Tropical Thermal Comfort and Adapted Tropical Green Residential Housing

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Thermal comfort belongs to the family of basic human needs in absence of which our actions can be hampered. Lasting thermal comfort in a tropical built modern environment, however, at most locations can only be achieved with energy consumption by electrical air condition systems accounting for more than 1/3 of the present tropical CO_2-emissions. In part 1 and 2 a concept for the optimum human thermal comfort for a standard residential building in tropical Malaysia will be revisited, questioning the still prevailing ASHRAE-standards by recent lead-user studies with the concept of the TTC (tropical thermal comfort). Based upon own considerations for low-energy and passive houses, in part 3 initiating experiments will be analysed. Hence, split air condition units and fans will be compared by a greener cooling concept based on aided outside ventilation. The results prove that by tolerating and encouraging higher TTC-set points the utilisation of fresh aided ventilation can substitute or even replace split air condition units.

KEYWORDS: Thermal Comfort, Residential Buildings, CO2-Emission, Green Cooling

1. INTRODUCTION: Definition and Practice of Thermal Comfort Revisited

TC provides an acceptable temperature for human beings. We define TC as the state of mind that expresses satisfaction with the temperature, humidity and velocity of the surrounding environment (according to the SO 7730 or, likewise, ASHRAE Standard 55). Together with a) environmental sustainability and b) long-term cost saving, c) maintaining thermal comfort for occupants of buildings or other enclosures is the third of the three important objectives of TRIPLE Green building architecture and engineering. Thermal comfort belongs to the family of basic individual needs. Presuming it is taken for granted, TC enables us in a concerted effort with other physical needs to climb up further the ladder of Maslow's renowned pyramid of needs. Conversely, in its absence, mainstream research holds that any thermal gain or loss above or beyond the following generic borderlines may generate a sensation of discomfort.

A typical Western conception keeps on believing that the inside temperature for offices should be 21.1° C on average with variations of +- 2.5° C (Thermal Comfort, Fundamentals volume of the *ASHRAE Handbook*, ASHRAE, Inc., Atlanta, GA, 2005). Of course, in a cold country every °C that has not to be heated can save tremendously energy and budget. In recent years, this figure for thermal comfort has been even proposed to be altered for European *offices* to 24.5° C, which means an enormous deviation from the internationally renowned ASHRAE-standard (Braatz, 2008). For *tropical* countries, Busch (1990) carried out a pioneering field study for Thai offices in Bangkok and found that the neutral temperature or effective temperature for the air conditioned buildings and naturally ventilated buildings was 24.5ºC and 28.5ºC, respectively. A similar range of "neutral" conducive temperature was determined for a Malaysian School (Ibrahim Hussein, M Hazrin A Rahman (2009), Based on PMV regression is 25.9ºC with a comfort range between 24.4ºC and 27.4ºC. The trendy increase of temperature in offices and public cooled down areas also follows the in-part demise of the common dress code with suits and ties translatable into the 2011 policy by the Malaysian government requesting all state-owned buildings to set-point the temperature not lower than 24°C.

Abdul Rahman (1995) in his ground-breaking study found that the most comfortable indoor temperature in Malaysia (tropical region) for *residential* areas ranges even from 25.5-28°C compared to the general recommendation by World Health Organization (1990) ranging from 18-28°C. UTM's researchers Sabarinah Sh.Ahmad, Nor Zaini Ikrom Zakaria, Mohammad Shayouty Mustafa, Mohd Ghadaffi Shirat concluded that a 2.5°C range between 26.1°C and 28.6°C is optimum in tropical countries even for adopted people from Northern countries (2007). Others and our own findings clearly confirm that the optimum residential area temperature for most tropical occupants in their privacy at its highest comfortable end should not exceed 28.6º C. Therefore, the researchers at UTM state "the comfort band for the KL area for all building types is between 23.6° and 28.6° C with an optimum medium temperature in Malaysian *households* of 26.1° C" with the upper space limit (USL) set at ***28.6°C***". To conclude, two reasons can be sorted out. 1) the lower cost when putting the highest set-point in a tropical warm country. 2) the perception by people living in tropical regions is different from those in temperate and cold regions (Wang and Wong, 2007; Singh et al., 2009). The perception is based on lifestyle and habits, and based on economic necessities. All of them contribute to the explanation of the following comparative depiction:

Northern countries	19.1	21.1	23.1	ASHRAE, 2005 (general)
"new approach"	22.5	24.5	26.5	Braatz, 2008 (offices)
Malaysia (KL)	23.6	26.1	28.6	e.g. UTM, 2007

Table 1: Comparison of different thermal comfort definitions

Devising a tropically adopted concept for thermal comfort with these higher temperature banding can cause a steep increment in terms of energy saving potentials by 4-7% of less CO_2 and energy cost with each degree centigrade the temperature is increased (Green Efforts Start at 24°C. In: The Star, 12/08/2011, 2). Unfortunately, even if the USL (upper space limit)-temperature is set to its highest end at 28.6°C, in a typical uninsulated concrete building -with the walls, windows, ceiling and roof as permanent heat traps- TTC cannot be achieved during a sunny / cloudy day even in kampong areas (Sanusi, 2010).

2. MATERIALS AND METHODS

Some ground-breaking experiments will find out in the near future which level of thermal comfort can be achieved by using different green building material and electricity for green cooling. We will start out and exemplify this set of researches with ventilating a typical residential area park = “Taman” house.
An estimated 60% of residential real estates in Malaysia consist of low-rise terrace, semi-detached and detached houses. Despite of whopping technological opportunities after 2000, these buildings are constructed the same way since the 1980s and 1990s when a growing number of residential areas were built with concrete and/or bricks. The growing minority is equipped with air-condition panels at least for the sleeping room. This system has a much higher emission, as one inverter driven unit consumes around 1,200W/h peak compared to those 55-85 W of a single ceiling fan to gain thermal comfort in a mid-seized living or sleeping room. Even in 2011, 1 ½ years after Malaysia’s Prime Minister announced the commitment to save 40% of CO_2 in Malaysia until 2020, the increasing number of those taman buildings fitted with air conditioners, are non-withstanding emitting a growing level of CO_2 as ever. In this respect, most of Malaysian households emit 3-4 KW/month/m^2 which equals on average to 341 kg CO_2/ month per unit (Universiti Kuala Lumpur, unpublished research paper 04/2011).
Ordinary taman houses without air conditioners can only in part be considered “thermally comfortable” with rare well-being TC-temperatures below 28-28.6 ºC, as they can only be run with ceiling fans and some stand-fans changing just the felt “ambient” temperature on the spot of the body they are blowing onto. In terms of the cooing load they certainly are much greener compared to their air conditioned benchmark companions, but in terms of their building envelope they are not green as they are not able to provide TC. As the already existing houses in 2012 will certainly represent more than 90% of the whole built environment in 2020, how can they be greened by retrofitting and increase their thermal comfort at the same time?

As a reference building, an ideal type case study was chosen, with some distinctive elements compared with other types of residential buildings. However, basically it might stand for the bulk of creating thermal comfort in Taman houses and, as they are constructed with the same material, low-rise buildings throughout the country.

2.1. Description of Reference Building and Experiments

The reference building with a built-in area of 83.6 m^2 and 271 m^3 is a semi-detached standardised house in a suburban Taman area on the mainland near Penang. It was chosen because like such as for many of them, their envelope is highly standardised and natural or aided shading is not provided. Sun-lit locations can be typically found in many areas where the existing trees and plants were indistinctively chopped during the construction, and landscaping is restricted to sawing grass on more or less unfertile soil. Following the same logics, the windows at the south front of this semi-detached building will be hit by the sun path 11 a.m. onwards, shining in at different angles until the sun goes down at an angle of 15 degree before it will vanish behind the shape of the adjacent neighbouring building. As a result, the windows of the West front will be hit 1.30 onwards until 45-60 minutes before the sunset.

Figure 1: Picture of the Ideal Type Taman Reference Building

The minimum requirement the team had to achieve is simple insulation and slight air-tightness of the building to create an experimental design deemed necessary to compare with a building based on the open air principle.
Therefore, within the building, the master bedroom and the adjacent washroom were separated by insulating wall and door:

1. The hot permeable ***Southern part of the building*** is mainly equipped with open louver windows. It may be based on the utopian idea of bringing back traditional thermal comfort of kampong houses into a modern built environment. As recent researches have found out, this concept cannot be utilised for a stand-alone low-energy house creating its own thermal comfort because of the air leakages.

2. Following this approach, the compartment in the South with prevailing louver windows was separated towards the ***Northern part of the building*** which predominantly was equipped with closable tinted, but -at this first research stage- not laminated single-glazed windows (4mm). Working on a low budget, as a first minimum requirement to run the thermal comfort system, the air-tight part requires a closed partition wall dividing it from the permeable part, insulation material underneath the roof and airtightness of the existing windows. At a later (optional more expensive stage) the heat transmission rate can be reduced further by installing insulation atop the suspended ceiling. Set-up of the experiment: The walls, the windows and the door.

2.2. Planning of Sequential Experiments

Step-by-step, within a research period of 5 months, the researchers tested all the different elements in terms of tropical thermal comfort (especially temperature, humidity and velocity / ventilation). Based on the following 4 experiments, at a later stage, operational costs and ROI of retrofitting with less or no air conditioning units can be scrutinised.

Experiment 1: Measurement of inside and outside day-/ night time temperature / humidity in a sequence of 10 days (3.1)

Experiment 2: Installation of Thermo Ventilation Tool -> Measurement with Cross-ventilation mode and suck-in mode during night time.

This experiment can be conceived of as an initial litmus test which can tell whether or not and to which extent an air-condition reduced future is feasible for the majority of residential houses (3.2).

3. RESULTS AND DISCUSSIONS: Analysis of Results

is performed by a statistical analysis with the software Minitab ® which is the prevailing tool for 6-Sigma-DMAIC-projects. The result will be presented together with recommended improvement measures and controlling tools to reduce deviation in terms of thermal discomfort.

3.1. 1st Experiment: Temperature and Humidity Log Readings *with comparison of inside and outside temperature / humidity before any green intervention (10 days)*

Due to the Malaysianised definition of thermal comfort elaborated in part 1, we set maximum 28.6ºC and a humidity of not exceeding 70% as the tropical USL (upper space limit) borderline of thermal comfort, neglecting velocity. In our own tropical thermal model based on longitudinal participant observation, given ventilation, hot temperatures contributes to more then 90% of thermal discomfort, and humidity only to 10% at its high ends. This is due to the finding during observation and interviewing that the absence of thermal comfort is the temperature with humidity having second importance.
We used two thermo loggers in this experiment, one outside and one inside the building. (13-21/08/2011) measuring temperatures (red lines) and humidity (yellow lines):

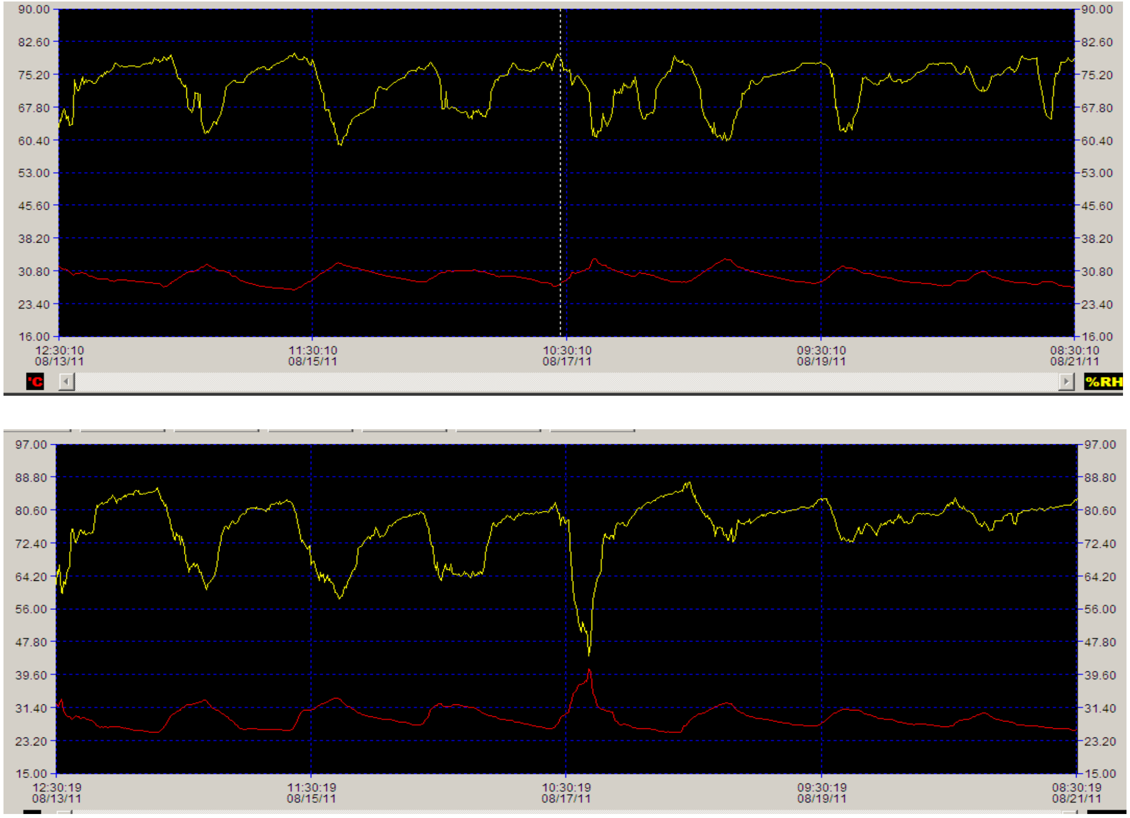

Figure 2: Inside and Outside Temperature and Rel. Humidity (RH)

These are the 3 major findings of comparing inside and outside temperatures:

1. The average inside *temperature* is slightly higher inside the building (30.7ºC), with the outside standard deviation (SD) being four times higher than inside. Whereas the temperature inside this bricks and concrete building is continuously too hot, the outside temperature will increase to 3ºC hotter during the daytime, but decrease up to a even 5 ºC colder during the nighttime.
2. The outside *relative humidity* (RH) during the daytime is often lower than the upper space limit of comfortable 60% during peak periods of sun shine. It tends to be slightly higher than inside at cloudy and rainy conditions. However, the RH gets significantly higher after the sun sets and during the nighttime.
3. A high *negative correlation between temperature and humidity* (r= -0.90) could be reported. That means the higher the temperature, the less the humidity and the other way round. In its extremes, this can result in indigestible temperatures of 34 ºC in the afternoon with an acceptable RH of 50%.

The set of measurement is consistent with only 2 anormalcies: (1^{st} chart) inside: when an extra dehumidifier was switched on (discussion in 2013) and (2^{nd} chart) outside: when the measurement tool was exposed to the sun for one hour and then returned to its original position in the shade.
Subsequently, in a 2^{nd} analysis, the daytime data was removed in order to find out whether the inside or outside temperature ***during the night time*** *(8 p.m. – 9 a.m.) could be cold enough to comply with the thermal comfort level of 28 °C– 28.6 °C.*
The nighttime outside temperature's average in 371 measurement points taken was 27.1°C with a standard deviation of 1.101, whereas the inside temperature was 28.4 °C (S= 1.078). If the theory of thermal comfort with the Upper Space Limit of 28.6 °C is true, this 1.3 °C might be the cutting edge in terms of creating better thermal comfort.

a) *The details in the time series plot show that, despite its decreasing tendency, by the stack effect the* ***inside temperature*** *in almost all cases remains too high above 28ºC and even 28.6ºC during the night between 8 p.m. before early morning until 9 a.m. and can create thermal comfort only on rainy days in the early morning (both black lines 14/15 and 20/21 August 2011).*

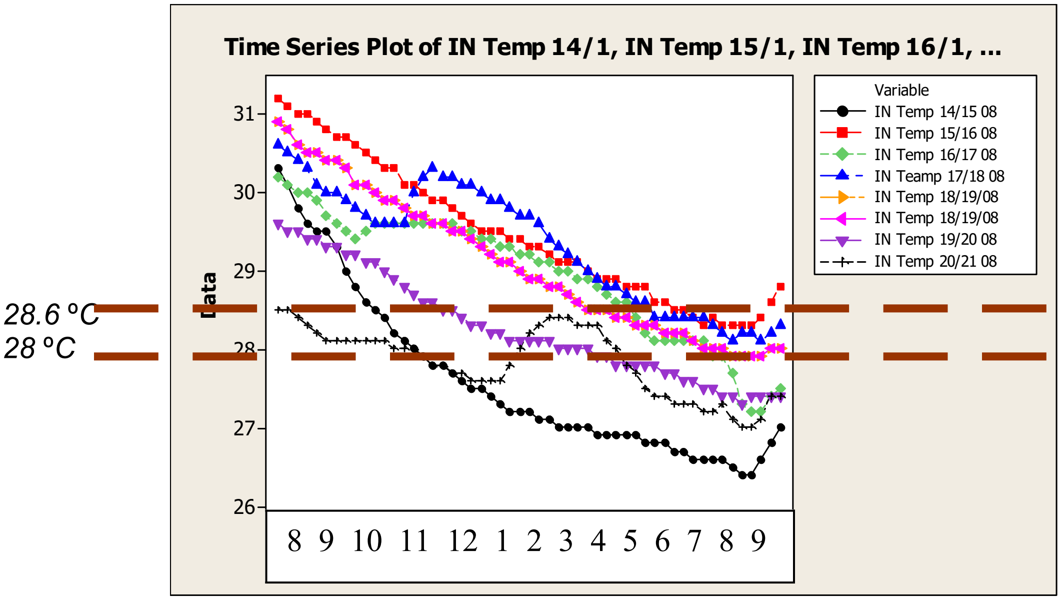

Figure 3: Inside Temperatures over 7 Nights

b) In contrast to the stack-effect represented during the readings of inside temperature, the look at the outside temperature varies as indicated below in figure 4. Like in a wooden Kampong house that cools down quickly after sun set it shows the same decreasing tendency with an average score of 28°C compared to 29°C inside. However, it depends on the weather situation whether the target 28°C-28.6° C is achievable after 9 pm or at the latest after 12am after the hottest day:

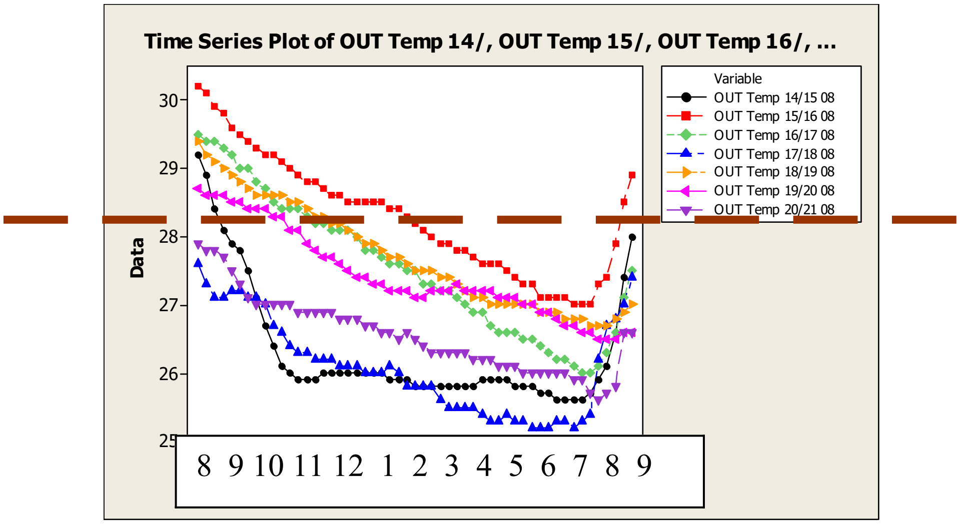

Figure 4: Outside Temperature over 7 Nights

As the chart shows, the critical hours where coolness from outside is not yet achieved, in all cases (except after rainy conditions) are between 8 pm and midnight. Between 12 a.m. and 2 a.m. the latest, the yielded outside temperature will be often in range with 28.6° C as the upper space limit for residential tropical thermal comfort. The following hypothesis has to be argued: "Nocturnal minimum air temperatures in night ventilated condition are still about 2.0 °C higher than the ambient air" (Ahmad, Supian and Doris Toe, Hooi Chyee, 2008).

3.2 . 2nd Experiment: Measurement of inside and outside temperature with installation and operation of Thermo Ventilator

Apart from the local fan technology, the thermo-ventilator used to breathe in and out consists of a motor with 18W peak performance for the fan, heat retaining fins, inclusive of noise reduction and air filter.

Figure 5: Thermo Ventilator

This device is usually installed into European airtight houses providing fresh air. In a tropical country, the ventilator provides a purposeful hybrid combination of the traditional approach which goes “back to nature” (open air principle) and the prevailing air condition systems. Heavily or unequally chilled buildings with inverter-based air condition units account for more than about 18 times compared to ceiling or stand fans. At a scenario of an old air condition unit consuming 2 KW/h their operational costs and CO_2 emission even accounts for roughly 30 times higher as by traditional ceiling or stand ventilation systems.

For this experiment, two units of modified thermo ventilators were used. One stand-alone unit repeatedly reversed the direction of its air flow direction in the following experiment a). In experiment b) one unit breathed air from inside to outside and the second unit, the outside-inside ventilator, was built in into the wash room’s window grill adjacent to the Master Sleeping Room (SR) which became a real-life ***experimental laboratory***:

Figure 6: Location of Outside-Ventilators

The other rooms and the hall (living room (LR)) were used as ***control room*** with no intervention of inside-outside ventilation activities. Apart from a wide variety of other variations, only two modes of operation were chosen to be presented in this paper:

a) Two-way flow air mode with one device

The thermo ventilator which worked as a stand-alone unit ran in an automated breathing-in/ out-mode with 18W: Every 50-80 seconds, the thermo ventilator changes its direction. As the results proved to have no impact on the temperature which stayed stably 3.09 ºC higher than the outside night temperature with no significant improvement compared to the control room, we abandoned this mode after 2 nights.

b) Two-way flow air mode (2 device, each 1-way-stream)

During 5 subsequent days, we installed one thermo ventilator to suck the inside air out, and a 2nd fan to harvest colder and fresh outside nighttime air into the test room. Within 2 nights, the temperature gap between inside and outside temperature with the ventilator sucking the colder outside air was reported at 1.49 º C on average with S^2 of 0.71º C inside and 0.42 º C outside. Conversely, the weaker 1-way operation nights had averaged in only 0.45 ºC decreased temperature. This can be considered a ground-breaking result, and longitudinal studies adapted to several locations are being conducted at the same time could verify its validity at probably reasonable investment costs. The exemplified results show the headway of progress:

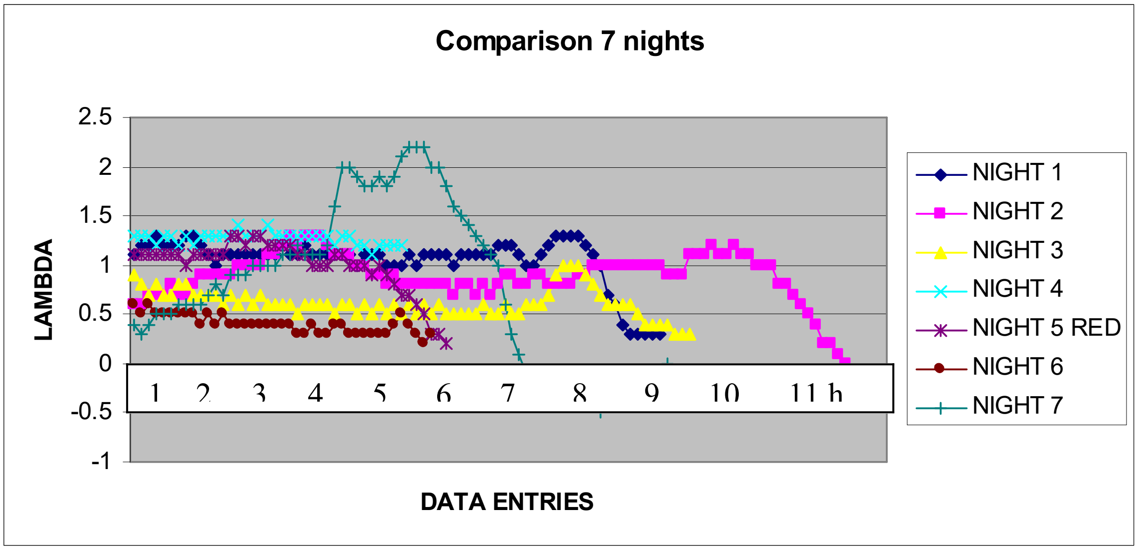

Figure 7: Duration of Below 28.6º C Values during Nighttime Ventilation: Thermo Ventilation Yield in Hours per Day

Typically, it took at LEAST 2 ½ - 4 h to harvest TC based compared to the already colder outside temperature. Depending on the cumulative outside temperature intake during the day, here are 3 typical examples of time lags until the thermo ventilator system yielded the target temperature of 28.6º C:
a) 10.38 p.m. – 1.08 a.m. ("green" night with heavy downpour before)
b) 2.18 a.m. – 4.58 a.m. ("yellow" night with typical sunny mornings followed by predominantly cloudy weather conditions during the afternoon).
c) In some remaining "red" nights, with stable mostly sunny / cloudy conditions during subsequent rain, that was only close to the upper space limit, but could not reach the targeted temperature.

Furthermore, comparing the outside temperature with the thermo-ventilated room (purple) and the control room with just an ordinary ceiling fan in operation (blue), the following result could be yielded in 3 ½ days of observation:

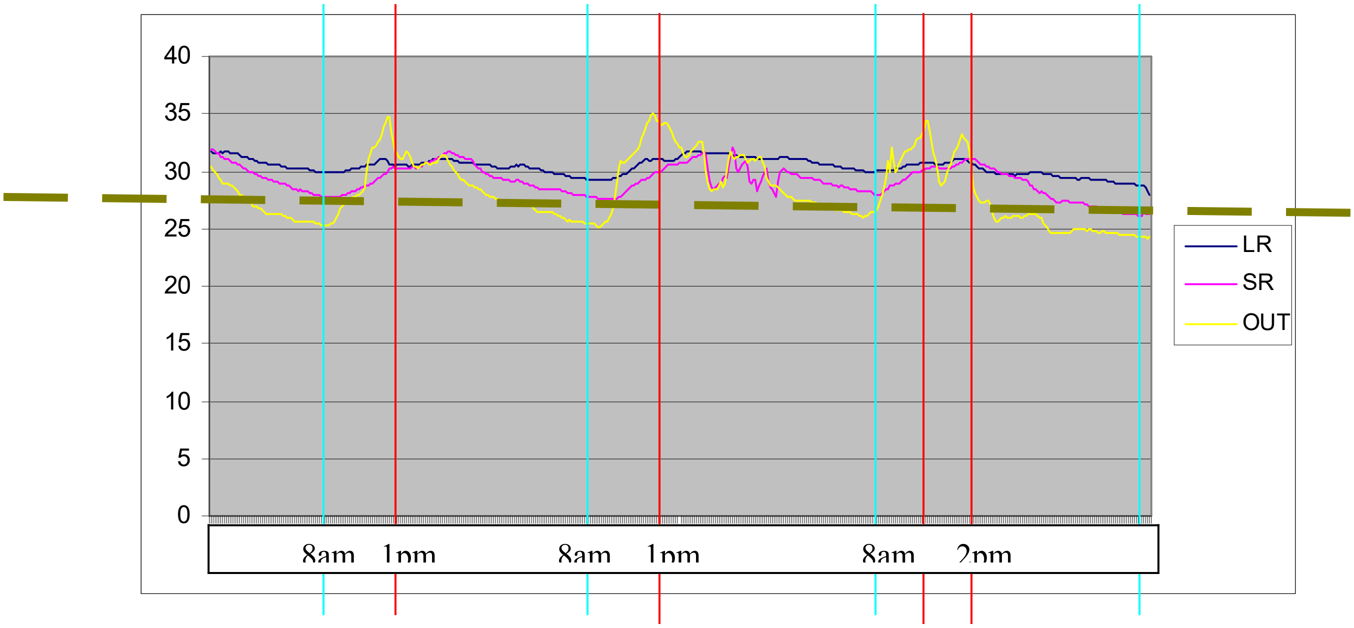

Figure 8: Run Chart Temperature 4 Days Comparison Sleeping = Experimental Room, Living = Control Room (LR) and OUT-side temperature

As the figure shows again, the thermal comfort zone could be gradually reached for the thermo ventilator during the nighttime at different times between midnight and usually 4.30 a.m., whereas in case of the fanned control room it remained always above the upper space limit. When the heat of a new day set in again, the experimental room (SR) gradually still kept the coldness for a few hours typically until 11 a.m. During the mornings, the lower temperature below the set point could still be achieved before the effect of the non-insulated building envelope would soon rise the temperature up again out of the TC-zone.
Our observations yielded the following average scores in the early morning with these temperatures:

Outside:	Inside: Experimental Room with Cross-Ventilation	Inside: Control Room with Ceiling Fan
26.5 C	27.9 C	29.9

DELTA **OUT-SR**: 1.4° C

DELTA **SR-LR**: 2 ° C

On average, despite the cooling effects of the night time temperature, the experimental room remains 1.2 ° C warmer than outside. Conversely, the control room still stays stuck at 1.4 ° C hotter than the thermo-ventilated area respectively 2.4 ºC compared with the minimum outside temperature.

3. Conclusion

1. Active night time harvesting of colder outdoor air temperature by thermo ventilators is possible at reasonable operational costs (see 5.). This system will actively breeze in fresh air and hence reduce the unhealthy indoor CO2-level caused by permanently closing the windows when fans or air condition units are in operation.
2. Outside night air harvesting alone will help to decrease the temperature only by 1.2 - 2ºC during 8 p.m. – 8 a.m. on average. By far, it will not always be capable to yield the derived Malaysian TC-zone of maximum 28.6ºC. Insulation measures of the windows, the roof, the ceiling and also the walls will help genuinely to reduce the temperature so that further cooling by electrical air condition is not longer required or can be substituted by a hybrid system.
3. Harvesting colder nighttime temperature naturally also implies a higher intake of humidity exceeding the official thermal comfort level as it does anyway during all nights in non-air conditioned rooms. In the five consecutive nights measured above, the average humidity was 75.8% and hence 3.9% higher than within the control room. Studies need to be conducted, how to reduce the humidity without increasing the temperature or – like in this experiment, to ignore / live with it and still feel quite comfortable.
4. At present, the obvious restrictions of the utilisation of the colder night time temperatures mentioned are still grounded in astonishingly high variations as well. On hot days with high heat intake in an uninsulated building, the cooling thermal comfort effect of the ventilation only started at 2.30-6.00 a.m. during our initial experiments. During longer hot periods, TC could nt achieved at all. However, it is expected by retrofitting enabling the building to reduce or even avoid the high daytime heat intake and make the system run effectively in at least 90% of all times between 10 p.m. and 12 p.m.
5. Finally, looking at the operational costs, cross ventilation is comparable to running a likewise operating ceiling fan, but –on the condition that occupants are always at home- the system incurs much less cost savings compared to different air condition solutions (peak):

a) Air Condition Unit	1,200 W/h (Inverter)- 2,000 W/h (non-inverter)
b) Ceiling Fan at speed level 4:	65-75 W/h
c) Cross ventilation with 2 gadgets	<50 W/h
Aid of ceiling fan during hot nights (max. at level 2)	25 W/h
c) TOTAL	75 W/h

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