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General particle concentration model and experimental validation for cleanrooms

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Abstract. Numerous research reports have demonstrated that the supply air volumes of cleanrooms areusuallyover-designed to satisfy air cleanliness classes, which may lead to enormous energy waste. In this study, five well-recognised international mathematical models for calculating cleanroom particle concentration were analysed, which are all based on uniform particle distribution in the cleanroom, indoor particle conservation, and mass airflow balance, and an improved and more general model has been established for calculating the minimum air change rates according to the expected air cleanliness class. Following the introduction of non-dimensional concentration correction factors, based on the least-squares method, the average relative error between the model-predicted and measured particle concentration is approximately 13.5%. Based on the improved model with correction factor, the test results demonstrate that the particle concentration depends mainly on the air change rate, particle emission rate and return airflow patterns, among others. When the air change rate per hour and ratio of particle concentrations between the return airflow and room average were varied from 40 h^{-1} to 120 h^{-1} and 0.7–1.3, respectively, the concentration consequently decreased by approximately 65% and 46%. The particle deposition caused by gravity can be neglected for small particles.

Keywords. Cleanroom; particle concentration; air change rate; model comparison; experiments.

1. Introduction

In a typical cleanroom, the airborne particle and microbe-carrying particle concentrations should be effectively controlled to meet stringent air cleanliness requirements for high-tech research, process, or manufacturing objectives. The increasing use of air cleaning technologies also accelerates the advancement of science and technology [1].

The manner in which to optimise the design of air change rates in cleanrooms has become a research hotspot in the air cleaning industry. This process requires tens or hundreds of supply air volumes to overcome the air resistance of multistage filtration, thereby consuming substantially more energy than a common air-conditioning room of the same volume [2]. In order to reduce energy, it is beneficial to be able to obtain minimal air change rates to meet air cleanliness levels in cleanrooms [3]. Instead of using the trial-and-error method to design the supply air volume, most designers of heating, ventilation, and air-conditioning use traditional experience or a 'cleanroom air cleanliness class versus supply airflow rates' table to obtain the recommended supply airflow volume, which ignores the indoor particle emission rate, filtration efficiency of outdoor and return air, particle deposition, and particles entering or being exhausted from the cleanroom. In general, the supply airflow volume has a significant influence on the particle concentration; however, the indoor air cleanliness class is not only controlled by air change rates [4]. Several numerical and experimental studies have demonstrated that different airflows and ventilation systems exhibit varying pollutant distributions and potentials for improving the air cleanliness of the cleanroom [5–9]. To save fan and thermal energy in cleanroom HVAC systems as well as maintain the required air cleanliness class, modeling technologies have been developed and published [10–12]. Thus, it is important to establish a more accurate model in order to provide an improved prediction of the airflow volume and fan energy consumption, thereby reducing potential energy waste [11–13].

According to a comparison of several local and global particle concentration models published in recent years, this study takes additional variables into consideration and establishes a more accurate general model. Once validated, the improved model can be used to examine the effects of the indoor particle emission rate, air change rate, return air particle concentration, and particle deposition of common

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cleanrooms, as well as to calculate their minimum air change rates according to the expected air cleanliness class.

2. Model establishment and validation

2.1 *Mathematical models for calculating cleanroom particle concentration*

Various mathematical models have been used in cleanroom guidelines and standards both locally and globally. Five well-recognised models for calculating the cleanroom particle concentration are illustrated as follows. The underlying hypothesis is that the clean air isperfectly mixed with the airborne particles in a cleanroom. Thus, we focus on the non-unidirectional cleanroom, of which the air cleanliness class is 6-8 [10].

Morrison, Brown *et al*, Kozicki *et al* and Jaisinghani proposed mathematical particle concentration models for cleanrooms [14–17]. Because they disregarded numerous critical factors, these early models appear to be too simple to be commonly used in the clean air industry for calculating the minimum air change rates based on the expected air cleanliness class of a room. As it contains additional variables, the improved model established by Sun [10–13] is more accurate than its predecessors. It was further validated by means of small-scale validation testing, and by introducing the correction factor, the gap between the theoretical results and measurements could be narrowed. The correction factor was selected as 0.3 with an optimised statistical fit for all prediction curves. For more complicated air cleaning systems, E_U can account for all of the filters installed in an air handling unit (AHU) unit in series. Therefore, designers of ventilation systems can calculate the minimum air change rates and potential cleanroom energy reduction.

$$C_S = \left(C_{SO} - \left(\frac{b}{a}\right)C_o\right)e^{-ant} + \left(\frac{b}{a}\right)C_o \tag{1}$$

$$a = (1 - r) + (E_U + E_H - E_U E_H)r \tag{2}$$

$$b = (1 - E_U)(1 - E_H)(1 - r) + \frac{G - D}{C_O n} \tag{3}$$

Xu [18] constructed models to calculate the indoor particle concentration for non-unidirectional and unidirectional airflow cleanrooms. In order to simplify the calculation, the mass-balance model for the unidirectional airflow cleanroom neglected infiltrated dust, dust deposition in the air duct, and indoor particle surface deposition. If the clean air-conditioning system uses a different filter combination, the particle concentration can be obtained by calculating the new total filtration efficiency of the outdoor and recirculating air. When several cleanrooms are connected in parallel or where partial purification equipment exists, the formula for the room particle concentration is more complex, but it is also based on uniform particle distribution in the cleanroom, indoor particle conservation, and mass airflow balance. The particle concentration for a non-unidirectional airflow cleanroom can be calculated by the corrected mass-balance model under different air distribution, supply outlet, and air change rates. Moreover, the author proposed a model to calculate the particle concentration of three different regions in non-unidirectional and unidirectional airflow cleanrooms. The particle concentration varied among the main, vortex, and return air regions. Because the particles emitted from the main region will first focus on the return air region, the particle concentration in the return air may be higher than the average particle concentration. The measurement results demonstrated that, for a non-unidirectional cleanroom with lower air change rates, the ratio of the particle concentration in the return air to that of the location 0.9 to 1.0 m above floor is approximately 1.25. For a high-efficiency particulate clean air-conditioning system, a correction factor can be applied to obtain the particle concentration in the main region based on Eq. (4). This factor can be obtained according to the airflow pattern, number of supply air outlets and air change rates.

$$C_S \times 10^{-3} = \frac{G \times 10^{-3} + C_o \times 10^{-3} n(1 - r)(1 - \eta_n)}{n[1 - r(1 - \eta_r)]} \tag{4}$$

$$\eta_n = 1 - (1 - E_1)(1 - E_U)(1 - E_H). \tag{5}$$

$$\eta_r = 1 - (1 - E_2)(1 - E_U)(1 - E_H) \tag{6}$$

Liu [19] improved certain previous models and proposed a model for non-unidirectional airflow in cleanrooms to obtain the indoor air particle concentration as well as confirm the air cleanliness classification. Compared to the model of X this model considered the particle deposition rate and infiltration. The measured results demonstrated that, when the air change rate is high, the calculated results can effectively represent the measured results; however, when the air change rate is low, the clean air cannot mix perfectly with the airborne particles in a cleanroom, making the difference between the calculated and measured indoor particle concentration significant. By means of theoretical and experimental analysis, the author found that the indoor average particle concentration was mainly dependent on the indoor emission rate, air change rate, airflow form, and particle source position, among other factors.

$$C_S = \frac{[1 - e^{-Ot}]I}{O} + C_{SO}e^{-Ot} \tag{7}$$

$$\mathrm{I} = \mathrm{n}[(1 - \mathrm{r})(1 - \eta_n)C_O] + G(1 - D) \tag{8}$$

$$\mathrm{O} = \mathrm{n}(\mathrm{r}\eta_r + 1 - \mathrm{r} + Q_{LA}/\mathrm{Q}) \tag{9}$$

Whyte [20] developed another general ventilation equation. The derivation of the 'ventilation equations' can be obtained in building services text books such as those of

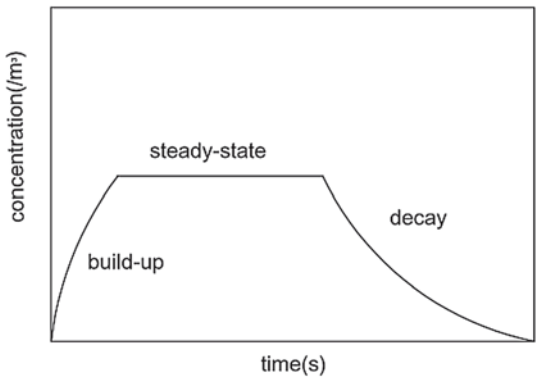

Figure 1. Build-up, steady state, and decay of airborne contamination in ventilated room.

Jones, and Eastop and Watson [21, 22], whereby the concentration of undesirable or toxic gases during the 'build-up', 'steady state', and 'decay' can be calculated, in the manner shown in figure 1. For a cleanroom in which the background concentration is zero, as people enter the cleanroom and the machinery begins to operate, the particle concentration starts to 'build up'. After a certain period, as the particle emission rate becomes balanced by the dilution of clean air, the particle concentration tends to reach a 'stable state'. When people depart from the cleanroom and the machinery is shut down, the particle concentration will 'decay' to a new concentration, which tends to be zero. Equations can be derived for various configurations of ventilation systems except for the most common ventilation system arrangement in cleanrooms [23].

$$M_{ST} = \left(\frac{G_m}{Q} + M_{SA}\right) \cdot (1 - e^{-nt}) + M_{SO} \cdot e^{-nt} \qquad (10)$$

The Russian Cleanroom Energy Efficiency Standard-56190 (GOST R 56190-2014) [24] presents a mathematical relationship between the particle concentration and air change rate based on the particle emission, process, and ventilation effectiveness. The advantage of this model is that it determines the efficiency factor of the ventilation system, which is 0.7 in the case of cleanrooms with non-unidirectional airflow. Moreover, for practical calculations, it can be assumed that the filtration efficiency is equal to 100% and air infiltration is absent. A theoretical comparison was conducted on the recovery time in the resting and operational stages.

$$C_{ST} = \left(C_{SO} - \frac{n_p}{k_1}\right) \cdot e^{-k_1 t/V} + \frac{n_p}{k_1} \qquad (11)$$

$$k_1 = 0.7 \cdot Q \qquad (12)$$

$$Q = n \cdot V \qquad (13)$$

By comparing several particle concentration models, this study aims to establish an improved model that includes additional variables and examine the effects of the indoor particle emission rate, air change rate, return air particle concentration, and particle deposition of common cleanrooms.

All these models for calculating the cleanroom particle concentration are based on the uniform distribution of particles in space as well as the conservation laws of the indoor particle and mass airflow. As indicated in table 1, the treatments of the particle concentration of the return airflow, particle deposition rate, and filtration efficiency of outdoor air differ in the above models. The UK model ignores surface particle deposition of particles ≤ 0.5 μm [25]. The Russian model (GOST R 56190-2014) considers the particle concentration of the return airflow to be 70% of the indoor average particle concentration and ignores the particle concentration from outdoor air and the high efficiency particulate air (HEPA) of recirculating air.

2.2 *Newly established general time-based model and its modifications*

As figure 2 displays, based on the uniform distribution of particles in space as well as the conservation laws of the indoor particle, the conservation of the total indoor particles can be established as follows:

Table 1. Comparison of five models.

Models	Wei Sun (USA, 2008)	Zhonglin Xu (China, 2003)	Junjie Liu (China, 2008)	W Whyte (2012)	Russia standard (2014)
Principles and assumptions	Uniform distribution of particles in space and conservation laws of the indoor particle				
Concentration of particles in return air	Concentration of particles in space				0.7 × concentration of particles in space
Deposition rate	Included	Ignored	Included	Large particles ≥ 0.5 μm	Ignored
Filtration efficiency of outdoor and recirculating air	≠ 100%			= 100%	
Included variables	C_S, C_{SO}, C_O, n, t, r, G D, E_U, E_H	η_n, η_r	D, η_n, η_r	M_S, M_{SO}, M_{SA}, Q, n, t, $G_m C_S$, C_{SO}, Q, V, t, G	
Complexity of the model	Complex	Simple	Complex	Complex	Simple

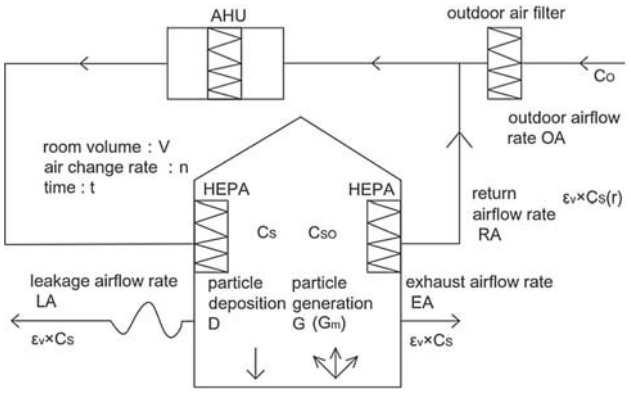

Figure 2. Basic cleanroom airflow configuration.

$$V \cdot dC_S = OA \cdot C_o(1-\eta_n)dt + RA \cdot \varepsilon_V C_S(1-\eta_r)dt + GVdt - RA \cdot \varepsilon_V C_S dt - EA \cdot \varepsilon_V C_S dt - LA \cdot \varepsilon_V C_S dt - DVdt \quad (14)$$

Disregarding the temperature difference between the outdoor and recirculating air, that is, assuming that they have the same density, the conservation of mass airflow is converted into the volume airflow, SA = OA + RA = RA + EA + LA:

$$V \cdot dC_S = [\varepsilon_V RA(1-\eta_r) - \varepsilon_V SA]C_S dt + [OAC_o(1-\eta_n) + (G-D)V]dt \quad (15)$$

Introducing r = RA/SA and n = SA/V:

$$dC_S = [\varepsilon_V r(1-\eta_r) - \varepsilon_V]nC_S dt + [(1-r)(1-\eta_n) + (G-D)/C_O n]nC_o dt \quad (16)$$

Factors α and β are defined as follows:

$$\varepsilon_V r(1-\eta_r) - \varepsilon_V = -\alpha \quad (17)$$

$$(1-r)(1-\eta_n) + (G-D)/C_O n = \beta \quad (18)$$

$$dC_S = -\alpha n C_S dt + \beta n C_o dt \quad (19)$$

If the indoor particle concentration is changed from the initial C_{SO} to C_S during time interval t,

$$C_S = (C_{SO} - C_o\beta/\alpha)e^{-\alpha nt} + C_o\beta/\alpha \quad (20)$$

If t $\rightarrow\infty$,

$$C_S = C_o[(1-r)(1-\eta_n) + (G-D)/C_O n]/[\varepsilon_V - \varepsilon_V r(1-\eta_r)] \quad (21)$$

$$\mathrm{n} = (\mathrm{G}-\mathrm{D})/\{C_S[\varepsilon_v - \varepsilon_v \mathrm{r}(1-\eta_r)] - (1-r)(1-\eta_n)\} \quad (22)$$

Effective air mixing isassumed in the derivation of the general time-based model; therefore, the concentration of particles depends only on time and not the spatial location. Air change rate, needed to produce the required particle concentration, can be calculated directly by Eq. (22). Moreover, this model can be modified into simple forms according to different assumptions or conditions and it should be used in non-unidirectional airflow cleanrooms.

The established general model, including additional variables and parameters, can bemodified into other equations according to the different assumptions or conditions [26]. Moreover, the general model can be utilised to obtain the minimum air change rate values in the design of ventilation systems, thereby making the cleanroom more energy efficient.

2.3 *Model validation and correction*

2.3a*Experiments*: In order to verify the accuracy of the general model, an experiment was conducted in a cleanroom. The volume of the cleanroom is approximately 30 m^3 (4.445 × 3.2 × 2.1 m). It uses a ceiling air supply, lateral air return at the bottom of the two sidewalls, and floor air return with 14 fan filter units (FFUs) (99.997% $\geq$ 0.3 μm) arranged side by side in two rows. Each FFU has an independent start-stop motor control and a speed control system. The air change rate in the room produced by one FFU can be adjusted from 15 to 70 h^{-1}. After turning on the FFUs, the cleanroom is pressurised relative to the adjacent corridor. The principle diagram of the system is illustrated in figure 3. The airflow pattern is ceiling supply and sidewall return, with two operational FFU units located in the middle of ceiling (indicated by the bold rectangle in figure 3). On the two sidewalls, there are three return air outlets, of which the total area is approximately 0.64 m^2 (3.2 × 0.3 m), and the height of the middle of return grilles measures 100 mm.

The indoor particle emission is generated by a homemade aerosol generator. The generator is set outside the cleanroom and uses a compressed air atomiser as well as poly-alpha-olefin (PAO) and polystyrene microsphere liquid to generate polydisperse aerosols. As illustrated in figure 4, the principle of the particle emission is as follows: the clean high-pressure air through the no. 1 high-efficiency filter and aerosol sprayer is mixed with additional clean high-pressure air through the no. 2 high-efficiency filter, following which the mixed air is sent into the indoor particle rack, which has eight particle emission holes of the same area to make the particle evenly distributed. The indoor particle rack is arranged 1.7 m above the floor. The generator can emit particles of 0.1, 0.3 and 0.5 μm; we focus on particles of 0.3 μm, which is common and regarded as the most difficult to filter, and it's also why the filter efficiency of particles of 0.3 μm is indicated on the HEPA.

Owing to the varying air change rates and particle emission rates in the cleanroom, the particle concentration was measured and compared to the calculated results in

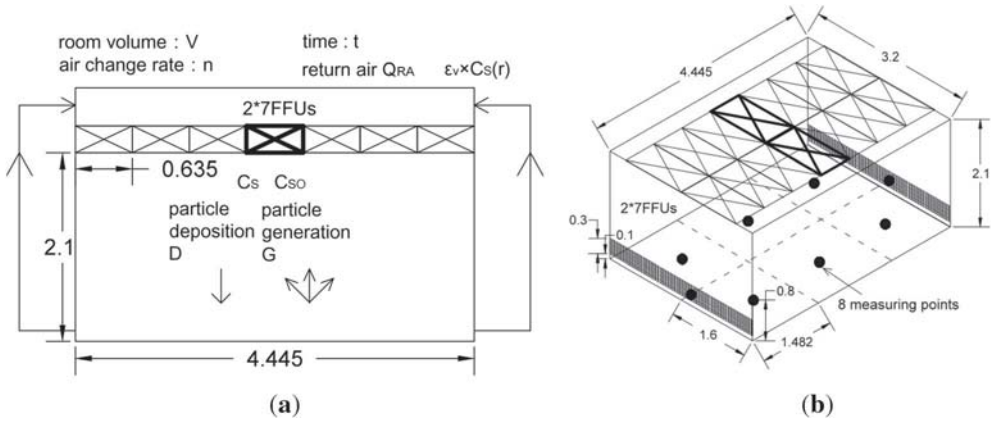

Figure 3. Cleanroom airflow configuration.

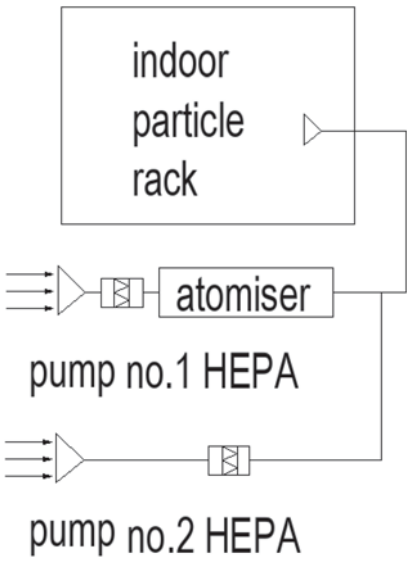

Figure 4. Schematic of particle emission.

Table 2. Experimental conditions

Case	Air change rate (h^{-1})	Particle emission rate (0.3 μm) (counts/m^3/h)
Case 1	40	1,369,718 to 2,080,539
Case 2	50	
Case 3	60	
Case 4	75	
Case 5	90	
Case 6	40	3,791,321 to 4,684,571
Case 7	50	
Case 8	60	
Case 9	75	
Case 10	90	

order to correct the general model. The experimental conditions are presented in table 2, while the test instruments and performance parameters used in the experiment are given in table 3.

The test matrix selection was conducted according to the cleanroom and associated controlled environments in ISO 14644-1. As indicated in figure 3, six sampling points at 0.8 m above the floor were arranged in the centre of six cleanroom sections, each of which measured 1.482 × 1.6 m. Furthermore, one measuring point was located next to each return air wall to measure the particle concentration of the return air. Thus, eight sampling tubes, which were placed at each measuring point, and one particle generating tube were introduced into the cleanroom through a small exhaust vent on the wall. In addition to the sampling tubes, particle generating tube and indoor particle rack, the home-made aerosol generator, airborne particle counter, and flowmeter were placed outside the cleanroom.

Each measurement point was read three times after the predicted recovery time of approximately 15 min. In order to ensure the stability and repeatability of the concentration reading, each measuring point was tested in two rounds from points 1 to 8, following which the average of two rounds of the particle concentration (0.3 μm) was taken as the measured result.

2.3b*Validation and correction*: Considering the various air change rates and particle emission rates, a comparison between the measured and calculated results is given in table 4. In general, the calculated results can represent the measured values and trends. Owing to various potential factors, such as the measuring points being placed at the height of the workbench, the stability of particle emission rate and the vortex air regions, a difference exists between the calculated values and measured data. The ratio of the calculated and measured values was respectively 0.5 and 0.3 for low and high particle emission rates while it was about 0.3 in some previous similar experiments from other literatures [11, 12, 19]. It might be because the higher air

Table 3. Test instruments and performance parameters used in experiment.

Test parameter	Test instrument	Instrument model	Test range	Resolution ratio	Accuracy
Particle concentration	Airborne particle counter	PMS Lasair III110	$\leq$ 9,999,999 counts	1 count/ft^3	0.1 μm at 1 CFM
Air velocity	Hot-wire anemometer	Testo 425	0 to 20 m/s	0.01 m/s	$\pm$ 0.03 m/s
Airflow rate	Flowmeter	Dwyer LZB-10WB	5 to 45 L/min	0.5 L/min	Level 2.5

Table 4. Comparison of measured data and calculations with different air change rates and particle emission rates.

Particle emission rate (counts/m^3/h)	Air change rate (h^{-1})	Calculated indoor particle concentration (0.3 μm) (counts/m^3)	Measured indoor particle concentration (0.3 μm) (counts/m^3)	Corrected indoor particle concentration (0.3 μm) (counts/m^3)
Low particle emission rate: 1,369,718 to 2,080,539	40	29,817	61,063	52,134
	50	35,089	57,573	66,229
	60	22,525	42,353	43,696
	75	22,193	45,806	50,249
	90	12,511	34,148	31,373
High particle emission rate: 3,791,321 to 4,684,571	40	88,858	249,897	224,850
	50	71,100	176,933	189,382
	60	61,819	178,639	187,657
	75	40,716	146,219	118,777
	90	33,702	115,389	120,734

change rates and the lower particle emission rates, the better air mixing is, and the closer the value is to 1. The non-dimensional concentration correction factors, based on the measured value, are established by the least-squares method, as indicated in Eq. (23), while the modified particle concentration can be calculated by Eq. (24). As demonstrated, k is the non-dimensional concentration correction factor, $C_S^{'}$ (counts/m^3) is the modified indoor average particle concentration at any time and $\bar{G}$ is the ratio of the actual particle emission rate to the benchmark particle emission rate, which is calculated by the particle concentration model according to the expected ISO Class 6 cleanliness.

$$\mathrm{k} = 0.375\bar{\mathrm{G}}^2 - 0.677\bar{G} + 0.623 \tag{23}$$

$$C_S' = C_S/k \tag{24}$$

The relative error between the modified and measured particle concentration is 12.03% for a high particle emission rate and 15.42% for a low particle emission rate, and overall, the average relative error is approximately 13.5%. It can be observed from figure 5 that the model-corrected results are strongly similar to the measured data compared to other particle concentration models. Besides, we also find that, the particle concentration decreases with an increasing air change rate under high particle emission rates, but increases by about 27% for 50h^{-1} under low particle emission rates due to a sharp rise in the particle emission rate.

Sun [11, 12] and Liu [19] took into account particle deposition, of which the value differs only slightly. Thus, we present the particle concentration as calculated by Sun instead of Liu. Whyte [20] used the same assumption as Xu [18], similarly, we present the particle concentration calculated by Xu instead of Whyte.

Using this modified model, design and operating engineers can evaluate the particle concentration by introducing the non-dimensional concentration correction factor k under various particle emission rates.

In order to verify the validity and accuracy of the existing and general models, the corrected results are compared with the experimental data from the literature [11, 12, 19]. As illustrated in figure 6, the corrected model exhibits preferable in accordance with the measurement data under high particle emission rates.

3. Sensitivity analysis of the general particle concentration model

3.1 *Effect of air change rate on particle concentration under different particle emission rates*

The general model considers the influences of numerous factors in addition to the air change rate. In order to examine the effects of various factors on the steady state concentration obtained from the corrected model, we

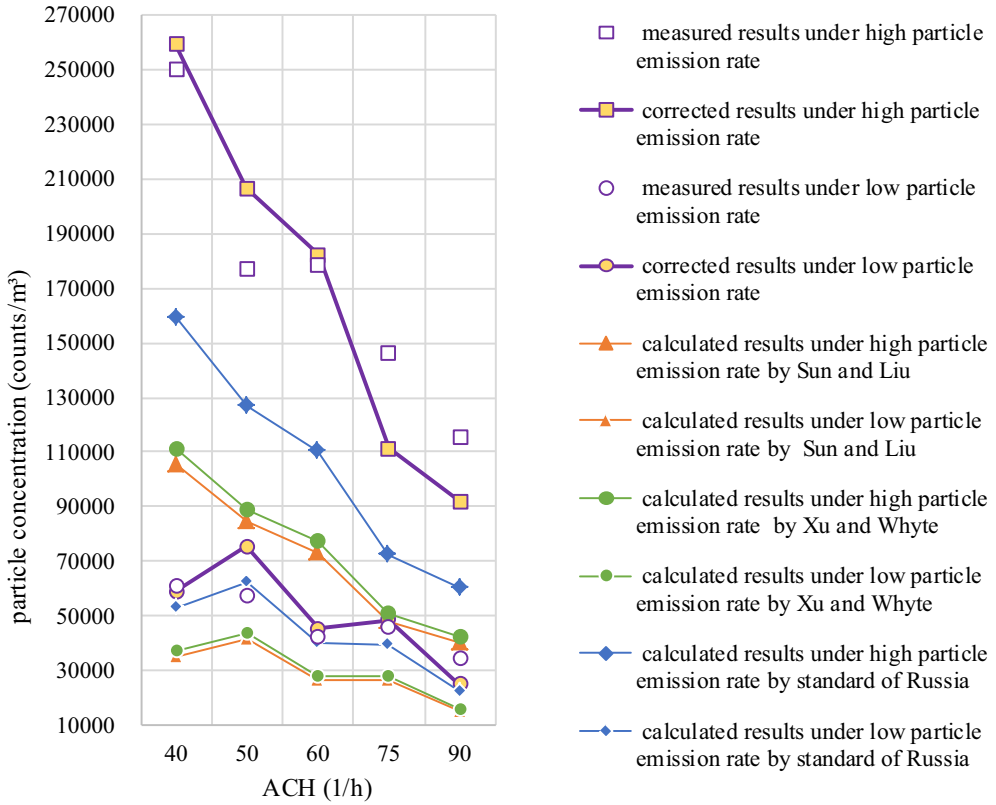

Figure 5. Comparison of measured, corrected, and calculated results (0.3 μm) with different air change rates and particle emission rates.

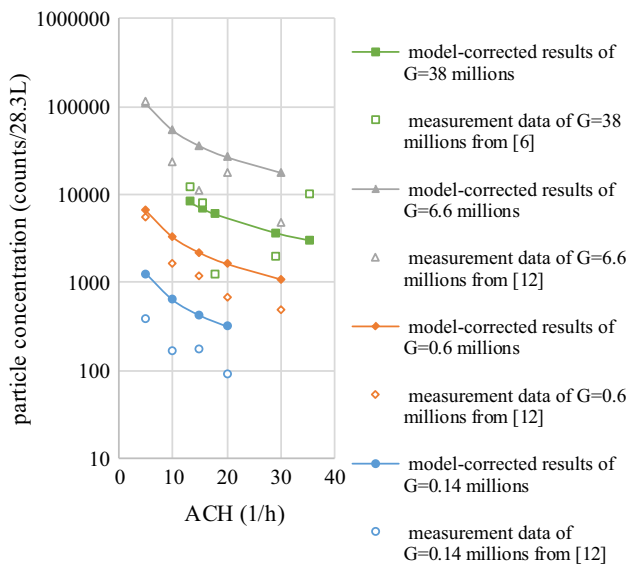

Figure 6. Comparison of model-corrected results and measurement data from literature [6,12] under various particle emission rates (counts/min).

conducted a sensitivity analysis. Figures 7, 8, and 9 indicate that the particle concentration changes with different particle emission rates, air change rates, return air particle concentrations and particle depositions, respectively. The basic condition is as follows: air change rate: 80 h^{-1}; high particle emission rate: 5×10^7 counts/(m^3 h) (0.3 μm); low particle emission rate: 5×10^5 counts/(m^3 h) (0.3 μm) [27]; particle deposition rate of particle emission: D = 0% counts/(m^3 h); filtration efficiency in the outdoor air loop and return air loop: 99.999% (0.3 μm); ratio of return air volume to supply air volume: 90%; ratio of return air to indoor air particle concentration: 1.25; particle concentration of outdoor air: 2×10^8 counts/m^3 (0.3 μm) [28].

Figure 7 demonstrates that the air change rate has a significant influence on the particle concentration. With the air change rates ranging from 40 to 120 h^{-1}, the particle concentration actually decreased by approximately 65%. In theory and the model, the concentration always decreases with an increasing air change rate. However, in practice, when the air change rate increases beyond a certain value, the airflow in the cleanroom may cause additional vortex areas and secondary blowing dust of particles, which is disadvantageous for particles to mix with clean air.

3.2 *Effect of return air particle concentration on particle concentration with different particle emission rates*

The efficiency factor, namely the ratio of the particle concentration of return and exhaust air to the average

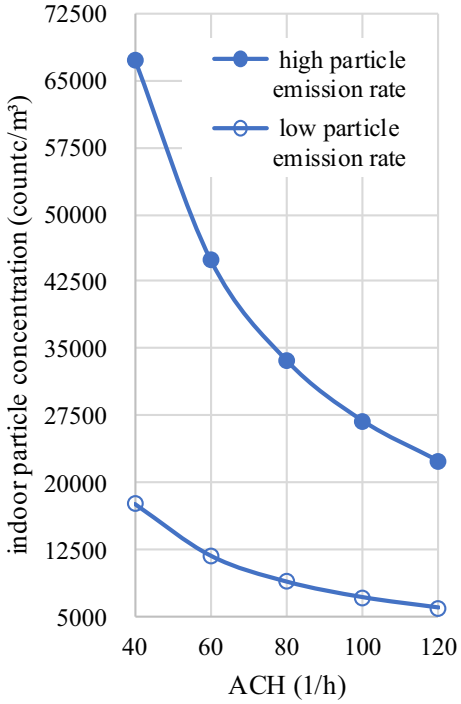

Figure 7. Effect of air change rate on particle concentration with different particle emission rates.

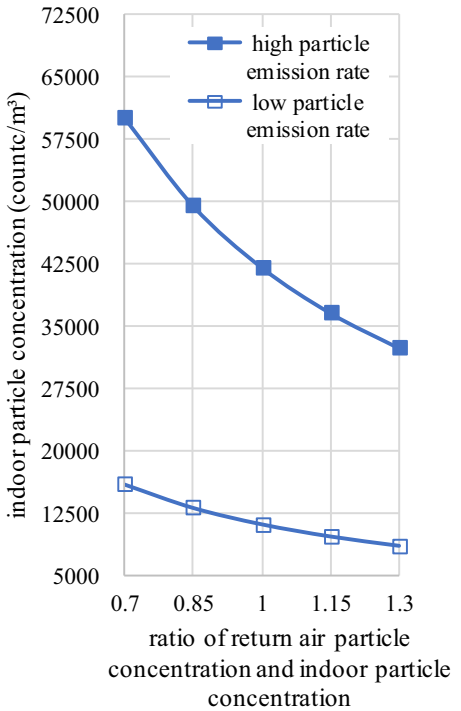

Figure 8. Effect of return air particle concentration on particle concentration with different emission rates.

indoor particle concentration, differs with various air change rates as well as return and exhaust airflow patterns. When the supply air volume is larger, the height of the

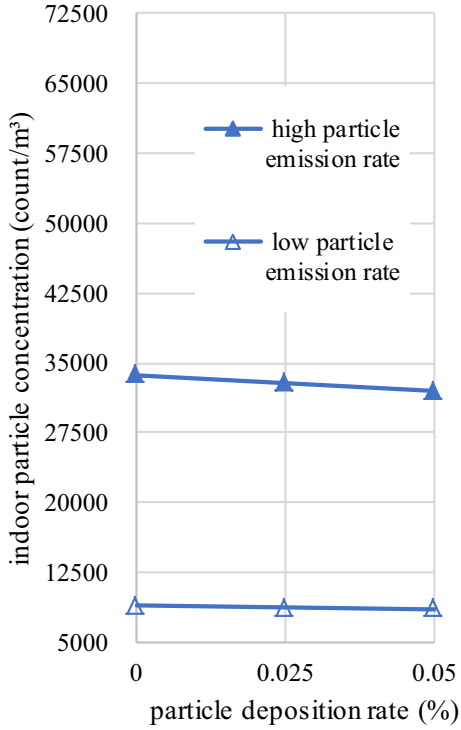

Figure 9. Effect of particle deposition rate on particle concentration with different emission rates.

return air outlets above the floor is lower, the airflow pattern is closer to unidirectional and the return airflow pattern is improved. The mean efficiency factor is approximately 1.25 for non-unidirectional cleanrooms [18].

According to figure 8, when the ratio of the particle concentrations of the return airflow and room average increased from 0.7 to 1.3, the indoor particle concentration decreased by 46%. This is because the particles of the recirculating air entering the cleanroom decreased through the HEPA filters of the recirculating air.

When the arrangement of the exhaust grilles is varied, the particle deposition rate exhibits a corresponding difference. Several studies have demonstrated that the performance of the ventilation system for diffusing the contaminant in the horizontal symmetric case is superior to that in asymmetric and vertical symmetric cases, yielding lower particle concentration [29].

3.3 *Effect of surface particle deposition on particle concentration with different particle emission rates*

The deposition mechanisms in cleanrooms are likely to be gravitational, Brownian diffusion, electrostatic attraction, and collision [25]. The particle deposition is dependent on the particle properties, such as particle size distribution, shape and density, the direction, surface area and roughness

of the settlement, the indoor airflows, the indoor static electric fields, the cleanroom surface, and the air temperature difference of the near surface. It is known that most deposition of large particles, i.e., > 2 μm, onto surfaces in cleanrooms is caused by gravity, whereas that of small particles, i.e., < 0.1 μm, is caused by Brownian diffusion [30, 31]. The deposition of small particles, i.e., 0.3 μm, can be neglected because gravitational deposition and Brownian diffusion are no longer a predominant mechanism, as opposed to air drag force in cleanrooms [18, 32]. Thus, small particles are quickly swept from the cleanroom with little time to deposit. Even taking into account the particle deposition rate, figure 9 indicates that the 2.5% and 5% deposition rates of the particle emission have no significant effect on the airborne particle concentration.

To conclude, an increase in the air change rate can reduce the particle concentration to a significant degree, but the effect on the particle concentration also depends on certain other parameters, such as particle emission and return air particle concentration. Using the general model, the particle concentration can be calculated under different conditions. However, owing to some other potential factors to affect cleanroom air cleanliness class and the limitations of experimental conditions, it should not be expected that the general model will accurately calculate the particle concentration. Overall, the new model prediction agrees with the experimental results in quality but not in quantity, and further research is required to increase the accuracy.

4. Conclusions

This paper presented a new model that was established to obtain the minimum air change rate for energy saving, while maintaining the expected air cleanliness class. The new model was corrected based on the measured data, and a comparison between the measured and model-predicted results demonstrated strong correlation, with an average relative error of approximately 13.5%. Moreover, the improved model exhibited preferable accordance with the experimental data from the literature under high particle emission cases.

The theoretical calculation results of the particle concentration sensitivity analysis for cleanrooms indicate that the particle concentration mainly depends on the air change rate, particle emission rate, and return airflow patterns. The particle deposition caused by gravity can be neglected for small particles.

Abbreviations

C_S	Calculated impurity particle concentration at any time in space, count/m^3
V, t, n	Room volume, m^3; Time; Air change rate, h^{-1}
Co	Impurity concentration in make-up air, count/m^3
r	Ratio of recirculating air volume to supply air volume
E_U, E_H	Filtration efficiency of air handling units, and HEPA filter efficiency in room
G	Rate of impurity emission in space averaged throughout the space, count/m^3/h
D	Rate of impurity deposition from air to surface in space, averaged throughout the space; it is suggested that a 5% deposition rate could be a good estimated value if the surface particle deposition rate is unavailable [11, 12]
η_n, η_r	Total filtration efficiency of outdoor air, and recirculating air
E_1, E_2	Primary filtration efficiency of outdoor air, and recirculating air
O, I	Factor calculated by formula (8), (9)
Q_{LA}, Q	Air leakage rate, m^3/h; Air volume supply rate, m^3/h
M_S	Concentration of contaminants in room at a given time, number/m^3
G_m	Release rate of airborne contaminants, number/s
M_{SA}	Background concentration of contaminants entering room in air supply, which can be assumed as zero because of the high particle removal efficiency of air supply filters, number/m^3
M_{SO}	Initial concentration of contaminants in room, number/m^3
n_p	Rate of particle emission in indoor air, count/s
k_1	Factor calculated by formula (9)
ε_V	Ratio of particle concentration in return and exhaust air to average particle concentration in room (GOST R 56190-2014); for cleanrooms with non-unidirectional airflow, $\varepsilon_V = 1.25$ (Xu, 2003)
α, β	Factor calculated by formula (17), (18)
OA, RA, EA, LA, SA	Rate of outdoor, return, exhaust, leakage, supply air volume, m^3/h
k	Non-dimensional concentration correction factor calculated by formula (22)

$\bar{G}$	Non-dimensional particle emission rate, which is calculated by the particle concentration model according to the expected ISO class 6 cleanliness
$C_S^{'}$	Modified impurity particle concentration at any time in space, count/m^3

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