Indoor Air Quality and Thermal Comfort: An investigation in office buildings in Hanoi, Danang and Ho Chi Minh City

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Abstract. Thermal comfort and air quality are basic factors of indoor environment. In office buildings, poor indoor air quality (IAQ) and low thermal comfort level may negatively affect occupants’ health and performance and eventually causes Sick Building Syndrome (SBS). In this research, the IAQ and thermal comfort were examined at a number of office buildings in the three Vietnamese cities of Hanoi (North), Danang (Central) and Ho Chi Minh City (South), which aims to assess the quality of indoor environment of office buildings in Vietnam. The results showed that the design and operation scheme play an important role for the achievement of the indoor air quality and thermal comfort. The collected data from field measurement and survey are expected to be concrete scientific basis for the revision of current standards and development of new standards in air quality of office buildings

1. Introduction

Indoor environmental quality is a concerned issue worldwide. Indoor air quality and thermal comfort are two important aspects of indoor environmental quality that receive considerable attention by building designers and operators. International and national standards prescribes conditions intended to foster environments that are acceptable to occupants. Although there is considerable monitoring on air quality and thermal comfort, there is far less observed data for evaluating occupants’ satisfaction across a large number of buildings using a systematic method, and using occupant opinions as a measure of building performance is still far from standard practice [3]. In recent years, the Center for the Built Environment (CBE) at the University of California, Berkeley has been conducting a web-based indoor environmental quality survey in office buildings. The anonymous, invite-style survey measures occupant satisfaction and self-reported productivity with respect to nine environmental categories: office layout, office furnishings, thermal comfort, air quality, lighting, acoustics, cleaning and maintenance, overall satisfaction with building and with workspace [4]. The questions asked in the survey have remained consistent over time to create a standardized database for benchmarking and analysis. The presented study was conducted for the humid tropical climate of Vietnam.

In fact, most of the buildings in Vietnam are passively ventilated if the weather is in favorable condition; therefore indoor air can be kept in equivalent quality to that of outdoor environment.
control outdoor air pollution and protect the health of the community, a standard on the ambient air quality entitled “QCVN 05:2013/BTNMT - National technical regulation on ambient air quality” and “QCVN 06:2009/BTNMT - National technical regulation on hazardous substances in ambient air” were issued. When buildings are closed for winter insulation or air conditioned, indoor air quality are mainly driven by internal pollutants. As response from legacy perspective, the permitted emittance of materials, recommended values of air-flow exchange factors and needed fresh air volume were introduced in the standards “QCXDVN 05:2008: Dwellings and Public Buildings - Occupational Health and Safety” and “TCVN 5687:2010: Ventilation-air conditioning - Design standards”. The standard “TCXDVN 306:2004 – Dwelling and public buildings - Parameters for micro-climates in the rooms” [4] mentioned the required micro-climate condition in civil buildings. However, there has not yet a national standards on IAQ regulating the threshold concentration of air pollutants in civil buildings.

This article describes research and developments in the past that had influence on how people thought and now think about indoor environment. The emphasis is on indoor air quality and thermal comfort.

1.1. Indoor Air Quality in office buildings, problems and challenge

In the context of rapid urbanization, the urban land area per capita decreased sharply in large cities. Therefore, built density of office buildings in major cities as Hanoi, Danang and Ho Chi Minh Cities are normally higher and completely dependent on the Heating and Ventilation and Air Conditioning (HVAC) system to control the indoor air quality. Poor buildings and poorly designed or maintained building HVAC systems and improper energy saving measures in buildings jeopardise our indoor environment. Poor outdoor air quality, as more and more occurring in densely populated areas, will require us to clean our buildings air intake carefully.

Studies on air quality in buildings in Vietnam are limited. There have been few studies on some indoor air pollution indicators which were conducted in some cities in Northern Vietnam in recent years such as [6], [7], [8] and [9]. Regarding air quality assessment in office buildings using air conditioners, there have been only 3 studies conducted as following. The first one is a study conducted by Huong NT et all [10] in 2001: air pollution parameters such as respirable dust, CO, CO₂, formaldehyde, VOCs and ozone in two office buildings in Hanoi were measured, sampled and analysed. The results showed that one of the reasons for poor air quality in office buildings is due to the problems caused by the HVAC system design such as: (i) inappropriate layout of the air diffuser causing low air exchange rate; (ii) taking fresh air from technical tunnels connected to car park area and from staircases. The second one is a study of Khanh NQ et all [10] in 2011, which conducted measurement, sampling and analyses of air pollution parameters such as PM10 respirable dust, total TSP dust, CO₂, CO, formaldehyde, VOCs and ozone in 4 office buildings in Hanoi. The results showed that: the concentrations of TSP dust and respirable dust were higher or approximately the permitted value when compared with the instructions in [12] and [13]; toxic gas concentration: only 2 of the 4 buildings were lower than the permitted value of the guideline in [12]; ozone concentrations in 4 buildings were approximately the same as in the instruction [12]; The concentration of formaldehyde in an office was higher than the recommended value of the guideline in [12] and [13]; because most of their office equipment such as tables, chairs, partitions were new. The last one is a study of Thuy L B et all in 2015 [14] on the levels of indoor air pollutants: PM₁₀, SO₂ and NO₂ in three offices in Hanoi; The results showed that: levels of indoor PM₁₀ concentrations, levels of hourly indoor NO₂ and levels of indoor SO₂ in the wet season and dry season well met the recommendation of WHO guidelines.

1.2. Thermal comfort, the indicators and methods of assessment

Acceptable range of temperature and humidity for people is called the thermal comfort zone. Thermal comfort is always influenced by microclimate factors (air temperature, air humidity, air velocity, average radiation temperature of surrounding surfaces) and subjective factors of people (activity, clothing, age, gender, habit, etc.). Since its inception, there have been many methods for
predicting thermal comfort in a space. Effective temperature (ET) was first proposed by Houghton and Yaglou in 1923 \cite{15}. ET integrates air temperature, air humidity, air velocity into a single environment indicator. In 1932, ASHVE (ASHRAE) published a nomogram representation of the ET index. They used the index ‘Effective Temperature’ (ET), which was used extensively over the next 50 years \cite{15}.

The most wellknown researchers in thermal comfort from the 1960s was Fanger’s new discipline (1970) \cite{17}. It is the model of thermal comfort - Predicted Mean Vote (PMV), focused on the relationship between the physical parameters of the environment (air temperature, mean-radiant temperature, relative humidity, air velocity), the physiological parameters of people (activity level and thermal resistance of the clothing) and the perception of comfort expressed by people themselves. As a follow-up to the PMV-index, Fanger introduced the PPD-index (Predicted Percentage of Dissatisfied), including human index, which predicted the percentage of the majority of respondents who feel satisfied (unsatisfied) with their environment. The thermal equilibrium method of the human body is used in ISO 7730 \cite{18} and ASHRAE 55 \cite{4}. This model is often applied to buildings that use air conditioning ventilation systems.

The 1980s saw the start of the discussion about adaptive principles related to thermal comfort. The initiator was Michael A. Humphreys \cite{19}. In 1997, Gail S. Brager and Richard J. de Dear \cite{20} developed an adaptive model of thermal comfort to predict the ET based on findings of body self-adjusting mechanism, which was applied to natural ventilation. This research was subsequently included in ASHRAE 55 \cite{4} and EN 15251 \cite{21}.

In Vietnam, since the 60s - 80s of the 20th century, there has been some Vietnamese scientists such as Dang PN, Con NH, Minh TX, Anh NH, Thiem TH, Phong DN conducting empirical studies about the thermal comfort conditions of people in low-rise office buildings and residential house. In which, the Vietnamese thermal sensation scale proposed by Dang PN \cite{22} was included in the Standard “TCXDVN 306: 2004 - Dwelling and public buildings - Parameters for micro-climates in the rooms” to determine the conditions for thermal comfort.

| Thermal sensation | Thermal sensation detail scale | Effective temperature (\(\varphi = 80\%\), \(v = 0.3 – 0.5\) m/s) | Air temperature °C |
|-------------------|--------------------------------|---------------------------------|---------------------|
|                   |                               | Winter                          | Summer              |
| Cool              | Cold                           | \(\leq 17.3\)                   | \(\leq 19.8\)       |
|                   | Slight cold                    | 18.5                            |                     |
| Comfort           | Upper comfort limit            | 20.0                            | 21.5                |
|                   | Neutral                        | 23.3                            | 24.4                |
|                   | Lower comfort limit            | 26.5                            | 27.0                |
| Warm              | Slight hot                     | 28.5                            |                     |
|                   | Hot                            | \(\geq 29.2\)                   | \(\geq 31.5\)       |

In recent years, there were some studies on microclimate conditions in educational and residential buildings such as \cite{23}, \cite{24}, \cite{25} and \cite{26}. However, only Huong N T \cite{10} and Khanh N Q \cite{10} conducted surveys to assess the microclimate environment in office buildings using ventilation and air conditioning system throughout the year. A research by Huong N T et al \cite{10} revealed that microclimate factors were always in the range of response to the type of office building with air conditioner. At the measurement locations (at a height of 1.5 m from the floor), the air temperature varied from 22–25 °C, the relative humidity 64–68%, air velocity 0.2–0.3 m/s. The degree of uniform distribution of temperature, humidity and air velocity depended quite clearly on the arrangement of the air diffuser. The survey results showed that: 84–89% staffs voted feel satisfied with temperature, 77–81% staffs voted feel satisfied with air humidity, 45–48% staffs voted feel satisfied with air velocity and 35–43% staffs needed higher air velocity. Findings by Khanh N Q et al \cite{10} showed that the air temperature in 4 office buildings ranged from 24–27 °C; humidity was 60–63%, air velocity was from
0.3–0.9 m/s. Research team used the SN thermal pollution assessment method in the annex of TCXDVN 306: 2004 [4] to assess the thermal sensation of office staffs. The results showed that all office staffs voted feel satisfied.

Thus, up to now, there has been no measurement survey to assess the air quality and thermal comfort in air-conditioned office buildings conducted simultaneously in all 3 regions: North, Central and South of Vietnam.

2. Methodology

In order to evaluate the air quality and thermal comfort in air-conditioned office buildings simultaneously in all 3 regions, two environmental survey methods were used including (1) measurements of IAQ and indoor microclimate parameters, and (2) questionnaire survey in three cities: Hanoi (North), Danang (Central) and Ho Chi Minh city (South).

2.1. Selection of buildings

7 office buildings with 3 office buildings in Hanoi, 2 office buildings in Danang city, 2 office buildings in HCM city were selected to sampling. In each building, 1 or 2 rooms were selected to survey and the total number of rooms is 8 rooms with 8 code buildings given in Table 2. All the main structural material of seven buildings was being concrete.

| City                     | Hanoi | Danang | Ho Chi Minh city |
|--------------------------|-------|--------|------------------|
| Building name            | A     | B      | C                | D    | E    | F    | G    |
| Total stories            | 6     | 14     | 34               | 12   | 6    | 20   | 12   |
| Age (yrs)                | 1994  | 2008   | 2014             | 2012 | 2016 | 2015 | 2004 |
| Investigated room        | in 6th floor | in 7th floor | in 20th floor | in 3rd floor | in 4th floor (named E1) and 6th floor (named E2) | in 10th floor | in 8th floor |
| Ceiling height (m)       | 2.9   | 2.75   | 2.7              | 3.0  | 2.7  | 3.3  | 2.6  |
| AC system                | Individual/cool | Individual/cool | Central/heat+cool | Central/cool | Central/cool | Central/cool | Central/cool |
| Ownership                | Government | Government | Government | Corporate | Corporate | Corporate | Private |

2.2. Survey period

Measurement was conducted in the hottest months of the summer and the coldest months of the winter in Hanoi while there was only a one-month monitoring during the hottest month in each city of Danang and Ho Chi Minh City. There were five measurement times in a day which were respectively: 8h - 8h30; 10h - 10h30; 12h - 12h30, 14h - 14h30; 16h - 16h30.

2.3 Measurement parameters and methodology

- **Air quality**
  - Parameters are measured for indoor air quality include: total of suspended TSP dust, PM$_{2.5}$ fine dust, CO$_2$, VOC. The location of the indoor TSP, PM$_{2.5}$, VOC sensors is in the middle of the room at a height of 1.2 m from the floor. The location of the CO$_2$ sensor is in the 1 point in the middle of the room or 4-5 points evenly distributed in the room, at a height of 1.2 m from the floor.
Parameters are measured for outdoor air quality include: total of suspended TSP dust, PM$_{2.5}$ fine dust, CO$_2$, VOC. The location of the outside air quality sensor is in front of the building, at a height of 1.5 m from ground.

- **Thermal comfort**
  - Indoor air temperature - $T_{in}$ (°C) and indoor air humidity - $\varphi_{in}$ (%) and indoor air velocity - $v_{in}$ (m/s) are measured at 5 points evenly distributed in the room, at a height of 1.5 m from the floor; while the and average radiation temperature of surrounding surfaces - $T_R$ (°C) is measured in the middle of the room, at a height of 1.2 m from the floor.
  - Outdoor air temperature - $T_{out}$ (°C) and outdoor air humidity - $\varphi_{out}$ (%) and outdoor air velocity - $v_{out}$ (m/s) are measured at a represent point at a height of 1.5 m from ground.

Thermal comfort is rated by the ET index and the PMV index. The ET monogram of ASHVE was used to calculate the ET indices. The CBE Thermal Comfort Tool of the University of California Berkeley was used to calculate PMV indicators.

### 3. Results and discussion

In Hanoi in winter season: three buildings (A, B and C) were measured in 18/1/2018, 31/1/2018 and 6/2/2018, respectively. 31/1/2018 and 6/2/2018 are very cold days. In Hanoi in summer season: A building was measured in 21/8/2018 ($T_{out} = 32.3–34.5$ °C, $\varphi_{out} = 69.0–81.2$ %), B building was measured in 4/7/2018 ($T_{out} = 36.0–38.4$ °C, $\varphi_{out} = 48.0–51.6$ %) and A building was measured in 6/7/2018 ($T_{out} = 33.2–37.2$ °C, $\varphi_{out} = 49.3–70.9$ %).

In Danang city: two building (D and E) were measured in 25/7/2018 ($T_{out} = 31.4–33$ °C, $\varphi_{out} = 58.5–64.6$%) and 26/7/2018 ($T_{out} = 30–31.7$ °C, $\varphi_{out} = 65.1–70.5$ %), respectively.

In HoChiMinh city: two building (F and G) were measured in 13/4/2018 ($T_{out} = 29–33.1$ °C, $\varphi_{out} = 60.6–76.9$ %) and 12/4/2018 ($T_{out} = 31–35$ °C, $\varphi_{out} = 52.4–68.7$ %), respectively.

Questionnaires of indoor environmental quality according to subjective people working in the surveyed rooms were asked at the survey date. 174 questionnaires sampling is collected.

#### 3.1 IAQ results

In Hanoi in winter season: The results from A,B,C buildings show that TSP and PM$_{2.5}$ are 0.03 - 0.08 mg/m$^3$ (mean = 0.056 mg/m$^3$) and 0.003 - 0.026 mg/m$^3$ (mean = 0.013 mg/m$^3$) in range, respectively; In summer season, TSP and PM$_{2.5}$ are 0.102 - 0.281 mg/m$^3$ (mean = 0.162 mg/m$^3$) and 0.053 - 0.110 mg/m$^3$ (mean = 0.083 mg/m$^3$) in range, respectively.

In Danang city with D, E buildings: the results show that TSP and PM$_{2.5}$ are 0.010 - 0.018 mg/m$^3$ (mean = 0.014 mg/m$^3$) and 0.001 - 0.004 mg/m$^3$ (mean = 0.0024 mg/m$^3$) in range, respectively; and TSP is 0.189 - 0.405 mg/m$^3$ (mean = 0.23 mg/m$^3$) in HoChiMinh city with F and G buildings.

![Figure 1](image-url). Total of suspended TSP dust, PM$_{2.5}$ and the difference in indoor and outdoor CO$_2$ concentration ($\beta^1$CO$_2$) in A,B,C buildings in Hà Nội.
Figure 2. Total of suspended TSP dust, PM$_{2.5}$ and $\beta$ difference in indoor and outdoor CO$_2$ concentration ($\beta$CO$_2$) in D,E buildings in Danang and F,G buildings in Ho Chi Minh city

The significant difference in indoor and outdoor CO$_2$ concentration was figured out from the investigation, where the level of Hanoi was top ranked (764 – 2468 ppm, mean 881.8 ppm), and followed by Da Nang (381–1012 ppm, mean 693 ppm) and Ho Chi Minh city (0,0–216 ppm, mean 100.8 ppm).

The VOC presence was detected only in the office buildings of Hanoi, which lied from 3.3–8.7 ppm (mean at 5.6 ppm) in building A, 0.1–0.3 ppm in building B and 0.1–0.2 ppm in building C.

3.2 Indoor Climate Measurement Results

In Hanoi in winter season: The results show that average indoor air temperature in A and B buildings without heating system and C building with heating system are 23.9 ºC, 19.7 ºC and 22.8 ºC (average outdoor air temperature, $T_{out}$ are 19.9 ºC, 14.7 ºC and 17.2 ºC), respectively; the average relative humidity in A, B and C buildings are 73.5 %, 48.1 % and 32.5 %, respectively.

In summer: the average indoor air temperature in 7 building with air conditioning system is from 24.2 – 28.5 ºC; the average relative humidity in 7 buildings are 38.7 – 60.3 %.

The average air velocity in winter and summer is 0.05 – 0.2 m/s.

The measured parameters were re-calculated into ET and PMV which were shown in figures from 3 to 6. PMV consume metabolic rate is 1.1 met (typing), clothing insulation is 0.5 clo in summer and 1.0 clo (building A) and 1.3 clo (building B) in winter without heating were calculated.

Figure 3. Effective temperature - ET in 3 buildings in Hanoi

Note: C building is heating; A building and B building are without heating in winter
3.3 Survey Responses
Figures 7 and 8 show the results of perception of comfort expressed by office staffs. In summer 82\% is satisfied with relative humidity from 38.7\% to 60.3\%; 16\% is dissatisfied due to low humidity and 2\% is dissatisfied due to high humidity; about air velocity: 61\% is satisfied, 34\% is dissatisfied due to low air velocity, 5\% is dissatisfied due to high air velocity.
Figure 9 illustrated the survey data on sick building syndrome perception of interviewed occupants. Feeling of sleepiness and lack of oxygen are the most frequent problems which took up of 22.5%, 18.75% and 14.3% in three buildings of A, B and E respectively. This observation was in line with what concluded from evaluation of air concentration.

**3.4. Discussion**

- **TSP và PM$_{2.5}$:** In international standards of ASHRAE [1], Singapore [27], Japan [28], Illinois (United State) [30], Taiwan [31], PM$_{2.5}$ threshold value is 15–65 µg/m$^3$, TSP is 150 µg/m$^3$. Currently Vietnam has not a IAQ Standard yet. So, we used standards of Singapore [27] (TSP = 150 µg/m$^3$) and Japan [28] (PM$_{2.5}$ = 35 µg/m$^3$, TSP ≤ 150 µg/m$^3$).

Figure 1 and Figure 2 shows that the concentration of TSP dust in the summer at surveyed buildings A, B, F, G all exceeded the standards of Singapore and Japan from 1.2 to 1.8 times, the highest is building A and building F, especially building F has the highest concentration in all survey periods of time.

PM$_{2.5}$ dust concentration at buildings A, B, C is from 1.51 to 3.14 times the value in standard of Singapore and Japan, particularly it is exceeded from 2.74 to 3.14 times in A building at 16h30, this building has a side adjacent to a high-traffic route from the South going through the center of the capital city of Hanoi and right next to the red-green intersection. D, E buildings in Danang city have concentrations of TSP and PM$_{2.5}$ are much lower the value in standards of Singapore and Japan. These are two buildings are modern architecture, central air conditioning and fresh air supply system operating year-round and located in new urban areas with the best surroundings compared to others.

- **VOC:** The VOC can be detected in A, B, C buildings only. These rooms had smokers, printers, photocopy machine in the office. At 8h30 - 10h30, building A has the highest VOC concentration from 1.1 to 2.9 times the value in Singapore's recommendation (3 ppm) [27].

- **CO$_2$:** Almost CO$_2$ concentrations is more than 1000 ppm, higher than Singapore standard (β*CO$_2$ < 700 ppm) [29]. CO$_2$ concentrations in buildings in HoChiMinh city is (β*CO$_2$ < 200 ppm). The highest CO$_2$ concentration is from 764 ppm to 2468 ppm at A building because of high occupation, no mechanical ventilation.

- **Humidity and wind velocity:** The average relative humidity in offices buildings with air conditioners is from 32.5% to 60.3% and the air speed is from 0.05 m/s to 0.2 m/s. Meanwhile, the standard TCXDVN 306: 2004, relative humidity is 80% and wind speed from 0.3 m/s to 0.5 m/s. Thus, the values of humidity and wind speed in TCXDVN 306: 2004 are not consistent with the actual use of air conditioners.

- **Thermal sensation in ET and PMV index:**
In winter season, the ET index in B and C buildings are cold and slightly cold, outside of thermal comfort zone, but the PMV index are in thermal comfort zone, are consistent with interview results. This shows that the ET sensing scale for the cold season according to TCXDVN 306: 2004 standard is not entirely consistent with the current thermal comfort.

In summer season, all average daily ETs are lower than the ET at neutral comfort in TCXDVN 306: 2004 standard.

In summer season, in A and B buildings: PMV index is 1.16 (PPD = 33%) and 1.27 (PPD = 39%), respectively, slightly warm. ET index is neutral comfort. Interview results show that > 90% and 63% of people in A and B buildings, respectively, interviewed is satisfied. Thus, the ET temperature sensing scale for the hot season according to TCXDVN 306: 2004 standard is more suitable for the thermal comfort of Vietnamese people than PMV index.

The results of the ET and PMV index in summer season in rooms E1 and E2 with central air conditioning are in the neutral thermal comfort zone. However, only 43–48% of respondents is satisfied, 30–36% feel slight cool and 18–22% feel slight warm. So, engineers need to pay attention to the uniformity in designing air conditioning systems.

4. Conclusion
The indoor environment has to fulfill two requirements in order to satisfy the occupants: (i) the health risk should be negligible and (ii) the indoor environment should be comfortable and pleasant. From the results, it can be conclude that, in general, thermal comfort in offices is in relatively good quality. IAQ indicators in the room through surveys and assessments showed that the IAQ of buildings are dependent strongly on the technical systems inside the building, especially the ventilation system. Currently, Vietnam has issued quite well and fully guidelines on the design and construction of air conditioning and ventilation systems. However, there is still a gap about the ability to control and operate these systems.

In winter, the effective design of building envelope for well-performed insulation and tightness can ensure comfort level, and therefore reduce heating costs and improve energy efficiency.

In summer when the temperature rises, the operation of air condition is needed, and the ventilation system should be operated as recommended by the standards for better energy efficiency, thermal comfort as temperature, humidity and air filtration issues, maintain indoor air quality. Therefore, Vietnam needs to quickly issue a new standard on air quality in residential buildings, and it is necessary to revise and update TCXDVN 306: 2004 to adapt current requirement.

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