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The development of fan filter unit with flow rate feedback control in a cleanroom

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Abstract

A new type of fan filter unit (FFU) systems was developed and evaluated in this study. Capable of controlling the volume airflow rate through a networked feedback control system, the innovative smart FFU systems can supply much more uniform airflow distribution at the exit of the FFUs than common FFUs that are commercially available in the market. The development of the smart FFU was described and the comparisons of exit airflow velocities between the smart FFU and other conventional FFUs were made. The measurements have shown that the velocity uniformity values of the exit airflow of the smart FFUs were less than 5.0% while the conventional FFUs showed the uniformity values in the range of 14.0–28.0%. In addition, the test results in this study demonstrate that smart FFU systems are capable of reaching preset airflow rates relatively quickly, i.e., within 5 s, and maintaining the stable airflow supply to the cleanroom.

Keywords: Cleanroom; Fan-filter unit; Contamination control; Energy; Airflow; Uniformity

1. Introduction

In recent years, fan filter unit (FFU) systems have been extensively installed in industrial cleanroom facilities, because of their state-of-the-art flexibility and easiness in installation and construction, and their effectiveness in controlling the level of particle concentration to achieve required cleanliness [1–3]. The improvement of FFU performance has been pursued to satisfy the various processes and the loading demands. Recent studies addressed the importance in testing and understanding energy performance of individual fan filter units [4–6]. A common, simple structure FFU with single fan-speed setting as shown in Fig. 1 normally has a lower first-cost but does not have the capability to adjust rotational speed thus often produces unstable or undesirable airflow pattern in cleanrooms. Because a fixed rotation speed does not necessarily result in a constant volume airflow rate, keeping the rotation speed unchanged may not maintain a satisfactory volume airflow rate if other conditions changed such as system resistance. FFUs with adjustable rotational speed as shown in Fig. 2 can provide multi-speed control for the fan within the unit. This allows step-by-step control of fan speeds that affect the airflow rates supplied through the unit. However, the magnitudes of speed feedback are normally not quantifiable or detectable with the simple functions to adjust rotational speeds. The speed controller may not accurately respond to the likely change of the environmental conditions (temperature, humidity, and particle concentrations) over time. For cleanrooms using FFUs with adjustable rotational speeds, the design and operation of certain air volume rates in cleanroom environment may require considerable time and can be very labor intensive. An improved version of FFUs, as shown in Fig. 3 with rotation speed feedback, can provide self-tuning rotational speeds while allowing the fan speed to deviate as needed. If the airflow velocity is critical for the specific process in cleanroom environment, it will be necessary to be able to adjust the optimized rotation speed in each individual FFU in order to achieve the required airflow velocity.

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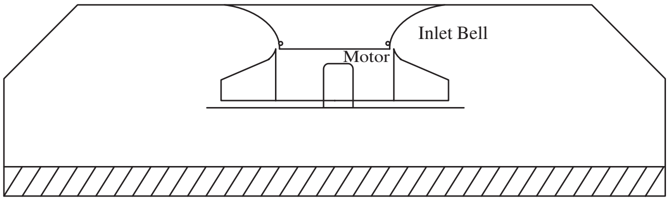

Fig. 1. Simple FFU.

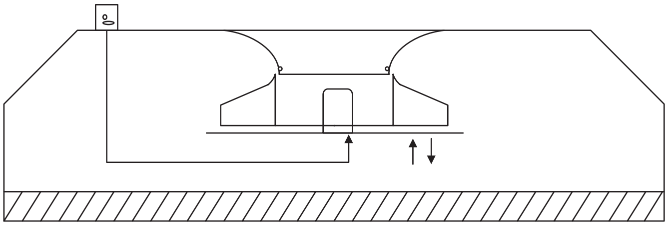

Fig. 2. FFU with adjustable rotational speed.

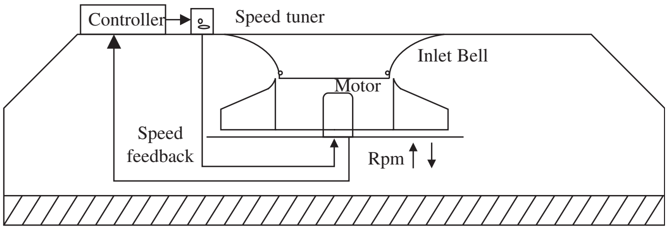

Fig. 3. FFU with rotational speed feedback control.

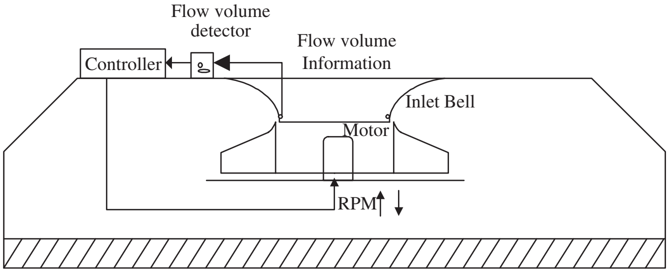

Fig. 4. FFU with volume flow rate feedback control.

Fig. 5. Pressure sensor installed at the entrance of the FFU inlet mouth.

Depending on the cleanliness specifications for specific processes, equipment, and tools, and operation to meet cleanroom classification standards [1–3], manufacturers usually build a cleanroom in which working areas require different airflow rates in order to satisfy respective cleanliness levels at different locations. To provide the best airflow quality of the cleanroom and to fit the various of process and loading demands, each FFU shall be able to operate, monitor, and control the airflows and to setup easily. The smart FFU system, shown in Fig. 4, has a flow rate feedback control loop by which each unit provides its own volume airflow rate. The units can then adjust and supply pre-assigned the volume flow rate through interacting with the control loop.

The smart FFU is intended to satisfy the demand for providing a good airflow pattern and stable controllable cleanliness levels in cleanroom environment. The key elements of developing smart FFU include (1) hardware development, including high-efficiency aerodynamics design of FFU based on CFD simulation, brushless direct current (BLDC) motor controller, and miniature differential pressure sensor; (2) software development, including microchip program on motor controller, network communication converter program, and a man-machine interface program.

High-efficiency aerodynamics design of smart FFU and BLDC motor controller were patented by ITRI, and are integrated into the smart FFU system. In order to detect the real time response of the smart FFU system, a differential pressure sensor is installed at the entrance of the FFU inlet mouth, as shown in Fig. 5. This device is linked to a pressure transducer that measures and monitors the pressure difference between the entrance of FFU and the ambience. The volume airflow rate, Q, is calculated and converted to the signal through the feedback control system, in which the feedback signal was compared to a user-assigned value. The motor speed is tuned up to provide the constant volume airflow rate. Thus, even if the environment loading was affected by personnel operation or equipment motion, the volume airflow rate for individual smart FFU can still remain constant or stable, and maintain or improve contamination control in locations of the cleanroom.

The network communication converter program provided capability of remotely monitoring the cleanliness levels within the entire cleanroom. The man–machine interface program can be easily operated by using the FFU layout editor to show FFU operating parameters, their setup, and FFU operational status Thus, each FFU can be easily set up, monitored, and controlled.

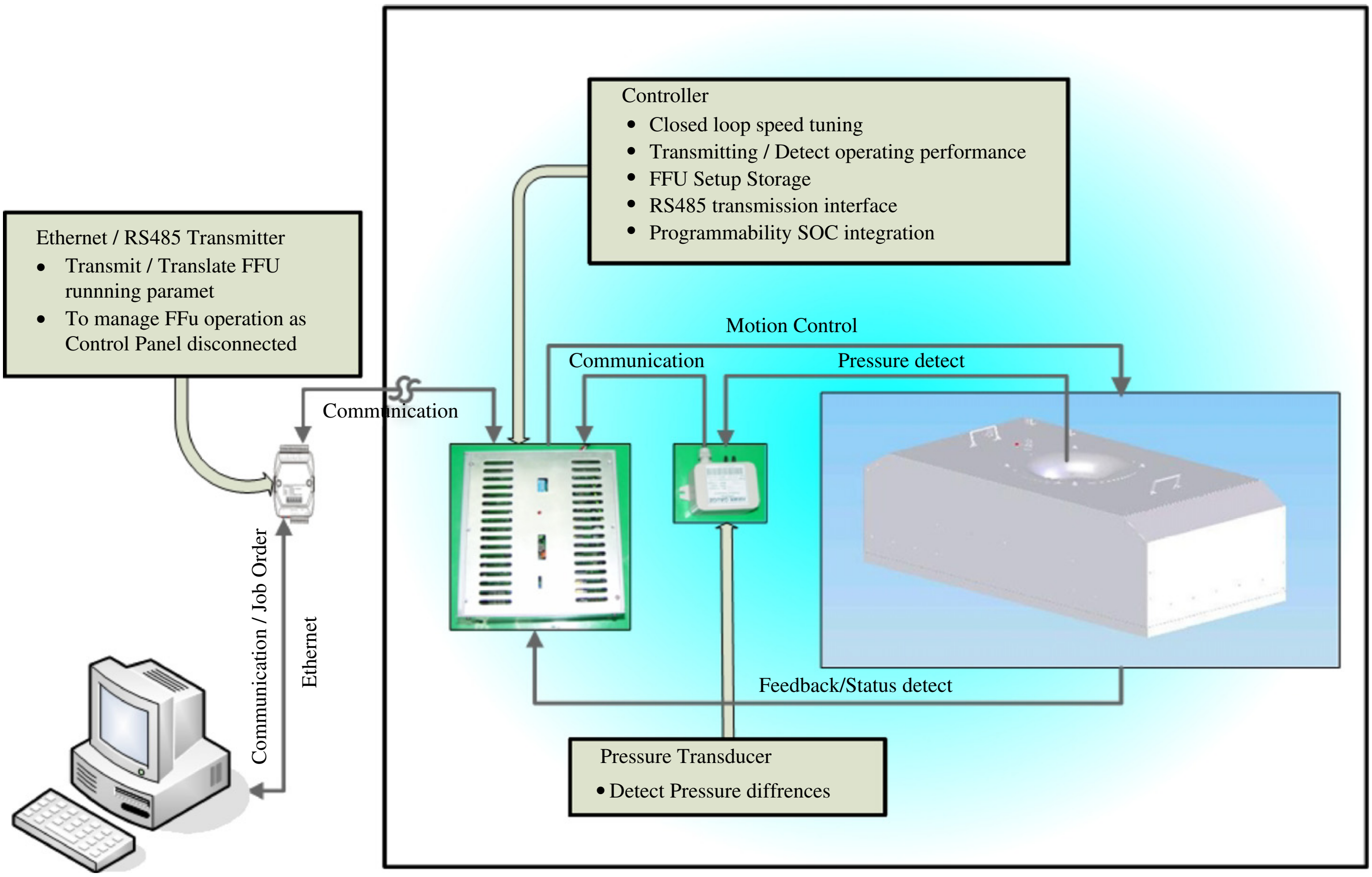

Fig. 6. Schematic diagram of a smart FFU.

The smart FFU system consisted of the four parts as shown in Fig. 6:

- FFU main body, with an FFU pressure sensor installed at the entrance of the FFU inlet mouth;
- Pressure transducer, used to detect the pressure difference and convert the pressure signal to voltage signal;
- Controller, used to provide the close-looped speed tuning to the FFU motor, transmitting the operating status to computer, storing the operation setup, and running the programmability (to spell out SOC) integration;
- Ethernet transmitter used to evaluate FFU operation parameters, managing FFU operation status, and communicating with the system administrator or operator to monitor and to control the airflows.

In the smart FFU system, a network system is constructed with the RS485 transmitter connecting converter with the control panel by the Ethernet shown in Fig. 7. Additional FFUs can be added throughout the cleanroom and connected to the network that enables the system administrator to monitor and control the FFU operation in the cleanroom.

2. Analysis

The shape of the FFU inlet mouth is similar to a nozzle and the characteristic of a flow nozzle can be applied. Thus, the volume airflow rate is calculated by the pressure difference between the entrance of smart FFU and the ambience [7]

$$Q = 265.7 \times Y \times \sqrt{\frac{\Delta P}{\rho}} \times C_n \times A_n, \tag{1}$$

where Q is the volume flow rate (m^3/min) at the testing condition, ΔP is the pressure difference (mmAq), ρ is the air density of the inlet mouth ($\mathrm{kg/m}^3$), C_n is the volume flow rate coefficient, Y is the expansion coefficient, A_n is the entrance area of the inlet mouth (m^2).

Even though the amount of volume flow rate can be calculated by Eq. (1), the specific parameters such as C_n and Y are the function of Q and ΔP. The values of C_n and Y need to be corrected. We obtained C_n and Y by tabulating the relation of Q and ΔP. In this study, the signal of pressure difference ΔP is conveyed to A/D signal through data processing and the volume flow rate Q is calculated. The digital signal is used to adjust motor controller through the feedback control system, and the

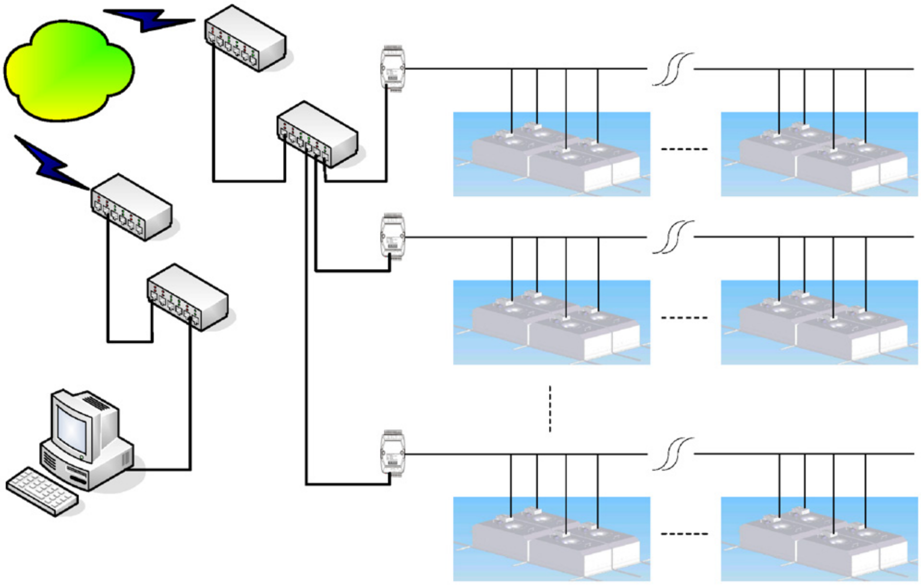

Fig. 7. Network system of smart FFU.

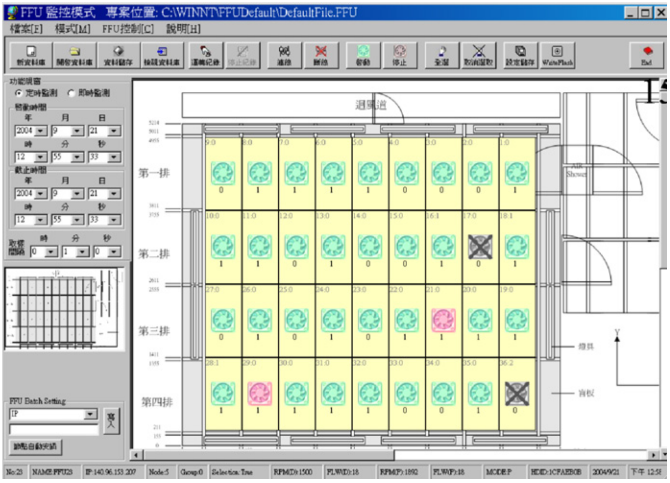

Fig. 8. Layout of the man–machine interface.

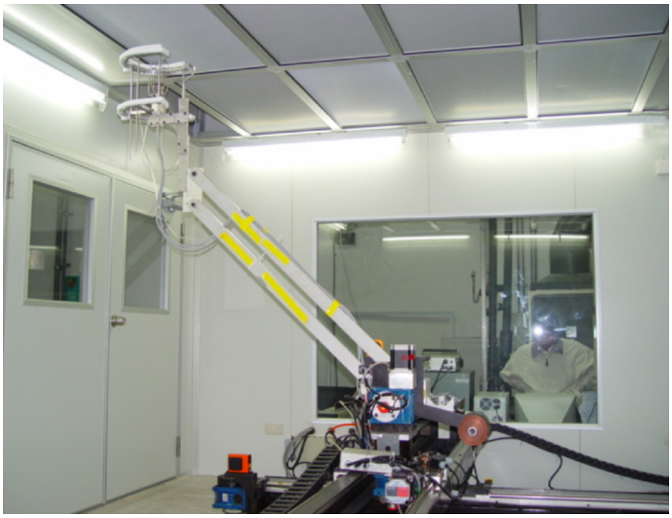

Fig. 9. Three-dimensional ultrasound anemometer and the in-house developed automatic traversing system.

instant difference of volume airflow rate from the assigned value (ΔQ) was calculated. The differential signal tunes up the motor speed to provide the new volume flow rate until the value (ΔQ) is within an acceptable range. The controlling logic can be either the traditional PID or the simplified P.

3. Experiment setup

The layout of the man-machine interface in the experimental cleanroom is shown in Fig. 8. The cleanroom was 6 m × 5 m × 2 m in dimension with a ceiling fully covered by 36 sets of 122-cm × 61-cm (or 4-foot × 2-foot) smart FFUs and a through-the-floor air return recirculation system. The cleanliness level of the cleanroom was set to meet ISO Class 4 of the cleanroom classification standards [1]. To precisely measure the flow velocity profiles, a 3-D anemometer was firmly placed on an in-house developed automatic traversing system. The traversing rig can be programmed to move the anemometer vertically and horizontally very precisely, e.g. with an interval of five centimeters as shown in Fig. 9.

There were six cleanroom facilities with FFU systems tested for their exit airflow velocity of FFU to compare with the cleanroom served by the smart FFU system in ITRI. Three-dimensional ultrasound anemometer measures the average speeds of the airflow delivered out of the face of fan-filter units in ITRI. The flow hood measures the in situ average speeds of the airflow rates of six cleanroom facilities with the accuracy of ±5% reading [8].

Table 1
Variations of rotational speed, airflow rate, and velocity of two smart FFU units

	Smart FFU 1 (column 2, row 4)			Smart FFU 2 (column 7, row 3)		
	Rotational speed (rpm)	Flow rate (m^3/min)	Flow velocity (m/s)	Rotational speed (rpm)	Flow rate (m^3/min)	Flow velocity (m/s)
Mean	1469	15.9	0.43	1393	15.9	0.43
Maximal	1534	16.8	0.45	1423	16.6	0.44
Minimal	1415	15.1	0.40	1356	15.3	0.41
Standard Deviation	16.8	0.26	0.01	11.1	0.21	0.01
Uniformity (%)	1.1	1.6	2.3	8.0	1.3	2.3

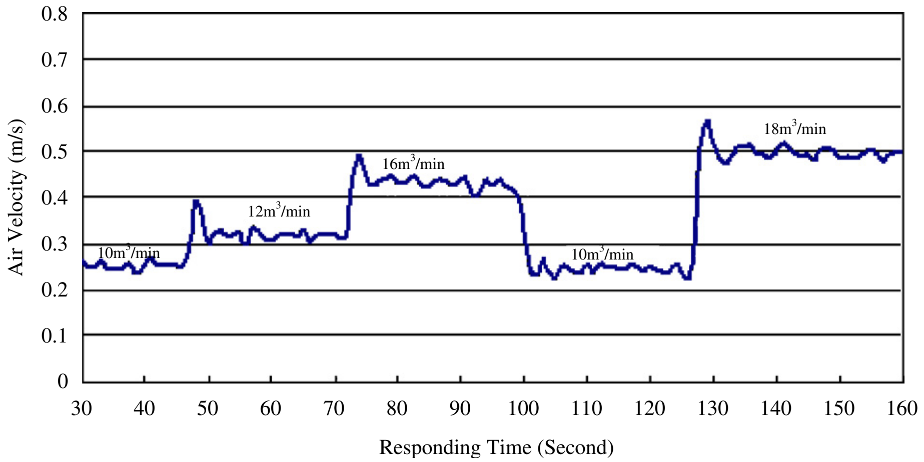

Fig. 10. Trend of actual airflow velocities at five airflow-rate set-points within a 20-second interval.

4. Results and discussions

Two of 36 smart FFUs, located at (column 2, row 4) and (column 7, row 3), were monitored continuously, with a testing duration of five days (120 h) and the recorded interval of 10 min. The test results are listed in Table 1. The standard deviation and uniformity were calculated using the following formula:

$$\text{Standard Deviation (SD)}: \sigma = \sqrt{\sum_{i=1}^{N}(v_i - \bar{v})^2 \Big/ (N-1)}. \tag{2}$$

Uniformity is defined as the relative standard deviation (RSD), namely, the ratio of standard deviation (SD) to the average of the measured value, e.g., airflow velocity. A higher RSD value indicates less uniform airflows. While a lower RSD value corresponds to more uniform pattern of the measured quantity

$$\text{Relative Standard Deviation (RSD)} = \sigma/\bar{v} \times 100\%. \tag{3}$$

The results showed that the air velocity uniformity of two smart FFUs was the same and the value was 2.3%. While the air velocity uniformity for the requirement of cleanroom facility should be less than 15% [9,10].

The sensitivity of the smart FFU system to varied airflow rates was also examined. We set the airflow rates from 10 to 18 m^3/min arbitrarily for every twenty seconds. The monitored results demonstrated that the response time for the smart FFUs to achieve the preset airflow rate was approximately 5 s as illustrated in Fig. 10.

In order to evaluate the network communication of smart FFUs for providing the stable cleanliness level of environment, we monitored eighteen of the symmetric array smart FFUs out of a total of thirty-six smart FFUs. We varied airflow rates from 13 to 18 m^3/min, corresponding to the airflow velocities ranging from 0.34 to 0.47 m/s. The measurements for the eighteen FFUs are shown in Table 2. The results showed that the exit velocity uniformity of the smart FFUs selected was under 5.0%, with the most uniform airflow at the uniformity value of 2.7% when the averaged airflow velocity was 0.37 m/s.

The air velocity uniformity within other six cleanroom facilities installed with conventional FFU systems was tested, while the average airflow velocity was in the range of 0.29 and 0.39 m/s. The velocity uniformity of the exit air flows of the conventional FFUs ranged from 14.0% to 28.0%. The comparisons were made with that of the experimental cleanroom with the smart FFU systems. The results are shown in Table 3. This indicates that the

Table 2
Airflow uniformity and stability of smart FFUs under six set points in the cleanroom

FFU No.	Set point of airflow rate					
	$13\,m^3/min$	$14\,m^3/min$	$15\,m^3/min$	$16\,m^3/min$	$17\,m^3/min$	$18\,m^3/min$
	Set point of flow velocity					
	0.34 m/s	0.37 m/s	0.39 m/s	0.42 m/s	0.45 m/s	0.47 m/s
	Measured flow velocity (m/s)					
1	0.32	0.38	0.39	0.42	0.43	0.47
2	0.35	0.36	0.37	0.42	0.43	0.44
3	0.38	0.38	0.41	0.42	0.43	0.47
4	0.33	0.36	0.37	0.40	0.41	0.42
5	0.33	0.35	0.38	0.39	0.40	0.45
6	0.32	0.37	0.37	0.40	0.42	0.44
7	0.36	0.38	0.39	0.44	0.44	0.46
8	0.36	0.37	0.40	0.44	0.45	0.47
9	0.34	0.37	0.41	0.42	0.43	0.44
10	0.33	0.37	0.39	0.39	0.44	0.46
11	0.36	0.39	0.41	0.42	0.44	0.46
12	0.33	0.37	0.37	0.39	0.42	0.46
13	0.33	0.37	0.38	0.40	0.47	0.49
14	0.35	0.39	0.42	0.42	0.44	0.46
15	0.34	0.36	0.42	0.43	0.44	0.45
16	0.34	0.39	0.42	0.43	0.44	0.46
17	0.37	0.38	0.44	0.45	0.46	0.48
18	0.33	0.39	0.39	0.39	0.40	0.45
Mean	0.34	0.37	0.39	0.41	0.43	0.46
SD	0.017	0.010	0.019	0.020	0.018	0.017
Air velocity uniformity (%)	4.9	2.7	4.9	4.8	4.2	3.8

Table 3
Comparison of airflow uniformity in six common cleanroom facilities with the smart FFU cleanroom

	Flow velocity (m/s)						
	LAB1	LAB4	LAB3	LAB4	LAB5	LAB6	Smart FFU
Mean	0.39	0.29	0.35	0.30	0.35	0.33	0.37
SD	0.100	0.070	0.060	0.060	0.050	0.060	0.010
Air velocity uniformity (%)	27.7	23.8	16.9	20.9	14.3	16.8	2.7

airflows in the conventional cleanroom was much less uniform than the one observed in the cleanroom equiped with the smart FFU system.

5. Conclusion

The smart FFU systems in this study demonstrate several advantages in achieving effective contamination control: (1) their effectiveness in producing relatively better and more uniform airflow pattern inside a cleanroom; (2) flexibility and expandability of individual FFUs to the entire cleanroom or portion of the cleanroom without incurring significant added costs to the implementation of the smart system; (3) easier monitoring and control performance of smart FFU system by the network communication and the man-machine interface monitoring. In addition, the study demonstrates that smart FFU systems are capable of reaching preset airflow rates relatively quickly, i.e., within 5 s, and maintain the stable airflow supply or recirculation to the cleanroom, while providing much more uniform airflow patterns out of FFUs than in conventional cleanrooms with commercially available FFUs.

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