manufacturing capacity.

In the purification mode, the primary and the secondary fans of experiment System C are linked, leading to pressure coupling. Therefore, if there is any variation in operating conditions, for example fan speed, between the primary (inlet) and secondary (exhaust) fans, a system imbalance that causes pressure fluctuations is created. This condition will continue until the system achieves a new balance. Of the

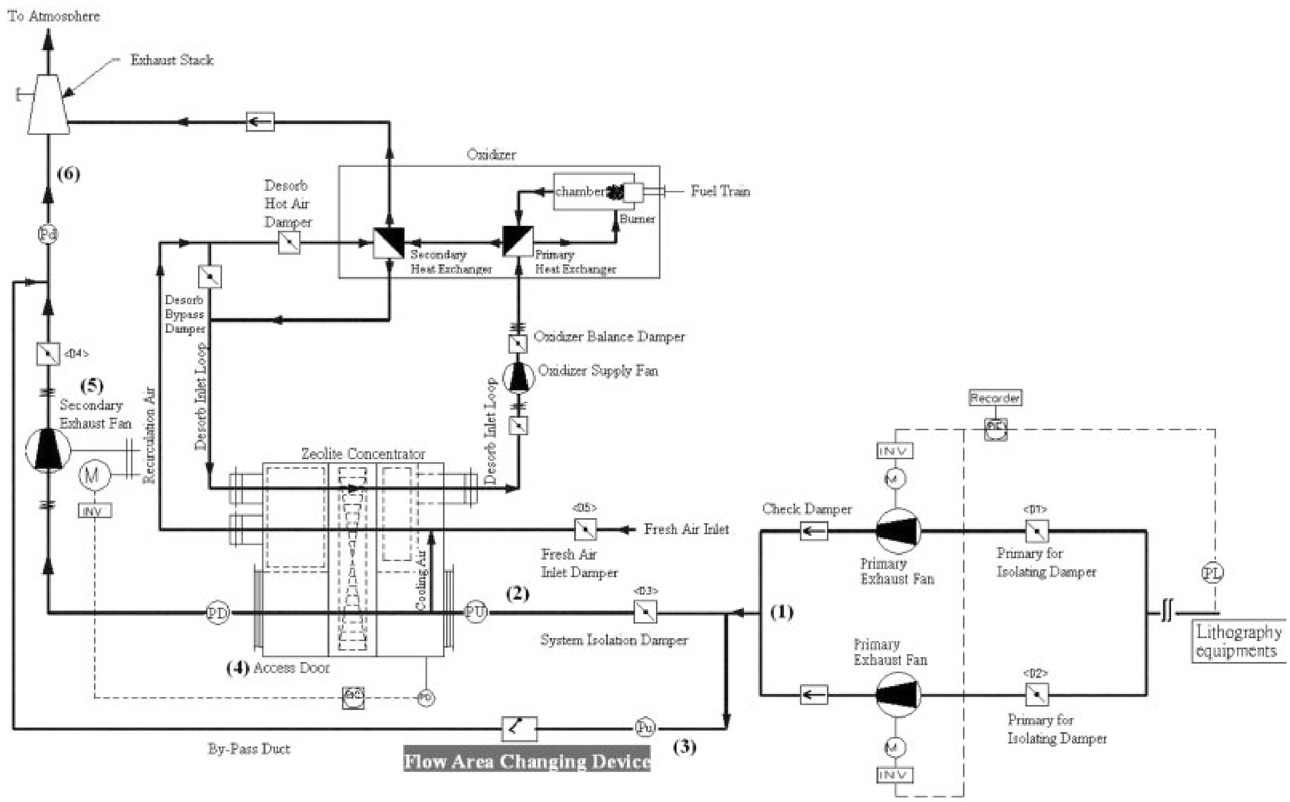

Figure 4. The process flow diagram and duct design of System D. *Which is different from System C because of it has the flow area changing device.

four experimental systems, System C operating in single purification mode potentially has the greatest pressure fluctuation. However, in the event of system switching, the secondary fans in System C can deal with the overall system pressure loss. Consequently, the overall pressure fluctuations of System C will be less than those of Systems A and B using single exhaust fan systems. For standard systems, System C is somewhat better, before the addition of DBDS, which is the improvement of this article.

The design of System D includes DBDS, comprising a flow area changing device with the standard bypass duct. Flow area changing device consists of the modified vane angle of back draft damper, whose area is less than the cross-section area of bypass duct. Thus, this device automatically adjusts its opening area depending on the pressure drop of flow direction and then achieves pressure balance. The flow area changing device permits full inlet of exhaust when the airflow is downstream and normal. Alternatively, when the airflow is upstream (forming a backflow), the flow area changing device reduces its opening area, to compensate for the differences in airflow between the primary and the secondary fan systems. The DBDS improves a standard system like C by enabling the primary and secondary fans to operate independently of pressure. System D thus maintains pressure stability within the system even in potential pressure loss situations (such as opening/closing of access door during operation, or secondary exhaust fan system failures). The results show that System D has the lowest pressure fluctuation, ranging from +0.1 to −0.1 mbar, of the four systems. Clearly, DBDS is highly efficient in minimizing pressure fluctuations within the HZRC system.

One of the main advantages of reducing pressure fluctuations is the improvement in the VOCs removal efficiency of zeolite concentrator. More importantly, the ultimate aim is to decrease the failure (shut down) frequency of the manufacturing process, caused by pressure fluctuation. The failure frequency of manufacturing process for System A and B is $\sim$1.5 times per year, whereas for system C, it is $\sim$0.8 times per year. In an 8 inch wafer manufacturing facility, if there are any failures during the lithography and photolithography process, the affected wafers must be discarded. The loss from one failure in the manufacturing process is about US $1,000,000.

If the maintenance department must stop or alter HZRC, or other central air pollution control device (APCD), a advance request needs to be submitted to the manufacturing department to stop the process, or change to other lines. Thus, if there are any unforeseen accidents on the APCD, the manufacture department cannot deal with such emergency without any disruptions. This results in significant monetary loss for the organization on the effected wafers. The stability improvement of DBDS on HZRC was demonstrated by installing 50 modules in manufacturing facilities across Taiwan. Since the installment in 1998,

Table 1. Pressure variation (P_L) neighbored on lithography equipments caused by the different test results of HZRC with flow control systems.

Operating mode	Flow process	Types of system: System A (mbar)	System B (mbar)	System C (mbar)	System D (mbar)
Purification (normal) running mode	(1)→(2)→(6)	4.5 ± 0.05	4.5 ± 0.05	5.0 ± 0.15	5.0 ± 0.05
Bypass mode	(1)→(3)→(6)	±0.05	±0.05	±0.05	±0.05
Normal mode changes to bypass	(1)→(2)→(3)→(6)	+0.05 to −0.6	+0.05 to −0.6	+0.15 to −0.35	+0.05 to −0.1
Bypass to normal running	(1)→(3)→(2)→(6)	+0.5 to −0.05	+0.5 to −0.05	+0.05 to −0.25	+0.05 to −0.1
Opening of access door of concentrator chamber	(1)→(2)→(4)Open→(6)	Pressure loss	Pressure loss	+0.25 to −0.05	+0.1 to −0.05
Closing of opened access door of concentrator chamber	(1)→(2)→(4)Close→(6)	—	—	+0.05 to −0.15	+0.05 to −0.1
Sudden stop of secondary fan	(1)→(2)→(5)Stop→(6)	—	—	+0.15 to −0.35	+0.1 to −0.05
Total pressure tolerance	—	+0.5 to −0.6 (+11.1 ~ −13.3%)	+0.5 to −0.6 (+11.1 ~ −13.3%)	+0.25 to −0.35 (+5.0 ~ −7.0%)	+0.1 to −0.1 (+2.0 ~ −2.0%)

there have not been any failures caused by pressure fluctuation in the manufacturing process at the installed sites.

System Operating Characteristics Comparisons

The operating characteristics of the four experimental systems are summarized in Table 2. Standard System C and the improved System D both incorporate exhaust fan systems installed at the upstream and downstream positions of the zeolite concentrator. When encountering variable airflow rate, systems incorporating two sets of exhaust fans (C, D) are superior to systems with only one (A, B). System D clearly outperforms the other three systems both in maintaining the pressure stability at the entry of the zeolite rotor, providing the convenience of opening/closing of the access door during operations and in reducing the pressure fluctuations between the exhaust fan systems.

System A incorporates an exhaust fan system installed at the downstream position of the zeolite concentrator, and processes VOCs at high negative pressure. Consequently, the exhaust gas is unlikely to leak from the zeolite concentrator chamber. In comparison, System B incorporates an exhaust fan system installed at the upstream position of the zeolite concentrator, which operates at high positive pressure. During processing of exhaust gas by System B, gas leakage can easily occur from the seams at the side of the zeolite concentrator chamber to the ambient air. Systems C and D use two sets of exhaust fan systems, located at the upstream and the downstream positions of the zeolite concentrator, respectively. In the purification mode, the zeolite concentrator was operated at negative pressure, preventing leakage of the VOCs containing exhaust gas from the zeolite concentrator chamber. Alternatively, in the bypass mode, the airflow in the bypass duct occurs under positive pressure, ensuring smooth air current flow. Additionally, because System D is equipped with DBDS, there is minimal pressure drop for the zeolite concentrator and bypass duct, even at the system entry and exit points.

Because of the influence of high negative pressure, cross contamination of the purified airflow with exhaust gas from the bypass duct is most serious in System A. Similarly, when operating at high positive pressure, cross contamination in System B is also severe. Systems C and D, in contrast, benefit from having two sets of exhaust fan systems for controlling airflow pressure. In the purification mode, the concentrator pressure for Systems C and D is negative and slightly negative, respectively. As a result, the possibility, and the volume of cross contamination of purified airflow, can be significantly minimized.

The initial setup costs for the dual exhaust fan systems (C, D) exceed those for the single exhaust fan systems (A, B). Despite this, because System C and D utilize the efficiency of the dual exhaust fan systems to control the desired exhaust capacity, the operating costs can be significantly reduced. The average load sustained by the dual exhaust fan systems is lower than that of the single exhaust fan systems because of the lowering average fan pressure. Therefore, the

Table 2. Operating characteristics of the four air flow control systems.

Item		System A	System B	System C	System D
1	Ability to control flow variations under the highly efficient performance of fan system	Poor	Poor	Good	Good
2	Ability to control the range of pressure variations at the entry of the system	Very poor	Very poor	Poor	Very good
3	Maintaining convenience during operations	Poor	Poor	Average	Good
4	Reducing pressure fluctuations between the primary and the secondary fan systems	N/A	N/A	Poor (pressure dependant)	Very good (pressure independent)
5	Pressure in concentrator	High negative pressure	High positive pressure	Normal mode Negative pressure Bypass mode Positive pressure	Normal mode Slight negative pressure Bypass mode Slight positive pressure
6	Reducing leakages of VOCs exhaust being processed by zeolite rotor concentrator	Very good	Poor	Good	Very good
7	Reducing cross contaminations from the bypass duct	Very poor	Poor	Good	Very good
8	Operating costs of the exhaust fan systems	High	High	Low	Low
9	System reliability	Poor	Poor	Good	Very good

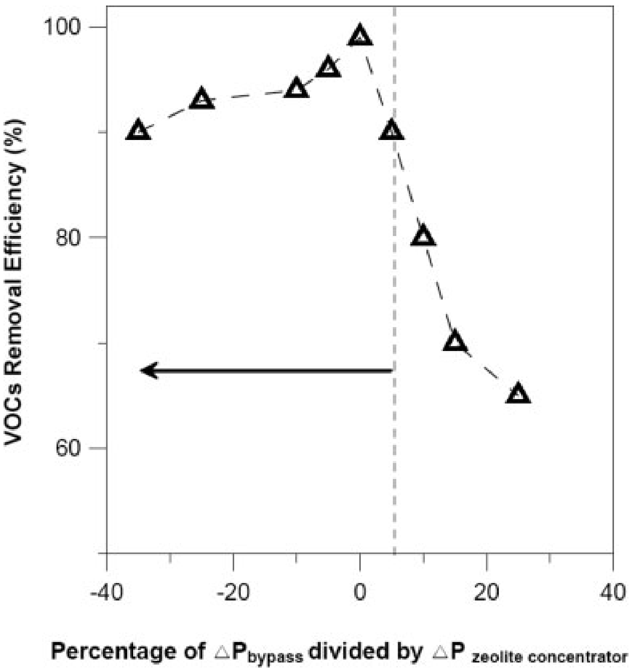

Figure 5. Percentage of ΔP_{bypass} divided by $\Delta P_{zeolite\ concentrator}$ influencing VOCs removal efficiency. *The pressure difference in the decoupled balancing duct (ΔP_{bypass}) was calculated by subtracting the pressure at the downstream (P_d) duct location from that at the upstream location (P_u); and the pressure difference in the zeolite concentrator ($\Delta P_{zeolite\ concentrator}$) was also calculated by subtracting the pressure at the entry (P_D) from that at the exit (P_U).

HZRC system with DBDS is the best in maintaining the pressure balance within a system, reducing the leakage of processed VOCs exhaust gas, minimizing cross contamination with the bypass duct, saving operating costs, or increasing system stability.

Relationships Between the Pressure Differences and the VOCs Removal Efficiency

The relationships between the bypass airflow directions and the percentage of ΔP_{bypass} divided by$\Delta P_{zeolite\ concentrator}$ affecting the VOCs removal efficiency are shown in Figure 5. The pressure difference in the decoupled balancing duct (ΔP_{bypass}) was calculated by subtracting the pressure at the downstream (P_d) duct location from that at the upstream location (P_u); and the pressure difference in the zeolite concentrator ($\Delta P_{zeolite\ concentrator}$) was also calculated by subtracting the pressure at the entry (P_D) from that at the exit (P_U), the average value of $\Delta P_{zeolite\ concentrator}$ is between 6 and 12 mbar. As the negative value of ΔP_{bypass} divided by $\Delta P_{zeolite\ concentrator}$ is reduced, more of the purified airflow would then be drawn back to the upstream location of the system. The negative values on the horizontal axis of Figure 5 indicate the backflow in the decoupled balancing duct. This situation results in that the backflow of the purified air current mixing with the VOCs exhaust gas, and then the concentration of VOCs reentering the zeolite concentrator is diluted. The VOCs removal efficiency is reduced by the continuously increasing processing flow and the decreasing VOCs concentration adsorbed by the zeolite concentrator. This phenomenon is consistent with the literature report [8]; the mass transfer will be lessened by the exceeding airflow (space velocity) and the below valve VOCs inlet concentration, which will also cause the adsorption efficiency to decrease.

Inappropriate control of the secondary fans causes the desired exhaust capacity to exceed that in the primary fan system. The result is a continual increase in the positive values of ΔP_{bypass} divided by $\Delta P_{zeolite\ concentrator}$. Consequently, more and more unprocessed exhaust gas bypasses the zeolite concentrator through the bypass duct. Rather than undergoing purification, this exhaust gas flows to the downstream location of the zeolite concentrator. The purified airflow and unprocessed VOCs exhaust gas are mixed, and then released to the atmosphere. The VOCs concentration increases when samples are taken at the exhaust stack. These outcomes are deemed to result from reductions in the efficiency of the HZRC system for VOCs removal. The percentage ofΔP_{bypass} divided by $\Delta P_{zeolite\ concentrator}$ between +5 and −35% could ensure the VOCs removal efficiency of HZRC system achieves above 90%, which is the standard of the air pollution regulation on semiconductor manufactures in Taiwan. While pressure drop was larger than the above range, especially the increasing positive value of ΔP_{bypass} divided by $\Delta P_{zeolite\ concentrator}$, the decreasing VOCs removal efficiency was in proportion to the increasing ratio. Therefore, pressure control in the decoupled balancing duct is important for optimizing the VOCs removal efficiency in the HZRC system, leading the ΔP values to approach or equal zero.

Decoupled Balancing Duct Design Principles

On the basis of the experimental results and the operating experience of more than 50 HZRC systems with DBDS operating in Hsinchu Science Park, Taiwan, the following principles ensure the correct design and control of DBDS:

1. The pressure drop in the decoupled balancing duct should be reduced.
2. The dimensions of the decoupled balancing duct should be based on the maximum bypass flow in the bypass mode (costs are also considered in this part of the design).
3. The minimal opening area of the flow area changing device should be determined based on the pressure drop resulting from the decoupled balancing duct operating at maximum reverse flow.
4. The desired airflow capacity of the secondary fans should be slightly greater or equivalent to that of the primary fans to avoid cross contamination in the decoupled balancing duct.
5. The frequency transformer controller for the primary fans system should be adjusted to increase its responsiveness to reduce pressure fluctuations resulting from airflow variations. Alternatively, the

frequency transformer controller for the secondary fans system should be adjusted to reduce its responsiveness.

6. When unexpected maintenance makes it necessary to open the access doors, all opening and closing operations should be performed slowly. Additionally, the principle of the first door to be opened being closed last should be enforced to minimize pressure drop.
7. Airflow disturbance can be minimized when the length of the decoupled bypass duct is set to be more than twice the internal diameter of the duct.

Although the issue of pressure fluctuation in manufacturing facilities other than semiconductor and TFT-LCD industries is less sensitive, the application of DBDS still has its significance. Minimizing pressure fluctuation not only reduces the loads on the exhaust fans, but also can extend the lifespan of the exhaust fans because of the decreased pressure variation. Furthermore, the cost difference between DBDS and the normal designs (like System C) is very minimal.

CONCLUSIONS

Performance of VOCs removal of a honeycomb zeolite rotor concentrator equipped with four air flow control systems in actual manufacturing settings have been evaluated. Installing exhaust fan systems at both the upstream and the downstream positions of the zeolite concentrator and adding a flow area changing device in the bypass duct (the DBDS) can yield pressure independence or decoupling between fan systems. The DBDS offers advantages of maintaining system pressure stability, improving VOCs removal efficiency, reducing cross contamination, minimizing leakage, and reducing operating costs. The combination of HZRC and DBDS has been widely employed for processing VOCs in the semiconductor and optoelectronics industries. The DBDS can also be utilized in similar air conditioning systems.

LITERATURE CITED

1. Chein, H.M., & Chen, T.M. (2003). Emission characteristics of volatile organic compounds from semiconductor manufacturing, Journal of the Air and Waste Management Association, 53(8), 1029–1036.
2. Gupta, A., & Crompton, D. (1993). Choosing the right adsorption medium for VOC control. Metal Finishing, 91(11), 68–72.
3. Gupta, A., & Stone, J. (1998). Rotary concentrator followed by thermal or catalytic oxidation—A hybrid approach to economical styrene abatement. Proceedings of the International Composites EXPO, Session 11-D, Nashville, TN, (pp. 1–5).
4. Lin, Y.C., Chang, F.T., Bai, H.L., & Pei, B.S. (2005). Control of VOCs emissions by condenser pre-treatment in a semiconductor Fab, Journal of Hazardous Materials, 120, 9–14.
5. Seguin, R.J., & Madden, W.C. (2001). Improvements in the operation of a VOC abatement device, Semiconductor Fabtech (13th Edition, pp. 99–102). London, UK: ICG Publishing Ltd.
6. Blocki, S.W. (1993). Hydrophobic zeolite adsorbent: A proven advancement in solvent separation technology, Environmental Progress, 12(3), 226–230.
7. Chang, F.T., Lin, Y.C., Bai, H.L., & Pei, B.S. (2003). Adsorption and desorption characteristics of VOC_S on the thermal swing honeycomb zeolite concentrator. Journal of the Air & Waste Management Association, 53(11), 1384–1390.
8. Mitsuma, Y., Yamauchi, H., & Hirose, T. (1998). Analysis of VOC reversing adsorption and desorption characteristics for actual efficiency prediction for ceramic honeycomb adsorbent, J Chemical Engineering Japan, 31, 253–257.
9. Mitsuma, Y., Yamauchi, H., & Hirose, T. (1998). Performance of thermal swing honeycomb VOC concentrator, J Chemical Engineering Japan, 31, 482–484.