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Tsutomu Fujita, Akira Sueda, Hitoshi Ura, Takeshi Shiraishi

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Tsutomu Fujita
Senior Researcher,
Construction Engineering Lab.,
Structure Res. Labs.,
Engineering & Construction Div.


Akira Sueda
Construction Engineering Lab.,
Structure Res. Labs.,
Engineering & Construction Div.


Hitoshi Ura
Staff Manager,
General Construction Marketing Sec.,
Building & Steel Marketing Dept.,
Engineering & Construction Div.


Takeshi Shiraishi
Manager,
Systems Planning & Data Processing Sec.,
Chiba Office, Kawasaki Steel Systems R&D Corp.

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1 Introduction

In high-technology industries making such products as semiconductors, liquid crystal displays, electronic devices and precision instruments, or in pharmaceutical and foodstuff industries, and in hospitals, it has become an important technical problem to maintain the spatial environment to a high cleanliness level. While the environment-cleaning technology is so comprehensive as to integrate many technologies, one of them is the airflow control for the cleanroom. Since indoor airflow fields largely affect the dispersion and sedimentation of fine airborne particles, the airflow control technology is considered to be particularly important.

Cleanrooms in general[1] can be classified into what is called "unidirectional flow type," in which high-performance air filters (HEPA or ULPA filters) are arranged in the ceiling or over one entire side-wall surface, the cleaned air is blown out from a wide area, and the floor is made of a grating structure, and the "non-unidirectional flow type," in which the cleaned air is blown out through fans and filters arranged at specific positions in the ceiling. The unidirectional flow type cleanroom can easily achieve a high cleanliness environment, but the facility investment cost is high. The non-unidirectional flow type generally has the opposite tendency.

Conceived to combine the advantages of both types, the line-type cleanroom[2] features two special units installed in the room; one being the air control unit to remove dust and other contaminants from the circulating air while adjusting the air temperature and humidity, and the other a duct-shaped supply unit with many small-diameter perforations on its wall surface to disperse and supply the cleaned air to the room.

The airflow field of the cleanroom is largely affected by the air supply and discharge patterns, and in particular, the effect from the air supply pattern is considered great. Now it is generally difficult to uniform the supply pattern of air blown out of many small-diameter perforations of the air duct wall. These points left major tasks involving the optimization of airflow fields yet to be solved.

Against such backdrops, we examined the pattern of the outlet airflow fields from the supply unit, and promoted a study to enhance the uniformity of indoor air-

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flow fields, and thus developed a line-type cleanroom of high efficiency. This report describes an outline, airflow fields and cleaning characteristics of the line-type cleanroom.

2 Outline of the Line-Type Cleanroom

Typical major specifications of the line-type cleanroom are listed in **Table 1**. This cleanroom is so controlled as to maintain the high cleanliness level of the indoor atmosphere with the air temperature and humidity to be within the prescribed ranges.

As shown in a general schematic diagram of the line-type cleanroom in **Fig. 1**, the pre-painted steel sheets are used as the wall material. Inside the room are fitted cleaning units (CU), which circulate and clean the indoor air, air control units (ACU), which circulate and clean the air and simultaneously control the air temperature and humidity, and supply units (SU), which supply the cleaned air from the vicinity of the ceiling to the indoor space. Cooling units are also provided outside the room. Inside the air control unit, a fan, HEPA filter, heater, cooling coil and humidifier are fitted. Indoor air which has been sucked in through the prefilter at the bottom of the ACU has, independently or together with fresh air taken in from outside the room, its temperature and humidity adjusted. The air is then cleaned of dust and other contaminants by the HEPA filter and is supplied to the inlet of the air supply unit attached to the ceiling. In addition, the cleaning unit is also provided with a fan and HEPA filter, and the cleaned air is similarly introduced to its supply unit.

Table 1 Main specifications of a line-type cleanroom

Item		Specifications
Room dimension	(m)	$13.1(W) \times 9.2(L) \times 2.7(H)$
Degree of cleanliness	(0.5 μm)	Class 5 (Federal St. 209D class 100)
Temperature	(°C)	23±2
RH	(%)	50±10
Outer air intake	(m^3/min)	24
Ventilation	(times/h)	73
Number of workers		10 persons
Indoor pressure	(Pa)	19.6

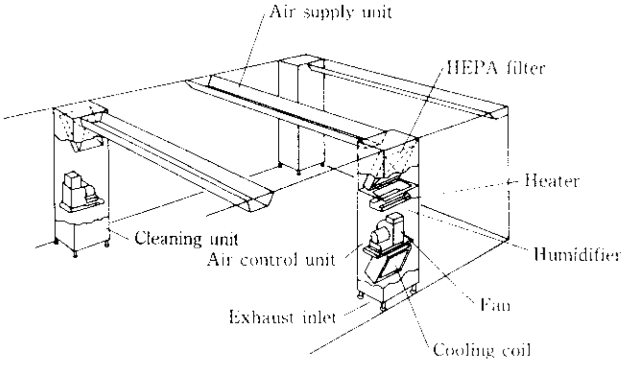

Fig. 1 Schematic illustration of a line-type cleanroom

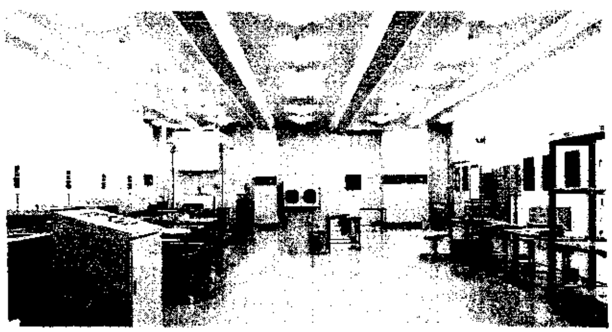

Photo 1 Line-type cleanroom applied to manufacturing electronic components

The configuration and equipment used in the line-type cleanroom offer the following advantages:

- Indoor air is less turbulent.
- Initial investment is relatively low, and the running cost such as for electricity expenses is low.
- Floor height can be lowered.
- Required installation space is small.
- Construction period is short.
- Up-grading is easy.

Cleanliness of Class 100 to 100 000 in Federal Standard 209D (Class 5 to 8 in JIS B9920) can be easily realized, and the line-type cleanroom is widely used in the manufacture of electronic devices, precision instruments, pharmaceuticals and foodstuffs, and in hospitals. **Photo 1** shows a typical line-type cleanroom.

3 Outlet Airflow from the Air Supply Unit

The behavior of outflow from branch tubes connected at intervals to a main duct has been examined and reported based on computer calculations, by taking into consideration the fluid friction loss, etc. in the duct.[3] However, no research results seem to be available concerning the air outflow pattern from a slender-shaped long duct having many small-diameter openings on the wall surface. When the divergent outflow portions permit a large pressure loss, resistors are generally fitted to the outlets to ensure uniformity of the outflow fields. However, since large pressure loss occurs, leading to an increase in power consumption, this way is usually disadvantageous. When the pressure difference between the inside of a long duct and the outside is small, it is generally difficult to uniform the air outflow fields from a duct consisting of perforated panels.

In order to investigate the air outflow fields from the supply unit of a line-type cleanroom, numerical simula-

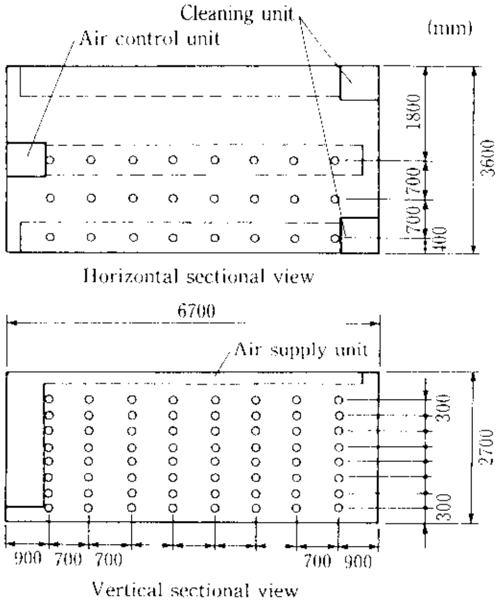

Fig. 2 Configurations and measuring points of the experimental line-type cleanroom

tions and experiments were carried out on the cleanroom model shown in **Fig. 2**. The spatial dimensions of the room were 3.6 m $W \times$ 6.7 m $L \times$ 2.7 m H. An air control unit was located near the wall, and a cleaning unit was located at each of the two opposite corners. Trapezoidal supply ducts with dimensions of 0.6 m $W \times$ 5.7 m $L \times$ 0.2 m H were fitted to the lower surface of the ceiling. These were constructed mainly from perforated metal sheets of an opening ratio of 25%.

For the numerical simulation, the general-purpose computational fluid dynamics codes by the finite difference method were used. To shorten the calculation time, simplification to a two-dimensional analysis was adopted. The calculation was conducted by assuming that the supply unit had a shape permitting a gradual decrease in the cross-sectional area of the flow passage from the upstream end towards the downstream end.

An example of the calculated outflow from the supply unit is shown in **Fig. 3** when the air flow rate at the inlet was 40 m^3/min. While a small variation can be seen, there is no wide fluctuation in the outflow fields, indicating that considerable degree of normalization has been obtained.

Next, in the cleanroom shown in Fig. 2, the measuring experiment for outlet airflow was carried out at positions 45 mm under the supply unit, using an ultrasonic three-dimensional anemometer. The supply unit had a shape that produced a gradual decrease in the cross-sectional area of the duct as already mentioned above. Further, the air flow rate through the supply unit was 37 m^3/min.

The experimental results are shown in **Fig. 4**. Although a slight variation can be seen along the longitudinal direction, it can be said that the outlet airflow pattern is normalized to a considerable extent and that its flow pattern is almost similar to the calculation results shown in Fig. 3.

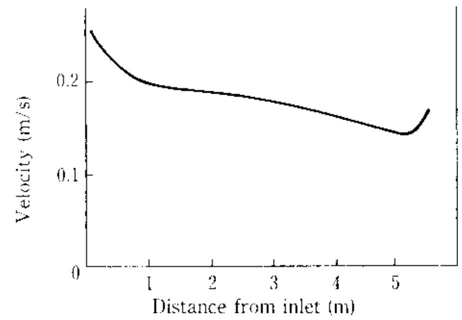

Fig. 3 Air velocity under the air supply unit (simulation)

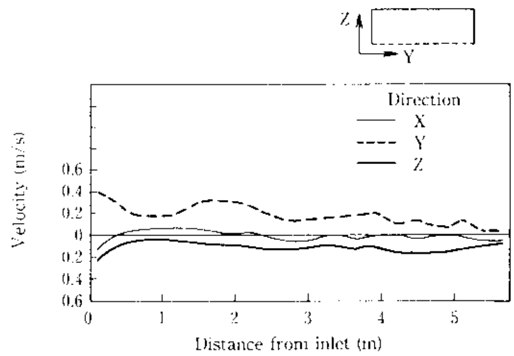

Fig. 4 Air velocity under the air supply unit (experiment)

The outlet airflow pattern from the small-diameter openings of the duct is greatly affected by the velocity of the main stream inside the duct, the static-pressure distribution, friction loss on the inner wall, the shape of the openings and the outflow loss. Here, considering these factors and aiming at minimizing outflow loss and improving airflow fields, numerical simulations and experiments were carried out with basic assumption that the cross-sectional shape of the supply unit interior airflow passage was gradually changed. The test results showed that the airflow fields from a slender duct formed with a perforated panel were normalized by using the above-mentioned supply unit. This arrangement is considered furthermore desirable for its comparative simplicity and for the output of the blast fan made smaller, proving useful for energy saving.

4 Indoor Airflow Fields

In order to further clarify the characteristics of indoor airflow fields, on top of the examination in Sec. 3, more experiments and simulations were carried out mainly on the line-type cleanroom.

4.1 Experiment

4.1.1 Experimental method

As the first step, the line-type cleanroom shown in Fig. 2 was operated, and measurements of the indoor airflow fields were taken. The air flow rates through the air control unit and cleaning units were 37 and 33 m^3/min, respectively. The measuring points are shown in Fig. 2, and the ultrasonic three-dimensional anemometer used for measurement. The same supply units were used as those described in Sec. 3.

Changes were then made, such as replacing the supply units with ducts and filters under the ceiling that were similar to those used in conventional non-unidirectional flow cleanrooms, in order to investigate the effects changing the outlet airflow pattern on the indoor airflow fields. The measuring points for the indoor airflow fields and method were the same those already mentioned, and the same construction for the exhaust inlets was also used.

4.1.2 Results and discussion

The airflow fields obtained from the experiments are shown in **Fig. 5** (a) for the central longitudinal cross section and lateral cross section, respectively, of the line-type cleanroom. No rotating or rising streams were found, and a nearly uniform, downward airflow can be seen, which would quickly remove dust and other contaminants. Similar airflow fields were also observed at other cross sections which are not shown in the figure. In addition, the turbulence energy at the measuring points was uniformly small, which is also not shown in the figure. Consequently it can be said that the indoor airflow fields of the line-type cleanroom are similar to those of the unidirectional flow cleanroom. While the airflow pattern shows an effect of the airflow velocity component in the longitudinal direction of the duct, which is blown out of the supply unit, the airflow pattern generally shows an obliquely downward stream which is directed to the lower suction ports of the cleaning units lying opposite. As a result, no stagnant area is apparent.

The velocity vectors in the central longitudinal cross section and lateral cross section are shown in Fig. 5 (b) for the case of a conventional non-unidirectional flow cleanroom. While strong downward streams exist, at locations away from the supply outlets, rising streams were frequently observed beneath the supply outlets. The turbulence energy was also large. Under such airflow conditions, dust will be liable to collect or be dispersed.

As already mentioned, it can be understood that the indoor flow fields are greatly affected by the outlet airflow patterns. The line-type cleanroom can, compared with the conventional non-unidirectional flow type, obtain better outlet airflow patterns, and for this reason, it can produce effective indoor flow fields.

4.2 Numerical Simulation of Flow Fields

4.2.1 Simulation model

Numerical simulations were first carried out on the cleanroom shown in Fig. 2. The flow fields in the room were divided into the mesh system shown in **Fig. 6**, half of the flow domain being considered, and were solved by the finite difference method. A three-dimensional, k-ε two equation turbulence model was used for the

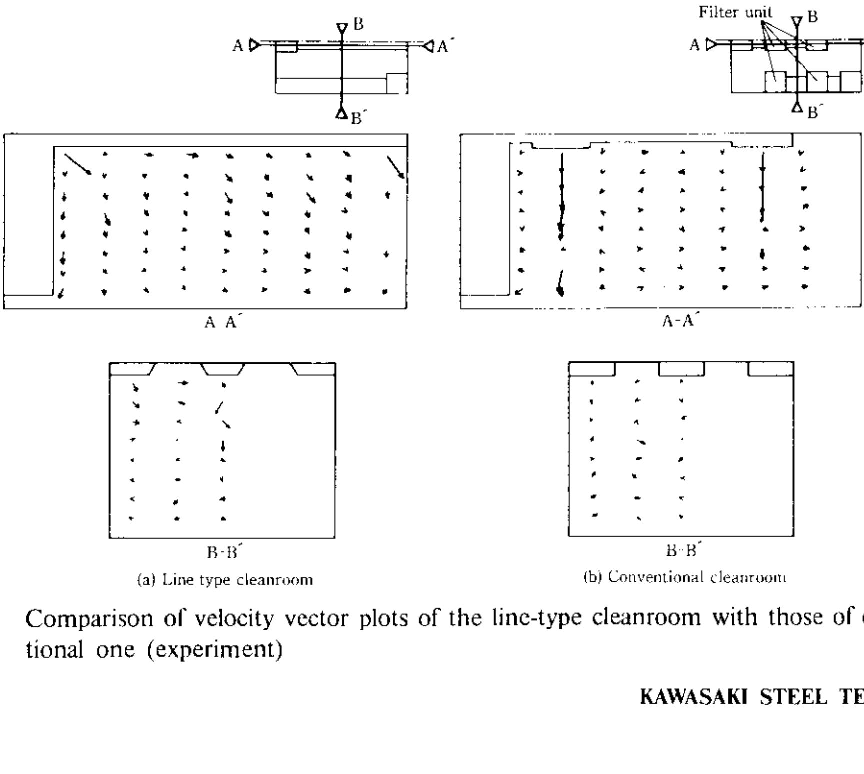

Fig. 5 Comparison of velocity vector plots of the line-type cleanroom with those of conventional one (experiment)

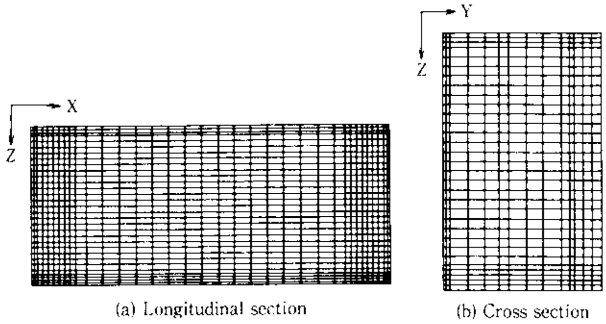

Fig. 6 Numerical mesh in half domain

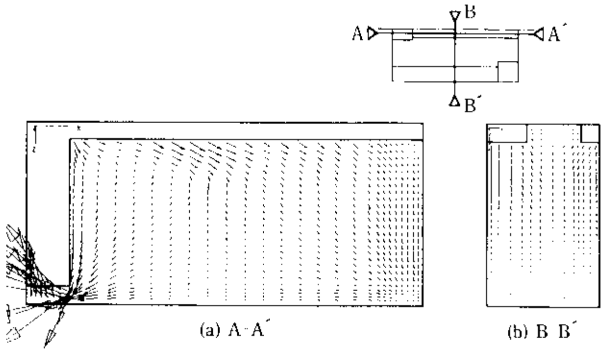

Fig. 7 Velocity vector plots of the line-type cleanroom, A-A' plane and B-B' plane (simulation)

numerical simulation, and the turbulence wall function was used for the boundary conditions. The experimental data described in Sec. 3 were used as the parameters for air supply inlet into the room.

Next, numerical simulations were made when a work table measuring 2 m L × 1 m W × 1 m H was placed at the center of the room shown in Fig. 2, and also when only one air control unit having the same dimensions as that in Fig. 2 was placed at one corner of the room, a supply unit was placed at the center and both units were connected by a duct. The latter simulation was done to investigate the case of a restriction in the arrangement of the air control unit. The boundary conditions were the same as those already mentioned, and the number of the meshes was 15 000 to 24 000.

4.2.2 Results

For the line-type cleanroom shown in Fig. 2, the simulated velocity vectors in the central longitudinal cross section and the lateral cross section are shown in **Fig. 7**. As with the experimental results in Sec. 4.2, nearly uniform downward streams were obtained over the entire area of the room, and it can be assumed that dust would be quickly removed. No rotating or rising streams were observed. Although the airflow pattern reveals an effect of the velocity component in the longitudinal direction of the duct, but as mentioned before, the airflow is towards the exhaust inlets opposite, and, as a whole, it is considered to be favorable. The experimental results and the simulated results are in comparatively good agreement, and the effectiveness of the simulation method was therefore confirmed. When the work table was arranged at the center of the room, the simulated velocity vector plots in the longitudinal cross section at the center of the room are shown in **Fig. 8**. Uniform flow fields can be seen without rotating or rising streams. Regarding the case in which a work table was arranged inside a conventional non-unidirectional flow type cleanroom, an analysis has been made in the past.[4] In that report, the generation of rising streams above the work table and rotating streams at the side of the table are shown. From these results, the effectiveness of the airflow fields in the line-type cleanroom can

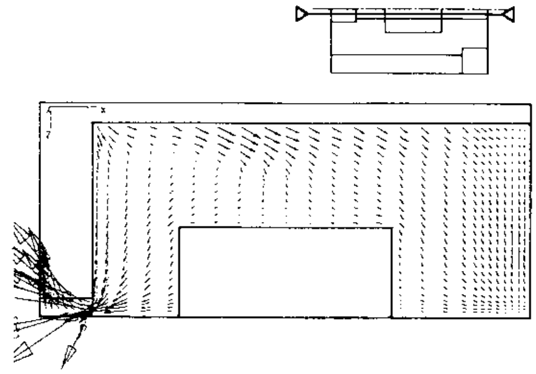

Fig. 8 Velocity vector plots in the center of the line-type cleanroom with a work table in the center of the room (simulation)

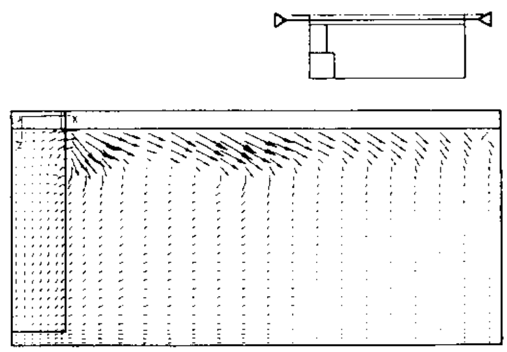

Fig. 9 Velocity vector plots in the center of the line-type cleanroom where air control unit and air supply unit are connected with connecting duct (simulation)

be understood.

When the air control unit was arranged at the corner of the room, the supply unit at the center, and the two units connected with a duct, the simulated velocity vectors in the central longitudinal cross-section are shown in **Fig. 9**. In the area far from the air control unit, the airflow velocity was reduced because it was far from the exhaust inlets. Consequently, the position of the exhaust inlets needs to be taken into account to optimize the airflow fields. Small swirls were also found, because little air was flowing into the bottom part of the connecting duct. However, these swirls were very small, and their effect on the cleaning characteristics is also considered small.

It can be concluded from the simulated airflow that in the line-type cleanroom, rotating or rising streams are not found, and as a whole, it gives desirable airflow field. Such a numerical simulation can also be used as a guideline for design when the indoor layout is changed.

5 Cleaning Characteristics

The cleaning characteristics were assessed on the basis of the results in Sec. 4 to investigate the effects of indoor airflow fields on cleaning capability.

5.1 Experimental Method

An experiment was conducted in order to compare the cleaning characteristics of the line-type cleanroom and of the conventional non-unidirectional flow type mentioned in Sec. 4. The number and arrangement of the air control and cleaning units were the same as those shown in Fig. 2. The airborne particle concentration of 0.5 μm or greater was measured with a particle counter at a height of 1 000 mm above the floor at the center of the room, and its change with time was investigated.

5.2 Results and Discussion

The experimental results for the cleaning characteristics of the line-type cleanroom and the conventional flow type cleanroom are shown in combination in **Fig. 10**. In the case of the conventional flow type, a cleanliness level above Class 100 in Federal Standard (Class 5 in JIS) was achieved, and the cleanliness then fluctuated within the range of particle concentration of 40 to 100 particles/ft^3. However in the case of the line-type cleanroom, after the cleanliness level of Class 100 had been reached, the particle concentration continued to drop to 10 particles/ft^3 or less. This can easily be assumed due to the better indoor airflow field that was shown by the experimental and simulated results. This indicates that the line-type cleanroom can achieve with comparative ease a high cleanliness environment to Class 100 and better. In other words, the line-type cleanroom can use a lower ventilation rate compared with conventional cleanroom to achieve an indoor environment to Class 100, for instance. This fact leads to reduced investment cost and running cost for the cleanroom.

It is concluded that the line-type cleanroom can achieve suitable airflow fields, has excellent cleaning characteristics, and is cost effective.

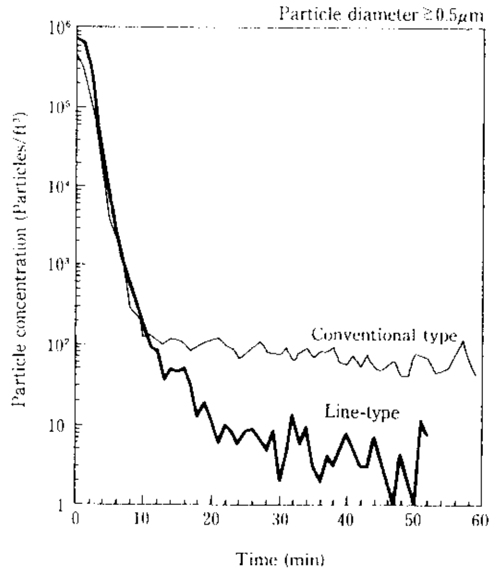

Fig. 10 Relationship between time and particle concentration

6 Conclusions

The airflow fields and cleaning characteristics of a line-type cleanroom were investigated by simulations and experiments. The results obtained can be summarized as follows:

(1) Indoor airflow fields are greatly affected by the supply patterns of cleaned air.
(2) A use of supply unit having a gradually reducing cross-sectional area in its flow passage will permit to obtain a satisfactorily normalized outflow field pattern along the longitudinal direction.
(3) Inside the line-type cleanroom, no rotating or rising streams are observed, with full expectations for almost uniform downward streams and a rapid removal of generated dust and other contaminants.
(4) Through numerical simulations, fairly certain estimations can be made of airflow fields of line-type cleanrooms for various layouts and arrangements.
(5) Its excellent cleaning characteristics permit to obtain a high cleanliness environment efficiently at a relatively simple facility setup.

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