Evaluation and Application of Thermal Mass and Nighttime Ventilation for Passive Cooling of Dwellings under Various Climatic Potentials(住宅のパッシブクーリングに利用する熱容量並びに夜間換気の各種気候条件下における評価とその応用)

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論文内容要旨

The main objective of passive cooling is to achieve indoor thermal comfort during the overheated period of the year. There are various methods for passive cooling, but the main emphasis in this present study is on cooling of the indoor space with thermal mass of a building by introducing the cooler outdoor air during the night and to utilize the cooling effect achieved, during the next day. For this purpose, shading from the incidence solar radiation also has a great significance.

Though the indoor thermal comfort depends on room temperature, mean radiant temperature, humidity and air flow, mainly the indoor air temperature has been analyzed here while assessing the performance of a passive system. The study has been carried out mainly in several parts :

1. Experiment using a passive solar test house with thermal storage floor and nighttime ventilation in a Japanese location.

2. Numerical simulation

[a.] Comparison between the computer simulation and experiment data.

[b.] Detailed parametric study for a Japanese location.

[c.] Comparative analysis for a few Japanese cities.

3. Field investigation of indoor thermal environment in residential buildings under different tropical climatic conditions in India.

4. Experiment during summer using scale models of Brick walls with RC slab on grade and flat RC roof construction, and evaluation of external insulation compared to conventional tropical building envelop in maintaining a stable indoor temperature.

5. Numerical simulation considering single zone model with earth-contact floor slab

[a.] Comparative evaluation of the scale model with measurement.

[b.]Development of a real scale model having single habitable zone.

[c.] Detail Parametric study considering the same model under the climatic background of one tropical location, and selection of parameters having distinct impact.

[d.] Comparative analysis for a few cities belonging to different climatic background considering the parameters selected from the previous step.

Chapter 1 describes the background, various levels of cooling strategies, cooling principles considered, the scope and objective of the study.

Chapter 2 illustrates the performance of a few passive cooling strategies in the Japanese context numerically, and also experimentally using a passive solar test house. To sum up the results:

- Natural ventilation in combination with thermal mass was found to be quite effective for space cooling. Among the preset volume of ventilations, 10 ACH during the night have shown reasonably good results.
- As the cases were carried out for short periods, some of those did not produce expected results possibly due to the impact of their previous case(s) which might have influenced the results of the following ones.
- The numerical method was found to have a fairly good level of correlation with the experiment results. The agreement error was within a limit of -17% to +5.5%.
- The parametric study revealed that nighttime ventilation with thermal mass can lower the daytime average indoor temperature by about 9 degC in some cities and, increasing depth of thermal mass or the rate of night ventilation do not produce any additional effect, beyond a certain extent. Increasing the surface area is rather beneficial.
- From the regional comparative analysis, Naha didn't appear to have much of outdoor temperature swing to produce noticeable impact of the cooling strategies adopted here. Osaka and Kagoshima have shown almost similar trend in this regard.
- As the solar radiation in some of the cities was rather high for the considered period, the effect of shading was quite distinct there compared to the other cities.

In Chapter 3, a field investigation to find the present state of cooling methods and indoor environment with occupant's response during the summer in some tropical cities is described. It is found that:

- Among all the samples, those from Calcutta and New Delhi have reflected the impact of lifestyle and building features on the indoor thermal environment.

- In general, the indoor environment was found to be quite stable. There was very little daily temperature fluctuation indoors due to massive construction, though the average indoor temperature lies 2-3 °C above than that of outdoor in many of the cases.

- It is observed that in the cases of single family detached houses, or apartment houses on the upper floor show a problem of overheating during the afternoon hours, due to the incident solar radiation on the roof slab. The rise in indoor temperature and its daily fluctuation were quite distinct in those cases compared to the adjacent spaces.

- The cases in moderate and composite climates were quite close to the comfort zone defined by ASHRAE (55-1992), compared to the samples in warm and humid regions. Except a few cases there was no complaint about the indoor environment, acclimatization (getting used to a condition) to the climate could be the main reason for this.

Having the feedback from the previous chapters on the impact of thermal mass in conjunction with nighttime ventilation, exposure of building mass during the overheated hours; a set of experiments have been conducted in newly built scale models constructed in the same way as in tropical countries by brick and RC. The purpose of the experiments was to investigate the summertime impact of night ventilation on building mass equipped with external thermal insulation. The results of these experiments have been illustrated in Chapter 4. The major findings are as follows:

- Nighttime ventilation can lower the indoor temperature to a great extent, but the benefit of heat removal during night from the thermal mass can not be utilized properly due the exposure of the building envelop to the incident solar radiation.

- Apart from shading the window, if the building envelop is thermally insulated, a proper utilization of the heat sink effect of the thermal mass during the daytime is possible.

- External thermal insulation protects the building mass from solar heat gain, and as a result produces a stable indoor temperature, provided there is some heat removal from the mass during the night.

Chapter 5 describes a numerical study with a single zone model of full scale under various tropical climatic background and aims to have a comparative performance analysis of the parametric variations under different tropical climatic potentials.
The main conclusions are as follows:

- From the comparison between measurement and calculation results under 0, 10 and 20 ACH of nighttime (18:00 PM to 6:00 AM in the next morning) ventilation, It is found that the measured and calculated values are in a good correlation, especially in the cases of 10 and 20 ACH. The agreement error is within a limit of

±15%.

- From the detail parametric study for one city, it becomes clear that night ventilation alone cannot result in a big drop in room temperature, if there is not any protection to the massive structure from the incident solar radiation.

- Insulating the building mass of conventional thickness and having a reasonable night ventilation results in better thermal environment compared to uninsulated mass of double thickness having the same rate (10 ACH) of night ventilation.

- For a heavier building mass with external insulation, nighttime ventilation rate has to be increased (sometimes, 20 ACH) to get better result. whereas for building mass of conventional thickness 10 ACH appears to be the optimum amount, beyond that it does not produce any additional benefit.

Chapter 6, the last chapter concludes this dissertation with conclusive summaries of different chapters, and a few directions for future research work.

Future research work

In the research work presented in this dissertation, the main focus for evaluation of indoor comfort has been passive control of temperature. But Moisture content also indeed plays a vital role in indoor thermal comfort. The control of moisture and its transportation via porous material is a definite direction of future research.

In the present study, research is based on a one-room model. This case is indeed far-fetched from a real life situation and thus in future it is envisaged to perform extensive studies on the basis of Multi-room model to capture the essence of real life conditions of indoor thermal comfort.

審査結果の要旨

地球環境の時代にあっては，夏の暑さを凌ぐために建物構造や形態を工夫すること（パッシブクーリング手法）によって，できるだけ冷房設備を使用せずに快適な環境を得ることが大切であり，特に熱帯地域にあり冷房設備が普及していない国では重要な課題である。

本研究は，日射遮蔽，熱容量並びに夜間換気をパッシブクーリングの手法として用いた場合に，インド各地の気候条件の下でどの程度の効果が期待できるかについて実験と数値計算によって明らかにしたものであり，５章よりなる。

第１章は序論である。第２章では日本の気候におけるパッシブクーリング手法の適用可能性について，東北大学構内に建設されたパッシブソーラー試験家屋を用いた実験と数値計算によって検討している。即ち，第一に，試験家屋を用いた実験では，床にレンガを敷き詰めて熱容量を持たせ，夜間換気を行ったときの基本的な性能を明らかにした。第二に，室内熱環境を予測するための数値計算手法を改良し，実験結果との照合によって精度を検証し，第三に，気候条件，建物の構成，換気量などのパラメーターを変化させて，パッシブクーリングの効果を明らかにした。その結果，蓄熱体の厚さ並びに夜間換気量は極めて有効であるが，その厚さや量には限界があること，那覇では外気温度の日変化が小さいので夜間換気の効果が得られないこと等を明らかにしている。

第３章では，インドの気候条件の異なる７都市における住宅合計２０戸を対象として，夏期の室内環境に関する実測調査を行っている。その結果，全般的に室内温度は極めて高く，ASHRAE の快適範囲からは大きくはずれているが，居住者はそのような環境に慣れて大きな不満は持っていないこと，建物構造はレンガや鉄筋コンクリートで作られているために熱容量が大きく，また，日射を遮蔽しているので室内温度の日変化が少ないこと，屋上が日射を受けるために最上階の部屋の室内温度は他の階の部屋に比べて高いことなどが明らかとなった。

第４章では，インドの建物に倣ってレンガ造の家屋模型（縮尺１／２）を２個作成し，一方は外壁の外側を断熱し，東北大学構内に置いて長期にわたる比較実験を行った。その結果，外断熱を行った上で夜間換気を行えば，日中は最大で他の家屋に比べ１０℃も低く抑えられることなどが明らかになった。

第５章では，実物の大きさの家屋モデルを対象としてインド各地の気象データを用いて数値計算を行い，外断熱と夜間換気の効果を推定した。その結果，それらのパッシブクーリング手法の効果が極めて大きく，外気温が４３℃のときに３５℃に抑えられることなどが明らかになった。

以上要するに本論文は，熱容量のある建物において夏の暑さを凌ぐためには日射遮蔽と夜間換気を行うことが重要であり，その適用の効果を定量的に明らかにしたものであり，熱帯地域における建物の設計に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。