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Evaluation of Thermal Comfort and Contamination Control for a Cleanroom

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Abstract: There has been a substantial increase in the working environment of cleanroom. Special garments are therefore dressed in all cleanrooms to control particles and microbiological contamination dispersed from personnel in cleanrooms. However, more tightly-woven fabrics of cleanroom garments will result in thermal comfort dissatisfaction. In this study, field tests of a cleanroom have been carried out in our newly constructed MEMS laboratory. The ASHRAE thermal comfort code was conducted to investigate thermal comfort of personnel based on field-testing data consequently. Furthermore, the effects of clothing on thermal comfort and contamination control have been assessed comprehensively. The results from computer simulation and field tests indicated that there existed optimum compromise between the predicted mean vote and airborne particle counts under different cleanroom garments. The contamination control could be achieved by proper types of garments with satisfied thermal comfort of predict mean vote between 0.5-1.0.

Key words: Cleanroom, thermal comfort, contamination, predict mean vote, particles, garments

INTRODUCTION

Modern manufacturing industries are increasingly turning to cleanroom technology for the development of new products. Products get contaminated and either malfunction or become hazardous to people without clean conditions. Therefore, it's critical to validate that the cleanroom is working correctly and achieving the contamination standards that it has been designed to fulfill. There has been a substantial increase in the working environment of cleanroom. Special garments are therefore dressed in all cleanrooms to control particles contamination dispersed from personnel in cleanrooms. It will result in thermal comfort dissatisfaction. Therefore, it's significant to validate that the cleanroom is working correctly and achieving the contamination standards without the sacrifice of thermal comfort.

Field-testing is to establish that the cleanroom performs correctly and achieves the contamination standards set down at the design stage. These standards are specified comprehensively in ISO 14644-1 (1999). A lot of valuable information describing cleanroom tests to evaluate and characterize the overall performance of cleanroom and clean zone system can be found in IEST-RP-CC006.2 (1993). It also contains the latest data and information on cleanroom testing methods and procedures. Furthermore, NEBB (1996) provides essential information on design consideration, requirements, techniques, equipments and comprehensive procedures for certified testing of cleanrooms.

Large amounts of contamination are dispersed from people in cleanrooms. The cleanroom industry has set considerable emphasis on minimizing the particles dispersed from cleanroom clothing. Accordingly, cleanroom clothing can sometimes be hot and uncomfortable. The thermal comfort of cleanroom garments should be assessed by comfortable indices. ISO 7730 Standard (1994) describes the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices and specifies acceptable conditions for thermal comfort. More information on thermal comfort standard could be found in the literature (Olesen and Parsons, 2002). The local differences between body segments caused by high radiant temperature have been investigated with their effect on thermal comfort (Atmaca *et al*., 2007). Besides, the evaluation of the optimum temperature based on PMV/PPD in cabins including human factors, thermal resistance of maritime police uniform and metabolic rate have been studied comprehensively (Jang *et al*., 2007).

Three-dimension air flow field for improving the ventilation performance of a minienvironment has been

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investigated in literature (Cheng and Hung, 2005). They found that the numerical and experimental approaches lead to useful information and the ventilation performance in the minienvironment may be improved enormously by adjusting the location of the HEPA filter. The influence of external perturbations on a minienvironment by experimental investigations was examined carefully (Rouaud *et al.*, 2004). It showed that the minienvironment and particularly the air curtain are strongly sensitive to perturbations. Besides, the detailed experimental measurements of air flow characteristics in a full-scale cleanroom have been extensively examined (Hu *et al.*, 1996). Velocity vectors, turbulent intensity, turbulence kinetic energy and velocity contours in the space domain were also presented. The specific experimental data are not only beneficial for cleanroom design but also helpful for evaluating of modeling in cleanroom air flow fields.

Computational Fluid Dynamics (CFD) simulation technique is a scientific technique that allows improvement of cleanroom configuration without interfering with normal manufacturing processes (Manning, 2005). A minienvironment for controlling the process area from ambient air contamination by a buffer zone through parametric has been studied extensively using CFD method (Hu *et al.*, 2002). In addition, a deterministic CFD model that incorporated fan-performance characteristics was also applied to investigate the air-recirculation performance of unidirectional flow cleanrooms. The CFD codes were successfully used to simulate the air currents and contamination decay in a model room as well as comparison of indoor particle concentration in different rooms (Zhao *et al.*, 2004). Besides, the STAR-CD code was employed to compute the airflow, temperature and concentration distribution in the lecture room with mixing ventilation system (Noh *et al.*, 2007). They performed the experimental and numerical studied on thermal comfort in the lecture room with cooling loads when the operating conditions were changed. Moreover, the numerical simulation using STAR-CD code has been conducted to investigate the dispersion of pollutant in a fan-filter-unit cleanroom (Chen *et al.*, 2007). The pollutant hot spots and peak pollutant concentration could be obtained from the simulation results.

In this study, field tests of a cleanroom have been carried out in our newly constructed Micro elector-mechanical system (MEMS) laboratory. The ASHRAE thermal comfort code was conducted to investigate thermal comfort of personnel based on field-testing data consequently. Furthermore, the effects of clothing on thermal comfort and contamination control have been assessed comprehensively. The results from computer simulation and field tests indicated that there existed compromise between the PMV and airborne particle counts under different cleanroom garments.

SYSTEM DESCRIPTION AND FIELD TESTS

It becomes obvious that a cleanroom enclosure is essential for both research projects and student training. The layout of cleanroom in MEMS laboratory of Mechanical Engineering Department is shown in Fig. 1. This facility with cleanliness level class 1000 (ISO class 6) consists of process area, etching area and lithography area. The measured cleanroom with the dimension of length(L)×width(W)×height(H) = 20×6×2.4 m. Another change area with air shower/air lock and visiting aisle is included in ancillary clean zone adjacent to the main process area. Fan-Filter Unit (FFU) type cleanroom was designed with HEPA filter of 36% coverage rate in process area. The specified design conditions are temperature 22±2 (°C), humidity 55±5 (%RH) and pressurization 15 Pa for main process area of cleanroom.

To verify the effects of clothing type on particle counts and thermal comfort, an environmental test section 1.3 m (L) × 1.3 m (W) × 2.2 m (H) along with an air shower were set up at the upper left corner of the cleanroom (Fig. 1). The schematic diagram of environmental test section was shown in Fig. 2. To remove particles from clothing and reduce dispersion in test section, personnel entered the air shower before testing. Figure 3a represents the snapshot of test section and the full-scale geometric model of the test section for CFD simulation has been established as shown in Fig. 3b. Types of garment system for tests including (a) attached hood coverage (b) two piece suit and (c) cleanroom coat were shown in Fig. 4. All of the different cases of cleanroom apparel combination with facemask and gloves were presented in Table 1. The effect of clothing type on contamination control and thermal comfort will be tested extensively. A certain amount of trade-off between contamination control and thermal comfort may be determined.

Field-tests including the particle counts at different occupancy state, airflow volume of FFU, temperature level, turbulent intensity and pressurization were carried out comprehensively. The airborne particle concentration tests were performed to determine the actual particle count level within the cleanroom at different occupancy state (at-rest and operational). Quantities measurements of airborne particle counts were made with a Met-One Model 3313 particle counter, sensitive to particles 0.3 μm, 0.5 μm or larger. The minimum number of sampling locations was determined by the square root of clean zone area (m^2) according to ISO standard 14644-1.

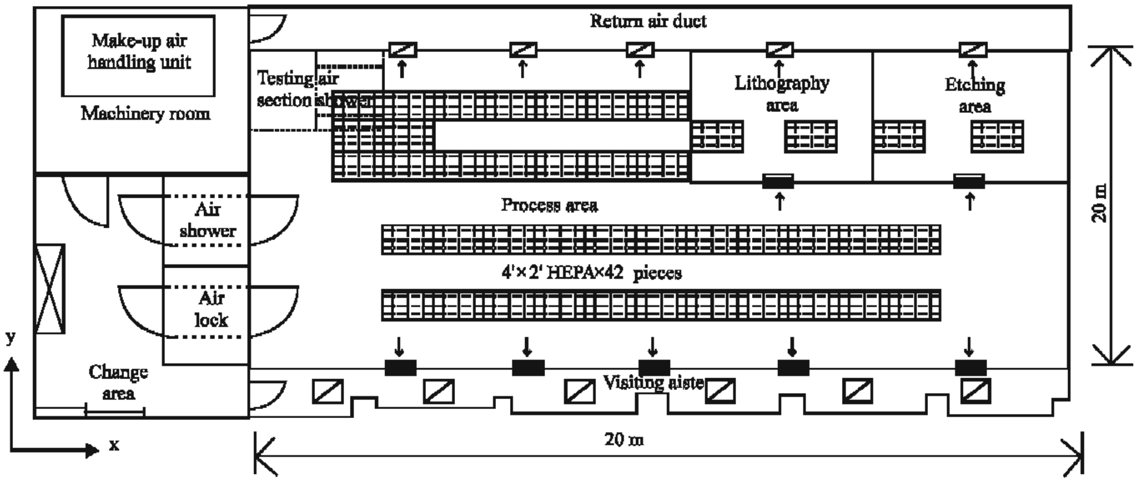


Fig. 1: Layout of cleanroom in MEMS Laboratory

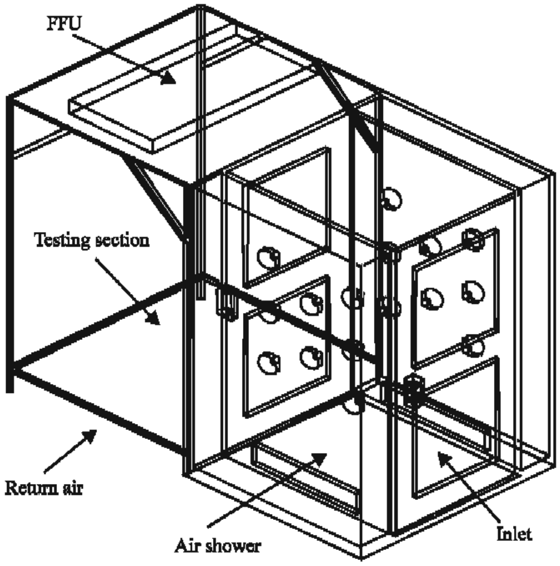


Fig. 2: Schematic diagram of environment testing section

Table 1: ISO thermal sensation scale

Scale value	Descriptor
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

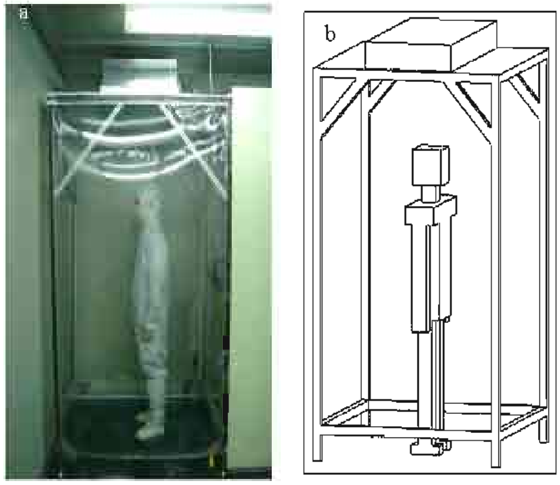


Fig. 3: Snapshot and geometric model of test section (a) test section (b) geometric model of test section for simulation

Consequently, 13 sampling locations were evenly distributed at the process area (Fig. 1). The airflow volume of each FFU was determined by an ALNOR Model 720 flow measuring hood for accuracy and repeatability.

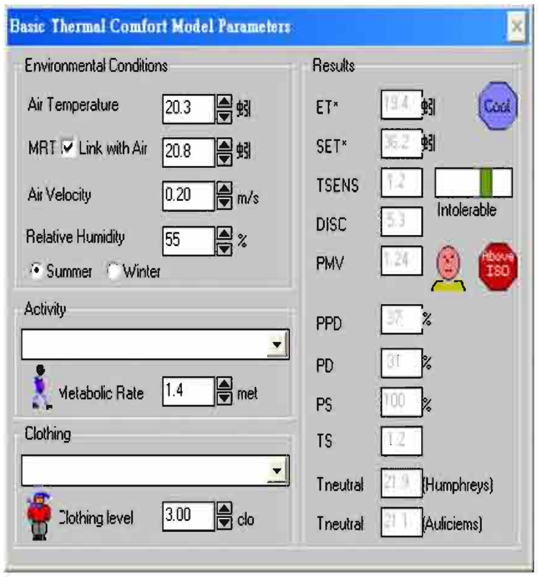
To provide reliable measurement data as the boundary conditions of CFD simulation, the temperature and face velocity of the FFU has been tested with an ALNOR Model 8585 thermal (hot-wired) anemometer. Additionally, the environmental conditions needed to evaluate the thermal comfort indices could be determined by an INNOVA 1221 thermal comfort data logger. Air temperature, mean radiant temperature (MRT) and relative humidity could on-site be recorded simultaneously. Furthermore, turbulence intensity is a very efficient parameter depicting the degree of turbulence which is defined as the ratio of standard variation of velocity fluctuation to the local mean velocity. Tests of turbulence intensity were carried out using an ANEMOSONIC Model UA6 ultrasonic anemometer to assess and verify the level of air flow disturbance.

Fig. 4: Types of garment system for testing (a) attached hood coverage (b) two piece suit and (c) cleanroom coat

THERMAL COMFORT MODELING AND NUMERICAL SIMULATION

According to the ISO 7730 Standard, the PMV index specifies acceptable conditions for thermal comfort. The PMV predicts the mean value of the votes of a large group of people on ISO thermal sensation scale, as shown in Table 1, i.e., +3 = hot, +2 = warm, +1 = slightly warm, 0 = neutral, -1 = slightly cool, -2 = cool, -3 = cold. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation. A commercial code developed by ASHRAE (Fountain, 1995) was adapted to evaluated thermal comfort of test section. The program predicts human thermal response to the environment using PMV-PPD thermal comfort model and allows to calculating the predicted thermal comfort for a human in space. Basic thermal comfort model parameters were shown in Fig. 5. The right-hand side of the screen allows access to the input variables while the left-hand sides present the output from the model. All of the environment conditions including air temperature, MRT, air velocity and relative humidity were adopted base on field testing data. The personal condition of activity defined by metabolic rate can be obtained easily from physiological data built in program. Clothing is defined in terms of clo unit (1 clo = 0.155 m^2-K/W). The selection and generation of clothing ensembles also can be calculated by programmed clo calculator automatically.

To asses the effect of different environment condition on thermal comfort index under various face velocity of FFU, another commercial CFD code, STAR-CD (2001), was used to simulate the temperature contours, velocity vector and turbulent kinetic energy of test section accordingly. The governing equations solved by STAR-CD include the three-dimensional time-dependent incompressible Navier-Stokes equation and k-ε turbulence equations. These formulated equations can be found in the STAR-CD user's manual as well as any CFD text books and will not be repeated here. In the present study, the full-scale geometric model of cleanroom is shown in Fig. 3b. It was assumed that the air flow field is homogenous, isotropic and three-dimensional. For the k-ε turbulence equation, the empirical turbulence coefficients were assigned as: $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.22$, $\sigma_{\varepsilon 1} = 1.44$, $\sigma_{\varepsilon 2} = 1.92$ and $C\mu = 0.09$, respectively. These values were widely accepted in CFD k-ε model. Full-scale simulation has been conducted and compared under different environment conditions.



Basic Thermal Comfort Model Parameters

Environmental Conditions
Air Temperature 20.3 蚓
MRT ☑ Link with Air 20.8 蚓
Air Velocity 0.20 m/s
Relative Humidity 55 %
● Summer ○ Winter

Activity
Metabolic Rate 1.4 met

Clothing
Clothing level 3.00 clo

Results
ET* 19.4 蚓
SET* 36.2 蚓
TSENS 1.2
DISC 5.3
PMV 1.24
PPD 37 %
PD 31 %
PS 100 %
TS 1.2
Tneutral 21.9 (Humphreys)
Tneutral 21.1 (Auliciems)

Fig. 5: Typical input and output ASHRAE thermal comfort model

RESULTS AND DISCUSSION

Figure 6 shows the airborne particle counts at different sample locations (Fig. 1) for particle size 0.5 μm and larger. The flow rate of air sampled at each measurement is 1 cfm (28.3 L m^{-3}) and the mean particle counts are recorded at each location for 3 times. It represents that the cleanroom meets the specified class 1000 (ISO class 6) cleanliness level at the state of at rest. However, at the specific sample location 13 in right-hand side of cleanroom, the particle counts exceed the specified level at operational state. Besides, to highlight the degree of turbulence especially at high particle concentration area, an ultrasonic anemometer was employed to the measurement of turbulence intensity in process area. The field testing data of turbulence intensity in percentage at interval of 1.2 m along x-axis are presented in Fig. 7. The legend of solid circle and hollowed circle represents the depth of y = 1.5 and y = 2.7 m, respectively, while the diameter of circle denotes the magnitude of airflow disturbance. The turbulence intensity displays higher percentage at right-hand side of process area and it corresponds with the highest particle counts at location 13.

Figure 8 represents the room air temperature about 20.3°C and mean radiant temperature (MRT) or global temperature about 20.8°C, respectively. The relative humidity (about 55%) and airflow velocity fluctuation (0.2 m sec^{-1} approximately) are shown in Fig. 8 as well. Different cases of cleanroom apparel type (Table 2) were examined to verify the particle counts in the test section. Clothing ensembles were defined and generated in terms of clo unit based on ASHRAE thermal comfort code. Figure 9 shows that more tightly-woven fabrics of cleanroom garment presents less particle counts which reveals better contamination control in test section. However, the PMV values vary from -0.07 to 1.31 which characterizes the dissatisfaction of thermal comfort. Personnel will prefer garments that give minimum of protection inevitably. Although contamination controls are preeminent, a certain amount of trade-off on thermal comfort may be necessary.

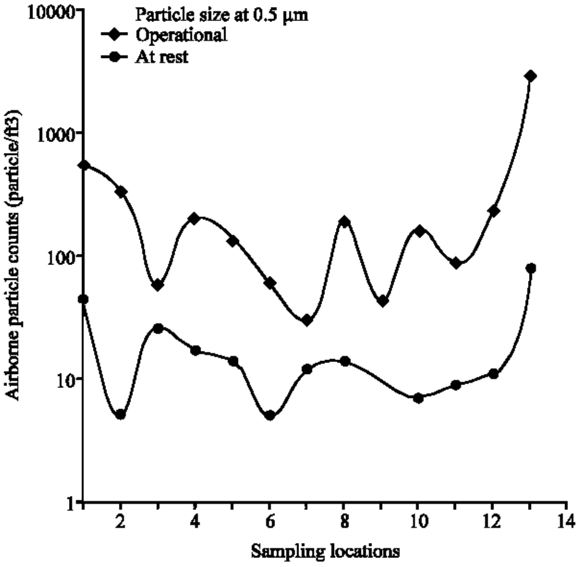


Fig. 6: Particle counts of sampling location at different occupancy state

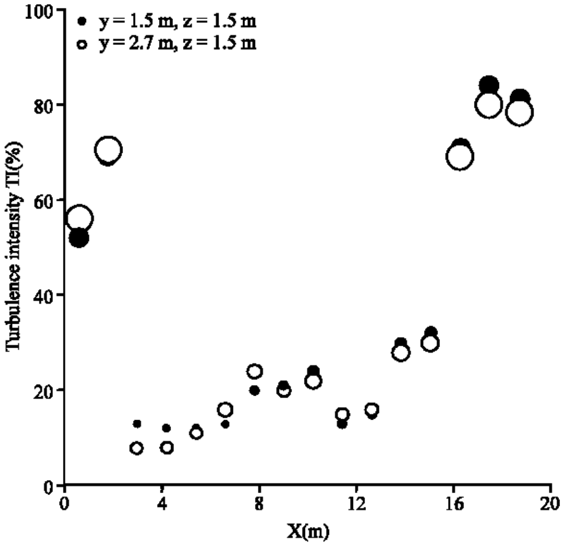


Fig. 7: Field testing of turbulence intensity at the process area

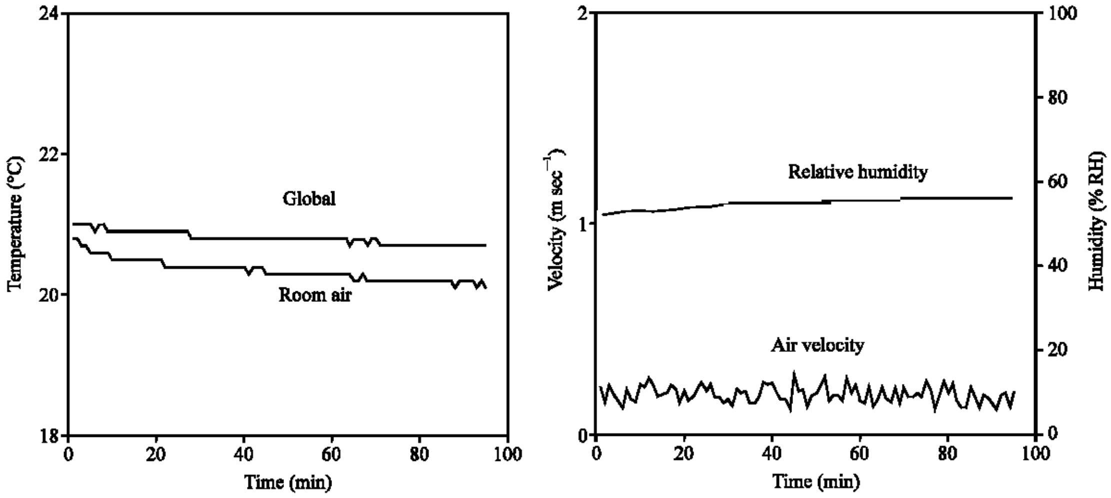


Fig. 8: Field measurement of environmental condition at testing section

Table 2: Different cases of cleanroom apparel

Cleanroom apparel types	Attached hood coverage	Two piece suit	Cleanroom coat	Without apparel
Facemask and gloves	1	5	9	13
Facemask only	2	6	10	14
Gloves only	3	7	11	15
Without facemask and gloves	4	8	12	16

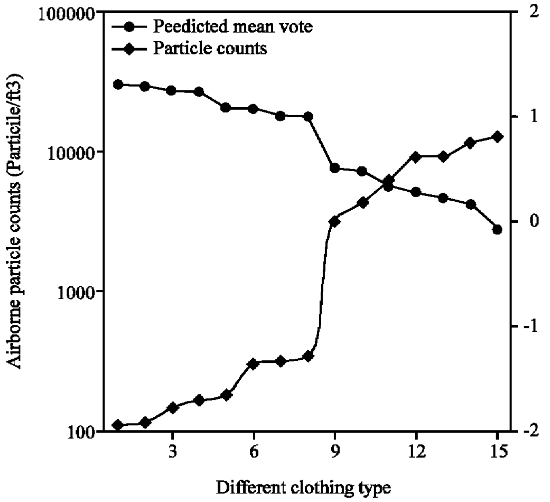
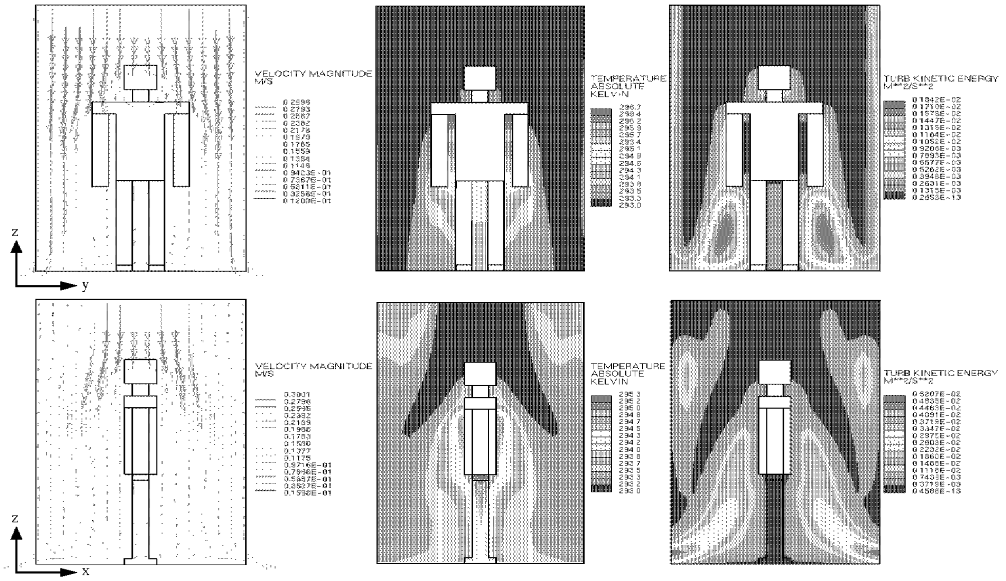


Fig. 9: The effects of clothing type on particle counts and thermal comfort



(a) (b) (c)

Fig. 10: Temperature contours and velocity vector at the test section (a) velocity vector (b) temperature contours and (c) turbulent kinetic energy

The full-scale CFD simulation of velocity vectors at x = 0.65 and y = 0.65 m in test section are displayed in Fig. 10a, which reveals the obvious eddies arisen in the vicinity of foot under the FFU face velocity of 0.3 m sec^{-1}. As shown in Fig. 10b, the temperature contours are observed under the assumption of human body as wall function with the thermal resistance of cleanroom clothing at 0.465 m^2-°C/W. It also demonstrates that the highest temperature contour occurs in the vicinity of human body with cleanroom garment, which reveals dissatisfaction of

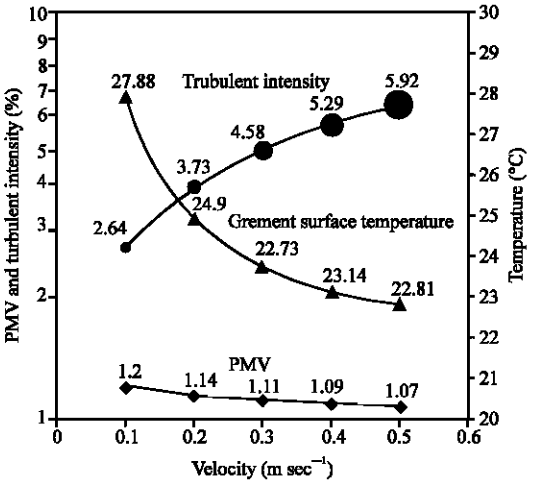


Fig. 11: Effect of face velocity of FFU on testing section environment condition and thermal comfort

thermal comfort. Besides, Fig. 10c presents the turbulent kinetic energy contours, which corresponds the velocity vector in Fig. 10a.

To verify the effect of face velocity of FFU on turbulent intensity, maximum garment surface temperature of test section and PMV indices, many cases were simulation based on field test data. Figure 11 shows the maximum garment surface temperature decrease as the FFU face velocity varies from 0.1-0.5 m sec^{-1}. It also reveals the improvement of cooling effect at the range of 0.2-0.4 m sec^{-1}, while the PMV value varies unapparently. However, the turbulent intensity increased with an increase in air velocity, which also specifies the worse contamination control at the test section.

CONCLUSION

This study investigated the trade-off of thermal comfort and contamination control assessment of a cleanroom in a MEMS laboratory. The field tests have been carried out comprehensively using many delicate instruments. The ASHRAE thermal comfort code was conducted to investigate thermal comfort of personnel based on field-testing data consequently. Furthermore, the effects of clothing on thermal comfort and contamination control have been assessed comprehensively. Cleanroom garment can sometimes be hot and uncomfortable. More tightly-woven fabrics will achieve better contamination control and result in thermal comfort dissatisfaction. Results in this study should provide valuable information to the facility engineer facing comprise between thermal comfort and contamination control in the cleanroom. The contamination control could be achieved by proper types of garments with satisfied thermal comfort of predict mean vote between 0.5-1.0.

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