Naturally Ventilated Urban Housing in Southern China

A research review on current energy efficient residential design code

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ABSTRACT: Since 2003, the Chinese Energy Efficient Residential Building Design Code for Hot Summer Warm Winter Climatic Zone (the Code) has been enacted with the aim that any new building design needs to be 50% energy efficient compared with conventional design. In this paper, however, the implicit air-conditioning methodology and assessment approach of the Code and its associated design requirements on built form, window size, and thermal properties of material have been critically reviewed. Through comfort study and climate analysis, it is revealed that the Code has not addressed the occupant perspective and that natural ventilation is highly suitable in Southern China. Through a series of parametric studies, it is concluded that thermal mass with controlled natural ventilation has great contribution to cooling load reduction; and that the Code should base its methodology and assessment approach on natural ventilation if genuine energy efficient designs are to be achieved; and that its design codes on built form, window size and thermal properties of material need to be revised to take ventilative cooling into consideration.
Keywords: air conditioning (AC), natural ventilation (NV), cooling set point (T_{csp}), surface to volume ratio (SVR), window to wall ratio (WWR), thermal inertia index (D value), diurnal cooling capacity (DCC).

PRELIMINARY REVIEW OF THE CODE

China is undergoing unprecedented urban housing development. To address the ever-increasing environmental degradation and energy consumption, a series of energy efficient building design codes have been enacted in the past 15 years for different climatic zones in China, among of which is the Energy Efficient Residential Building Design Code for Hot Summer and Warm Winter Zone (the Code) applied primarily to Southern China, a region characterized by warm and humid climate.

The Code appears ambitious in its target that any new housing design needs to reduce heating and cooling loads by 50% compared with conventional practice. However, its methodology and energy assessment approach are contentious, requiring that any new design not in line with any of its obligatory codes needs to be assessed with a reference case in a thermal simulation tool under fixed air change rate of 1 ac/h with heating set point (T_{hsp}) of 16^0C and cooling set point (T_{csp}) of 26^0C [1].

It is obvious that this simulation condition is parallel to continuous air conditioning with little respect to occupant's perspective. According to a comfort survey done by the author, most people in Southern China prefer natural ventilation (NV) over air-conditioning (AC) and resort to AC only when adaptive efforts have been made and internal environment is still beyond their comfort expectation. Moreover, the occupancy pattern is mostly intermittent rather than continuous (Fig.1). Thus, the annual cooling load (53 kwh/m^{2}y) of a code-binding residential unit based on the Code's assessment model is much higher the current average household cooling load of 2-5 kwh/m^{2}y in Southern China [2].

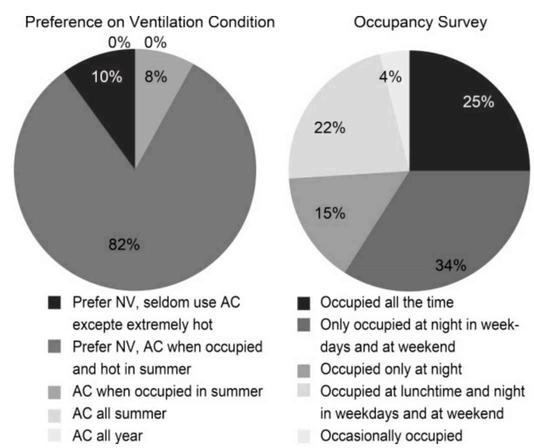

Figure 1: diagrams of comfort study on preference towards ventilation condition and occupancy pattern done by author with 100 participants of various ages in Southern China

Under this implicit methodology, some of the Code's regulations on built form, window size and thermal properties of material tend to promote design measures in favor of AC buildings rather than NV buildings. For example, the Code regulates certain limits of window to wall ratio (WWR) in relation to orientations and shading coefficient of window, and limits of surface to volume ratio (SVR) to control solar gain. However, the sizing of windows and the compactness of built form affect not only the amount of solar gain, but the effectiveness of ventilative and conductive heat loss. Many literatures [3][4] argue that well-shaded large windows and more spread-out built form should be adopted in hot and humid regions. Another example is the Code's provision on thermal property of material in which envelope elements with high insulation and capacity are encouraged by regulating certain limits of thermal transmittance (U value) of walls and roofs in relation to their thermal inertia index (D value). It is also demonstrated that when thermal resistance of envelope elements exceeds certain limits of insulation level i.e. U<0.5 W/m^{2}K for roofs and 0.7 W/m^{2}K for walls, no more thermal mass is required. However, in a predominantly NV building in Southern China where the temperature difference between indoor and outdoor tends to be small, the role of thermal insulation is limited and at times may be counteractive as it stops the internal heat from dissipating outwards [5]. Besides, the adoption of thermal mass in warm and humid climate is controversial in many literatures [6] [7]. Furthermore, according to Givoni [6], the effect of mass in NV buildings is largely dependent on diurnal cooling capacity (DCC) of building fabrics rather than thermal inertia of building envelope (D value).

Through above preliminary review of the Code, some research questions can be raised as follows:

- Is the T_{csp} of 26^{0}C regulated for energy performance assessment in the Code appropriate for NV housing in Southern China? If no, what will that be?
- How is the climatic suitability of NV in Southern China? To what extent can NV contribute to reducing cooling demand?
- The Code regulates a certain degree of SVR (0.35 for corridor type and 0.4 for tower type) to control heat loss. In a NV building, what kind of built form should it have?
- The Code regulates certain WWR in relation to orientation and shading coefficient to control solar gain. But in a NV building, what should be the appropriate window size?
- The Code favors insulation over thermal capacity. So, is thermal mass beneficial in Southern China? How should building envelope be thermally insulative?

Thus, research hypotheses can be established as:

To promote genuine energy efficient design, the Code should use natural ventilation instead of implicit air-conditioning as its methodology and assessment approach; and the associated design requirements on built form, window size and thermal properties of materiality need to be revised to the requirements of a naturally ventilated building.

THERMAL COMFORT IN NV HOUSING

The T_{csp} of 26^{0}C stipulated in the Code seems to base on the comfort standard of ISO 7730 under the restrictive condition of airspeed of 0.3 m/s and clothing value 1.0 clo that common in AC buildings [6], disregarding the possibility of occupant adaptation. However, a higher comfort temperature will be derived by a simple modification of environmental and behavioral parameters. Table 1 shows the result of a comfort study in UC Berkeley Thermal Comfort Program. As shown in case 1, a simple modification of clothing value from 1.0 to 0.5 as common in housing can increase the comfort limit from 26^{0}C to 27.6^{0}C. While respecting the usual humidity level of 75% common in summer in Southern China, upper limit of comfort temperature can be further extended to 29^{0}C in case (1+2) with increased air velocity from 0.25 m/s to 1.5 m/s, which is generally desirable in housing. Considering the lower comfort expectation as Givoni [6] suggested in developing countries like China, the upper comfort limit could be even increased to 29.7^{0}C as shown in case (1+2+3) where PPD increases from 10% to 20%.

Table 1: Comfort study in UC Berkeley Thermal Comfort Program.

Case	DBT (degC)	Airspeed (m/s)	RH	Clo	PPD
Base Case	26.0	0.3	50%	1.0	10.0%
C1: changing the clo	27.6	0.3	75%	**0.5**	10.0%
C(1+2): changing airspeed	29.0	**1.5**	75%	0.5	10.0%
C(1+2+3): changing PPD	29.7	1.5	75%	0.5	**20.0%**

The expandability of comfort range can be further demonstrated by the adaptive comfort approach as suggested by many literatures [8][9]. Based on Humphrey's neutral temperature equation and mean monthly temperature in Guangzhou, a preliminary comfort zone for Southern China is derived with the monthly neutral temperatures extending 2.5^{0}C on either side of them (Fig. 2). However, this comfort zone has to be modified taking into account of the effect of humidity and air movement [6][9]. In terms of humidity, the upper humidity limit of 17 g/kg is adopted under still air conditions [6]. In terms of airspeed, Givoni [6] suggests an acceptable airspeed limit of 2 m/s for housing. But considering the requirements of night-time occupation, the acceptable airspeed is revised to 1.5 m/s. Based on the cooling effect equation suggested by Nicol [9], the cooling effect of airspeed 1.5 m/s is equivalent to about 4^{0}C. Since the adverse effect of humidity is alleviated by the increased airspeed, the upper humidity limit can be extended to 20 g/kg, which is the average humidity level in July in Southern China. Thus an upper limit of comfort temperature 31^0C can be derived by adopting an acceptable airspeed of 1.5 m/s under the high humidity level of 20 g/kg which is common in Southern China (Fig. 3).

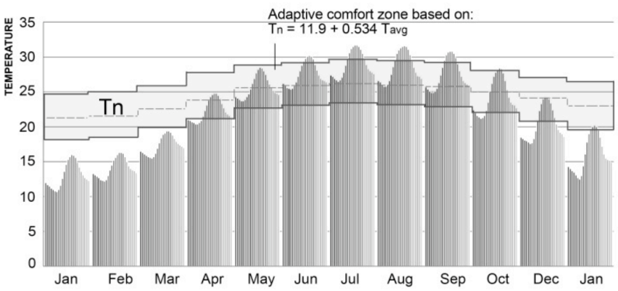

Figure 2: Monthly diurnal average temperature of Guangzhou with derived adaptive comfort range (Weather data from [10])

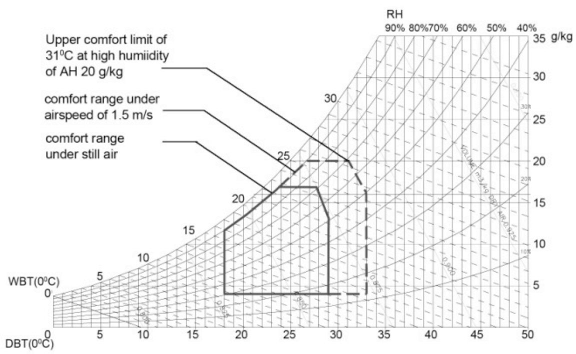

Figure 3: Psychrometric chart showing comfort range in still air condition(solid line) and with enhanced airspeed of 1.5 m/s (dash line) in Southern China (after Givoni [6]).

CLIMATATIC SUITABILITY OF NV

Fig. 2 shows the monthly diurnal average temperature of Guangzhou. By integrating the adaptive comfort range in the temperature profile, it can be seen that the average outdoor air temperature is mostly within comfort zone. This is further demonstrated by Fig. 4 showing the cumulative frequency of outdoor DBT. As can be seen, the hours exceeding upper comfort temperature 31^0C represents just 6.5% of the entire year, while there are around 50% of the year between 21^0C and 31^0C when ventilative cooling is needed, and 44% below 21^0C when only fresh air requirement through NV is needed. Also, due to the high daily minimum temperature (average 23^0C in May and 26^0C in July) and small diurnal temperature range of 4.5 to 6^0C in hot months, the effectiveness of thermal mass coupled with nocturnal ventilation in Southern China seems comparatively limited, which will be further tested in next section.

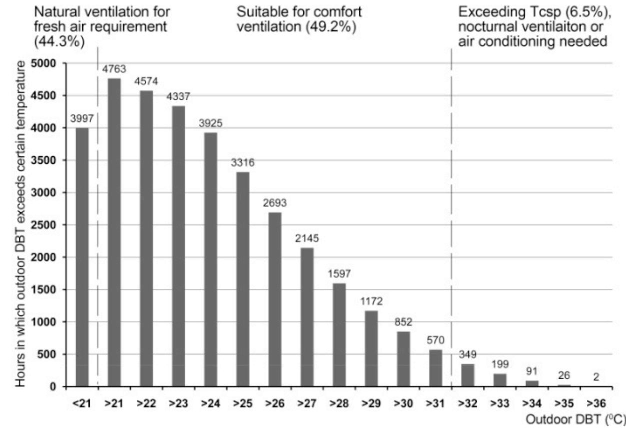

Figure 4: Cumulative frequency diagram of hours of outdoor DBT. (Weather data from [10])

PARAMETRIC STUDIES

In order to test the research hypotheses, a series of parametric studies, including built form study, window size study, thermal insulation, thermal mass study and ventilation study have been undertaken in Tas, a dynamic building simulation tool with integrated natural and forced airflow. The base model is a code-binding typical 3-bedroom one-staircase-two-unit type unit (Fig.5). Parameters such as SVR, WWR and material properties in the base model, shown in Table 2, are all based on Code's requirements.

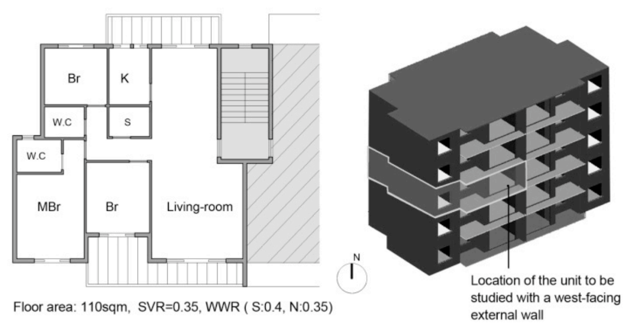

Figure 5: Plan and axonometric view of base model for parametric study in Tas (version 9.0.9d)

Table 2: Base case definition in Tas

Base Case Definition		Discriptions	
Weather file		The Chinese standard weather file of Guangzhou from Energyplus weather data	
Internal conditions	Ventilation	AC	Fixed air change rate 1ac/h with Tcsp of 26 degC
		NV	Controlled natural ventilation with external windows and doors open to fully open (40% window size) from 23 to 25 degC, and close at 30 degC, with Tcsp at 31 degC
	occupancy	4W/m² from 6pm to 8am 1W/m from 8am to 6pm	
	lighting gain	5 W/m² from 6pm to 11pm and 0 for the rest.	
	equipment	5 w/m² from 6pm to 11pm and 1 w/m² for the rest	
Material	Roof	150mm concrete with external polystyrene sheet 30mm thick, U=1.0 W/m2.K and TTC=5.2h	
	External wall	110mm thick brick wall with external polystyrene sheet 20mm thick,U=1.4 W/m² .K and TTC=3.9	
	Internal wall	Fibre board with internal cavity, U=2.3 W/m².K and TTC=0	
	Window	single glazing with U value of 5.6 w/m² .k	
	Floor/Ceiling	110mm concrete,U=7.0 W/m² .K and TTC=1.8h	

In **built form study**, two case units of same floor area as base case but with larger SVR of 0.45, one with deep-porch and one without (Fig.6) have been simulated to be compared with the base case which has a code-binding SVR of 0.35. In **window size study**, two case units with larger WWR (0.5 in north and 0.55 in south), one without louvre windows, one with external louvers on additional window areas, have been simulated to be compared with the base case which has a code-binding WWR (0.35 in north and 0.4 in south). In **thermal mass study**, a lightweight case unit (Table 3) is simulated to be compared with the heavyweight base case. In **thermal insulation study**, two case units with external wall of different insulation levels, namely high insulation (U=0.6) and no insulation (U=5.2) are simulated to be compared with the base case (U=1.4). In order to investigate the effect of ventilation, a **ventilation study** has also been carried out, in which three cases with various ventilation conditions, namely 1 ac/h, 10ac/h (10ac/h at night time from 10pm-6am, 1ac/h for the rest) and 24-hour natural ventilation (with window opening all the time) have been simulated.

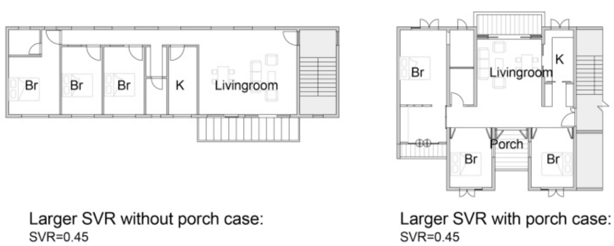

Figure 6: Plans of the two case units in built form study

Table 3: Material definition of lightweight case unit

Case	Building Element	Discription	U Value (W/m2.K)	Time Constant(h)
Heavyweight Base Case	Ceiling/floor	110mm concrete with 20mm tile	7.2	3.5
	External wall	110mm brick with 20mm external polystyrene expanded sheet	1.4	3.8
Lightweight Case	Ceiling/floor	Steel frame with timber floor and lightweight plaster ceiling	5.6	0
	External wall	metal sheet as external surface, lightweight plaster as interna surface and 20mm polystyrene expanded sheet in between	1.4	0.9

Results and discussion Table 4 shows the results of annual cooling load of all the study cases in two ventilation and comfort conditions, namely controlled natural ventilation in which openings will be open to fully open when the indoor DBT increases from 23^{0}C to 25^{0}C and close when the indoor DBT exceeds 30^{0}C with thermostat set at 31^{0}C, and code-based AC mode with fixed 1ac/h and T_{csp} of 26^{0}C. It can be easily seen that the cooling load of the base model in NV condition (314 kw/y) represents only 5.9% of that in AC condition (5319 kw/y). This further demonstrates that the code-based AC mode greatly over-estimate cooling load of housing units in Southern China which are predominantly naturally ventilated.

Table 4 Summary of results of parametric studies under two ventilation conditions in Tas

Ventilation scenario & comfort limit	Study	Case	Base case cooling load	New case cooling load	Load change percentage
Natural ventilation with Tcsp of 31degC	Built form	Larger SVR without porch	313817	345450	10.08%
		Larger SVR with porch	313817	298500	**-4.88%**
	Window size	Larger WWR	313817	334860	6.71%
		Larger WWR with louvres	313817	314580	0.24%
	Thermal insulation	High insulation	313817	306900	**-2.20%**
		No insulation	313817	326300	3.98%
	Thermal mass	lightweight envelope	313817	648762	**106.73%**
	Ventilation	Change to 1/ACH	313817	738379	**135.29%**
Code-based: fixed 1ac/h with Tcsp of 26degC	Built form	Larger SVR without porch	5318537	5985880	12.55%
		Larger SVR with porch	5318537	5646890	6.17%
	Window size	Larger WWR	5318537	5510428	3.61%
		Larger WWR with louvres	5318537	5408090	1.68%
	Thermal insulation	High insulation	5318537	5088912	**-4.32%**
		No insulation	5318537	5635991	5.97%
	Thermal mass	lightweight envelope	5318537	5467608	2.80%
	Ventilation	Change to NV	5318537	4591061	**-13.68%**

It can be seen from **built form study** that adopting a spread-out built form without any self-shading feature will increase cooling load in both AC and NV conditions, by 10.1% and 12.6% respectively. However, the built form case of large SVR with porch can reduce cooling load by 4.88% in NV condition. The reason is that a spread-out form with self-shading feature can result in more ventilative and conductive loss at night without necessarily causing more solar gain at daytime. Similarly, the results of **window size study** show that increasing window size without any shading measure will lead to load rise by 6.71% in NV condition and 3.61% in AC condition. But with louvers on additional window area, there is just as little as 0.24% load increase in NV condition. This is because the increased window area may enhance the effectiveness of ventilative cooling without introducing much more solar gain. From **thermal insulation study**, it can be seen that while thermal resistance of building envelope has moderate effects on energy consumption in both ventilation conditions, the effects are less significant in NV conditions, in which load reduction in high insulation case is 2.2% versus 4.32% in AC condition; and load increase in no-insulation case is 3.98% versus 5.97% in AC condition. A detail examination on the performance of internal DBT of the living-room and westerly-facing master bedroom (Fig. 7) indicates that indoor DBT of west-facing master bedroom in no-insulation case would be much higher than that of high-insulation case.

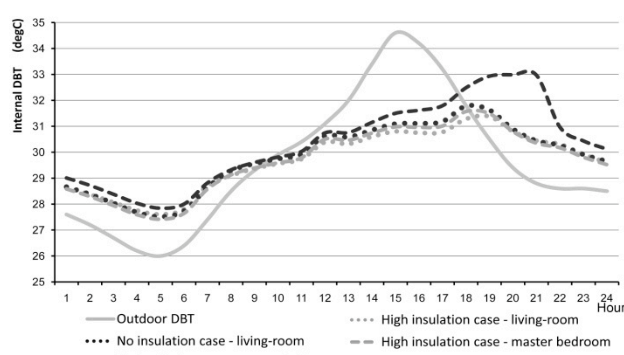

Figure 7: Comparison of internal DBT of living-room and westerly master bedroom in two insulation studies case units.

Figure 8 shows the comparison of effects of all the studied parameters. It is obviously illustrated that thermal mass and ventilation condition have much greater effects on energy consumption when Tcsp is set at 31^0C than those effects of them when Tcsp is set at 26^0C (106.7% versus 2.80% in thermal mass study; 135.3% versus 13.7% in ventilation study), as well as than those moderate effects of the other parameters, namely SVR, WWR and thermal insulation in both NV and AC conditions. This demonstrates that with the raising of Tcsp (from 26^0C to 31^0C in this case), thermal mass coupled with controlled natural ventilation becomes a viable strategy due to the fact that available minimum air temperature (normally about 25-26^0C in hot months) could be 5-6^0C below the upper comfort temperature.

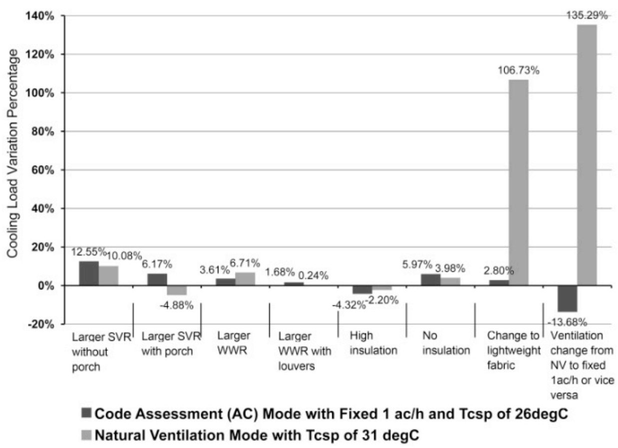

Figure 8: Comparison diagram of cooling load of various parametric studies between NV and AC mode.

RESEARCH OUTCOMES

Based on the above analyses, it becomes clear that ventilative cooling has great climatic potential and thus great effects on cooling load reduction for urban housing in Southern China. It is also revealed that various parameters, namely built form, window size, thermal resistance and capacity will exhibit different effects in NV mode from those in AC mode. In this section, the design requirements of these parameters for NV urban housing and the revision of the Code will be presented.

Ventilation condition and control The most critical revision of the Code is that its implicit AC methodology should be revised to promote genuine NV, i.e. its energy assessment condition needs to be changed from 1 fixed air change rate with Tcsp of 26^0C to controlled NV with higher Tcsp (say 31^0C). While NV can be controlled and overridden by occupants, preferably it can be controlled by automatic system so that internal thermal mass won't get warmed up by incoming hot air at daytime, and can be cooled down timely when the ambient temperature drops down with the absence of the occupants. Moreover, this condition is based on the assumptions that enough airflow rate and air movement can be achieved. Since wind is quite unreliable and often inhibited by adjacent buildings, NV needs to be supplemented by a whole-house exhaust fan when wind effect alone cannot meet the required airflow rate; and by electric fans to deliver the desirable air movement in major occupant areas whenever needed.

Built form The provision on upper limit of SVR in the Code is too simple, disregarding the potential of ventilative and conductive heat loss when outdoor DBT drops down below comfort temperature. Apart from the fundamental decision on housing types, orientation, plan depth, one good solution to resolve the conflicting needs between controlling solar gain and enhancing ventilative cooling is to adopt a more articulated built form while incorporating self-shading built form or architecture elements, such as deep porches or buffer spaces (Fig. 9). Hence, a SVR taking account of shading condition of the envelope is recommended. This concept is demonstrated by the following formula in calculating the actual exposed surface area that should be accounted for SVR:

$$S_{cal} = \sum (S_i \times \sigma \times \eta) \quad (1)$$

Where:
S_{cal}: the actual exposed surface area for calculation of SVR;
S_i: the real surface area of each surface of envelope;
σ: the coefficient of orientation (the ratio of solar radiation of a surface in relation to that of tilted horizontal surface in un-shaded condition);
η: the coefficient of shading condition.

While this formula needs to be further developed (beyond this paper), it clearly promotes the type of built form that is beneficial to natural ventilation while addressing solar control.

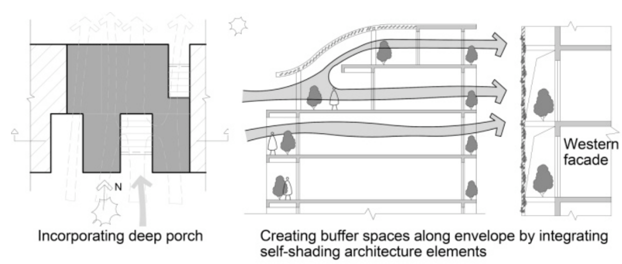

Figure 9: Built form recommendation diagram

Window sizing As window size study shows, increasing window size without corresponding enhanced shading will increase cooling load moderately. In sizing windows, issues such as orientations, wind condition, the required airflow rate, achievable shading coefficient (SC) of windows have to be considered. In order to control solar gain while enhancing ventilative cooling at night, large well-shaded openings should be considered. One good solution is to include at least two types of openings for a window: a solar-transmitted type for daylight, view and ventilation, and a solar-excluded type exclusively for ventilation. Thus, solar-transmitted type openings will be sized based on the requirements of daylight and view while any additional need for ventilative cooling is provided by the solar-excluded type which is normally in the form of open-able opaque louvers and shutters (Fig. 10).

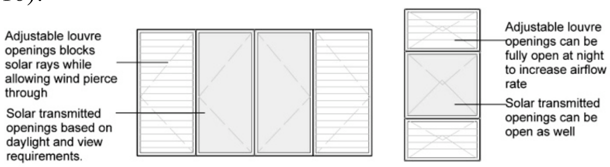

Figure10: Elevation detail for window examples with solar-excluded and solar-transmitted panes.

The provision of upper limits of WWR in the Code seems restricted and disregards the ventilative potential of large openings when sufficient shading is provided. Instead, WWR should be regulated in relation to orientations and SC of windows. For a particular wall in certain orientation, WWR limits should increase with the corresponding decrease of SC. Additionally, to control solar gain and achieve desirable ventilation effect, careful positioning and detailing of the windows are equally important. However, they are beyond this paper.

Thermal resistance The Code applies the same limits of U value for walls (1.5 W/m^2K) and roofs (1.0 W/m^2K) respectively without consideration of their orientations and shading conditions. It has been demonstrated in above thermal insulation study that thermal insulation has limited load-saving potential to an entire building or unit but may have considerable impacts to thermal comfort condition of those rooms with un-shaded roofs or east/west facing walls. Therefore, thermal resistance of building envelope elements should respond to the intensity of solar radiation impinged on their external surface. Assuming adopting light-color external finishes while taking into account of actual construction cost, a moderate limit of U value 2.0 W/m^2K is considered enough for south/north facing walls or well-shaded roofs and east/west facing walls; but for un-shaded roofs and east/west facing walls, a limit of U value 1.0 W/m^2 K needs to be regulated.

Thermal capacity It has been demonstrated in above thermal mass study that thermal mass coupled with natural ventilation plays a significant role in energy saving. Thus, the Code is commendable in recognizing the benefit of thermal mass by regulating a lower limit of thermal inertia index (D value of 3 and 2.5) for walls and roofs, although it places thermal insulation over thermal mass. However, the D value is just applied for envelope elements, disregarding the mass effects from internal building fabric such as internal walls, floor and ceilings. Moreover, D value hasn't taken into account the effect of the relative locations of thermal insulation and capacitive materials of envelope elements as suggested by Givoni [6].

Therefore, the Code should adopt the diurnal cooling capacity (DCC) as the index of the mass effect of building element or the entire buildings, which takes into account not only the thermo-physical properties of the material (especially the interior surface material), but also the exposed area and the convective coefficient of building fabrics. In this regard, internal building fabrics are preferable to be thermally heavyweight while keeping partitions along airflow path permeable as much as possible. These thermally massive fabrics should be well-protected from solar rays but well exposed to internal air movement.

CONCLUSION

In this paper, it has been revealed that the Code's implicit air conditioning methodology and energy assessment approach disregard the occupant's perspective and thus the significant energy-saving potential of natural ventilation in urban housing in Southern China. Through parametric studies, it is concluded that, when Tcsp is changed from 26^0C to 31^0C, thermal mass coupled with controlled natural ventilation has a much greater contribution to cooling load reduction. It has also been demonstrated that the corresponding design requirements on built form, window size and thermal properties of material need to be revised towards naturally ventilated buildings if genuine energy efficient housing designs are to be achieved.

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