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Studies on Comparison of Particle Concentration Models for Cleanroom

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Abstract

Many independent reports have indicated that cleanroom supply airflow rates are often over-designed to meet the air cleanliness classes, over-supply can cause significant energy waste. It is of great significance to find a more reliable model which can be used to calculate the required air change rate based on a cleanliness class. This paper analyzes 4 well-recognized international particle concentration models for cleanrooms based on uniform distribution of particles, mass airflow balance and indoor particle conservation. This study evaluates the models in perspectives of their assumptions, considered parameters, and application limitations. An improved model is further proposed with examples. The research outcomes can provide a good theoretical support for energy-efficient cleanroom study and design.

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Keywords: Cleanrooms; Particle concentration; Air change rate; Constitutive models; Characteristic analysis

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1. Introduction

Cleanroom is a room where the concentration of airborne particles and microbe-carrying particles are controlled to meet air cleanliness class. Air cleaning technologies have become more commonly utilized in industrial applications following a rapid advancement in science and technology [1].

Higher volume of airflow rate and higher air distribution resistance by multistage filtration often cause cleanrooms to consume much more fan energy than ordinary air-conditioned commercial rooms of the same floor sizes, this is one of the main challenges in cleanroom industry [2]. It is beneficial to analyze the justifications of the required air change rate in order to find possible solutions to significantly reduce energy consumption while maintaining the room cleanliness class [3]. Most design and operating engineers use traditional experience or opinion based "room cleanliness class versus air change rate" table to find a possible air change rate for design, this "table" methodology ignores many other "critical variables" such as room particle generation, filter efficiency, particle surface deposition, particle entry through air supply, particle exit through return and exhaust air. Thus, establishment of a more accurate model is a key to reduce cleanroom fan energy waste [4,5].

This paper is to theoretically evaluate several international particle concentration models published in recent years, and propose a more comprehensive and improved model.

Nomenclature

C_{ST}	impurity particle concentration at any time in space, count/m^3
C_{SO}	initial impurity particle concentration in space, count/m^3
a	factor calculated by formula (2)
b	factor calculated by formula (3)
n	air change rate
t	time
Co	impurity concentration in makeup air, count/m^3
r	ratio of recirculating air and supply air
E_U	filtration efficiency of air handling units
E_H	HEPA filter efficiency in room
G	rate of impurity generation 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
η_n	total filtration efficiency of outdoor air
η_r	total filtration efficiency of recirculating air
E_1	primary filtration efficiency of outdoor air
E_2	primary filtration efficiency of recirculating air
M_{ST}	concentration of contaminants in a room at a given time, g/m^3
G_m	release rate of airborne contaminants, g/s
M_{SA}	background concentration of contaminants entering room in the air supply, which can be assumed to zero because of the high particle-removal efficiency of air supply filters, g/m^3
V	room volume
M_{SO}	initial concentration of contaminants in a room, g/m^3
n_p	rate of particles emission in the indoor air, count/s
k_1	factor calculated by formula (9)
ε_V	efficiency factor of ventilation system, namely the ratio of the particle concentration in return air and average particle concentration in room; for cleanrooms with non-unidirectional air flow, ε_V =0.7
α	factor calculated by formula (14)
β	factor calculated by formula (15)

2. Models

2.1. Particle concentration models for cleanrooms

In recent years, some particle concentration models were published in international cleanroom design guidelines and standards, some well-recognized models are illustrated as follows, perfect air mixing was commonly assumed in their derivations of all these models:

- Wei Sun (USA, 2008) [4,5]

As Figure 1 shows, E_1 is the filtration efficiency of outdoor air, E_2 is the filtration efficiency of return air, ε_V is the efficiency factor of ventilation system, namely the ratio of particle concentration in return air and particle concentration in room. When $E_1 = E_2 = 0$, $\varepsilon_V = 1$, the concentration of particles can be calculated as follows:

$$C_{ST} = (C_{SO} - (\frac{b}{a})C_o)e^{-ant} + (\frac{b}{a})C_o \quad (1)$$

$$a = (1 - r) + (E_U + E_H - E_U E_H)r \quad (2)$$

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

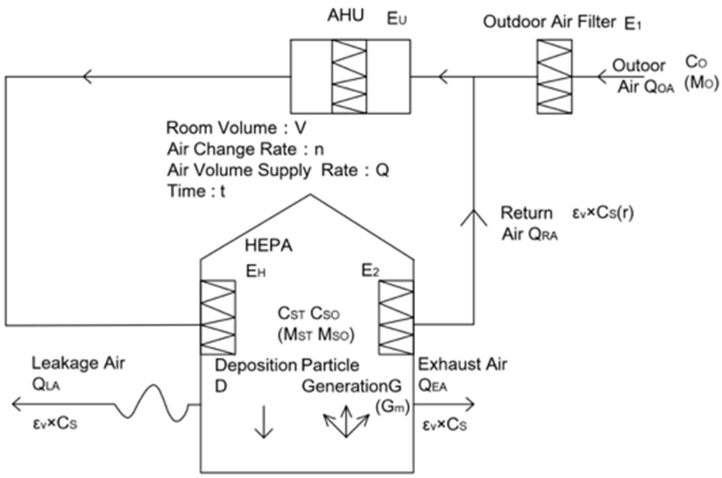

Fig. 1. Basic cleanroom airflow configuration.

Several US mathematical models were proposed by Morrison (1973) [6], Brown et al. (1986) [7], Kozicki et al. (1991) [8] and Jaisinghani (2001) [9]. These earlier time models may be over simplified and have not been commonly utilized in industry to calculate air change rate based on desired room air cleanliness due to ignoring many critical elements. A new model proposed by Sun (2010) is more descriptive and inclusive (more variables and parameters) than previous models, this improved model has been adopted into IEST's Recommdedated Partices RP-12.3 (2015), ASHRAE Cleanroom Design Guide (2017), and some manufacturer's software (Comfil, 2012), this new model may provide a better approach to calculate the required air change rate, and to further analyze the possible cleanroom fan energy reduction options.

- Zhonglin Xu (China, 2003) [10]

As Figure 1 shows, when D=0, ε_V =1, the concentration of particles can be calculated as follows:

$$C_{ST} \times 10^{-3} = \frac{G\times10^{-3}+C_O\times10^{-3}n(1-r)(1-\eta_n)}{n[1-r(1-\eta_r)]} \cdot \{1-\left[1-\frac{C_{SO}\times10^{-3}n[1-r(1-\eta_r)]}{G\times10^{-3}+C_O\times10^{-3}n(1-r)(1-\eta_n)}\right]e^{-nt[1-r(1-\eta_r)]}\} \quad (4)$$

$$\eta_n = 1-(1-E_1)(1-E_U)(1-E_H) \quad (5)$$

$$\eta_r = 1-(1-E_2)(1-E_U)(1-E_H) \quad (6)$$

- Jones (UK) (2002) and Eastop & Watson (UK) (1992) [11,12,13]

As Figure 1 shows, when $E_1 = E_U = E_2$ =0, Q_{LA}=0, r=0, ε_V =1, the concentration of particles can be calculated as follows:

$$M_{ST} = \left(\frac{G_m}{Q}+M_{SA}\right)\cdot(1-e^{-nt})+M_{SO}\cdot e^{-nt} \quad (7)$$

The general ventilation equation can be used to calculate the airborne contaminants during the build-up, steady state, and decay to design and test the air supply system of cleanrooms, in the manner shown in Figure 2. But, in the current standards such as ISO 14644-1 and FS-209E, the cleanliness is based on the maximum allowable particle concentration in the cleanroom (count/m^3) instead of the particle mass concentration.

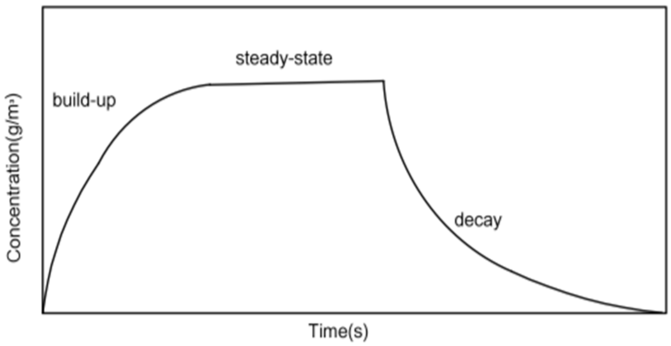

Fig. 2. Build-up, steady state, and decay of airborne contamination in a ventilated room.

- Cleanroom energy efficiency standard-56190 (Russia) (2014)

As Figure 1 shows, when D=0, Q_{LA}=0, η_P=η_{out}=1, ε_V =0.7, the concentration of particles can be calculated as follows:

$$C_{ST} = \left(C_{SO}-\frac{n_p}{k_1}\right)\cdot e^{-k_1 t/V}+\frac{n_p}{k_1} \quad (8)$$

$$k_1 = 0.7\cdot Q \quad (9)$$

$$Q = n\cdot V \quad (10)$$

2.2. Model comparison

These four models for cleanrooms are all based on uniform distribution of particles, and the principles of mass airflow balance and indoor particle conservation. As shown in Table 1, variables such as particles exit through return and exhaust air, deposition, and filtration of outdoor air are treated differently in these four models. Russian model assumes the concentration of particles exit through return and exhaust air isn't the concentration of particles of indoor air; UK model considers that deposition of particles ≤0.5μm can be ignored [11]; Russian model assumes the filtration efficiency of outdoor and recirculating air to be 100%. The last row in Table 1 shows all included variables in these models.

Table 1. Comparison of four models.

Models	Wei Sun (USA, 2008)	Zhonglin Xu (China, 2003)	Jones (UK, 2002) and Eastop & Watson (UK, 1992)	Russia standard (2014)
Concentration of particles in return and exhaust air	concentration of particles in space	concentration of particles in space	concentration of particles in space	0.7×concentration of particles in space
Deposition rate	included	ignored	large particles ≥0.5μm	ignored
Filtration efficiency of outdoor and recirculating air	included	included	=100%	=100%
Included variables	C_{SO}, C_O, n, t, r, G, D, E_U, E_H	C_{ST}, C_{SO}, C_O, n, t, r, G, η_n, η_r	M_{SO}, M_{SA}, Q, n, t, G_m	C_{ST}, C_{SO}, Q, V, t, G

2.3. Newly proposed general time-based model and its variations

As Figure 1 shows, as an improved approach, indoor particle balance equation can be proposed as follows:

$$V \cdot dC_S = OA \cdot C_o(1-\eta_n)dt + RA \cdot \varepsilon_V C_S(1-\eta_r)dt + GVdt - RA \cdot \varepsilon_V C_S dt - EA \cdot \varepsilon_V C_S dt - LA \cdot \varepsilon_V C_S dt - DVdt \quad (11)$$

Ignorance of temperature difference, mass airflow balance becomes volume airflow balance:

$$\mathrm{V} \cdot \mathrm{dC_S} = [\varepsilon_V \mathrm{RA}(1-\eta_r) - \varepsilon_V \mathrm{SA}]\mathrm{C_S dt} + [\mathrm{OAC_o}(1-\eta_n) + (\mathrm{G}-\mathrm{D})\mathrm{V}]\mathrm{dt} \quad (12)$$

Introduce r and n, then,

$$dC_S = [\varepsilon_V r(1-\eta_r) - \varepsilon_V]nC_S dt + \left[(1-r)(1-\eta_r) + \frac{G-D}{C_O n}\right]nC_o dt \quad (13)$$

Define parameters a and b as following:

$$\varepsilon_V r(1-\eta_r) - \varepsilon_V = -\alpha \quad (14)$$

$$(1-r)(1-\eta_n) + \frac{G-D}{C_O n} = \beta \quad (15)$$

$$dC_S = -\alpha n C_S dt + \beta n C_o dt \quad (16)$$

If room particle concentration changes from the initial C_{SO} to C_{ST} during the time interval t,

$$C_{ST} = (C_{SO} - (\frac{\beta}{\alpha})C_o)e^{-\alpha nt} + (\frac{\beta}{\alpha})C_o \tag{17}$$

The general transient model can be expressed in simplified forms under various assumptions or conditions.

- Variation 1:

When return air filter is ignored, and particle exit through return, exhaust and leakage air steams has the same concentration as the average room particle concentration, then ε_v=1, Equation (17) becomes Equation (1).

- Variation 2:

When D=0, ε_v=1, Equation (17) is simplified to Equation (4).

- Variation 3:

Q=nv/3600, the main source of particles in a typical cleanroom is generated from personnel. The density of skin particles is 1100kg/m^3 [14]. Assume the skin cell 33~44μm [11]. It is g_p (g/particle) that density multiplies diameter of skin cell. Then, $G_m = GVg_p/3600$, likewise, M_{SO} and M_{SA} can be calculated, particle count-based Equation (17) can be converted into mass-based Equation (7). By this time, it is assumed that D=0, ε_v=1, and η_n & $\eta_r \neq$100%.

- Variation 4:

When D=0, Q=nV/3600, and η_n & $\eta_r \neq$100%, we obtain Equation (8).

Thus, the proposed general model can be modified into different simplified equations, and it is more comprehensive (includes more variables and parameters), which can be used for design of air supply systems and energy-efficient cleanroom.

3. Further Analysis

In the current standards, the cleanliness is based on the maximum allowable particle concentration in the cleanroom (count/m^3) instead of the particle mass concentration. To compare the above particle concentration models, we calculate the particle concentration (count/m^3) according to Equation (7).

As a case study for example, a mixed airflow cleanroom has following parameters: (1) air change rate n=60~120 h^{-1}; C_O=2×10^5 particles/L(0.3μm); G=1000 particles/(m^{3}h) (0.3μm); r=90%; E_1=E_2=70% (5μm); E_U=95% (0.5μm); E_H=99.999% (0.1μm); D=5% of G; ε_v=0.7 [4,5,10,15]. When personnel enter an empty cleanroom, the particles concentration may vary, but an average concentration in the cleanroom can be calculated. This concentration is important, as it is the concentration to which product is exposed, and it should not be exceeded a concentration limit of the ISO standard [11]. Graphical charts (examining the steady-state concentration of particles in space of different models) are illustrated in the Figure 3.

4. Discussion

When the included variables shown in the Table 1, such as particle concentration through return and exhaust air, deposition rate, and filtration efficiency of outdoor and recirculating air vary, the resulting average particle concentration in room will be changed as well. It is clear that when the air change rate increases, the room concentration of particles decreases. From Figure 3, we find: 1) The room particle concentration in Equation (7) and (1) is a bit lower than those in Equation (8) and (4) because of considering deposition of particles; 2) The concentration in Equation (8) is higher than that in Equation (4) because of considering lower concentration of particles exit through return and exhaust air; 3) The concentration in Equation (1), (4), and (17) is much higher than the concentration in Equation (7) and (8) because of considering filtration efficiency not 100%.

Thus, we can infer that the supply air filtration efficiency and the efficiency factor of ventilation system influence the concentration of particles in space most. Practically, blind increasing of filtration efficiency will lead to significant cost of investment and energy waste, instead, we can change the airflow of cleanrooms to tend the concentration of particles exit through return and exhaust air to indoor air. We can also find the general model is more comprehensive and accurate, which contains more variables and parameters.

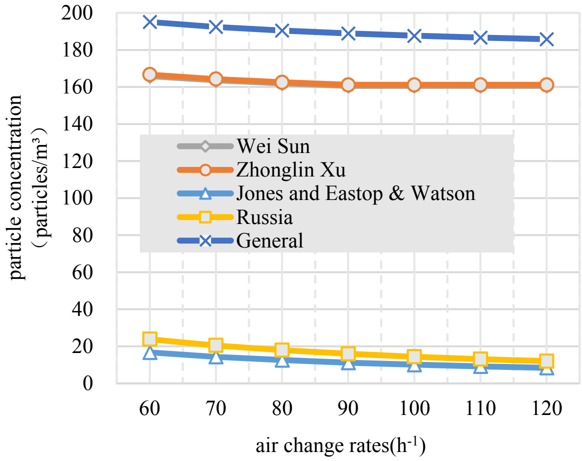

Fig. 3. Concentration of particles in space calculated by models with different air change rates.

To find out the influence of particles exit through return and exhaust air in the concentration of particles, take general models as an example, we calculate the concentration of particles in space with different efficiency factors when air change rate is increased from 60 to 120. From Figure 4, we can find that when the efficiency factor increases, particles exit through return and exhaust air increases, the concentration of particles in space decreases. Though particles of recirculating air entering cleanroom increases too, after some filtration, the particles of recirculating air entering cleanroom have been too low to increase the concentration of particles in space. But, when the air change rate is high, the concentration of particles in space is not that influenced by the efficiency factor, namely, the concentration of particles exit through return and exhaust air. Thus, research of the concentration of particles exit through return and exhaust air can help to reduce the significant energy waste of cleanrooms, which is needed to be extensively studied.

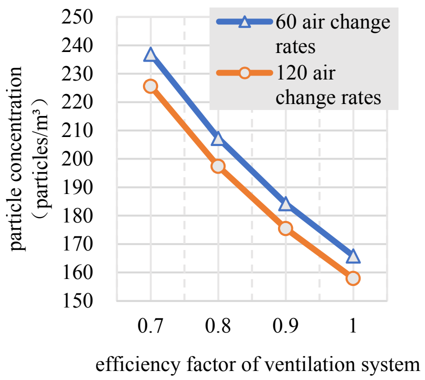

Fig. 4. Concentration of particles in space calculated by general model with different efficiency factors under 60, 120 air change rates.

5. Conclusions

- Many independent reports have indicated that supply airflow rate for cleanrooms are often over-designed to meet the air cleanliness class, which leads to significant energy waste. It is of great significance to find a more relevant model which can be used to calculate the required air change rate based on a cleanliness class.
- The well-recognized models are same in nature except for some different variables. Based on these models, we propose a general model which is more comprehensive and possibly more relevant to various real-world applications.
- According to the case examples, we inferred the efficiency factor, namely the concentration of particles exit through return and exhaust air influences the concentration of particles in space to a large extent.

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References

[1] H. Wang, R. Li. Air Cleaning Technology. China Machine Press, 2007.
[2] W. Liu, J. Liu. The Theoretical Calculation and Experimental Research on The Classification of Air Cleanliness for Non-unidirectional Flow Cleanroom. BUILDING SCIENCE, 2010, 26(10): 76-83.
[3] Z. Xu. New Development of Air Cleaning Technology. BUILDING SCIENCE, 2013, 26(10): 34-40.
[4] W. Sun, J. Liu, John M. K. Flyzik, et al. Development of Cleanroom Required Airflow Rate Model Based on Establishment of Theoretical Basis and Lab Validation., California Energy Commission (CEC), Research Report, 2008.
[5] W. Sun, J. Liu, John M. K. Flyzik, et al. Development of Cleanroom Required Airflow Rate Model Based on Establishment of Theoretical Basis and Lab Validation. ASHRAE TRANSACTIONS, 2010, 116(1):87-97.
[6] Morrison, P.W. Environmental control in electronic manufacturing. Van Nostrand Reinhold, 1973.
[7] Brown, W.K., C.A. Lynn. Fundamental clean room concepts. ASHRAE Transactions, 1986.
[8] Kozicki, M., P. Robinson, and S. Hoenig. Cleanrooms, facilities and practices. Van Nostrand Reinhold, 1991.
[9] Jaisinghani, R.A. Air handling considerations for cleanrooms. InterPhex Conference, March 20-22, Philadelphia, 2001.
[10] Z. Xu. Air Cleaning Technology Principle. 3. Beijing Science Press, 2003.
[11] W. Whyte, W. M. Whyte, T. Eaton. The application of the ventilation equations to cleanrooms. Clean Air and Containment Review, 2012, (12): 4-8.
[12] Jones WP. Ventilation and a decay equation. Air conditioning engineering (fifth edition), 2002.
[13] Eastop TD. and Watson, WE. Mechanical services for buildings. Longman Scientific and Technical, 1992.
[14] W. Whyte, K. Agricola, M. Derks. Airborne particle deposition in cleanrooms: Relationship between deposition rate and airborne concentration. Clean Air and Containment Review, 2016, (25): 4-10.
[15] R. Wang. Characteristic of atmosphere particles in China. HV&AC, 2008, 38(5): 10-12.