

# A climate analysis tool for passive heating and cooling strategies in hot humid climate based on Typical Meteorological Year data sets

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## Abstract

Through a newly developed climate analysis tool, this paper examines the potential of improving thermal comfort under the climates of Vietnam thanks to passive strategies. A Building climatic chart for Vietnamese was proposed based on Fanger's theory [1] and the comfort zone of this chart was then extended by calculating the effects of passive heating and cooling strategies. Typical Meteorological Year weather data are used for extracting and graphically printing of hourly environmental parameters on the psychrometric chart and for climate analysis, subsequently. The limitation and the scope of this method are also specified.

The climates of three climatic regions in Vietnam have been used as case studies using all year, seasonal and monthly analysis. The results show that natural ventilation is an effective cooling solution as thermal comfort improvement varies with the climatic zones, increasing from 24.8% in Hanoi, 22.1% in Danang to 32.0% in Hochiminh city. Meanwhile, passive solar heating is only effective under the climate of Hanoi. Direct evaporative cooling also shows great cooling potential for comfort improvement but probable elevated humidity is not expected. Total possible comfort in a year of each location indicates that further climate modification methods are inevitable to achieve comfort during extreme weather conditions, especially in Hanoi.

Keyword: *climate analysis; passive strategy; hot humid climate; thermal comfort; Vietnam*

## 1. Introduction

A full understanding of local climate is the main requirement for the designs of climate responsive architecture towards sustainable development. This requirement indicates that designer should be supported by suitable weather-analysis tool rather than relying completely on statistical climatic data from other providers. However, application of environmental support tool among design community in hot humid climate seems rather limited. Wong [2] conducted a survey on the application of environmental design tools among designers in Singapore. The results revealed that almost architects examined did not employ such tools in their works and that consultations with building scientists are rare. This means that designers are likely hesitant to use sophisticated tools or commercial tools, which may impose a burden on their time and budget. Therefore, a simple tool for climate analysis used in preliminary design is essential. Recently there has been some weather tools developed for climate analysis [3; 4]. Due to the criteria implemented, they are design support tools aimed to apply in temperate and cold climates where occupant tends to use HVAC systems more frequently. Under hot humid climate, naturally ventilated buildings are very common and thus occupant's comfort criteria may differ significantly. This paper proposes a simple method for climate analysis by which the potential of comfort improvement by using passive cooling and heating strategies could be derived. As being presented in detail, this method also allows user to modify the thermal comfort model and algorithms to meet specific requirements or conditions of a climate.

The method proposed will be carried out through three steps: (1) proposal of an appropriate comfort zone on Building psychrometric chart for people living in hot humid climate; (2) extracting and printing of climate data on this chart; and (3) quantitative analysis and assessment of thermal comfort, heating and cooling potential of passive strategies. Three climatic regions in Vietnam are investigated as case studies.

Vietnam generally has tropical monsoon climate [5]. Whole territory of Vietnam is located in the tropics, in the Southeast edge of the Asian continent, bordering the East Sea (part of the Pacific Ocean). The climate of Vietnam is strongly influenced by trade winds, which often blows at low latitudes. As the territory of Vietnam largely spreads from the North to the South, in this analysis 3 typical sites, including Hanoi (21° North), Danang (16° North) and Hochiminh city (10° N) which represent 3 climatic regions in the North, Centre and South of Vietnam, have been selected (see Fig. 1).



Figure 1: Map of Vietnam which shows selected sites of the present study

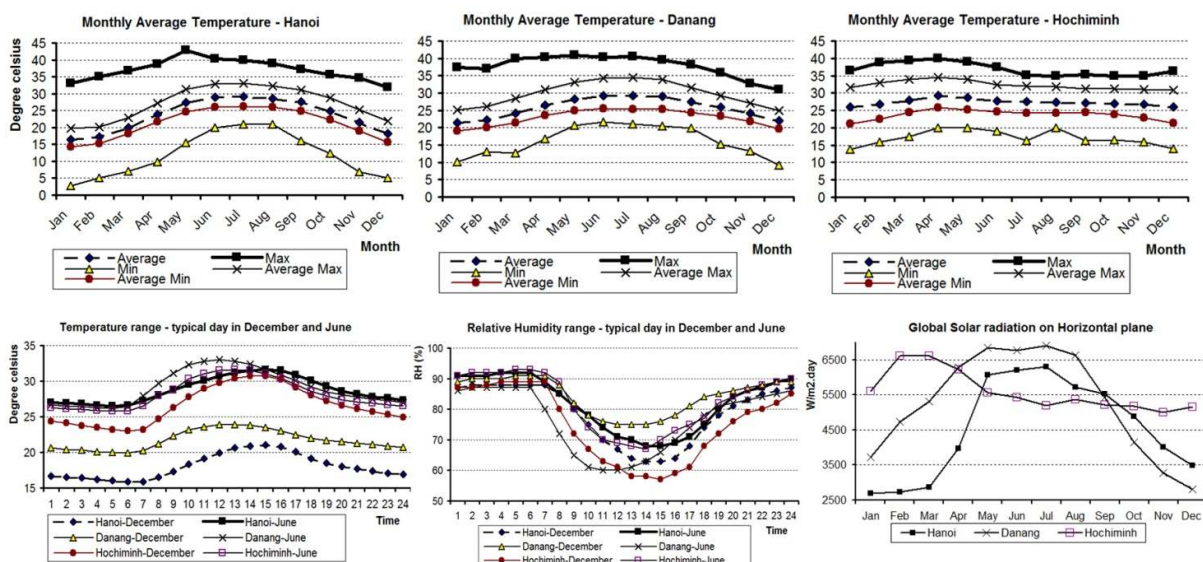


Figure 2: Statistical data of temperature, relative humidity and solar irradiation in Hanoi, Danang and Hochiminh city.

Fig. 2 summarizes main statistical climatic data of the 3 sites from reference [5]. Differences in geographical characteristics and latitudes of the three climatic regions cause some climatic

distinctions. Hanoi has 4 separated seasons with a fairly cold winter, but the lowest temperature hardly falls below 5°C. The highest temperature can reach 40°C. In Danang, the climate is basically tropical monsoon. There is no cold winter. Lowest temperatures is often well above 15°C. The highest temperature may sometimes exceed 40°C. Hochiminh city has typical hot and humid climate with monsoon all year round. There are annual dry hot and rainy warm seasons corresponding to two inhomogeneous monsoons in the region. Rainfall is quite large. High average air temperature and solar radiation during the year indicate that cooling demand would be dominant. Abundant wind around the year offers a great potential for passive cooling and indoor air quality improvement.

In Vietnam, air relative humidity is always high and reaches around 90% at night. The daily amplitudes to temperature variation are quite small and almost below 7 °C, even in summer. This is because high relative humidity and cloudy sky act as a "blanket" preventing radiation loss from the earth and prevent air temperature from dropping much further.

## 2. Comfort zone for people living in hot humid climate of Vietnam

The comfort zone on Building psychrometric chart is well known as an important indicator using in climatic analysis and establishing of climatic design strategies. The earliest efforts to establish the comfort zone and the building climatic chart could be found in some publications [6; 7; 8]. However, it is still an *argument* that under a specific condition the comfort zone for different climatic regions is unchanged. Based on steady-state heat balance theory of Fanger [1], ASHRAE [9] reported that under steady-state condition, “*people cannot physiologically adapt to preferring warmer or colder environments, and therefore the same comfort conditions can likely be applied throughout the world*”. However, the conventional comfort zone proposed by ASHRAE standard 55 [10] seems inappropriate for Vietnamese because of the fact that it omits the effect of humidity adaptation of people living in hot humid climate. In this standard the upper comfort limit of 0.012 kg<sub>water</sub>/kg<sub>dry air</sub> is rather stringent because this requirement is hardly satisfied in hot humid climate where relative humidity usually exceeds 80%.

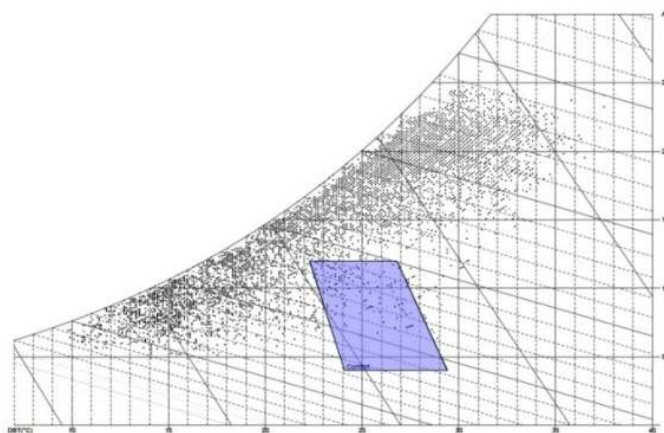


Figure 3: Incorrect prediction of comfort zone for Hanoi by weather tool [3]

Some computer weather tools have failed in predicting comfortable period of the climates of Vietnam because they used inappropriate comfort boundaries. The comfort zone for Hanoi proposed by Climate consultant software [4] using comfort model of ASHRAE standard 55 [10] indicates that only 4.9% of total time of a year should be comfortable. Also in Hanoi, Fig. 3 shows the comfort prediction of another weather tool [3] in which Szokolay's method [11] was adopted. The significant weakness of this method is that a 'steady-state' condition was imposed (clothing =

0.57 clo, metabolic rate = 1.25 met, wind speed was not mentioned), but the ‘adaptive comfort model’ of Auliciems [12] ( $T_n = 17.6 + 0.31 \times T_{o,av}$ ) was employed to find neutral temperature. According to this prediction, only 2.5% of total time in a year is considered comfortable. Actual locally measured percentage of satisfied people is currently not available due to the lack of outdoor comfort survey in Vietnam. However based on the data of 7 comfort surveys in naturally ventilated buildings in hot humid South-East Asia [13], we found that 2113 of 3271 (64.6%) votes were on [-1, 1] and 961 of 3271 (29.4%) votes were on [-0.5, 0.5] of ASHRAE seven-point scale. These actual percentages of satisfied people of South-East Asia reveal that the predictions given by these computer weather tools [3; 4] may significantly underestimate the actual comfort potential of the climates of Vietnam.

In Vietnam air humidity hardly falls below 60% which is around the upper limit of ASHRAE comfort zone. These indicate that it is essential to create appropriate thermal comfort boundaries for Vietnamese as well as other people living in the tropics, considering their adaptation to very humid environment. This paper therefore proposes a revised thermal comfort zone on the Building psychrometric chart for Vietnamese based on the Fanger’s ‘steady-state’ thermal comfort theory [1] as shown in Fig. 4. Field surveys on thermal comfort have pointed out that Fanger’s comfort model worked fine in ‘steady-state’ thermal environment such as that of air-conditioned buildings [14]. In naturally ventilated buildings, human thermal adaptations and fluctuating thermal stimuli may generate some deviations of occupants’ thermal perception. Hence, the conditions for comfort may be extended well beyond conventional comfort boundary. This study makes some modifications on the conventional comfort zone and implements some Control Potential Zones (CPZs) to take human adaptations into account, including: expanding upper humidity limit, varying clothing insulation, cooling by natural ventilation and water evaporation, heating by solar energy. The revised comfort zone and its CPZs are therefore able to apply in both naturally ventilated and air-conditioned buildings.

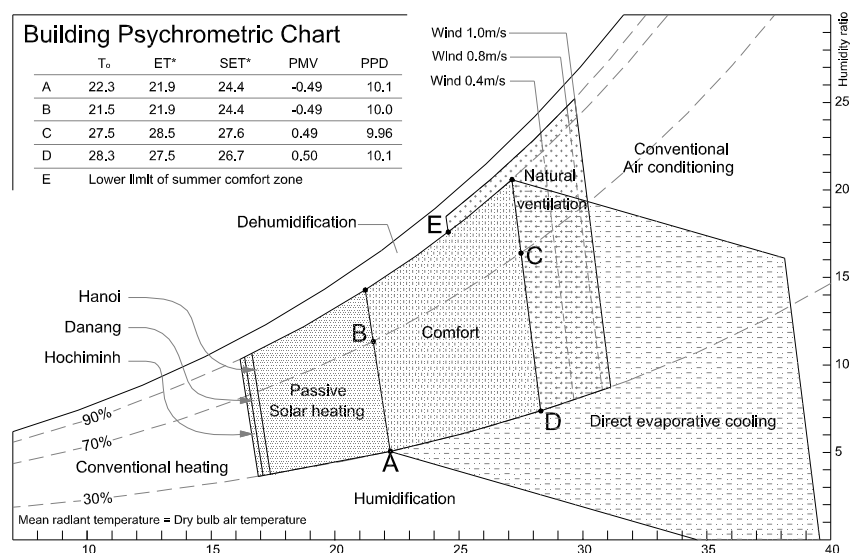


Figure 4: Comfort zone proposed for Vietnamese and its control potential zones

The comfort zone in Fig. 4 is established for normal Vietnamese in sedentary work ( $60W/m^2 - 1$  met) under still air condition (0.15 m/s). Clothing insulation values may vary from 0.5 clo to 1 clo, reflecting the change of clothing style to suit seasonal weather. The environmental condition inside this comfort zone is expected to satisfy 80% of occupants, based on 10% of predicted whole-body dissatisfaction given by PMV-PPD index and 10% possible dissatisfaction caused by local discomfort, e.g. draught, cold floor, radiant temperature asymmetry.

The cooler and warmer boundaries of the comfort zone are defined by the PMV-PPD index. These boundaries are lines AB and CD in Fig. 4. Point inside these boundaries would satisfy  $-0.5 \leq \text{PMV} \leq 0.5$  and  $\text{PPD} \leq 10\%$  correspondingly. Point B and C rely on 70% relative humidity because PMV-PPD model becomes a little inaccurate at relative humidity higher than 70% [15]. These lines nearly coincide with the lines of constant effective temperature  $ET^*$ .

The lower humidity lever of the comfort zone in Fig. 4 was set at 30% relative humidity because it hardly falls below this threshold in humid climate. On the other hand, Vietnamese are not acquainted with the discomforts caused by dry air such as dry nose, throat, eyes, skin and lip cracks.

The upper humidity limit is more complicated due to the lack of specific study on this issue. ASHRAE standard [10] specifies the upper humidity ratio limit at  $0.012 \text{ kg}_{\text{water}}/\text{kg}_{\text{dry air}}$ . This limit is mainly based on the requirements for hygiene and for avoiding condensation - mould growth in the ducts of HVAC system [16] rather than on human thermal comfort. In fact, under hot humid climate building surface temperatures are normally closed to or higher than ambient air temperature due to solar heat gain, thus the climate itself reduces the potential of condensation and mould growth on building surfaces, allowing the higher acceptable humidity limit.

Olgyay [7] proposed around 78% relative humidity as upper limit for U.S. inhabitants living in moderate climatic regions. In his book, Givoni [8] suggested that upper limit could be enlarged to 90% relative humidity and up to 93% with ventilation. Pham [17] conducted a small comfort survey in Vietnam in 2002; his results revealed that over 80% of subjects found to be thermally comfortable at  $28.5 - 29.5^\circ\text{C}$  and 90% relative humidity. Adaptive comfort approach and standards [10; 18] do not indicate any humidity limit for thermal comfort, provided that adaptive opportunities are allowed. Based on 3054 thermal sensation votes of people living in hot humid South-East Asia, the correlation and the regression coefficient between relative humidity and comfort temperature was found very low ( $T_{\text{comf}} = 0.073 \text{ RH} + 22.77$ ,  $R^2 = 0.056$ ) [13], revealing minor effect of relative humidity on thermal perception. Based on above-mentioned studies and findings, the upper limit of the revised comfort zone was established at 90% relative humidity. During hot weather, this humidity limit may be even extended to 95% under the effect of wind of  $0.8 - 1 \text{ m/s}$  because air movement can eliminate stuffiness and accelerate evaporation of sweat and heat diffusion.

### 3. Comfort control potential zone by using passive cooling and heating strategies

In this paper, **indirect** passive cooling and heating strategies (e.g. **indirect** evaporative cooling, thermal mass and night purge, indirect solar heating) were excluded as they are related to other building parameters, occupancies and equipments. Hence, only **direct** passive cooling and heating measures which are directly related to the climate were examined in subsequent sections.

#### 3.1 Passive cooling by natural ventilation

The convective - evaporative heat exchange between a person and surrounding environment is partly influenced by air movement. The extension of comfort zone by air movement depends on occupant's clothing, activity and different between skin/clothing and the air temperature. Both ASHRAE standard [10] and ISO 7730 [15] recommend a maximum wind speed of  $0.82 \text{ m/s}$  for sedentary activity. However, this limit is mainly based on requirement of stabilization of loose clothes and papers rather than human discomfort caused by draught. Recent field survey on occupants' wind preference in hot humid climate indicates that minimal air velocity values obtained based on 80% and 90% acceptability were close to or above  $0.8 \text{ m/s}$  [19]. It is not difficult to create thermal comfort for a person exposed to a wind velocity of  $1 \text{ m/s}$  [1] and under overheated



conditions air velocities up to 2 m/s may be welcome [11]. The air movement of 1 m/s is therefore adopted in the CPZ by natural ventilation shown in Fig. 4. Temperature offset above warmer limit of comfort zone by elevated air velocity is simply followed the calculation method recommended by these two standards [10; 15]. Point E lies on the lower summer comfort boundary corresponding to clothing insulation of 0.5 clo. This extension neglects the effect of humidity on cooling potential of air movement because this effect is rather minor.

### 3.2 Passive cooling by Direct evaporative cooling

Direct evaporative cooling is a process where water evaporates directly into the airstream, reducing the air's dry-bulb temperature and raising its humidity, but wet-bulb temperature is always unchanged. In Vietnam, relative humidity usually drops to 60% to 70% at noon during summer period (around June, July and August), enabling greater use of evaporative cooling. Particularly, much harsh climate can be found in some provinces located between Danang and Hanoi where very hot and dry condition (42 °C and 30% relative humidity) may occur during summer months due to the Föhn wind from Laos. In fact, this cooling method has been widely used for outdoor or industrial environment in Vietnam; thus, its potential should also be investigated.

In direct evaporative cooling, the total heat content of the system does not change, therefore it is said to be *adiabatic*. The cooling performance or leaving air temperature of the cooler may be determined:

$$T_{LA} = T_{DB} - (T_{DB} - T_{WB}) * \varepsilon \quad (1)$$

where

$T_{LA}$  = Leaving air dry-bulb temperature;  $T_{DB}$  = Inlet Dry-bulb temperature;  $T_{WB}$  = Inlet Wet-bulb temperature;  $\varepsilon$  = Efficiency of the evaporative cooler.

Direct evaporative cooler can be completely passive (e.g. water pool, hand sprayer system, water-evaporative wall system, evaporative cooler driven by solar energy), partly passive (e.g. evaporative electric fan) or active (e.g. swamp cooler). The cooler efficiency usually runs between 80% and 90%. Under typical operating conditions, an evaporative cooler will nearly always deliver the air cooler than 27°C. A typical residential swamp cooler in good working order should cool the air to within 3°C – 4°C of the wet-bulb temperature [20]. Primarily based on previous experiment of other authors, Givoni [21] stated that ambient air can be cooled by 70–80% of the dry-bulb - wet-bulb difference. This observation led him to a comfort limit of ambient dry-bulb temperature of 42°C controlled by direct evaporative cooling. Based on an experimental investigation of porous ceramic evaporators for building cooling, Ibrahim et al. [22] found that dry-bulb temperature easily dropped of 6–8°C at a mean air velocity of 0.08–0.10 m/s, accompanied by a 30% increase of relative humidity. It is impractical to lower dry-bulb temperature more than 11°C by direct evaporative cooling [11]. The upper comfort limit was therefore extended 11°C along wet-bulb temperature line.

### 3.3 Passive heating using Solar energy

The basic principle of passive solar heating involves allowing solar irradiation into building through solar aperture (e.g. trombe wall system, massive masonry wall, south-facing glazing façade, and sunspace), then using this energy to warm up the internal environment. It is quite sophisticated to precisely quantify the periodic heat flows between the Sun, building and its surrounding. To get a very approximate idea of how effective a passive solar system is, building energy balance and steady-state heat transfer model are used. Assume a typical south-facing space (e.g. an apartment or

an office) in a building of 100 m<sup>2</sup> floor area (10 m x 10 m x 3.3 m) with 33 m<sup>2</sup> external south-facing wall; direct solar gain is controlled by 10 m<sup>2</sup> south-facing window (small window is to prevent overheating); no heat exchange with adjacent spaces and no internal heat gains.

The energy flow through the window  $Q_w$  can be estimated on the following basis [9]:

$$Q_w = (SHGC) * I_s * A_w - U_w * A_w * (T_i - T_o) \quad (2)$$

The energy flow through the external wall  $Q_c$  is calculated as [23]:

$$Q_c = U_{ew} * A_{ew} * (T_i - T_{sol-air}) \quad (3)$$

In the above equation, the concept Sol-air temperature is used to include the heat flux from the Sun and sky on the wall surface. Assume no difference between outdoor air temperature and sky mean radiant temperature, Sol-air temperature is defined as:

$$T_{sol-air} = T_o + \frac{I_s * \alpha}{h_o} \quad (4)$$

The energy flow caused by air infiltration through crack and openings  $Q_v$  is calculated as:

$$Q_v = 1004 * 1.204 * \frac{N * V}{3600} * (T_i - T_o) \quad (5)$$

where

$Q_w$ ,  $Q_c$ ,  $Q_v$  = instantaneous energy flow through window, wall and ventilation, W; SHGC = Solar heat gain coefficient, dimensionless;  $I_s$  = solar irradiance on south-facing surface, W/m<sup>2</sup>;  $U_w$  = window overall coefficient of heat transfer (U-factor), W/m<sup>2</sup>.°C;  $A_w$  = total projected window area, m<sup>2</sup>;  $T_i$  = indoor air temperature, °C;  $T_o$  = outdoor ambient temperature, °C;  $T_{sol-air}$  = Sol-air temperature, °C;  $U_{ew}$  = external wall thermal transfer value (U-value), W/m<sup>2</sup>.°C;  $A_{ew}$  = external wall area, m<sup>2</sup>;  $T_{sol-air}$  = Sol-air temperature, °C;  $\alpha$  = solar absorbance of the external wall, dimensionless;  $h_o$  = conductance of the air film on the wall surface, W/m<sup>2</sup>.°C, taken as 10 to 20 at wind speed of 1 m/s [23]; 1004 = volumetric specific heat of the air, J/kg.°C; 1.204 = density of air at 20 °C and standard pressure, kg/m<sup>3</sup>; N = number of air change per hour; V = volume of the space, m<sup>3</sup>.

The space achieves energy balance at  $T_i$  and  $T_o$  (evaporation heat loss can be omitted), thus:

$$Q_s - Q_c - Q_v = 0 \quad (6)$$

Assume that external wall is 220mm light yellow cavity brick wall with  $U_{ew} = 1.6$  W/m<sup>2</sup>.°C and  $\alpha = 0.3$ ; the window is 5mm single glazing - vinyl frame with U-factor = 5.2 W/m<sup>2</sup>.°C and average SHGC = 0.45;  $h_o = 15$  W/m<sup>2</sup>.°C; air change rate N = 0.8 ACH; indoor temperature at the lower limit of comfort zone  $T_i = 22.3$ °C at RH = 30% (see Fig. 4); average solar irradiance ( $I_s$ ) on south-facing wall in the coldest month of Hanoi, Danang and Hochiminh city are 166, 175 and 184 W/m<sup>2</sup> [5], respectively. Thus  $T_o$  for Hanoi, Danang and Hochiminh city are 17.4°C, 17.1°C and 16.9°C. These are lowest temperature at which heat delivered by a passive solar system can compensate to maintain indoor comfort temperature.

It is necessary to mention that the efficiency of a passive solar system strongly depends on building designs, solar system type and many design variables of the system. The above model considers a

typical design in standard condition and some assumptions, the given result is therefore simply a reference.

#### 4. Plotting weather data on the Building psychrometric chart using Typical Meteorological Year weather data set

The Typical Meteorological Year (TMY) files for more than 2100 locations of the world can be obtained from the opened database of the U.S. Department of Energy [24]. More than 1000 other weather files of other locations distributed under license from Meteotest<sup>1</sup> can also be found in TRNSYS thermal simulation package.<sup>2</sup> Some computer-aided weather tools can create weather file with acceptable accuracy by interpolating monthly weather data provided by user. A TMY data set provides users with a reasonably sized annual data set that holds hourly meteorological values for a 1-year period that typify conditions at a specific location over a longer period of time, such as 30 years. Consequently, hourly weather data of any season, any month or any day can be separately extracted. In this step, hourly meteorological parameters of Hanoi, Danang, and Hochiminh city were graphically printed on the psychrometric chart using hourly data of TMY weather files. Due to space constrain, only the climate of Hanoi was presented in Fig. 5. The comfort zone and its CPZs in Fig. 4 were then superimposed. All analysis and statistics were carried out on this 2-layer psychrometric chart from which comfortable, potentially comfortable and uncomfortable period can be determined.

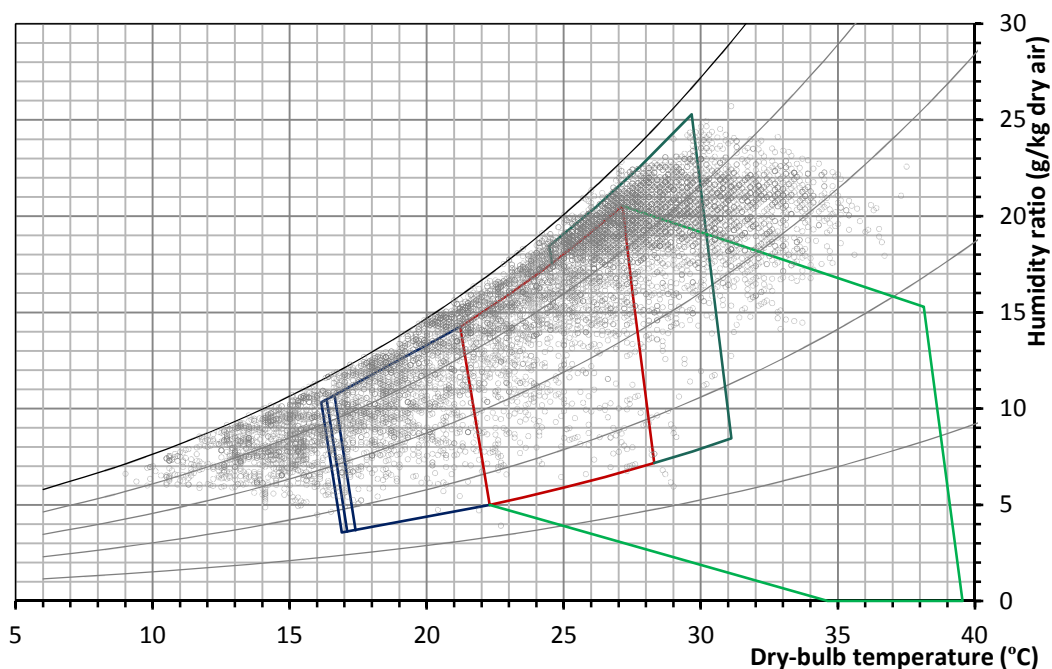


Figure 5: Hourly plot of Hanoi weather data on Building psychrometric chart at standard atmospheric pressure (101.325 kPa)

In Fig. 5, hourly conditions of a year are presented by the scattered cloud on the temperature-humidity Cartesian coordinate system. Each point is therefore presented by its x-coordinate (temperature) and y-coordinate (humidity ratio). Hourly temperature is always available in the

<sup>1</sup> Meteotest, Fabrikstrasse 14, 3012 Bern, Switzerland

<sup>2</sup> University of Wisconsin Madison. TRNSYS energy simulation software package. Available at <http://sel.me.wisc.edu/trnsys/index.html> [Last accessed 13 Feb 2012]



weather file. Hourly humidity ratio is converted from hourly relative humidity available in weather file. Following steps could be followed, giving an acceptable accuracy of conversion.

At standard atmospheric pressure (101.325 kPa), water vapor saturation pressure  $p_{ws}$  of saturated air is derived by Hyland and Wexler equation [25] (for higher accuracy, the method in [26] should be used):

$$\ln p_{ws} = C_1 / T + C_2 + C_3 T + C_4 T^2 + C_5 T^3 + C_6 \ln T \quad (7)$$

Then partial pressure of water vapor  $p_w$  is calculated by the definition of relative humidity:

$$\phi = \frac{p_w}{p_{ws}} \bigg|_{t,p} \quad (8)$$

Then humidity ratio  $W$  is given by (in [9] – chapter 1):

$$W = 0.621945 \frac{p_w}{p - p_w} \quad (9)$$

where

$p_{ws}$  = water vapor saturation pressure, Pa

$p$  = standard atmospheric pressure, Pa

$p_w$  = partial pressure of water vapor, Pa

$W$  = humidity ratio, kg water vapor/kg dry air

$T$  = absolute temperature, K = °C + 273.15

$\phi$  = relative humidity

$C_1 = -5.800\ 2206\ \text{E}+03$

$C_2 = 1.391\ 4993\ \text{E}+00$

$C_3 = -4.864\ 0239\ \text{E}-02$

$C_4 = 4.176\ 4768\ \text{E}-05$

$C_5 = -1.445\ 2093\ \text{E}-08$

$C_6 = 6.545\ 9673\ \text{E}+00$

These calculations are automatically executed by spreadsheet (e.g. Microsoft Excel<sup>®</sup>), providing hourly humidity ratio of a whole year.

The next step is to identify whether a point locates inside or outside the zones investigated of the building psychrometric chart and to calculate number of points inside the boundaries. First, the mathematical function of each boundary is defined ( $f(x)$ : temperature → humidity ratio). Each zone, e.g. comfort zone, normally consists of 4 boundaries. Points and number of points inside these boundaries are then identified and calculated by an IF-THEN-ELSE logic in Spreadsheet. All these processes have to be done only once and later can be employed many times with a single mouse click.

## 5. Results

### 5.1 All year assessment

All year weather data of each site were plotted on the building psychrometric chart. For all sites, the air is always very humid and sometimes saturated (see Fig. 5). Fig. 6 shows all year cumulative comfort potentially achieved by using various passive cooling and heating strategies and their combinations. The weather in Hanoi is found to be naturally comfortable in only 23.0% of total time of a year whereas in Danang and Hochiminh city this value was around 37%, revealing that the climate of Hanoi seems more severe than the others. It is worthy of note that Hanoi experiences both cold-humid and hot-humid weather pattern. This type of climate is really a challenge to any designer because of the fact that the building must be both ‘opened’ using lightweight materials in summer and ‘closed’, well-insulated in winter. Very high humidity in winter also raises the possibility of saturated water on external building envelop, causing mould growth and structure damages. On the contrary, both Danang and Hochiminh city has warm-humid winter and hot-humid summer where only overheating period should be taken into account in building design.

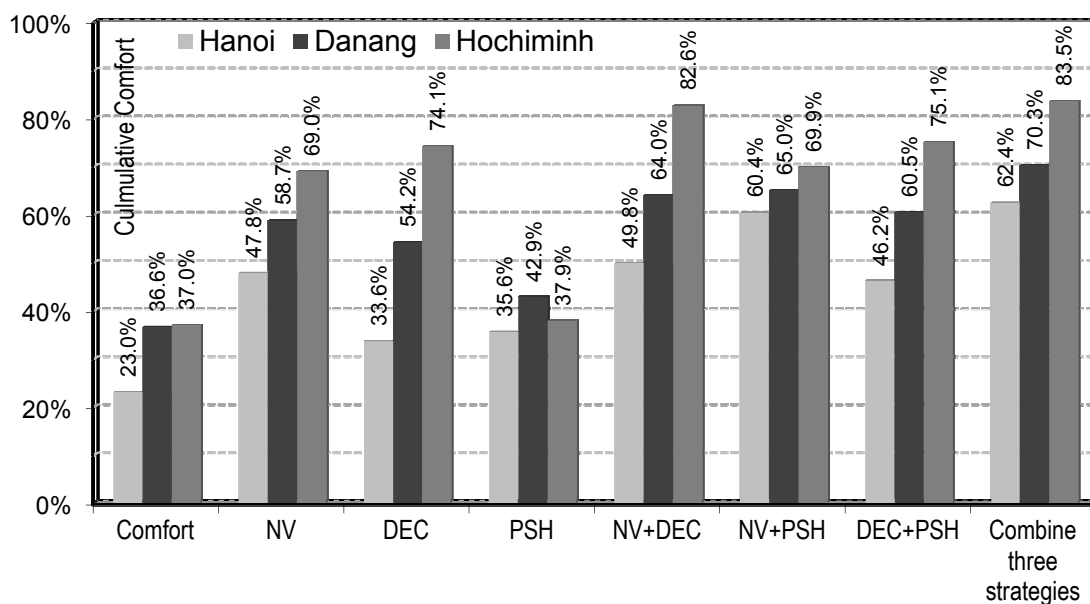


Figure 6: All year cumulative comfort using passive heating and cooling strategies (NV: natural ventilation; DEC: direct evaporative cooling; PSH: passive solar heating)

Table 1: Potential comfort improvement by each strategy

Passive strategies applied	Comfort improvement (%)		
	Hanoi	Danang	Hochiminh
Natural ventilation (NV)	24.8	22.1	32.0
Direct evaporative cooling (DEC)	10.6	17.6	37.2
Passive solar heating (PSH)	12.6	6.3	0.9
NV + DEC	26.8	27.4	45.6
NV + PSH	37.6	28.4	32.9
DEC + PSH	23.2	23.9	38.1
Combine all strategies	39.4	33.65	46.6

The percentage of comfort improvements by each passive strategy are separately listed in Table 1. In Hanoi, natural ventilation proves to be the most effective strategy for comfort improvement (24.8% of a year). Comfort improvement by passive solar heating (12.6% of a year) is valuable because heating season is quite short. Total comfort potential of a year is only 62.4%, revealing that

Hanoi mainly relies on many other solutions to yield all year comfort. In Hochiminh city, natural ventilation is an extremely effective solution by which the comfort period can be nearly doubled. Direct evaporative cooling is also a good promise because it may provide comfort for over 74% of total time. Nearly 84% of total time would be thermally acceptable if all strategies were combined, revealing that passive solutions must be considered as the first choice in building design in Hochiminh city. Danang geographically locates in the centre of Vietnam; consequently the climate characteristics and comfort improvement in Fig. 6 show a climatic transition from Hanoi to Hochiminh city. It can be seen that passive solar heating is not very important in Danang (improvement of 6.3%) and does not play any role in Hochiminh city (improvement of 0.9%).

The discomfort period shown in Fig. 5 helps designer determine appropriate building design to modify the climate. It also reveals hints to select heating, cooling and dehumidification system for the building and to size these systems preliminarily. For the sites where data of extreme years such as Design Summer Years or Design Winter Years are available, further analyses on these data using this method may give building scientists more useful inputs.

## 5.2. Four-season and 12-month assessment of the climate in Hanoi

A further analysis was carried out to examine the potential of comfort improvement of these strategies in each season and each month in Hanoi. The weather data of each month and each season were plotted on the graph shown in Fig. 4. The results are reported in Fig. 7 and 8, respectively.

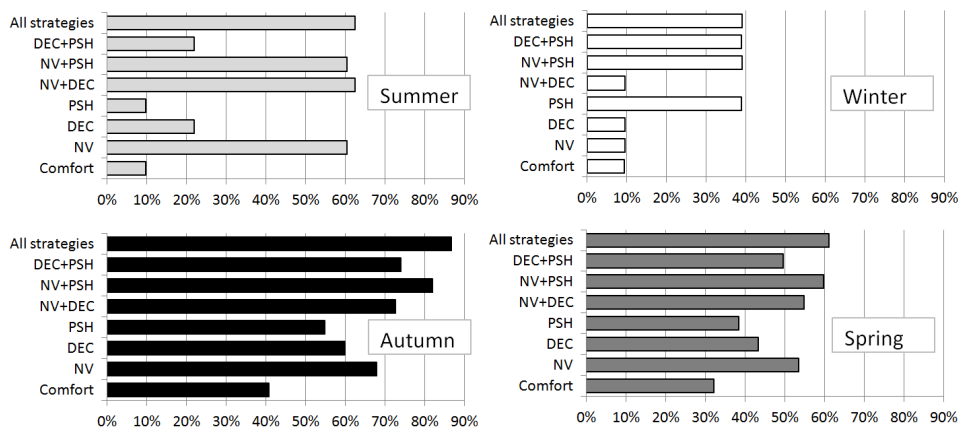


Figure 7: Cumulative comfort during 4 seasons in Hanoi by passive strategies (NV: natural ventilation; DEC: direct evaporative cooling; PSH: passive solar heating)

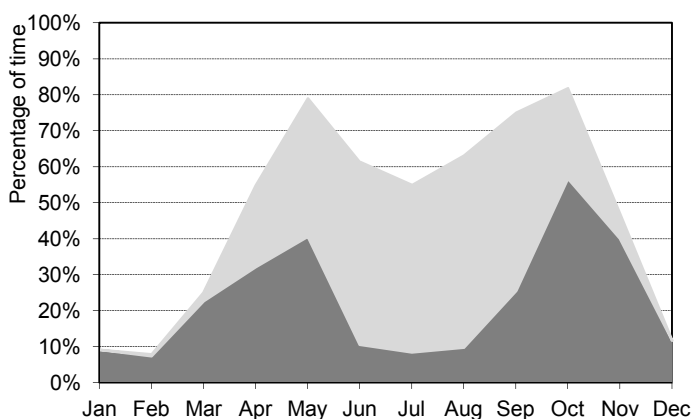


Figure 8: Natural comfort and cumulative comfort by natural ventilation during 12 months in Hanoi

Fig. 7 shows that in winter, comfortable time occupies only 10% of the season and only passive solar heating would be effective. In other seasons, natural ventilation would provide comfort at least of 54% of the total time. Under humid condition, natural ventilation offers many advantages, e.g. improvement of indoor air quality and prevention of mould growth. Other strategies as well as combination of various strategies are not recommended because comfort improvement is not noticeably higher. This analysis reveals that natural ventilation and passive solar heating are among the most important passive solutions for Hanoi and should be the greatest concern of designer.

Natural comfort and cumulative comfort during 12 months by natural ventilation is presented in Fig. 8. According to this, natural ventilation is effective from April to the end of September. The most effective period falls within summer (from June to the end of August), confirming that natural ventilation would significantly reduce building cooling load and energy consumption. Maximum comfort occurs in mid-spring and mid-autumn. Fig. 7 and Fig. 8 also reveal that during winter natural comfort is extremely low (below 10%) due to the cold weather and that passive solar heating would be able to raise comfort up to 40%. Further suitable heating solutions and building designs are therefore needed to keep indoor environment comfortable.

## 6. Discussion and conclusion

This paper describes in detail a simple method to analyze hot humid climate in preliminary stage of climate responsive design. This paper found that natural ventilation and direct evaporative cooling almost have similar cooling effectiveness. Direct evaporative cooling often requires sophisticated equipments and may raise the air humidity and mould growth on walls and clothes. Natural ventilation is low-cost, easy to apply and provides good indoor air quality, but it strongly relies on natural wind and building configuration as well as building location. Since Vietnam has hot and humid climate, natural ventilation in most cases would be the better choice for passive cooling because the increase of air humidity due to direct evaporative cooling is not expected for humid climate. Passive solar heating should only be employed in Northern Vietnam, giving a noticeable result.

Under the climate of Vietnam, relying completely on these three passive solutions to maintain thermal comfort is not feasible but there is a significant potential of comfort improvement. In bioclimatic approach, building must be a good passive system to modify the climate through passive designs and strategies. By deeply understanding the climate, architect must play a key role in creating climate responsive shelter for a comfortable environment without using modern energy dependant systems. A wise building occupancy and management would also contribute to this target. An interesting question arises as to how to build a passive or zero energy building under such climate types of Vietnam. Further work on this issue is clearly necessary.

This method has its own limitations as hourly weather files are required for the analysis, but current data resources are available for limited number of locations (about 3100). For a certain location, weather file can be manually created using computer-aided tools (e.g. weather tools or commercial Meteonorm) with acceptable accuracy providing that sufficient input data exist. The method proposed in this paper is rather simple and can provide reliable result. The graphical presentation of the result may help architect and engineer to get familiar with this tool quicker. This method can be used and modified by any architect, designer... without much computational effort. It can be refined and applied by software programmers who focus on computer weather analysis tools and thermal comfort assessment in building simulation.

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