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PERFORMANCE OF LAMINAR-FLOW CLEANROOMS IN HOT-HUMID CLIMATES

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ABSTRACT

Future information age technology will demand cleaner and more cleanrooms for the manufacture, assembly and repair of electronic components. Many special processes can be very sensitive to trace contaminants which are not removed by conventional air conditioning, filtering and distribution. High efficiency particulate air filters, high velocity streamline air flows, relatively dry air, clean ducts and plenums, cooling, noise reduction and perhaps disinfection are needed. Tropical countries with high humidities and airborne biological contaminants impose additional problems in particulate load, dehumidification, condensation, corrosion and environmental health. We look at how these may pass over into cleanrooms.

KEYWORDS

Air conditioning, airflow pattern, velocity profile, contaminant removal, dehumidifaction.

INTRODUCTION

Cleanrooms have been built on a large scale in Singapore since 1984 with a technology and experience directly imported from non-tropical countries like the USA, Japan and Europe. There is a growing uncertainty in the performance of cleanrooms for their future operation, cleaning, maintenance, upgrading and energy costs.

Cleanrooms of a downward laminar type were tested and evaluated in Singapore for airborne particle count, airflow velocity and uniformity, temperature and relative humidity uniformity, sound pressure level, air pressure, airflow parallelism and by observation.

Generally the cleanrooms tested complied with their particle count classification (10 count/ft^3 at 0.5 μm), adequate pressurisation (0.05 iwg), had marginally low velocity profiles (0.41 - 0.51 m/s). They often failed in air parallelism (over 4 inch edge bench) possibly because the aisles had lower excursions through high variation velocity (±20%). Particle counts were often exceeded during startup after intermittent shutdowns. Noise was generally excessive under the fans with many locations over 69dBA. Here, reverberation from the acoustically hard metal surfaces made the room uncomfortable. Fan inverter frequency settings indicated aisles were run at 87% the power of the work zones. Cleanrooms were slightly warmer and drier. Temperatures met the required criteria (21 ± 1°C db), but humidity (45 ± 5%RH) was lower by about 5%RH. Psychrometrically the aisles gained 0.6°C db and lost 1.5%RH, whereas the task area gained 0.1°C db from the spatial loads. Task air flows were (0.42 x 2.4) = 1 m^3/s.m^2 = 1000 l/s.m^2, aisle flows (0.3 x 2.4) = 720 l/s.m^2 over 46% the area, average 870 l/s.m^2 for the plant. This means (1.18 x 870 x 0.1) = 100 W/m^2 sensible heat, (3025 x 870 x 0.000 0024) = 6 W/m^2 latent heat was being removed including those from process, instrumentation, plant and people (9 W/m^2 sensible, 6 W/m^2 latent).

Issues centre about the high costs for cleanroom construction, operation and management. They can be **100 fold more demanding than offices.** The classification should be as high as possible for the process; waifer fabrication 1-100, electronics, biological 100-10,000. By definition (0.5μm) HEPA filters will remove bacteria and fungi so the transfer into the cleanroom from outside is less a problem. However, viruses and remnant bacteria could be disinfected by UV radiation before the supply fan but not on the filter material as that would decompose it. Cleanrooms should be run continuously to justify the cost and to maintain classification. Higher operating humidities should be considered to reduce the high cooling-dehumidification load in humid tropics. Process tunnels and local contaminant exhaust ports should be used to lower the overall demand for cleaner air. Lower static pressures save power so a local return through wall chases from the floor plenum rather than duct return is possible. A local return ceiling blower arrangement is not favoured here because of the many units to maintain and their high noise level. Side directed task lighting can save electrical power.

Cleanroom performance specifications are reviewed for possibly increasing humidity to a range 45-55% RH ± 5% air temperature 21-23°C ± 1°C to reflect humid, tropical dehumidification. Whatever the values they must be held steady to within ±0.1°C, ±2%RH so that the electronic equipment does not drift excessively. Continuous recirculation is advocated but with unoccupied conditions air flows may be reduced to 1/10 of their operational value, 0.04 m/s, to maintain the classification during startup. Weighted noise levels are reduced to 57 dBA, perceived speech interference level 50 PSIL, preferred noise criteria PNC-46, noise criteria NC-47 for team interaction. Fan noise in low octave band frequencies must be solved. With coastal locations sodium concentrations should be specified less than 0.1 $\mu g/m^3$. Hydrocarbons should be less than 1 ppm. Low magnetic field flux 1 mG, electrostatic potentials ± 50V, vibration to 0.1 μm should reflect the use of electronic equipment. Lighting needs to be sufficient for clarity at about 700 lux illuminance. However, with task lighting directed from the sides, rather than from the "offending zone" overhead, 650 lux would give good clarity. This avoids the veiling images of bright lamps that reduce the task contrast.

Cleanrooms 100 fold more demanding than offices

Many business people, planners, architects and economists fail to realise the density of technology represented in a cleanroom. In general we can think of the environmental demands as a **100 conventional offices** or an **advanced technology facility as a 100 storey office** building. For class 1 and 10 cleanrooms, for integrated circuit and semiconductor manufacture, the **comparison of conditioning air with a modern office** has the following features.

125	fold	Capital cost for investment in conditioning air
120	fold	Annual cost to operate the conditioned air
125	+fold	Particle decontamination for cleanliness
100	fold	Power loads for moving air and removing thermal loads
50	fold	Air flow volume through the plant
15	fold	Air velocity in the spaces
30	fold	Outside air changes to remove moisture and contaminants
3	fold	Time of operation for continuous processing
2	fold	State pressure to keep dust out

Cleanrooms require a longer commissioning period to test the systems before use then often a year to decontaminate to the classification for production. Capital is quite intensive at about 40,000 S$/m^2 for the facility without the process equipment. A new waifer fabrication plant class 1 and 10 about 10,000 m^2, is likely to require a total power of 40 MW or 1% of Singapore's electrical power. This is 5 kW/m^2, running 3660 kWh/m^2.mth, 550 S$/m^2.mth electricity, 50 fold on office.

Special low-dust garments must be worn in cleanrooms. Caps, masks, gloves, shoes add to a "100 fold inconvenience" in preparing to do and doing tasks compared with an office routine.

Airborne particle count

Cleanrooms were divided into grids to provide location points for the instrument sensors. An airborne particle counter was used using an isokinetic probe, continuous particle size-selective sampler with a laser scattered particle light analyser for 0.3 μm and 0.5 μm sized particles. Sample rate 1 ft^3/min

Particle counts were recorded and checked against their designated Classification by Federal Standard 209E (USA) for count/ft^3 at 0.5 μm size particles. Criteria for finer 0.3 μm counts are 3 fold those of 0.5 μm. Overall there was good compliance with particle counts. Generally 0.5 μm counts were a **tenth of the classification. Finer 0.3 μm counts** ranged 2 to 18 fold the 0.5 μm, averaging **9 fold, which indicates marginal compliance** and process contamination rather than people alone. High spots were at workstations where people and processes added particulates. Cleanrooms with intermittent use, such as in university research, showed higher startup counts.

Airborne particle count is the main criterion for cleanroom acceptance. Operators monitor and control to the classification because of the extremely high costs involved in production and litigation if quality is compromised.

Pressurisation

Fans need to provide static pressure to keep out contaminated air, overcome the resistance of fans, filters and ducts, then a velocity pressure to move the air. Electrical power to the fans directly relates to this pressure so it is important to minimise it. Typical pressure drops are as follows:

Room Pressure (Federal Std 209E)

Cleanroom to Change Room	0.05 iWG*	1.3 mm WG	1.26km/m^2
Change Room to Outside	0.05 iWG	1.3 mm WG	1.26kg/m^2
Filter			
HEPA New	0.60 iWG	15.4 mm WG	15.1kg/m^2
HEPA Prefilter	0.50 iWG	12.8 mm WG	12.6kg/m^2
Accumulation with age	0.50 iWG	12.8 mm WG	12.6kg/m^2
Plenums, floor grid, local return	0.40 iWG	10.3 mm WG	
Duct return	0.80 iWG	20.5 mm WG	
Fan centrifugal 4-6 iWG			
axial 1-3 iWG	1.50 iWG	38.5 mm WG	
Velocity space 0.0002 iWG	-	-	
	4.40 iWG	112.9 mm WG	

*iWG = inches water gauge

Eliminating a duct return may save 18% pressure and choosing axial fans 40% pressure. However an early replacement of a HEPA filter would be costly but prefilter replacement could save power and money, say 6%. Note pressurisation of the space itself is only about 2-3% of the pressure needed, most is needed to drive the air through the system.

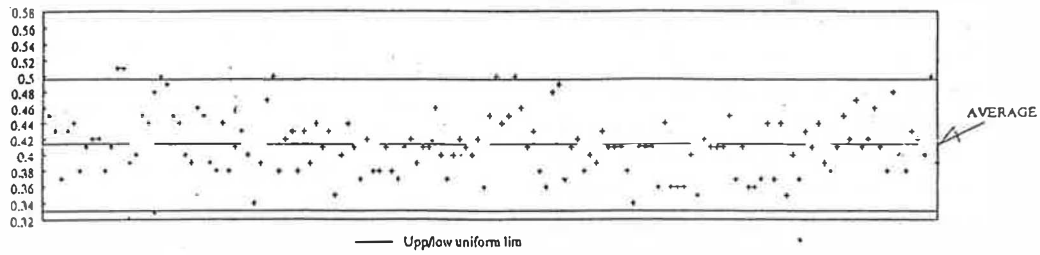
With unoccupied or unused cleanrooms air flows may be reduced 10 fold to avoid airborne particles settling. This significantly reduces the pressure and power requirement for recirculating air. Air intake flows represent only 3-4% of the supply air but these fans are important for maintaining a static pressure for the cleanroom of 0.10 iWG. To handle this range variable pitch axial fans are usually used. However, to realise the economy of such an investment cleanrooms should be used continuously. In this regard university and industrial research facilities are being linked in technology parks.

Velocity profiles

High velocity, very clean air at 85-105 ft/min, 0.43-0.54 m/s, over the task or process is important for cleaning or cleaning particles from surfaces during fabrication and assembly. If highly contaminated this is directly exhausted, often filtered to remove toxic metals or pathogens. Generally it passes across the people to pick up their contaminants of dust, moisture, CO_2, pathogens, into the aisles, and through the return in the floor or wall. Aisles have lower velocities to keep the particulates suspended and purged from surfaces at 60-80 ft/min., 0.3-0.4 m/s.

Standards are difficult to set for the **velocity profiles** because they are **altered with the movement of people, equipment and processes.** Figure 1 illustrates a typical scatter for air velocity readings with an air velocity sensor. The average 0.41 m/s just misses the 0.425 m/s criterion but falls within the variation of ±20%. This is probably not critical, but management should watch out for surface clearing production quality and any difficulties in people performing tasks. Another approach is to have local clean air jets on the task to the exhaust or return, from a central compressor or a local blower.

0.44	0.38	0.51	0.48	0.39	0.38	0.47	0.43	0.40	0.38	0.39	0.40	0.45	0.41	0.37	0.43	0.41	0.36	0.41	0.36	0.40	0.38	0.42	0.38
0.45	0.41	0.51	0.50	0.46	0.41	0.50	0.39	0.44	0.41	0.41	0.42	0.50	0.43	0.41	0.41	0.41	0.36	0.41	0.37	0.37	0.41	0.46	0.43
0.43	0.42	0.39	0.49	0.45	0.43	0.38	0.44	0.41	0.38	0.41	0.41	0.44	0.38	0.42	0.41	0.41	0.40	0.45	0.44	0.43	0.45	0.41	0.42
0.37	0.42	0.40	0.45	0.39	0.40	0.42	0.41	0.37	0.37	0.46	0.40	0.45	0.36	0.38	0.41	0.36	0.35	0.37	0.37	0.41	0.42	0.38	0.40
0.43	0.38	0.45	0.44	0.38	0.34	0.43	0.43	0.42	0.41	0.40	0.42	0.50	0.48	0.40	0.38	0.44	0.42	0.41	0.44	0.44	0.47	0.48	0.50
0.44	0.41	0.44	0.40	0.44	0.39	0.38	0.35	0.38	0.42	0.37	0.36	0.46	0.49	0.39	0.34	0.36	0.41	0.36	0.35	0.39	0.41	0.40	0.39



AVERAGE VELOCITY = 0.41 m/s ± 0.05
UPPER UNIFORMITY LIMIT = 0.50 m/s
LOWER UNIFORMITY LIMIT = 0.33 m/s
NO. OF POINT OUT OF RANGE = 7
PERCENTAGE OF UNIFORMITY = 95.1 %

Figure 1 Air Velocity Profile in Work Zone

Laminar flow

Parallel air flows are preferable over work areas to minimise a mixing of less clean air from the room by turbulence and induction. However equipment, process shapes and people obstruct the flow to produce eddies. In fact puffs of wind from various angles are better at dislodging surface dust. Turbulent flow rather than laminar scales down directly in effect.

The hanging thread test (64 in. long) for air flow parallelism showed considerable spread of the downward column of air. Set 4" inboard of the table edge the threads spread 0 to 18" beyond thus not complying with the specification. The middle of the benches would be turbulent and relatively still. **Back vents** along the benches would solve this problem. Reasons for the spread rest in a lower aisle velocity for the downward flow.

A more important indicator would be if the threads were moving in and out of the air column. The boundary between the different air velocity streams can create vortices which would effectively mix the air. However, there seemed to be no significant difference in particle count between the air streams so this does not indicate a problem. Some laboratories have a plastic sheet dropped from the ceiling to ensure separation and laminar flow. We believe the issue is that laminar flow ensures a projection of the high velocity air streams but turbulence can be beneficial so long as the general direction and velocity can be maintained over the work area.

Exhaust ports to remove contaminants need a housing to prevent inductive mixing with the local air. Housings can be a smooth bell shape, a funnel or a perforated shroud rather than the usual hole-in-the-wall.

Noise

Noise from high volume high velocity fans is a problem in cleanrooms. Although the glass fibre HEPA filters may attenuate higher frequencies the lower frequency bearing rumbles and air flutters are difficult to eliminate. Further, cleanrooms have acoustically hard surfaces that reverberate sound. Although this may add only a few dB in loudness the reiteration in speech patterns can be disturbing. Headgear covers the ears and frequently there is a mask or face protection. The acoustical effects isolate the people in the space, low frequencies "drum" in the "shell", one's own sounds like breathing, speech, tinnitus are reinforced producing a claustrophobic sensation. Speech articulation is important between these skilled professionals so we suggest a lower sound pressure level, particularly in the lower frequencies. For team interaction 10 ft, 3+m, apart a perceived speech interference level of **50 PSIL,** a preferred noise criteria of PNC-46, a noise criteria of **NC-47**, and an "A" weighted sound pressure level of **57 dBA** is suggested.

Industrial noise criteria are generally adopted, usually about 69 dBA. Our tests showed many locations under fans or supply ducts exceeded this value. It is extremely difficult to "correct" for this noise as it usually comes from lower frequency mechanical vibrations of the fan. **Vibration mountings, well balanced fan blades,** well lubricated roller bearings, **duct vibration isolators** are the solutions. **Fan tips must be shrouded** but acoustical pods and duct liners will have little effect. Axial fans must be mounted in straight ducts with gradual symmetrical transitions to avoid an asymmetrical loading of the fan blades. Sharp transitions caused the structural failure of 1.2m diameter exhaust fans by an asymmetrical loading of the blades, and unbalanced supply fan blades caused a nauseating subaudible rumble in our laboratory (Halldane, consulting). If you have a quiet cleanroom find out why it is so good.

Psychrometric conditions

Air temperature, dry bulb °CDB; relative humidity, %HR; dew point temperature °CDP; humidity ratio, HR, kg/kg dry air; are important parameters. Let us set some extreme bounds as follows.....

Air temperature, is set by the need for people to exchange their metabolic heat to the environment, equipment to not overheat, warm enough for surfaces not to condense water vapour or form mist, close to outside temperatures to economise the conditioning of intake air.

Ranges **(21-23)(22-25)** °CDB for dry winter and dry summer outside, lower range for dehumidification without coil reheat. Cleanroom 21°C (Europe), 22.5°C (old Federal). Variation in room temperature ±1°C, in control of temperature ±0.1°C to avoid excessive drift in electronic instrumentation.

Relative humidity, is set by the need for dry cooling coils, minimum corrosion from moisture, absorbing water vapour from people, plants and process, avoiding condensation and biological growths, electrostatic changes on surfaces, dry enough for surfaces not to condense water vapour or mist, close to outside humidity to economise the conditioning of intake air.

Ranges 30- **(45-55)** - 70% RH upper value for dehumidification with return reheat. Cleanroom 45% RH (Europe, Federal), 50% RH (old Federal). Variation in room relative humidity ±5% RH, in control of humidity ±2% RH to avoid electronic drift.

Humidity ratio is set by dry bulb and relative humidity, dew point for condensation, close to outside humidity ratio to economise the dehumidification in humid climates and humidification in cold dry ones.

Range (0.007 - 0.010) HR, (9-14)°C DP

Temperature and relative humidity were recorded. Values were generally about 22°C DB and 39% RH for a class 10 laboratory. However a class 100,000 for optoelectrics was 25-27°C DB, 81-82% RH which was far too warm and humid even for the basically robotic processes.

Outside air in our humid tropics is 24-32°C DB, 0.020 HR, 25°C DP. This is drawn down to the 9-14°C DP by wet coils at about 10°C condensing at the water vapour. Then it is **reheated some 11°C DB by mixing with dry recirculated air**, gaining the heat mainly from the equipment and lighting. Outside air make up must take the humidity load of the space, people sweat. Any additional load from humid processes must be exhausted separately because we must keep the **return cooling coils dry** and moisture out of the HEPA filters. In the tropics we do not need heating coils.

Biological cleanrooms may harbour virus, bacteria, fungus that may propagate under higher humid conditions. Should this become a problem the return plenum and ducts could be disinfected using ultra violet radiation from lamps in reflective chambers before the return fan. Filter materials, paint, fabrics, gaskets, ... should not be irradiated as they are likely to decompose under the UV. Our conventional laboratory at 60-70% RH grew growths on glass and plastic plates stored for two years in a draw. These were hard white crystal-like patterns which any camera enthusiast can tell you about in the tropics.

Lighting

Lighting is essential for the visual inspection tasks of cleanroom processes. Originally these were of a "visibility" or "detection" nature to see flaws through slight changes in the pattern. For visibility 1000 lux illumination against a dark background was ideal although very glary and visually tiring. Nowadays detection tasks are done with sophisticated optoelectrical systems as part of an automated process.

Today our visual tasks are of a **"clarity"** nature that require **clear forms** to see patterns and colour. For clarity the peak performance is about a 60 fL contrast equating to about 650 lux, 60 fc illumination; more light decreases clarity. Most materials have a gloss, even ink, so lamps and bright areas must not reflect as mirrors in the task as this would veil what you are looking at ("veiling glare"). Luminaires above and to the sides of people are the best positions, rather than above and ahead ("offencing zone", down the middle of benches). Today we also have more **"self-luminous" tasks** with their own light, like computer monitors and TV screens. Here we need a background ambient lighting of about 210-320 lux, 20-30 fc for adaptation.

"Cave-like" rooms are being created with illumination - efficient parabolic reflectors. These give patches of light on a bench task and very dark ceilings. Today it is even more important to have light coloured floors, walls, ceilings, and benches or desks to brighten the whole space. The luminaire reflectors should provide the old "batwing" distribution for even illumination.

Contaminant exhaust

Outside air make up for removing people's sweat is probably sufficient to maintain carbon dioxide levels below 1000 ppm. Higher flows are needed with process exhaust ports with toxic gases and metal particulates.

We have monitored contaminant exhaust rates and developed a very simple "half-life"method for tracing the transient concentrations in terms of the air changes per hour for the exhaust. It has been suggested to exhaust at least 0.75 ac/h (air change/hour) to reduce inside carbon dioxide CO_2 levels to 1000 ppm for clear thinking of people in sedentary tasks at 7 person/100m^2 density, by admitting outside intake air at a significantly low ambient about 300 ppm, but reduced during smog alerts with high carbon monoxide CO, nitrogen oxides NO_x, carbon dioxide CO_2 and temperature. Well a cleanroom has 30-40 fold this minimum requirement so the problem now is intaking CO at over 3ppm during smogs.

In Singapore questionnaire studies we have discovered that a "stuffy" feeling related to CO_2 over 1000 ppm and CO over 3ppm; then "headaches" to higher CO. It means that **cleanrooms are more sensitive to outside air pollution episodes** and processes involving high exhaust rates should be minimised during those periods.

ACKNOWLEDGEMENT

The paper is based on a report of Research Project RP 890049, "Cleanroom performance in hot humid climates", National University of Singapore, with M.A. Haque as the principal investigator. John F. Halldane has been very helpful in developing the research direction.

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