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Performance impact of indoor environmental policy implementation for airside systems in Hong Kong Grade A offices

L.T. Wong[a], K.W. Mui[a], C.T. Cheung[a], E.W.M. Lee[b], M.C. Lee[c]

[a]*Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong, China.*

[b]*Department of Building and Construction, City University of Hong Kong, Hong Kong, China.*

[c]*Department of Interior Design, National Taichung Institute of Technology, Taiwan, ROC.*

Responsible author: K.W. Mui
Email: behorace@polyu.edu.hk, Tel: (852) 2766-5835;
Fax: (852) 2765-7198

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Abstract

Air-conditioned offices in the subtropics are recommended to operate within specified ranges of indoor temperature, relative humidity, air velocity and carbon dioxide concentration for thermal energy conservation. As environmental discomfort leads to productivity loss, this study investigates the impact of an indoor environmental policy on Grade A offices served by different airside systems in terms of energy consumption, thermal comfort and productivity loss. Occupant thermal response is specifically considered as an adaptive factor in the evaluation of energy consumption and productivity loss. Simple Monte Carlo sampling technique was applied to determine the input parameters referenced from literatures for simulation. The findings indicate that the reduction of clothing value improves thermal sensation and should be addressed in the environmental policy to ensure a thermally comfortable indoor environment.

Practical application

This study is a useful reference source for evaluating indoor thermal environmental policies for air-conditioned offices in subtropical climates. Implication of clothing value in thermal sensation should be addressed in the environmental policy to ensure a thermally comfortable indoor environment of air-conditioned offices.

Keywords: air-conditioned office; airside systems; clothing value; energy,
productivity, thermal comfort

1. Introduction

Energy conservation is now a global concern and some scientists suggest that at least half of the current energy consumption should be cut over the next 50 years to avert a future global warming disaster [1]. An energy policy study for subtropical climate showed that a Mechanical Ventilation and Air-conditioning (MVAC) system was an essential feature for an acceptable office environment and responsible for half of the total electrical energy consumed in an air-conditioned building [2]. In Hong Kong, the commercial sector, whose buildings are nearly all air-conditioned, accounted for 60% of the total annual energy consumption [3].

60% of the office buildings in Hong Kong can be classified as Grade A [4]. A Grade A office provides a desired indoor environment which has effective and well-maintained central air-conditioning. The types of airside systems commonly used in Hong Kong Grade A offices are the variable air volume (VAV), constant air volume (CAV) and fan coil unit (FCU) systems [2]. The VAV system is particularly popular as it can lower the supply fan power consumption (hence the operating cost) during part-load operations [5].

In addition to improvement on equipment efficiency, building schemes, increment of indoor temperature and reduction of ventilation rate can be an immediate response to energy saving request in an air-conditioned space [6, 7]. A number of concerns were observed in poorly managed offices and sensitivity on indoor quality, bacteria growth, loss of productivity and thermal discomfort were studied [8-12]. An indoor air quality (IAQ) policy for offices and public places (known as the IAQ certification scheme) launched by the Hong Kong Environmental Protection Department (HKEPD) [13] gives the objectives for achieving a satisfactory office environment: CO_2 exposure level = 800-1000 ppm, air temperature = 20-25.5°C, relative humidity = 40-70% and air speed < 0.2 ms^{-1}. Maintaining acceptable thermal conditions for the occupants by a higher indoor temperature set point, however, is one of the primary apprehensions in many air-conditioned office buildings [14]. Surveys of Hong Kong air-conditioned offices revealed that the occupants preferred a slightly cool environment and had a tendency to wear more clothes in overcooled workplaces [9, 15]. Since an eco-efficient air-conditioning system conserves energy but not necessarily suits the thermal needs of all occupants, factors besides eco-efficiency such as occupant discomfort and worker productivity should be included for assessing environmental impact in office buildings [12, 16-19].

Although thermal energy consumption for air-conditioned office buildings in Hong Kong have been registered [2, 14] and energy conservation opportunities during off-peak periods in air-conditioned offices have been studied[5], the performance of the IAQ policy has not been evaluated in relation to different airside system types. This study aims to fill the gap by investigating the impact of an indoor thermal environmental policy on Hong Kong Grade A offices served by different airside systems in terms of energy consumption, thermal comfort and productivity loss.

2. Survey of office environmental conditions

In this study, the indoor environment conditions of Hong Kong Grade A offices were extracted from HKEPD objectives and literatures. The environmental parameters of the assessed offices are summarized in Table 1 and categorized from Cases A to E according to various data sources and airside system types. These parameters included CO_2 level, air temperature, relatively humidity and local air speed. Case A was the design target conditions referenced by HKEPD objectives [13]. Case B was the base case in this study which contributed from 422 Grade A offices with mixed airside system were surveyed[11, 20]. The remaining cases were all Grade A offices referenced by Leung [21], where Cases C, D and E were respectively denoted 1021 offices served by VAV systems, 252 offices served by CAV systems and 101 offices served by FCU systems. Surveying methods were in compliance with HKEPD objectives[13], where each sampling point was obtained for an 8-hour average of the assessment parameters in every 500 m^2 floor area. Extra points were measured if the surveyed office area exceeded 500 m^2. The sampling sites were randomly picked from all regions for office development such that they covered a wide range of open-plan or enclosed offices and conference rooms. Human activities and dress codes in these offices were noted to be similar. All surveyed environmental parameters listed in Table 1 were assumed normally distributed ($p \geq 0.05$, Shapiro-Wilk test).

In Cases C, D and E, significant differences were observed for the relative humidities and air speeds ($p \leq 0.05$, t-test), except for those air speeds of Cases C and E. Mean temperatures were comparable ($p > 0.1$, t-test) yet variations were significantly different among all cases ($p < 0.05$, F-test). Besides, Cases C, D and E had significantly higher indoor air temperatures and much lower air speeds ($p < 0.0001$, t-test), and there were significant relative humidity differences in them ($p < 0.0001$, t-test) except for Case C, as compared with the base case (Case B). Since significant differences in surveyed parameters were observed between Cases B, C, D and E, it was suggested that a thermal environment in Hong Kong Grade A office could be associated with the airside system.

Additional thermal energy is required for fresh air cooling to dilute indoor air pollutants and CO_2. Excessive energy was thus preserved if the indoor air temperature and CO_2 concentration were high in the corresponding offices. The environmental conditions in the assessed offices would deviate from their design values and it could be related to the operations of various airside system types. This study showed an acceptable environmental condition could be maintained using a narrower range of parameters, as compared with the base case.

3. Simulation model

3.1 Thermal energy consumption

A developed mathematical model of thermal energy consumption for Hong Kong office buildings was adopted in this study and outlined below [14]. It should be noted that for a standard Hong Kong office floor of an area = 230-6600 m^2, a window-to-wall ratio r_w = 0.25-0.64 and a floor envelope U-value U_{ww} = 2.4-2.7 W m^{-2} K^{-1}, the model will under-predict the fabric load by 2.5% on average [14, 22].

Taking the conductive heat gain through the building envelope E_{en}, ventilation heat load E_{ve}, and all other internal loads E_{in} including the occupant thermal load E_{oc}, lighting load E_{li} and electrical equipment load E_{eq} into account, the normalized annual thermal energy consumption for an air-conditioned office E_c is approximated by,

$$E_c = E_{en} + E_{ve} + E_{in}\,;\; E_{in} = E_{oc} + E_{li} + E_{eq} \tag{1}$$

The building envelope energy consumption E_{en} can be determined using a multivariate regression model given below, where T_s is the indoor air temperature, L_{max} is the maximum floor length, L_f is the floor length, W_f is the floor width, A_f is the floor area, V_f is the floor volume, U_{ww} is the average U-value of the floor envelope, r_w is the window-to-wall ratio, S_c is the shading coefficient, and ε is an error term approximated by a logarithmic distribution with a logarithmic mean of 1 and a logarithmic standard deviation of 1.4623.

$$\tilde{E}_{en} = 27749 T_s^{-0.8833} A_f^{-0.7861} V_f^{0.2205} r_w^{0.3936} L_{max}^{0.3670} U_{ww}^{0.3591} S_c^{0.4948} + \varepsilon \text{ ; } L_{max} = \max(L_f, W_f) \tag{2}$$

The average U-value of the floor envelope U_{ww} is the sum of window U_{wd} and wall U_{wl} U-values weighted by the window area A_{wd} and wall area A_{wl},

$$U_{ww} = \frac{A_{wd} U_{wd} + A_{wl} U_{wl}}{A_{wd} + A_{wl}} \text{ ; } r_w = \frac{A_{wd}}{A_{wd} + A_{wl}} \tag{3}$$

By defining N_d as the number of working days per year, Φ_c the indoor CO_2 concentration and O_a the occupancy factor, the normalized annual energy consumption for ventilation E_{ve} can be estimated by a regression equation,

$$E_{ve} \approx 1.25 \times 10^9 \Phi_c^{-2.01} T_s^{-0.33} O_a^2 N_d \tag{4}$$

Based on the total operating hours in a year N_h, the thermal energy consumption for the internal loads E_{in} is the sum as shown below, where K_0 is a coefficient for unit conversion, P_{oc} is the normalized per occupant thermal load while P_{li} and P_{eq} are the normalized thermal loads for lighting and other electrical equipment respectively,

$$E_{in} = E_{oc} + E_{li} + E_{eq} = K_0 \left(\sum_{i=1}^{N_h} O_a P_{oc,i} + \sum_{i=1}^{N_h} P_{li,i} + \sum_{i=1}^{N_h} P_{eq,i} \right) \tag{5}$$

3.2 Productivity loss

The productivity loss D (%) of an office worker can be expressed by combining the productivity losses in thinking tasks T_k (%) and typing tasks T_p (%) with a thinking-to-overall task ratio α,

$$D = \alpha T_k + (1 - \alpha) T_p \tag{6}$$

T_k and T_p measured in laboratory environments were correlated with the occupant-preferred mean thermal sensation vote γ_* [23],

$$T_k = 1.5928\gamma_*^5 - 1.5526\gamma_*^4 - 10.401\gamma_*^3 + 19.226\gamma_*^2 + 13.389\gamma_* + 1.8763 \tag{7}$$

$$T_p = -60.543\gamma_*^6 + 198.41\gamma_*^5 - 183.75\gamma_*^4 - 8.1178\gamma_*^3 + 50.24\gamma_*^2 + 32.123\gamma_* + 4.8988 \quad (8)$$

Fanger's predicted mean vote (PMV) [24] index γ, a measure of occupant acceptance of the thermal environment, is a function of indoor air temperature T_s, relative humidity R_h, local air speed v_s, radiant temperature T_r, occupant metabolic rate M_e and clo value C_L, i.e. $\gamma \sim \gamma(T_s, R_h, v_s, T_r, M_e, C_L)$. Mathematical expressions of γ were addressed in the open literature [25]. Some field studies of direct measurement for thermal acceptability reported a narrower operative temperature range for 80% thermal acceptability than the values specified in current design guidelines. Evaluated by Mui and Wong [9], a narrow thermal comfort acceptance range of PMV was found when compared to Fanger's chamber tests[24]. With a correlation coefficient R=0.988 ($p<0.001$, t-test), the thermal sensation vote (TSV) γ_* obtained from the field measurements in Hong Kong air-conditioned offices can be correlated with γ as follow [9],

$$\gamma_* = 3.86\,\gamma + 3.05; \; -3 \le \gamma_* \le +3 \quad (9)$$

The estimation of clo value has long been recognized as a critical weakness in the field of research methodology and also in the application of standards and comfort indices to the 'real world' [7, 9, 14]. However, many air-conditioned workplaces in Hong Kong are overcooled and their occupants have a tendency to wear more clothes. For the best estimate of energy saving, occupants should adjust their clothing so that the maximum thermal acceptance can be obtained. The clo value (1 clo = 0.155 m^2 °CW^{-1}) noted in this study for an occupant sitting on an office chair with a pair of walking shorts and a short-sleeved shirt on was 0.46 and that for a standing occupant wearing thermal long underwear and a pair of insulated overalls was 1.37 [25].

To simulate the maximum occupant acceptance of a given thermal environment ϕ_{max}, a wider range of clo values account for unobserved cases in typical Hong Kong air-conditioned offices (i.e. C_L = 0.3-1.7 clo) is assumed [19],

$$\phi = \phi_{max};\ 0.3 \le C_L \le 1.7 \qquad (10)$$

3.3 Simple Monte Carlo sampling

Impacts of the indoor environmental policy on the assessed offices were analyzed in terms of thermal energy consumption, probable occupant thermal acceptance and productivity loss. Based on Table 1 and the entire Hong Kong air-conditioned office building stock, simulations were performed for Hong Kong Grade A offices grouped as: Case A, offices maintained under the design target conditions; Case B, base case offices; Case C, offices served by VAV systems; Case D, offices served by CAV systems; and Case E, offices served by FCU systems.

Table 2 summarizes the input parameters required for the evaluation. The simple Monte Carlo sampling (SMS) technique [26] was used to sample the input parameters in Equations (1) to (10) for Cases A to E listed in Table 1. Prior to map the thermal environmental conditions, the input parameters $\zeta_i \in \tilde{\zeta}_i$, in each simulation i, were determined using the following expression with a pseudo-random number x for the corresponding descriptive distribution functions $\tilde{\zeta}_i$ itemized in Tables 1 and 2,

$$\zeta_i = \zeta_{i,x}\ ;\ \int_{-\infty}^{\zeta_{i,x}} \tilde{\zeta}_i \, d\zeta_i = x \tag{11}$$

For simplicity, Gaussian distribution was assumed for all input parameters listed in Tables 1 and 2. Simulations were repeated 10,000 times for each case and the corresponding changes of the expected energy consumption and its variance were 0.02% and 0.03% respectively for further simulations to be conducted.

4. Result and discussion

Figure 1 shows the annual thermal energy consumption per unit floor area for Grade A offices in Hong Kong. The observed energy consumption was 586 kWh m^{-2} yr^{-1}, 965 kWh m^{-2} yr^{-1}, 661 kWh m^{-2} yr^{-1}, 1090 kWh m^{-2} yr^{-1} and 861 kWh m^{-2} yr^{-1} for Cases A, B, C, D and E respectively. It revealed that under the design target conditions, the maximum potential energy savings was 39%. Average thermal energy reductions were 31% and 11% for offices served by VAV and FCU systems respectively. For those offices served by CAV systems, however, 13% of the thermal energy was consumed for indoor CO_2 dilution in maintaining satisfactory IAQ. It was also noted that some offices did not fully meet the design target requirements, for example insufficient fresh air intake to dilute indoor CO_2 concentration, excessive thermal energy reduction could thus be resulted. This can be seen in the bottom 30% of Case C in Figure 1, as compared with Case A. It was also observed that similar thermal energy consumption of the bottom most 10% in Case D as compared with the top most 10% in Case A.

Simulated occupant thermal sensation is presented in Figure 2. The TSV distributions showed that Case A was not significantly different ($p>0.1$, Chi-square test) whereas Cases C, D and E were significantly different ($p<0.05$, Chi-square test) from Case B. Taking $-0.5 \leq \gamma_* \leq 0.5$ as the acceptance threshold [25], 94%, 92%, 65%, 72% and 71% of the occupants respectively in Cases A, B, C, D and E were found satisfied with their perceived thermal environments. Probably, most occupants in Cases A and B had successfully adjusted their clothing to maintain maximum thermal comfort. The outcome reflected that in reality, certain level of thermal discomfort complaints existed.

Distributions of the clo values for Cases A to E, among which significant differences were observed ($p<0.01$, t-test), are exhibited in Figure 3. The average clo values were 0.59 clo, 0.73 clo, 0.47 clo, 0.45 clo and 0.45 clo for Cases A to E respectively. According to a regional study of thermal comfort in office premises carried out in Hong Kong, the average was 0.73 clo in summer [27]. Very similar results were obtained from the base case simulations. For a clo value of 0.3 or below, it was found that 9%, 7%, 30%, 36% and 29% of the occupants in Cases A, B, C, D and E were required to adapt to the thermal environment respectively. For a minimum clo value of 0.3 hypothetically imposed in Case C, 4.4% of the occupants ($\gamma_* \geq 2.5$) would feel hot, 6.7% ($1.5<\gamma_* \leq 2.5$) warm and 24% ($0.5<\gamma_* \leq 1.5$) slightly warm, as illustrated in Figure 4. That indicated an obvious improvement on thermal sensation. In other words, including the reduction of clo value in the environmental policy can help to ensure a thermally comfortable indoor environment.

Figure 5 shows the predicted productivity loss among office workers in typing and thinking tasks. For a thinking-to-overall task ratio $\alpha=0.5$, the average productivity losses for Cases A, B, C, D and E were 5.1%, 4.9%, 9.8%, 11.5% and 9.3% respectively. The results demonstrated that occupants in an air-conditioned office preferred a slightly cool environment. As the occupants in Cases C, D and E were not satisfied with the warmer environments they were in, higher productivity losses amid them were expected. Therefore, Case B is preferred to be used in office.

5. Conclusion

Air-conditioned offices in the subtropics are recommended to operate within specified ranges of indoor air temperature, relative humidity and air velocity for thermal energy conservation. As productivity loss due to thermal discomfort in an overly warm office environment is a concern that cannot be ignored, this study investigated some indoor environmental policies for Hong Kong Grade A offices. Occupant thermal response was specifically considered as an adaptive factor in the evaluation of thermal energy consumption and productivity loss for these offices which were grouped into 5 Cases A – E. Using the entire Hong Kong air-conditioned office building stock, probable office thermal environments were determined via Monte Carlo simulations and the corresponding energy consumption and productivity loss were assessed.

Notwithstanding the excessive thermal energy reduction observed in some existing offices (e.g. 31% in Case C), low thermal acceptance rate (65%) and high productivity loss (9.8%) indicated that the offices might not fully satisfy the design target requirements. A hypothetically imposed minimum value of 0.3 clo in Case C showed not only an improvement in occupant acceptance (up to 89%) but also potential thermal energy savings and worker productivity enhancement. In order to ensure a thermally comfortable indoor environment, dressing allowable of the reduction of clo value should be addressed in the environmental policy for Grade A offices in Hong Kong.

This study is a useful reference source for building designers and policymakers to evaluate indoor thermal environments, especially air-conditioned offices in subtropical climates, with respect to energy consumption, thermal comfort and productivity loss.

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References

1. Pacala S and Socolow R. Stabilization Wedges: Solving the climate problem for the next 50 years with current technologies. *Science*. 2004; 305: 968-72.
2. Mui KW. Energy policy for integrating the building environmental performance model of an air conditioned building in a subtropical climate. *Energ Convers Manage.* 2006; 47: 2059-69.
3. EMSD(Electrical and Mechanical Services Department). Energy End-use Data 2012. Hong Kong, China: Electrical and Mechanical Services Department, The Energy Efficiency Office Press, 2012.
4. RVD(Rating and Valuation Department). Hong Kong property review 2008. Hong Kong, China: The Government of the Hong Kong Special Administrative Region Press, 2008.
5. Wong LT and Mui KW. A transient ventilation demand model for air-conditioned offices. *Appl Energ*. 2008 85: 545-54.
6. Lam JC, Wan KW, Liu D and Tsang CL. Multiple regression models for energy use in air-conditioned office buildings in different climates. *Energ Convers Manage*. 2010; 51: 2692-7.
7. Yamtraipat N, Khedari J, Hirunlabh J and Kunchornrat J. Assessment of Thailand indoor set-point impact on energy consumption and environment. *Energ Policy*. 2006; 34: 765-70.

8. Mishra AK and Ramgopal M. Field studies on human thermal comfort - An overview. *Build Environ*. 2013; 64: 94-106.
9. Mui KW and Wong LT. Neutral temperature in subtropical climates - a field survey in air-conditioned offices. *Build Environ*. 2007; 42: 699-706.
10. Mui KW, Wong LT and Hui PS. Risk of unsatisfactory airborne bacteria level in air-conditioned offices of subtropical climates. *Build Environ*. 2008; 43: 475-9.
11. Wong LT, Mui KW and Hui PS. A statistical model for characterizing common air pollutants in air-conditioned offices. *Atmos Environ.* 2006; 40: 4246-57.
12. Lee MC, Mui KW, Wong LT, Chan WY, Lee EWM and Cheung CT. Student learning performance and indoor environmental quality (IEQ) in air conditioned university teaching rooms. *Build Environ*. 2012; 49: 238-44.
13. HHKEP(Hong Kong Environmental Protection Department). Indoor air quality certification scheme for offices and public places. Hong Kong, China: Environmental Protection Department Press, 2003.
14. Wong LT, Mui KW and Shi KL. Energy impact of indoor environmental policy for air-conditioned offices of Hong Kong. *Energ Policy* 2008; 36: 714-21.
15. Fong KF, Chow TT and Li C. Comfort zone of air speeds and

temperatures for air-conditioned environment in the subtropical Hong Kong. *Indoor Built Environ*. 2010; 19: 375-81.

16. Akimoto T, Tanabe S, Yanai T and Sasaki M. Thermal comfort and productivity – Evaluation of workplace environment in a task conditioned office. *Build Environ*. 2010; 45: 45-50.
17. Chen AL and Chang VWC. Human health and thermal comfort of office workers in Singapore. *Build Environ*. 212; 58: 172-8.
18. Thomas LE. Evaluating design strategies, performance and occupant satisfaction: a low carbon office refurbishment. *Build Res Inf*. 2010; 38: 6810-624.
19. Wong LT and Mui KW. Efficiency assessment of indoor environmental policy for air-conditioned offices in Hong Kong. *Appl Energ*. 2009; 86: 1933-8.
20. Hui PS, Mui KW, Wong LT and Leung CH. Benchmarking indoor air quality for 'Grade A' offices in Hong Kong. *Joint Symposium 2009 on building sustainability under one sky*. Tian Yu Hotel, Tianjin, China. 2009, p. 1-7.
21. Leung CHJ. Simplified assessment of indoor air quailty in air-conditioned office in Hong Kong. MEng dessertation. Hong Kong: The Hong Kong Polytechnic University, 2009.
22. Yu CHP and Chow WK. A discussion on potentials of saving energy use for commercial buildings in Hong Kong. *Energy*. 2007; 32: 83-94.

23. Kosonen R and Tan F. Assessment of productivity loss in air-conditioned buildings using PMV index. *Energ Buildings*. 2004; 36: 987-93.

24. Fanger PO. *Thermal comfort*. New York: McGraw-Hill, USA, 1972.

25. ASHRAE (American Society of Heating RaACE. Thermal Environmental Conditions for Human Occupancy, ANSI/ASHRAE standard 55-2010. Atlanta, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers Press., 2010.

26. Binder K. *Monte Carlo simulation in statistical physics: an introduction*. 4th edn. New York: Springer USA, 2002.

27. Chan WT, Burnett J, de Dear R and Ng CH. A large-scale survey of thermal comfort in office premises in Hong Kong. *ASHRAE Technical Data Bulletin* 1998; 14: 76-84.

Nomenclature

A	area (m^2)
C_L	clo value (clo)
D	productivity loss (%)
E	annual thermal energy consumption (kWh m^{-2} yr^{-1})
K	constant
L	length (m)
M_e	metabolic rate (met)
N_d	number of working days in a year (d yr^{-1})
N_h	number of operating hours in a year (h yr^{-1})
O_a	occupancy factor (hd m^{-2})
P	normalized thermal load (kW m^{-2} yr^{-1})
p	p-value of a statistic test of significance
R	correlation coefficient
R_h	relative humidity (%)
r_w	window-to-wall ratio
S_c	shading coefficient
SD	standard deviation
T	temperature (°C)
T_k	thinking task
T_p	typing task
U	U-value (W m^{-2} K^{-1})
v	velocity (ms^{-1})
V	volume (m^3)
W	width (m)
Φ_c	indoor CO_2 concentration (ppmv)
α	thinking-to-overall task ratio
ε	error term
ϕ	occupant acceptance of the thermal environment
γ	predicted mean vote (PMV)
γ_*	thermal sensation vote (TSV)

Superscript

~	distribution function

Subscript

0,1,2,…of conditions 0,1,2,…

c	of an air-conditioned office
en	of conductive heat gain through building envelope
eq	of electrical equipment
f	of floor
i	of the i-th item
in	of internal loads
li	of lighting
max	of maximum
oc	of occupants
r	of radiant
s	of indoor air
ve	of ventilation
wd	of window
wl	of wall
ww	of floor envelope

Table Captions

Table 1. Indoor environments of Hong Kong Grade A offices

Table 2. Floor characteristics of air-conditioned office buildings in Hong Kong

Figure Captions

Figure 1. Annual thermal energy consumption for Grade A air-conditioned offices

Figure 2. Occupant thermal sensation; (Case average TSV index shown in brackets)

Figure 3. Expected occupant clo values (clo≥0.3) at preferred air temperatures of 22.6 to 23.6°C

Figure 4. Thermal response of the occupants for five cases

Figure 5. Potential productivity loss among office workers in: (a) typing tasks; (b) thinking tasks

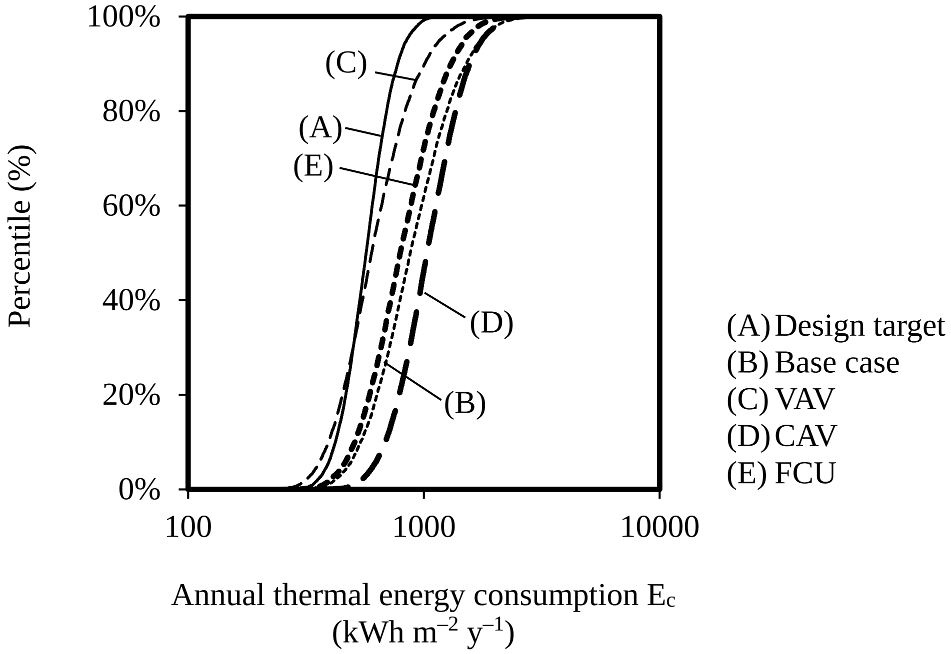
Table 1. Indoor environments of Hong Kong Grade A offices

Case (Sample size N)	CO_2 level Φ_c (ppm)	Air temperature T_s (°C)	Relative humidity R_h (%)	Local air speed v_s (ms^{-1})
(A) Design target [13]	800–1000	20–25.5	40–70	≤0.2
(B) Base case (N=422) [11]	450–2000 (641)	13.4–27.8 (22)	20–80 (60)	<0.05–0.41 (0.27)
(C) VAV (N=1021) [21]	500–1668 (851)	18.2–26.6 (23.1)	20–80 (60)	<0.05–0.35 (0.07)
(D) CAV (N=252) [21]	500–933 (552)	18.5–26.7 (23.2)	31–76 (57)	<0.05–0.24 (0.06)
(E) FCU (N=101) [21]	500–1082 (674)	20.5–25.0 (23.0)	53–74 (62)	<0.05–0.17 (0.07)

[a] Averages are shown in brackets beside their respective value ranges.

Table 2. Floor characteristics of air-conditioned office buildings in Hong Kong

Parameter	Range (average)
Floor area A_f (m^2)	200–3000 (900)
Floor space volume V_f (m^3)	600–15000 (3500)
Floor length and width L_f, W_f (m)	14–54 (30)
Window-to-wall ratio r_w	0.2–0.8 (0.5)
Wall U-value U_{wl} (W m^{-2} K^{-1})	0.57–3.41 (2.0)
Window U-value U_{wd} (W m^{-2} K^{-1})	2.97–6.16 (4.5)
Shading coefficient S_c	0.1–0.9 (0.47)
Occupancy factor O_a (hd m^{-2})	0.05–0.12 (0.074)
Normalized per occupant thermal load P_{oc} (kW hd^{-1} m^{-2} yr^{-1})	94–170 (128)
Normalized thermal load for lighting P_{li} (kW m^{-2} yr^{-1})	10–30 (18)
Normalized thermal load for other electrical equipment P_{eq} (kW m^{-2} yr^{-1})	5–25 (12)
Number of operating hours in a year N_h (h yr^{-1})	2600–2800


100%
80%
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Percentile (%)
(C)
(A)
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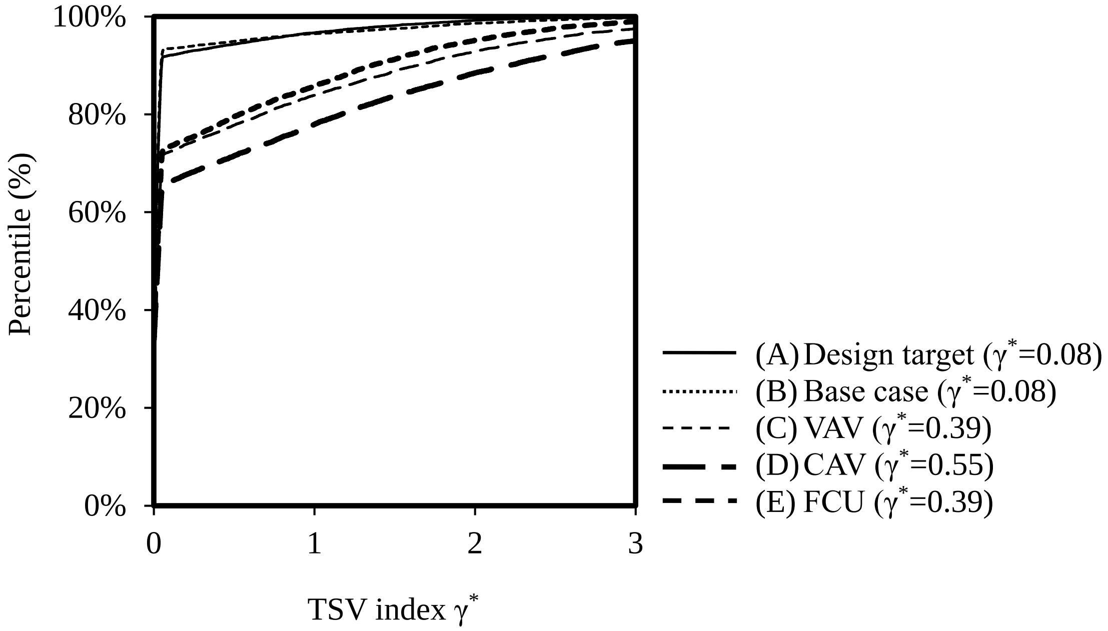
(D)
(B)
100
1000
10000
Annual thermal energy consumption Ec
(kWh m–2 y–1)
(A) Design target
(B) Base case
(C) VAV
(D) CAV
(E) FCU

Figure 1



100%
80%
60%
40%
20%
0%
Percentile (%)
0
1
2
3
TSV index γ*
(A) Design target (γ*=0.08)
(B) Base case (γ*=0.08)
(C) VAV (γ*=0.39)
(D) CAV (γ*=0.55)
(E) FCU (γ*=0.39)

Figure 2

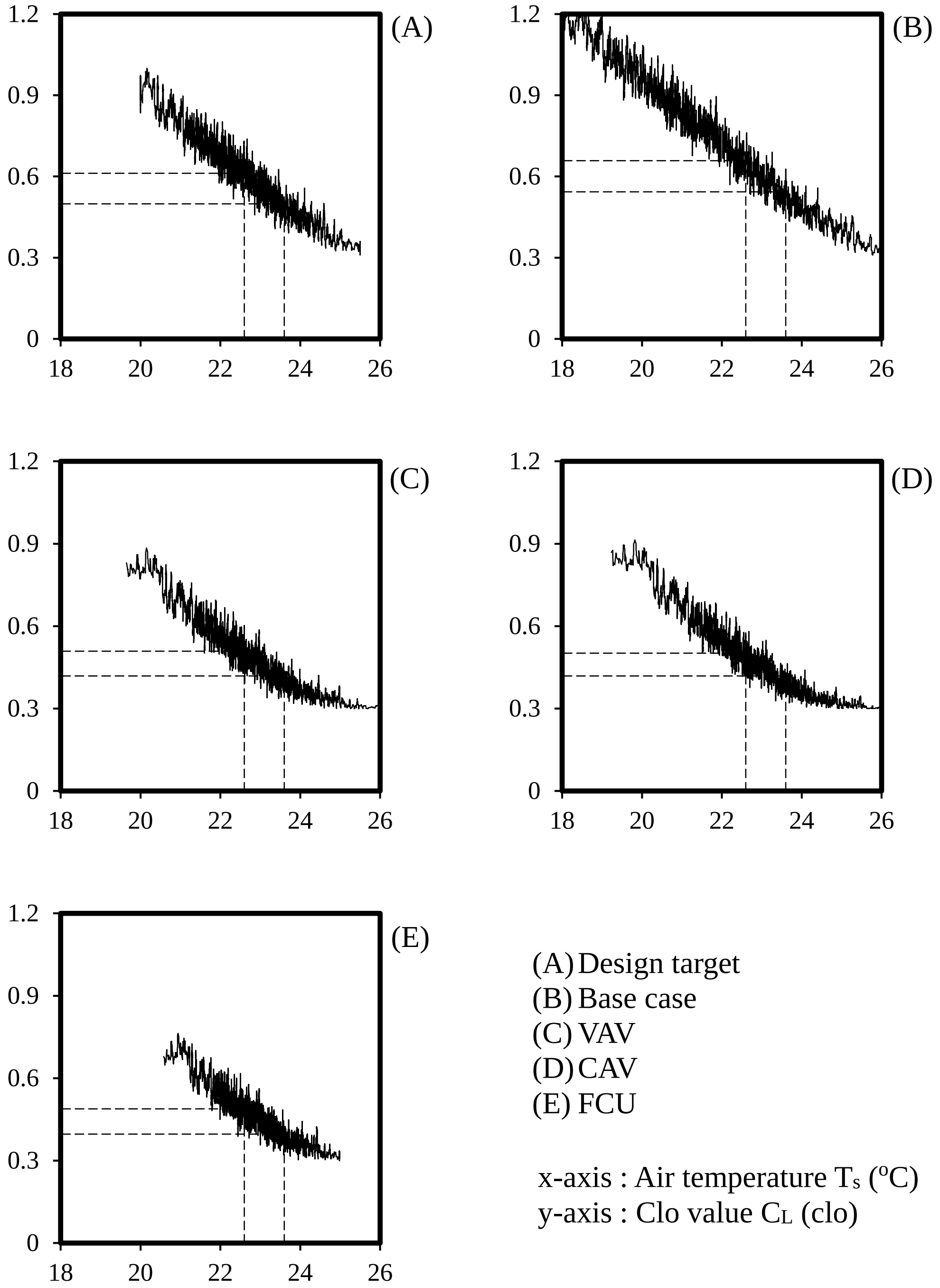
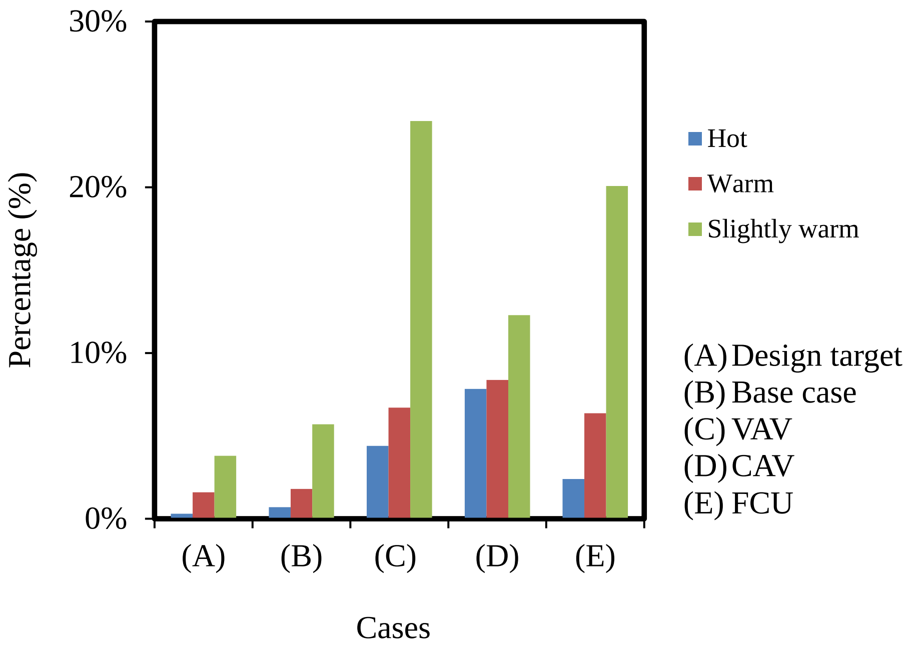
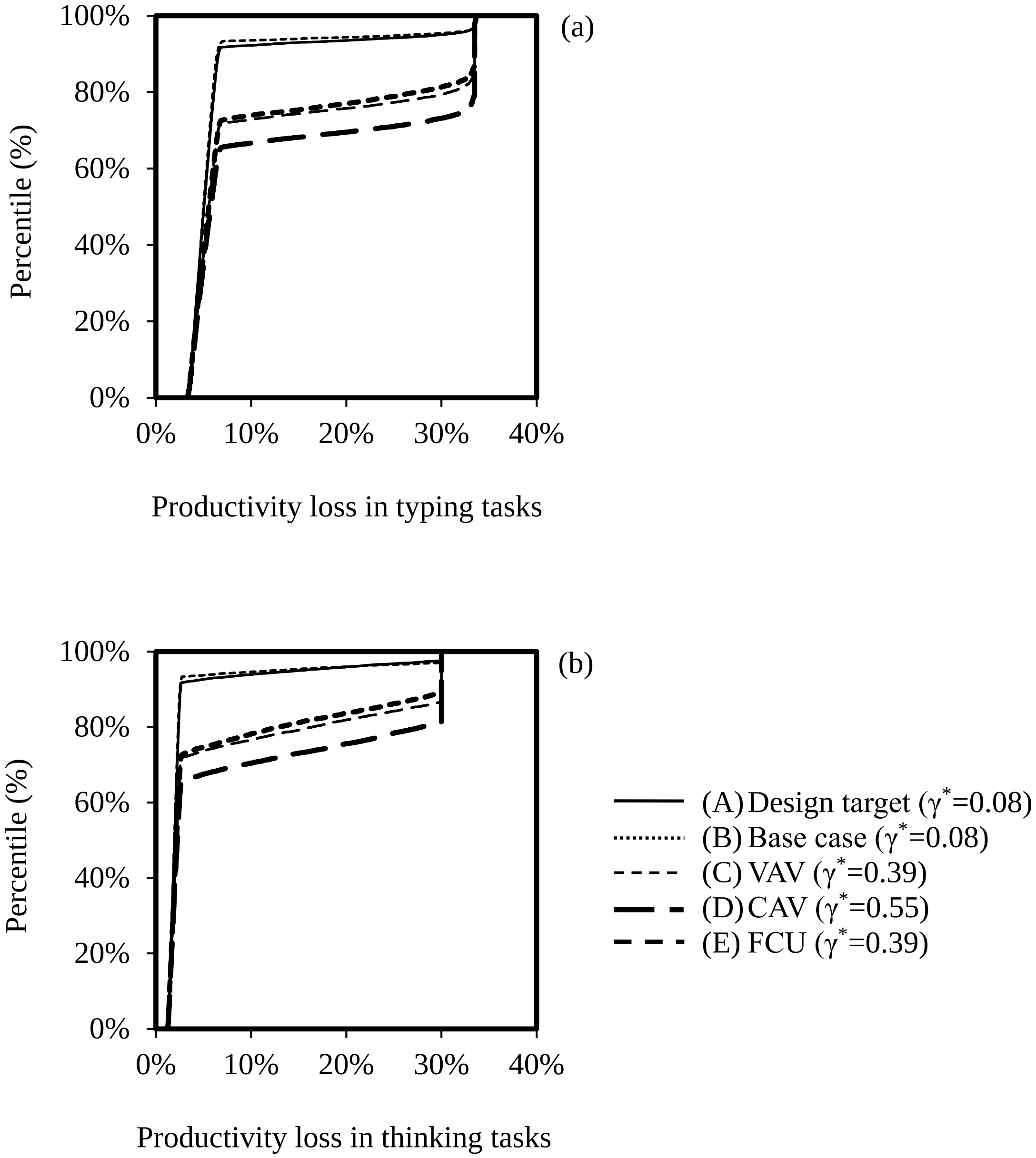

(A)
(B)
(C)
(D)
(E)
1.2
0.9
0.6
0.3
0
18
20
22
24
26
(A) Design target
(B) Base case
(C) VAV
(D) CAV
(E) FCU
x-axis : Air temperature Ts (°C)
y-axis : Clo value CL (clo)

Figure 3



30%
20%
10%
0%
Percentage (%)
Hot
Warm
Slightly warm
(A) Design target
(B) Base case
(C) VAV
(D) CAV
(E) FCU
(A)
(B)
(C)
(D)
(E)
Cases

Figure 4



100%
80%
60%
40%
20%
0%
Percentile (%)
0%
10%
20%
30%
40%
Productivity loss in typing tasks
(a)
100%
80%
60%
40%
20%
0%
Percentile (%)
0%
10%
20%
30%
40%
Productivity loss in thinking tasks
(b)
(A) Design target (γ*=0.08)
(B) Base case (γ*=0.08)
(C) VAV (γ*=0.39)
(D) CAV (γ*=0.55)
(E) FCU (γ*=0.39)

Figure 5