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Studies on the indoor air quality of Pharmaceutical Laboratories in Malaysia

Y.H. Yau *, B.T. Chew, A.Z.A. Saifullah

Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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Abstract

This study was conducted to determine the comfort conditions of Pharmaceutical Laboratories in Malaysia. Four laboratories were selected as investigation sites. The Heating, Ventilating and Air Conditioning (HVAC) system of the laboratories must be designed for providing good indoor air quality (IAQ) to the workers in the laboratory and keeping the expensive equipment in good condition. For the investigations, a number of measurement equipments were used to obtain the IAQ data of the laboratories (i.e. dry bulb temperature, air humidity, air flow velocity, carbon dioxide (CO_2) concentration, etc.). Some random subjective assessments on the workers in the laboratories were made to acquire information on the workers such as their thermal comfort rating, activity level and their clothing conditions. In this study, air temperature for Laboratories 1, 3 and 4, are 22.38, 20.53 and 19.50 °C, respectively, slightly below the ASHRAE recommended air temperature. Besides, the total volatile organic compound (TVOC) for Laboratories 2 and 3 shows high TVOC concentration in the wash room and chemical room, which are 22.8 and 6.5 ppm, respectively. The study in terms of thermal satisfaction indicates an average performance of the air-conditioning system exists in the Pharmaceutical Laboratories.

Keywords: Malaysia; Pharmaceutical Laboratory; HVAC; IAQ; Thermal comfort

1. Introduction

Malaysia has a hot and humid climate. Air conditioning during office hours is essential to provide thermal comfort in the building space (Ismail et al., 2009). However, in recent years, the sick building syndrome (SBS) has become a common issue in Malaysia. This is due to the construction of buildings designed to be energy-efficient with air conditioning systems, but poor maintenance and services of the HVAC system resulting in increase of indoor air pollutants (IAP) levels (Berardi et al., 1991).

It is important to have development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In order to achieve sustainable development of buildings, IAQ should not be neglected. In a more recent survey conducted by the International Facility Managers Association, IAQ and thermal comfort were the top operational issues in all types of buildings (John et al., 2001).

In this paper, we report on an IAQ investigation at several Pharmaceutical Laboratories in Malaysia. Note that until now, there has not been any study conducted

* Corresponding author. Tel.: +60 3 79675210/79675204; fax: +60 3 79675317/79677621.
E-mail addresses: yhyau@um.edu.my (Y.H. Yau), chewbeeteng@um.edu.my (B.T. Chew), saifullah@um.edu.my (A.Z.A. Saifullah).
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on pharmacies in Malaysia. In fact, pharmacy-laboratories are a venue where facilities are provided for medicine research. The installation of the HVAC system to the laboratory plays an important role in controlling the comfort, IAQ, aseptic conditions and suitable indoor thermal conditions for creating an ideal working environment to researchers and staff. The IAQ and thermal comfort in the laboratory is important as it may affect the work and health of the researchers and staff.

A very clean indoor environment for pharmaceutical goods and thermal comfort for productivity and satisfaction of indoor building occupants are the characteristics of a Pharmaceutical Laboratory. To ensure a clean environment the IAQ must be maintained within the acceptable limit suggested by ASHRAE. A Pharmaceutical Laboratory always has a chemical and a washing room where TVOC concentration is obviously too high. There should be an increased ventilation rate for better dilution in order to keep the TVOC concentration below the standard limits. In order to minimize the energy use the temperature set point for room air should be in between 22.5 and 26.0 °C.

2. Theory of IAQ and thermal comfort

2.1. Supply of air quality

Particulate or dust control consists of removal, of source, local exhaust, common dilution ventilation, wetting, filtration and utilization of individual protective tools such as respirators. Filtration can be a useful control and might be cheaper than common ventilation, even though an increased pressure drop across a filter increases the fan power necessities, and maintenance increases the system operating cost (ASHRAE, 2009).

The required level of filtration can be decided by considering the supply of air change rate in the room, particulate concentration of the air entering the filters, internal particulate generation rate and desired room air quality. The internal particulate generation rate in room is unpredictable. A high-efficiency particulate air (HEPA) filter is recommended since it is 99.97% efficient and recognized as ISO Class 8 spaces for most applications. HEPA filters are used when maximum removal of airborne microorganisms is necessary.

2.2. Conditions for an acceptable thermal environment

The recommended thermal comfort condition by ASHRAE Standard 55 (2004) is in the range between 22.5 and 26 °C and 30–60% relative humidity (RH). The indoor temperature and humidity must be kept within the acceptable range as defined by ASHRAE Standard 55 (2004) for prevention of the staff from sweating in the laboratory. But, this may increase human particulate and microbial generation rates. Cold and dry air, frequent skin wetting and low indoor RH will cause skin itchiness (ASHRAE, 2009). Therefore, the desired temperature and humidity should be set to avoid this from happening.

High level of humidity comes with moisture problems where fungi growing on buildings especially *Stachybotrys* and *Penicillium*, produce mycotoxins that cause cough, irritation of eyes, skin, respiratory tract infections, joint ache, headache, and fatigue (Tapani et al., 2000). In some cases, instead of providing essential good indoor air to the occupants, air-conditioning systems have become ‘highways’ for deadly disease to travel to the whole building (Lian et al., 2007).

Every person may have different thermal sensation about the surrounding conditions. Thermal sensation are subjectively described by feelings termed hot, warm, slightly warm, neutral, slightly cool, cool and cold. Discomfort may be caused by outdoor air temperature, infiltration rate, clothing, activity level and the health of occupants. Moreover, thermal dissatisfaction may be caused by local thermal discomfort, undesirable heating or cooling of one particular part of the body. As an individual’s satisfaction is different, the ASHRAE standard is to specify a thermal environment which is acceptable by at least 80% of the staff. Predicted Percentage Dissatisfied (PPD) is used to estimate the thermal satisfaction of the occupants. Note that PPD less than 20% is good (Hamdi et al., 1999).

2.3. Indoor air quality

IAQ can be defined as the air quality inside a building that will lead to the comfort and health of the occupants. IAQ is influenced by gases, microbial contaminants or particulates that bring to poor health conditions. A poor IAQ can be the major factor that leads to SBS (IAQ Management Group, 2003). The ‘cause’ that can be identified and attributed directly to airborne building contaminants is referred as Building Related Illnesses (BRI) (Menzies and Bourbeau, 1997). The ‘cause’ can be mainly divided into physical factors, chemical factors and biological factors. The physical factors include temperature, humidity, and air movement to dust, lighting and noise, while chemical factors include pollutants arising from paint, carpets, new furniture, environmental tobacco smoke (ETS), drapes, cosmetics asbestos and insecticides (Marmot et al., 2006).

For the biological factors, microorganisms play the main role. Inhalation of bacterial, fungal and micro algal spores can cause an allergic reaction. In fact, good IAQ is required for a healthy indoor work environment. Poor IAQ can cause a variety of short-term and long-term health problems including allergic reactions, respiratory problems, eye irritation, sinusitis, bronchitis and pneumonia. IAQ problems can be due to indoor air pollutants or to inadequate ventilation. Assuming no contamination in the local air surrounding the building, good IAQ is possible by providing adequate ventilation and distribution within the space; for example if the design meets the requirements as specified in ASHRAE Standard 62.1 (2007). However the other factors affecting occupants, such as light and noise are not included in IAQ assessment.

(a) *Carbon dioxide*CO_2 is the most common indoor air pollutant emitted by human beings. The levels of CO_2 indoor are dependent upon the number of people present and degree of metabolic activity carried out within the air space. ASHRAE Standard recommends maximum level of 1000 ppm for continuous CO_2 exposure. CO_2 is a key parameter for assessing indoor IAQ and ventilation efficiency (Syazwan et al., 2009). The ventilation that has insufficient fresh air intake can contribute to a high level of CO_2 in certain area in the building (Ooi et al., 1994). Furthermore, the reduction of CO_2 indicates that there is a large increase in the ventilation rate which improves the effectiveness in providing fresh air to the occupants' breathing zone. There are studies found that a ventilation rate of 10 Ls-1 to 20 Ls-1 per person will decrease the symptoms of sick building syndrome (SBS) and attain a better air quality (Seppanen et al., 2004).
(b) *Carbon monoxide*Carbon monoxide (CO) is a toxic, colorless, odorless and tasteless gas. It is the by-product of incomplete combustion of carbon-containing materials in an oxygen-deficient environment. It can be dangerous if the concentration of CO is high within the air space. The adverse health effect of high concentration of CO includes headaches, sore eyes, runny nose, dizziness, vomiting and loss of consciousness. The Malaysian Code of Practice recommends that CO exposure must not exceed 10 ppm within an air space to ensure a healthy and safe environment. Berardi et al. stated that the concentration of CO should be low at the range of 0.01–3 ppm (Berardi et al., 1991). The CO concentration above 10 ppm is significantly associated with SBS symptoms such as dizziness, fatigue and headache (Samet, 2004).
(c) *Volatile organic compounds*Volatile organic compounds (VOC) are one of the gaseous contaminants that exist in both industrial and non-industrial environment. VOCs that could be found indoors are from building substances, furniture, cleaning goods, office equipments and individual care products. Some of the health conditions that are caused by VOCs are perception of smells, mucous membrane annoyance, exacerbation of asthma, fatigue, difficulty in focusing and carcinogenicity (ASHRAE, 2009). ASHRAE recommends the threshold limit for TVOC to be below 3 ppm.
(d) *Formaldehyde*Formaldehyde is a common very volatile organic compound (VVOC) found within an air space. It is an organic compound with the formula HCOH and its use is widespread in the manufacturing industry. However, occupational exposure to HCOH above 0.1 ppm can cause headaches, sore throat, difficulty in breathing and asthma. HCOH is classified as a known human carcinogen by the Environmental Protection Agency of the United States. Therefore, it is important to keep it below 0.1 ppm in an air conditioned space. HCOH may be present in food, either naturally or as a result of contamination (Suh et al., 2000).
(e) *Respirable particulate matter (dust particles)*Respirable particulate matter (RPM) refers to a range of substances that remain suspended in the air, and comprise mixtures of organic and inorganic substances. Particles that are inhaled are generally less than 10 μm (PM10). The effects associated with exposure to RPM are irritation effects, which, if left uncontrolled, can further result in airways constriction and respiratory illness. The maximum limit of inhaled dust particle is 0.15 mg/m^3 (DOSH, 2005).

According to ASHRAE (2009), the size of particles from less than 1 to 10 microns is classified as RPM. These particles may be inhaled deep into our lungs due to its tiny size and may be potentially hazardous to human health depending on the source of the particles. Tobacco smoke possesses particle sizes of 0.01 micron to 1 micron in diameter. The standard ISO 14644 clean room classification states the status of air cleanliness in clean rooms and clean zones.

Regarding laboratory standards, the laboratory area needs to satisfy at least ISO 14644 Class 7 where the ambient air contains less than 352,000 particles (0.5 μm) in diameter per cubic meter of air. Therefore, it is recommended that the laboratories must maintain the air quality between class 7 or 8 of ISO 14644.

2.4. Thermal comfort optimization and energy savings

Thermal comfort optimization and energy savings can be achieved by some control strategies for reducing energy use and maintaining acceptable indoor air conditions related to thermal comfort (McQuiston et al., 2005). Therefore, the concept of thermal comfort should be included first into a control strategy.

An approach having two strategies to define thermal comfort for the occupants is addressed by a comfort zone defined in a psychometric chart. To improve the thermal comfort, five control algorithms using the two approaches are implied. These algorithms assume a SIMO (single input, multiple outputs) building system with indoor temperature and RH as measured variables and the power applied to the HVAC system as the single manipulated variable. These algorithms use model based predictive control fundamentals.

The first control algorithm assures the signal lying within a comfort bound while minimizing energy use. The second algorithm assures the same while optimizing the RH. The third algorithm uses optimized temperature and RH to evaluate the optimal value for the input power based on a cost function. The fourth algorithm is a Predicted Mean Vote (PMV) based-predictive control calculating the control signal which optimizes the PMV index relating to thermal comfort. And, the fifth control algorithm optimizes the energy use and maintains the PMV index within acceptable conditions.

3. Methodology

In this research, four pharmacy laboratories were selected to carry out the IAQ audit. The selected four laboratories are labeled as Laboratory 1 (Level 3, Block C1), Laboratory 2 (Level 4, Block C4), Laboratory 3 (Level 4, Block C3), and Laboratory 4 (Level 2, Block C4). The room layouts of these laboratories are shown in Appendix A to C. Note that Laboratories 2 and 3 have the same room layout as shown in Appendix B.

(a) Walkthrough inspection was the process carried out to identify potential factors that influence IAQ of the laboratory.
(b) The data collected in field measurements include indoor air temperature, RH, air velocity, HCOH, CO_2, CO, TVOCs and particles presented in air. The list of instruments and accuracy for all instruments are shown in Table 1. This data was compared to the ASHRAE standard for further assessment.
(c) A set of questionnaires were prepared to determine the degree of thermal comfort achieved by the laboratory staff. In fact, the thermal sensation of the human body is the main role determining the degree of thermal comfort achieved. It is closely correlated to the health status, clothing style, level of activity carried out in the laboratory. Therefore, the subjective

Table 1
List of instruments.

Type of instruments	Measurement parameter	Accuracy
TSI Alnor thermo Anemometer (Model 440-A)	• Temperature • Relative Humidity • Air velocity	*Operating range* Temperature: −10–60 °C RH: 0–90% Velocity: 0–30 m/s *Accuracy* Temperature: ±0.3 °C RH: ±3% Velocity: ±3% of reading or ±0.015 m/s, whichever is greater *Resolution* Temperature: ±0.1 °C RH: 0.1% Velocity: 0.01 m/s
KIMO Thermocouple thermometers (TK100)	• Globe temperature	*Operating range* From −200–1300 °C *Accuracy* ±1.1 °C or ±0.4% of reading, whichever is greater *Resolution* 0.1 °C
Kanomax IAQ Monitor (Model 2211)	• Carbon monoxide • Carbon dioxide • Temperature • Relative humidity	CO: ±3% of reading or ± 3 ppm, whichever is greater. CO_2: ±3% of reading or ± 50 ppm, whichever is greater. Temperature: ±0.5 °C RH: 2–79% RH: ±2.0% RH 80–98% RH: ±3.0% RH
Formaldemeter htv-m	• Formaldehyde	*Operating range* 0–10 ppm as standard (0–12.3 mg/m3 @ 25 °C). *Accuracy* 94% of all instrument readings meet the NIOSH criteria for an acceptable method when measuring 0.3 ppm of formaldehyde over a relative humidity range of 25–70%. The NIOSH criterion for acceptability is that all results fall within 25% of the true value at the 95% confidence level. *Resolution*0.01 ppm *Precision* 2%
Portable VOC Monitor (PGM-7600)	• TVOC	0–2000 ppm: ±2 ppm or 10% of reading. >2000 ppm: ±20% of reading.
Aerotrak Handheld Optical Particle Counter (TSI 8220)	• Particle count	Average count ±5% of STD

measurement plays an important role in IAQ assessment. A sample of the questionnaire is shown in the Appendix.

4. Results on thermal comfort

Generally, there are three main parameters for determining the thermal comfort level in a conditioned space, i.e. temperature, humidity and movement of the space air (ANSI/ASHRAE Standard 55, 2004). These parameters were obtained by carrying out field measurements in the laboratories. The measurements were taken at different points in each place. These measured values were tabulated together with the standard reference values and presented in Table 2. The detail measurements at the diffusers and at 1 m below the diffuser were shown in Tables 3–6.

4.1. Air temperature

First of all, we used the temperature at 1 m below the diffuser as the effective temperature as it is closer to the indoor temperature. From Table 2 we found that the overall air dry-bulb temperature recorded in the space is 22.38 °C for Laboratory 1, 22.97 °C for Laboratory 2, 20.53 °C for Laboratory 3 and 19.50 °C for Laboratory 4. Average temperature for Laboratories 1, 3 and 4 was slightly below the recommended range for acceptable indoor air temperature of 22.5–26.0 °C in ASHRAE Standard 55 (2004). This was further proved by the survey where most of the staff's votes were biased to the cool thermal sensation in the subjective measurement section.

Table 2
Results of thermal comfort in Laboratories 1 to 4.

	Temperature (°C)	Air velocity (ms^{-1})	RH (%)
Laboratory 1	22.38	0.16	59.76
Laboratory 2	22.97	0.08	49.10
Laboratory 3	20.53	0.09	59.92
Laboratory 4	19.50	0.09	63.50
ASHRAE Standard	22.5–26.0	<0.25	30–60

4.2. Relative humidity

In the current study, the measurement showed that the overall laboratory environment is not humid. The average RH was calculated as 59.76% at Laboratory 1, 49.10% at Laboratory 2, 59.92% at Laboratory 3 and 63.50% at Laboratory 4. The data shows that the humidity at the fourth laboratory has exceeded the maximum recommended level of 60% RH by ASHRAE Standard 55 (2004). However, in a tropical country, as reported by Zuraimi and Tham, 2008, the outdoor air is usually very hot (air temperature 30 °C) and humid (90% RH) throughout the year (Zuraimi and Tham, 2008). Thus, Singapore NEA Standard (Satish, 2007) has recommended 70% as the maximum allowable RH for indoor air. Since Malaysia is a tropical country and very near to Singapore, therefore, we can say that the humidity in all the laboratories is still in the acceptable range.

4.3. Air velocity

In the current study, the air velocity was measured at many points of each room normally occupied by the staff. As shown in the Table 2, the air velocity at Laboratory 1 can vary from 0.08 ms^{-1} to maximum of 0.23 ms^{-1}, at Laboratory 2 can vary from 0.08 ms^{-1} to maximum of 0.11 ms^{-1}, and at Laboratory 3 can vary from 0.03 ms^{-1} to maximum of 0.16 ms^{-1} and 0.03 to 0.19 ms^{-1} at Laboratory 4. The average velocity for Laboratories 1–4 is 0.16, 0.08, 0.09 and 0.09 ms^{-1}, respectively. The entire air flow rate is lower than the maximum limit recommended by the ASHRAE Standard 55 (2004) of 0.25 ms^{-1}. Thus, the staff should not feel any air draft in the center of the

Table 3
Temperature and air velocity in Laboratory 1.

Diffuser	Temperature (°C)		Velocity (m/s)	
	At diffuser	1 m below diffuser	At diffuser	1 m below diffuser
1	16.8	22.5	0.48	0.08
2	14.5	22	1.33	0.12
3	15.2	22.4	0.56	0.12
4	15.7	21.9	0.84	0.18
5	14.9	21.2	1.24	0.23
6	17.2	23.6	0.68	0.47
7	16.5	23.4	0.78	0.10
8	16.1	23.3	1.06	0.14
9	15.5	21.9	1.07	0.08
10	18.3	21.6	0.65	0.11
Overall	16.07	22.38	0.87	0.16
ASHRAE Standard	22.5–26.0		<0.25	
Singapore NEA Standard	22.5–25.5		<0.25	

Table 4
Temperature and air velocity in Laboratory 2.

Diffuser	Temperature (°C)		Velocity (m/s)	
	At diffuser	1 m below diffuser	At diffuser	1 m below diffuser
1	13.2	23.1	0.65	0.09
2	13.9	23.6	0.96	0.08
3	13.1	23.3	0.40	0.09
4	13.8	23.4	0.43	0.08
5	15.5	23.6	0.52	0.09
6	15.3	23.6	0.67	0.09
7	14.4	22.7	0.48	0.11
8	13.5	22.8	0.49	0.05
9	14.5	20.6	0.66	0.08
10	28		0.75	
Overall	14.13	22.97	0.58	0.08
ASHRAE Standard	22.5–26.0		<0.25	
Singapore NEA Standard	22.5–25.5		<0.25	

Table 5
Temperature and air velocity in Laboratory 3.

Diffuser	Temperature (°C)		Velocity (m/s)	
	At diffuser	1 m below diffuser	At diffuser	1 m below diffuser
1	13.5	20.9	1.10	0.07
2	13.8	20.4	0.95	0.07
3	13.5	19.3	1.52	0.11
4	13.7	17.2	1.40	0.06
5	15.5	21.7	0.39	0.03
6	14.8	22.1	0.44	0.12
7	14.0	21.4	0.48	0.16
8	14.1	21.4	0.52	0.10
9	14.9	20.4	1.17	0.09
Overall	14.20	20.53	0.89	0.09
ASHRAE Standard	22.5–26.0		<0.25	
Singapore NEA Standard	22.5–25.5		<0.25	

Table 6
Temperature and air velocity in Laboratory 4.

Diffuser	Temperature (°C)		Velocity (m/s)	
	At diffuser	1 m below diffuser	At diffuser	1 m below diffuser
1	20.9	21.9	1.00	0.08
2	15.9	20.1	1.13	0.09
3	16.0	20.9	0.87	0.03
4	15.8	19.3	1.11	0.08
5	15.3	18.6	1.45	0.14
6	15.6	17.6	1.13	0.19
7	15.4	19.3	0.90	0.11
8	15.7	18.6	1.25	0.07
9	15.6	19.2	1.25	0.07
Overall	16.24	19.50	1.12	0.09
ASHRAE Standard	22.5–26.0		<0.25	
Singapore NEA Standard	22.5–25.5		<0.25	

room. The maximum velocity measured can reach up to 0.47 ms^{-1} in some readings, mainly because of the diffuser is connected to the main duct that has higher air flow instead of distributed ducts that has lower air flow. Besides, all the readings were taken at 1 m below the diffuser. Hence, high air velocity reading is expected. The diffuser flow area was measured as 0.36 m^2. The air flow rate was measured in m^3/h. The reading was then converted to air flow velocity using Eq. (1).

$$\text{Air flow velocity, } v = \frac{Q}{3600A} \quad (1)$$

where, Q = air flow rate in m^3/h, and A = cross section area of diffuser.

5. Results on indoor air quality

5.1. Carbon Dioxide

According to ASHRAE Standard and Malaysia Code of Practice on IAQ, the concentration of CO_2 is recommended below 1000 ppm for continuous 8 h of exposure. From the measurements, the concentration of CO_2 in each of the pharmacy- laboratory is located in the range of 400–700 ppm as shown in Table 7. It is considered safe to occupants inside the laboratory. Humans are the main source of CO_2 within an air conditioned space as a result of respiration activity. Therefore, the concentration of CO_2 at the breathing zone 1.6 m from ground is slightly higher compared to other levels.

5.2. Carbon monoxide

The data collected in each of the laboratories show an acceptable value of CO within the air space. The concentration of CO is found in the range of 0–3 ppm which is relatively low compared to the ASHRAE recommended CO exposure limit, 10 ppm as shown in Table 7. The concentration of CO is found to be equally distributed within the entire laboratory air space.

5.3. Total volatile organic compound

Based on the data obtained from the measurements, it is observed that TVOC concentration is significantly low at three laboratories, especially in Laboratories 2 and 4, while Laboratory 3 shows a little high TVOC concentration. As observed, TVOC meter counts average 2.6 ppm at Laboratory 1, 1.3 ppm at Laboratory 2, 3.5 ppm at Laboratory 3 and 0.5 ppm at Laboratory 4 as shown in Table 7. Nonetheless, the results based on averages cannot fully show the actual concentration of TVOC in the laboratories. For instance, the average TVOC concentration for Laboratory 2 should not reach 1.3 ppm since the range just varies from 0.3 to 1.6 ppm for point 1 to point 9. For point 10, there is an obvious increase of the TVOC concentration as the place is the chemical room with the existence of many chemical compounds which are highly vaporized under normal conditions.

Furthermore, Laboratory 3 also shows a similar condition to Laboratory 2 because the position of point 10 is the washing room where the chemicals are washed from the beakers which results in high concentration of chemical compounds exposed to the air. In general, the results indicate that there is no concern on TVOC concentration for all the laboratories but only for some specified rooms which are the chemical room and the washing room where the TVOC concentration are significantly high, since 3 ppm of TVOC is suggested as limit of exposure by DOSH (2005). During the inspection process, we observed that there was no construction or painting completed recently. There was no new furniture or carpets as source of TVOC emission. All these factors may contribute to the reason why the TVOC concentrations of all the laboratories are significantly low compared to the limit of exposure.

5.4. Formaldehyde

The concentration of HCOH collected in each of the laboratories fluctuates from 0.039 to 0.058 ppm, 0.035 to 0.058 ppm, 0.029 to 0.038 ppm and 0.026 to 0.053 ppm for Laboratories 1–4, respectively. The average concentration of HCOH is found to be 0.0465, 0.0428, 0.0323, and 0.0386 ppm for each of the laboratories as shown in Table 7. Thus, the ventilation system maintains the concentration of HCOH below the exposure limit of 0.1 ppm (DOSH, 2005).

5.5. Particulate pollutants

The minimum, maximum and average amount for all particles counted in each laboratory is shown in Table 8. Hence, by comparing the measured data in Table 8 and ISO 14644 standards, all the particles counted in each laboratory is within the acceptable range between class 7 and 8. This statement is further supported by the thermal environmental survey which shows that none of the staff experienced the symptoms stated such as dry eyes, headaches, dry skin, stuffy nose, breathing difficulty and tiredness. These symptoms are caused by high concentration of particles in the surrounding environment.

Table 7
Indoor air pollutant in Laboratories 1 to 4.

	Average CO, ppm	Average CO_2, ppm	Average TVOCs, ppm	Average HCOH, ppm
Laboratory 1	2.5	504.11	2.6	0.0465
Laboratory 2	0.9	511.35	1.3	0.0428
Laboratory 3	1.5	475.15	3.5	0.0323
Laboratory 4	0.73	488.41	0.5	0.0386

Table 8
The measured particles per cubic meter in the four laboratories.

Laboratories	Measured particles per m^3	$PM_{0.1}$	$PM_{0.5}$	PM_1	PM_3	PM_5	PM_{10}
Laboratory 1	Minimum	5.06E + 07	3.96E + 05	1.49E + 04	2.10E + 03	0.00E + 00	0.00E + 00
	Maximum	2.15E + 08	2.16E + 06	5.06E + 04	2.42E + 04	1.76E + 04	1.06E + 04
	Average	7.61E + 07	6.55E + 05	2.69E + 04	9.58E + 03	5.47E + 03	3.86E + 03
Laboratory 2	Minimum	2.28E + 07	1.43E + 06	7.70E + 04	6.60E + 03	2.20E + 03	0.00E + 00
	Maximum	4.04E + 07	3.12E + 06	3.49E + 05	5.59E + 04	2.81E + 04	1.52E + 04
	Average	3.41E + 07	2.28E + 06	1.70E + 05	2.77E + 04	1.42E + 04	5.39E + 03
Laboratory 3	Minimum	4.31E + 07	3.37E + 06	2.27E + 05	1.06E + 04	0.00E + 00	0.00E + 00
	Maximum	5.86E + 07	5.17E + 06	6.36E + 05	1.02E + 05	2.56E + 04	1.06E + 04
	Average	4.98E + 07	3.88E + 06	3.09E + 05	3.17E + 04	1.17E + 04	4.02E + 03
Laboratory 4	Minimum	4.98E + 07	3.78E + 06	2.03E + 05	1.06E + 04	2.11E + 03	0.00E + 00
	Maximum	6.80E + 07	5.31E + 06	3.31E + 05	3.19E + 04	1.49E + 04	1.05E + 04
	Average	5.61E + 07	4.33E + 06	2.61E + 05	1.93E + 04	6.36E + 03	2.31E + 03

6. Subjective assessment

Generally, 6–8 persons were involved in the survey for each laboratory. Among the staff, females are more than male staff. In terms of their activity level during the working period, there were just two types of activities which are either sitting quietly in the laboratory or doing some light activity or standing around. This clearly reveals that all the staff in the laboratory are working in a relaxed and low activity level environment.

With regard to the clothing of staff, it can be divided into five categories which are:

(i) Trousers with short-sleeve shirts.
(ii) Trousers with short-sleeve shirt plus suit jacket.
(iii) Trousers with long-sleeve shirts.
(iv) Trousers with long-sleeve shirt plus suit jacket.
(v) Baju kurung (traditional clothing for Malay females)

Observation on the clothing can be related to the thermal comfort level of the staff working in the laboratories. Because, the thermal comfort level experienced by individual staff in a space mainly dependent on the clothing and activity level of that particular individual.

The thermal comfort level is divided into 7 categories as recommend by Nicolas et al. which are hot, warm, slightly warm, neutral, slightly cool, cool and cold (Nicolas et al., 2008). The information gathered through our subjective assessment includes gender, activity level, clothing insulation and also thermal comfort level of each staff working in the laboratory. The results of the questionnaire survey are shown in Table 9.

The response from majority of the staff on their thermal comfort level is biased to the slightly cool or cool sensation. There are some staffs who felt quite comfortable and convenient to be working in the laboratories which reflect their satisfaction in the working environment. Nonetheless, there are about 10% of staffs who felt slightly warm in the laboratory.

The average indoor air temperature for three laboratories are slightly below the recommended value by Nicolas et al. (2008) although the measured air velocities in these laboratories are within the recommended value according to ASHRAE Standard. As the air temperature is too low

Table 9
Results of questionnaire survey in the four laboratories.

	Gender (person)	Activity level (person)	Clothing insulation (person)	Thermal comfort vote (person)
Laboratory 1	Male: 2	Seated quite: 2	Trousers, short-sleeve shirt: 2	Neutral: 3
	Female: 4	Light activity, standing: 4	Trousers, long-sleeve shirt: 1	Slightly cool: 1
			Trousers, long-sleeve shirt plus suit jacket: 3	Cool: 2
Laboratory 2	Male: 3	Seated quite: 3	Trousers, short-sleeve shirt plus suit jacket: 3	Slightly warm: 2
	Female: 4	Light activity, standing: 4	Trousers, long-sleeve shirt: 1	Neutral: 5
			Trousers, long-sleeve shirt plus suit jacket: 3	
Laboratory 3	Male: 2	Seated quite: 2	Trousers, short-sleeve shirt: 2	Slightly warm: 1
	Female: 5	Light activity, standing: 5	Trousers, long-sleeve shirt: 4	Neutral: 3
			Trousers, long-sleeve shirt plus suit jacket: 1	Slightly cool: 2
				Cool: 1
Laboratory 4	Male: 2	Seated quite: 6	Trousers, short-sleeve shirt plus suit jacket: 2	Slightly cool: 1
	Female: 6	Light activity, standing: 2	Trousers, long-sleeve shirt: 1	Cool: 2
			Trousers, long-sleeve shirt plus suit jacket: 3	Cold: 5
			Baju kurung: 2	

and the activity level for most of the staff in the laboratories is just sitting quietly and doing some low activity or standing only, using up a little energy for doing their routine work and consequently they feel a cool sensation during working hours. The health and behavior of the staff also affects their judgment of the thermal comfort level. The citizens of Malaysia are used to the higher outdoor temperature (30 °C), and the staffs of these laboratories complain about the cold air temperature.

In the survey analysis, it is discovered that those who complained about the warm condition in the laboratory were wearing long-sleeve shirts or wearing suit jackets. Just wearing a short-sleeve shirt or not wearing the suit jacket may cause them to feel comfortable in the laboratory. It might also be that during some of the days, when the weather is too hot reaching 38–40 °C outdoors. As a consequence the indoor temperature might increase which causes the staffs inside the laboratory to feel slightly warm during their working period.

For the evaluation of thermal comfort, the RH and air velocity for the four laboratories are below the maximum limit of the standard. However, the air temperature for Laboratory 1 (22.38 °C), Laboratory 3 (20.53 °C) and Laboratory 4 (19.50 °C) is not within the recommended range for acceptable indoor air temperature of 22.5–26.0 °C as in the ASHRAE Standard 55 (2004). For the evaluation of IAQ, the CO_2, CO and HCOH concentration is within the acceptable limit. Although the TVOC for Laboratories 2 and 3 shows high concentration in the washing room and chemical room, the TVOC concentration in other places is low and achieves the ASHRAE standard. The particulate pollutants counted in the four laboratories are in the acceptable range between class 7 and 8. The objective assessment which consists of evaluation of thermal comfort and evaluation of IAQ is summarized in Table 10.

Since the temperature found in Laboratories 3 and 4 are slightly below the ASHRAE recommended air temperature, therefore it is suggested to increase the temperature set point for room air to 24 ± 1.5 °C by reducing the cooling load of the air-conditioning system. Besides, it can be introduced as a laboratory routine so that an adequate and proper thickness of clothing is used for the staff. As the concentration of TVOCs in chemical room (Laboratory 2) and washing room (Laboratory 3) is found to be in excess of the exposure limit, it is recommended to increase the ventilation rate for better dilution purposes to keep it below the acceptable limit.

7. Conclusion and recommendation

The average indoor air temperatures in three laboratories are slightly below the recommended acceptable range of 22.5–26 °C in the ASHRAE Standard 55 (2004). Subjective measurements also show that most of the staff is biased towards a slightly cool or cool sensation. The humidity level of all the four laboratories is below the maximum allowable value of 70% RH according to the Singapore NEA Standard and the air velocities in these laboratories is within the limit of 0.25 ms^{-1}.

Since most of the occupants feel slightly cool in the laboratories, the indoor air temperature could be increased to a level that the occupants will feel neutral. The cooling load of the air-conditioning system could then be decreased when increasing the room temperature. Hence, the decreasing of cooling load could lead to energy saving to the building.

CO_2, CO and HCOH concentration and the particulate pollutants counted in each laboratory are within acceptable standards for health and a safe environment. Only TVOC concentration in the chemical room (one laboratory) and washing room (another laboratory) are found to be in excess of the limit of exposure, 3 ppm. The ventilation rate has to be increased for the purpose of better dilution to keep it below the acceptable limit.

Table 10
Summary of the evaluation of the thermal comfort and the evaluation of the IAQ.

	Parameter	Laboratory 1	Laboratory 2	Laboratory 3	Laboratory 4	ANSI/ ASHRAE Standard 55	Singapore NEA Standard	Malaysia DOSH Standard
Evaluation of the thermal comfort	Air temperature, °C	22.38	22.97	***20.53***	***19.50***	22.5–26.0		
	RH, %	50.76	49.10	59.92	***63.50***	<60	<70	
	Air velocity, ms^{-1}	0.16	0.08	0.09	0.09	<0.25		
Evaluation of the IAQ	CO_2, ppm	504	511	475	488	<1000		<1000
	CO, ppm	2.5	0.9	1.5	0.7	<10		<10
	TVOC, ppm	2.6	***1.3*** (washing room: 22.8 ppm)	***3.5*** (chemical room: 6.5 ppm)	0.5	<3		<3
	HCOH, ppm	0.0465	0.0428	0.0323	0.0386	<0.1		<0.1
	Particulate pollutants	Particles count in each laboratory are located in the acceptable range between class 7 and 8 under ISO 14644						

The IAQ assessment in this paper shows that an average performance of the ventilation and air-conditioning system is practiced in the Pharmaceutical Laboratories in Malaysia.

Practical implications

The new conclusions from the study of the Pharmaceutical Laboratories in this paper could be used as an important guide for building services engineers and researchers in the tropics. The intention is to minimize energy usage in the HVAC systems in Pharmaceutical Laboratories operating in the tropics while maintaining an acceptable thermal comfort and an IAQ level that improves the performance and well-being of the occupants.

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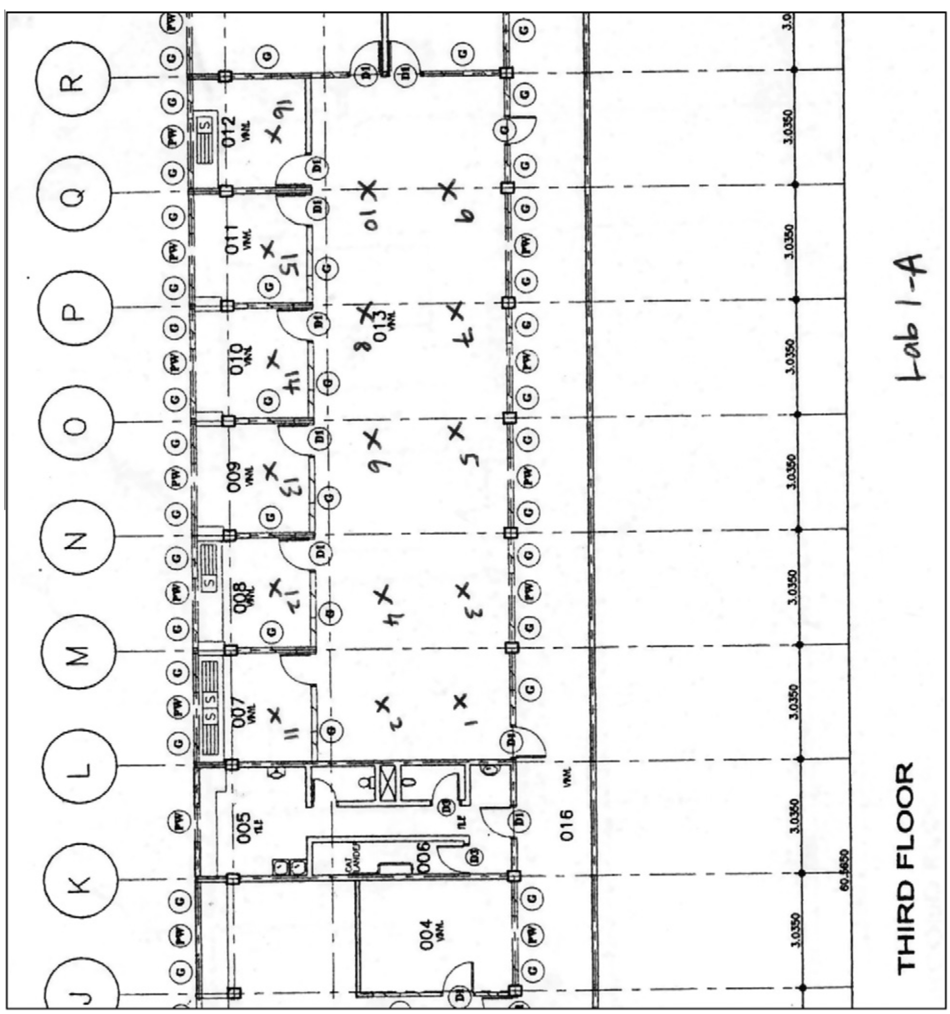
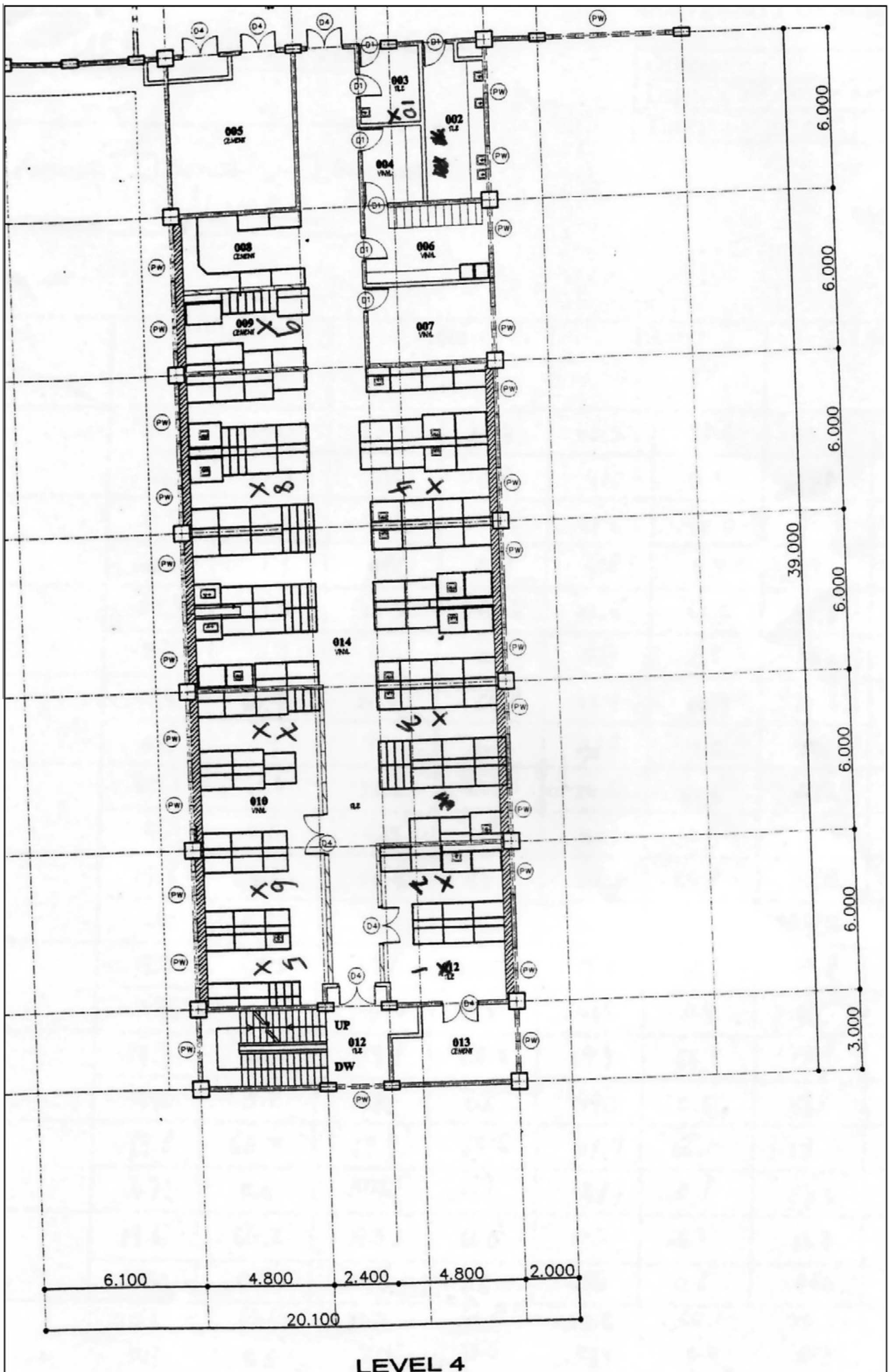
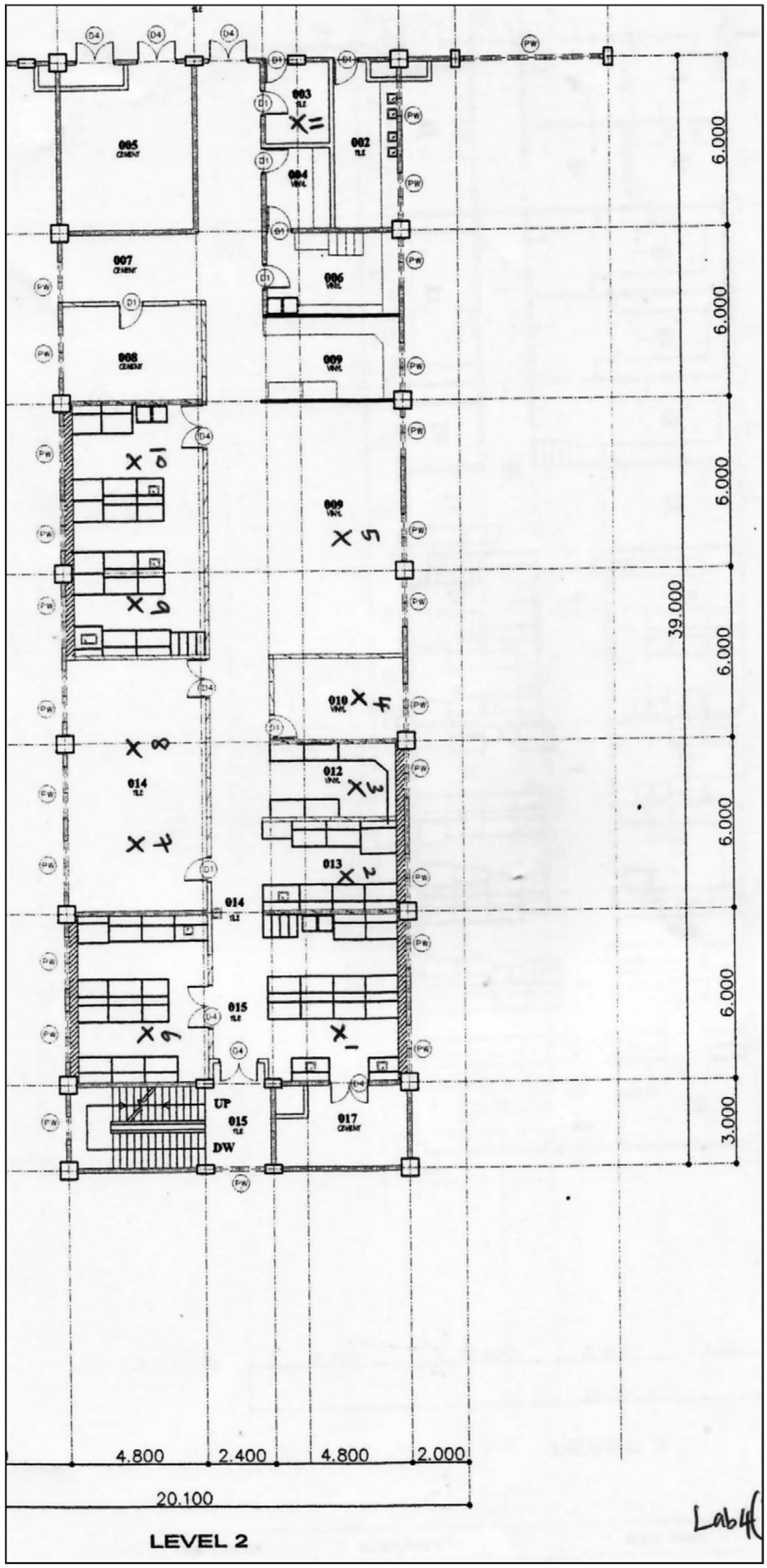
Appendix A. Room layout of Laboratory 1



Appendix B. Room layout of Laboratories 2 and 3



Appendix C. Room layout of Laboratory 4



Appendix D. Thermal environment survey

This survey is part of a study to evaluate the current thermal comfort conditions of the selected buildings. We appreciate your feedback in this evaluation.

1. Occupant's Name:					
2. Gender:	Male ☐		Female ☐		
3. Date:					
4. Time:					
5. Occupant location:					
6. Sky:	Clear ☐	Mixed(sun & clouds) ☐	Overcast ☐		
7. Do you often experience the following symptoms? Dry eyes ☐ Dry or irritated throat ☐ Rash or irritated skin ☐ Watering eyes ☐ Headaches ☐ Lethargy or tiredness ☐ Block or stuffy nose ☐ Flu-like symptoms ☐ Dry skin ☐ Runny nose ☐ Chest tightness or breathing difficulty ☐					
8. Have you ever had asthmatic problems? ☐					
9. Have you ever suffered from sinusitis? ☐					
10. Have you ever suffered from eczema? ☐					
11. Are you currently a smoker? ☐					
12. Do you wear contact lens? ☐					
13. Occupant's Clothing *Please refer to the attached table on clothing ensembles. Place a check mark next to the articles of clothing that you are currently wearing as you fill out this sheet. If you are wearing articles of clothing not listed in the table, please enter them into the space provided below.* Clothing:					
14. Occupant Activity Level *(Tick the one that is most suitable)* Reclining ☐ Seated quite ☐ Standing relaxed ☐ Light activity, standing ☐ Medium activity, standing ☐ High activity ☐					
15. How would you describe your typical level of thermal sensation? Hot ☐ Slightly Cool ☐ Warm ☐ Cool ☐ Slightly Warm ☐ Cold ☐ Neutral ☐					
16. How would you describe the cleanliness? Unsatisfactory ☐ ☐ ☐ ☐ ☐ ☐ ☐ Satisfactory					

17. Do you detect any odour?

Yes ☐ No ☐

If yes, please indicate against the relevant sources (You may tick more than one box)

Cigarettes ☐ Carpet ☐
Stationary ☐ Food ☐
Others ☐

18. How would you describe the indoor condition in this area? Please tick only one box per scale. The boxes with thin edges represent the ideal point on each scale

a) Air movement	Still	☐ ☐ ☐ ☐ ☐ ☐ ☐	Draughty
b) Air quality	Fresh	☐ ☐ ☐ ☐ ☐ ☐ ☐	Stuffy
	Odourless	☐ ☐ ☐ ☐ ☐ ☐ ☐	Smelly
	Clean	☐ ☐ ☐ ☐ ☐ ☐ ☐	Dusty
c) Lighting	Too dark	☐ ☐ ☐ ☐ ☐ ☐ ☐	Too bright
	Steady	☐ ☐ ☐ ☐ ☐ ☐ ☐	Flickering
	No glare	☐ ☐ ☐ ☐ ☐ ☐ ☐	Too much glare
	Very uniform	☐ ☐ ☐ ☐ ☐ ☐ ☐	Very uneven
	Satisfactory overall	☐ ☐ ☐ ☐ ☐ ☐ ☐	Unsatisfactory overall
d) Acoustics	No noise from ventilation system	☐ ☐ ☐ ☐ ☐ ☐ ☐	Too much noise from ventilation system
	No other noise	☐ ☐ ☐ ☐ ☐ ☐ ☐	Too much other noise

Table on Clothing Ensembles

Descriptions	
Trousers, short-sleeve shirt	
Trousers, long-sleeve shirt	
Trousers, long-sleeve shirt plus suit jacket	
Trousers, long-sleeve shirt plus suit jacket, vest, T-shirt	
Trousers, long-sleeve shirt plus long sleeve sweater, T-shirt	
Trousers, long-sleeve shirt plus long sleeve sweater, T-shirt plus suit jacket, long underwear bottoms	
Knee-length skirt, short sleeve-shirt (sandals)	
Knee-length skirt, long sleeve-shirt, full slip	
Knee-length skirt, long sleeve-shirt, half slip, long-sleeve sweater	
Angle-length skirt, long-sleeve shirt, suit jacket	
Walking-shorts, short-sleeve shirt	
Long-sleeve coveralls, T-shirt	
Overalls, long-sleeve shirt, T-shirt	
Insulated coveralls, long-sleeve thermal underwear tops and bottoms	
Athletic sweat pants, long-sleeve sweatshirt	

References

ANSI/ASHRAE Standard 55, 2004. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta GA.

ASHRAE Standard 62.1, 2007. Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta GA.

ASHRAE Fundamentals, 2009. Indoor Environmental Health. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta GA.

Berardi, B.M., Leoni, E., Marchesini, B., Cascella, D., Raffil, G.B., 1991. Indoor climate and air quality in new offices: effects of a reduced air-exchange rate. International Archives of Occupational and Environmental Health 63, 233–239.

DOSH, 2005. Code of Practice on Indoor Air Quality, Ministry of Human Resources. Department of Occupational Safety and Health, Malaysia.

Hamdi, M., Lachiver, G., Michaud, F., 1999. A new predictive thermal sensation index of human response. Energy and Buildings 29 (2), 167–178.

IAQ Management Group, 2003. Guidance Notes for the Management of Indoor Air Quality in Offices and Public Places, The Government of the Hong Kong Special Administrative Region.

Ismail, A.R., Jusoh, N., Zulkifli, R., Sopian, K., Deros, B.M., 2009. Thermal Comfort Assessment. A Case Study at Malaysian Automotive Industry. American Journal of Applied Sciences 6 (8), 1495–1501.

John, D.S., Jonathan, M.S., John, F.M., 2001. Indoor Air Quality Handbook. McGraw-Hill, United States of America.

Lian, K.S., Inangda, P.S.N., Ramly, A., 2007. Sources of Indoor Air Quality Problem in a New Hospital in Malaysia. The 6th International Conference on Indoor Air Quality, Ventilation & Energy Conservation in Buildings, Sendai, Japan.

Marmot, A.F., Eley, J., Stafford, M., Stansfeld, S.A., Warwick, E., Marmot, M.G., 2006. Building health: an epidemiological study of "sick building syndrome" in the Whitehall II study. Occupational and Environmental Medicine 63 (4), 283–289.

McQuiston, F.C., Parker, J.D., Spitler, J.D., 2005. Heating, Ventilating and Air Conditioning Analysis and Design. John Wiley & Sons, Inc., United States of, America.

Menzies, D., Bourbeau, J., 1997. Building-related illnesses. Journal of Medicine 337 (21), 1524–1531.

Nicolas, L.G., Mireille, G., Denis, G., Russell, N.D., Cecilia, C.C., Benoit, L., 2008. Air change rate and concentration of formaldehyde in residential indoor air. Atmospheric Environment 42 (10), 2424–2428.

Ooi, P.L., Goh, K.T., Heng, B.H., Toh, Y.H., 1994. Epidemiological investigations into an outbreak of building-associated illness in Singapore. Asia-Pacific Journal of Public Health 7 (4), 201–205.

Samet, J.M., 2004. Indoor air pollution. A public health perspective. Indoor Air 3 (4), 219–226.

Satish, B., 2007. Indoor Air Quality Audit based on Singapore National Environment Agency (NEA) Guidelines. PR Log (Press Release), Singapore.

Seppanen, O.A., Fisk, W.J., Mendell, M.J., 2004. Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. Indoor Air 9 (4), 226–252.

Suh, H.H., Bahadori, T., Vallarino, J., Spengler, J.D., 2000. Criteria air pollutants and toxic air pollutants. Environmental Health Perspectives 108 (4), 625–633.

Syazwan, A.I., Juliana, J., Norhafizalina, O., Azman, Z.A., Kamaruzaman, J., 2009. Indoor air quality and sick building syndrome in malaysian buildings. Global Journal of Health Science 1 (2), 126–135.

Tapani, T., Kari, R., Tom, J., Kaisa, H., Eeva-Liisa, H., Outi, L., Seija, K., Pirkko, K.K., Helena, M.R., Tari, H., 2000. Mycotoxins in crude building materials from water-damaged buildings. Applied and Environmental Microbiology 66 (5), 1899–1904.

Zuraimi, M.S., Tham, K.W., 2008. Indoor air quality and its determinants in tropical child care centers. Atmospheric Environment 42 (9), 2225–2239.