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【論　文】
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COMBINED EFFECT OF EARTH COOLING AND VENTILATION ON PASSIVE COOLING OF DWELLINGS

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1. Introduction

There are two aspects to discuss utilization of earth cooling for passive cooling of dwellings. One is thermal characteristics of the earth, ground and soil as a cooling heat source or sink. The other is transmission of the cooling heat from its source to rooms or spaces where it is needed. Underground constructions[1] and semi-underground constructions[2] have earth-contact floors[3] and walls, where the earth as the cooling source is directly connected with the rooms by convection and radiation. Earth cooling tubes[4], on the other hand, have the cooling sources apart from the rooms, and the air introduced into the cooling tube is cooled by convective heat exchange and conveyed to the rooms.

We investigated thermal characteristics of the earth under buildings by numerical simulations in our previous studies[5),6)]. They showed that the ground surface temperature in a crawl space is the lowest among the surface temperatures in a building in summer because of solar shading and water evaporation. Therefore the ground surface in a crawl space can be a cooling heat source for dwellings in summer. As to the cooling heat transmission, we consider a system using ventilation. Namely the outdoor air introduced into the crawl space is cooled by the convective heat exchange with the earth surface ; then, it is led to the rooms and is eventually exhausted through the attic to the outdoors.

In this paper, we examine the combined effect of earth cooling and ventilation on passive cooling of dwellings, by field experiments of model houses. Thermal performance of two model houses, one of which is applied to the passive cooling system, is compared with each other. The feasibility and the prospect of the passive cooling system are discussed with these experimental results and some additional numerical simulations.

2. Outline of the Experimental Houses

Two experimental houses of the same structure were built. One of them was re-formed after confirming the sameness of their thermal performance to examine the combined effect of earth cooling and ventilation.

2.1 Structure of the model houses

Two experimental houses of the same structure were built in Chikushi campus of Kyushu University in Kasuga-shi, Fukuoka-ken. A bird's-eye view of the experimental houses is shown in Fig. 1. Each experimental house is divided into 3 spaces ; the attic space, the room space and the crawl space. A plan of the room space is shown in Fig. 2. Figure 3 shows a section of the house and its measuring points of air temperature, surface temperature, globe temperature and relative humidity. The walls of the experimental house are made of 11 mm plywood boards painted

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white. The room space side of walls is heat insulation layers of 30 mm polystyrene. The roof is composed of 0.6 mm steel sheets painted brown and shingles of 6 mm plywood. The ceiling is made of 6 mm plywood boards and a 50 mm layer of polystyrene. The floor is 11 mm plywood boards and the basement is 100 mm cement bricks. The room space has two windows on its southern and northern side. Both the crawl and the attic space have also their own openings on their southern and northern side. The floor and the ceiling have ventilation openings, from the crawl space to the room space and from the room space to the attic space, respectively. All the windows and the openings can be closed and air-tightened if necessary. In this paper, all the windows are closed through all the experiments. The temperatures in the experimental house are measured with thermo-couples, and the relative humidity of the room space is done with a high-polymer hygrometer.

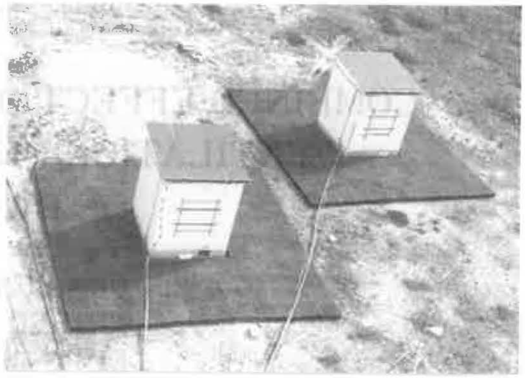


Fig. 1 A bird's-eye view of the experimental houses.

On the roof of a 5-story building adjacent to the experimental houses, weather condition was observed; its items were global solar radiation, atmospheric radiation, outdoor air temperature, dew point temperature, wind direction and wind velocity.

2.2 Sameness of two experimental houses

In the latter part of this paper, we estimate the combined effect of earth cooling and ventilation by comparison of the thermal performance of these two experimental houses. Therefore the sameness of these two experimental houses should be confirmed before the re-formation. The two experimental houses were named Model A and Model B, respectively. Model B would be re-formed as a passive cooling house using the combined effect of earth cooling and ventilation.

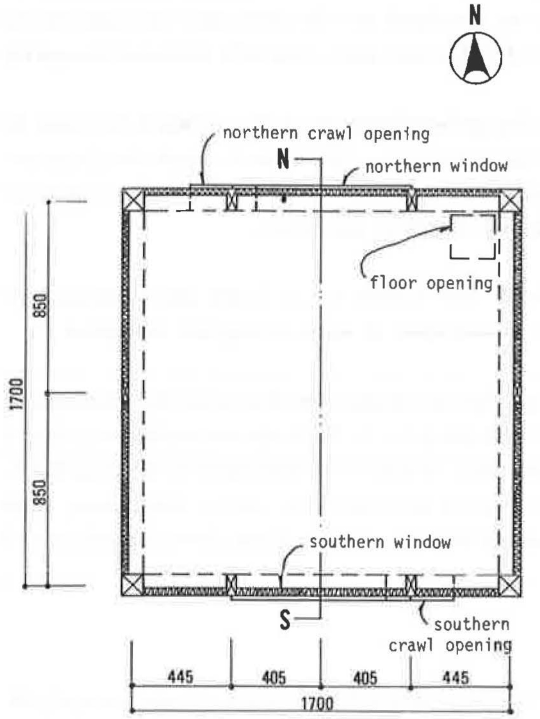


Fig. 2 A plan of the room space in the experimental house.

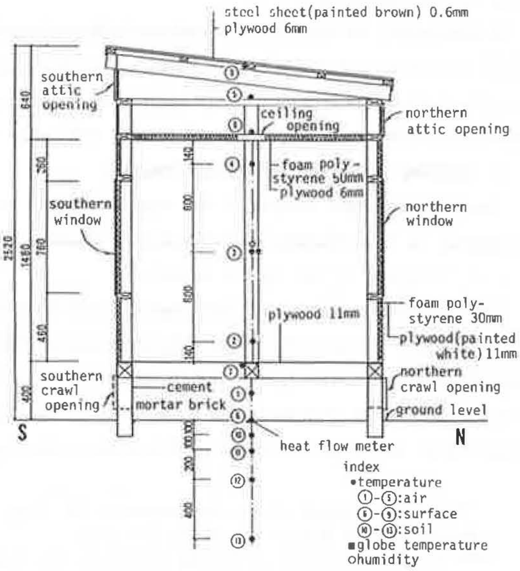


Fig. 3 A south-north section of the experimental house and measuring points.

The experiment to confirm the sameness of both Models' thermal performance was carried out from 25th to 27th of July in 1987 on condition that all the openings were closed. Figure 4 shows the comparison between the temperature fluctuation of Model A and that of Model B. In both Models, the highest temperature in the daytime is found in the attic space, and the lowest and stable temperature is the soil temperature at the depth of 80 cm. However the temperature differences at each point between Models are slight, at largest 1.5°C in the attic spaces.

The air-tightness of the experimental houses is examined with a pressure method[7]. The relation between indoor-outdoor pressure difference and air leakage in two Models is shown in Fig. 5. The air-tightness of Model A is the same as that of Model B when the pressure difference varies from 0.5 mmAq. to 10 mmAq. By these experimental results, we conclude that Model A and Model B are the same in thermal characteristics and air-tightness.

2.3 Re-formation of experimental house

One of the experimental houses, Model B, was re-formed to examine the combination effect of earth cooling and ventilation. To obtain the air flow route, the outdoors~the crawl space~the room space~the attic space~the outdoors, the following four openings were opened; the northern crawl opening, the floor opening, the ceiling opening and the southern attic opening. To promote the convective heat exchange between the air and the ground surface, the crawl space of Model B was divided into two parts by guide plates installed at 8 cm height above the ground surface. The air flow route in Model B is shown in Fig. 6. The outdoor air flows into the crawl space through the northern crawl opening. Then it goes through the narrow space between the guide plate and the ground surface. In the crawl space, the water in the soil evaporates to the air and absorbs latent heat from the ground surface. Therefore the ground surface temperature can be maintained lower, and the air is cooled by convective heat exchange with the ground surface. After being cooled by the ground surface, the air enters the room space through the opening in the floor. The air in the room space enters the attic space through the ceiling opening, and finally goes out to the outdoors by way of the southern opening of the attic space.

A small electric fan (30 W) was fitted at the ceiling opening to provide driving force for the air movement. It caused a ventilation rate about 150 m^3/h. The ventilation rate was calculated by the sectional area and the air flow speed of an opening, and air flow speed was measured by a hot-wire anemometer. In this paper, we only examine the results of the forced ventilation caused by the electric fan. However experiments using natural ventilation, using wind pressure and stack effect as the driving force for the air movement shown in Fig. 6, are to plan in near future.

3. Experiments of combined effect of earth cooling and ventilation

We show here two kinds of experimental results, Experiment No. 1 and No. 2. Model B was intact after its re-formation in these experiments. As to Model A, all of the windows and openings were closed in Experiment No. 1, but the openings in the attic and the crawl space were opened in Experiment No. 2. The combined effect of earth

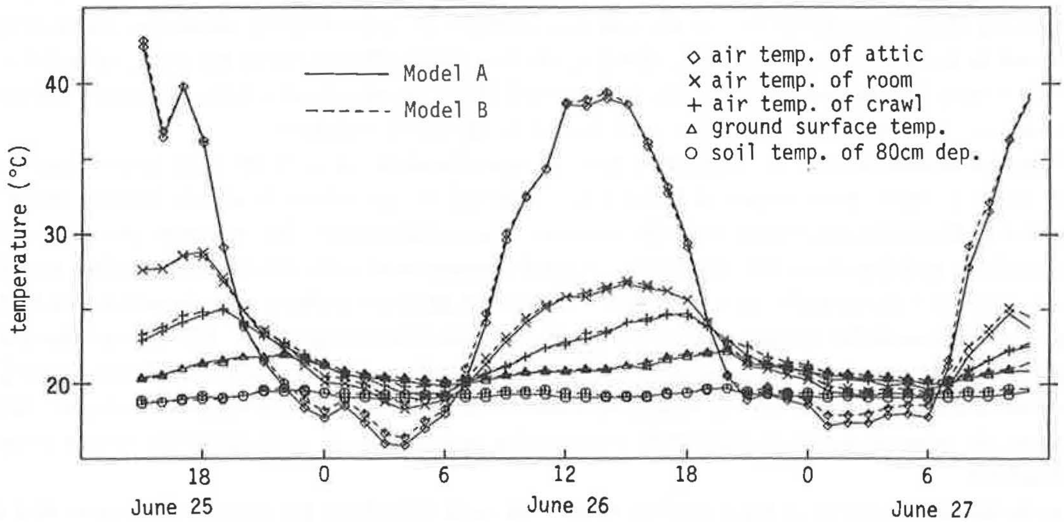


Fig. 4 Temperature fluctuations in the experimental houses, Model A and Model B, when all the openings are closed.

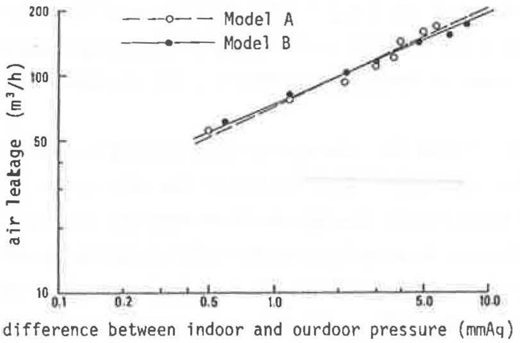


Fig. 5 Relations between indoor-outdoor pressure difference and air leakage in the experimental houses, Model A and Model B, when all the openings are closed.

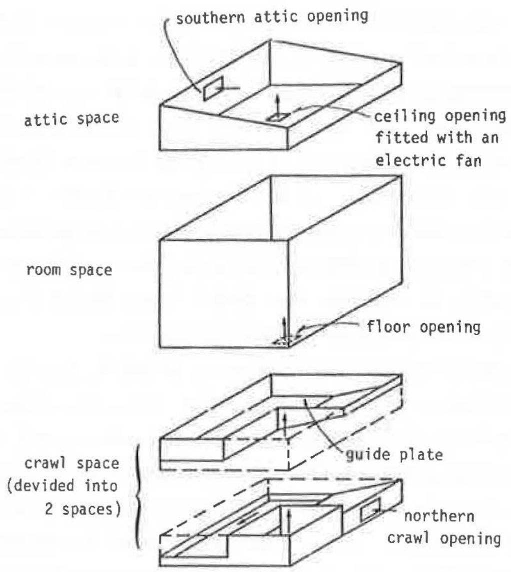


Fig. 6 An illustration of the airflow route in the experimental house to utilize combined effect of earth cooling and ventilation.

cooling and ventilation and its characteristics are examined by comparison of thermal performance between two experimental houses.

3.1 Results of Experiment No.1

The results of Experiment No.1 from 14th to 15th of September in 1987 are shown in Fig. 7. The room space of Model A has well heat insulated walls and ceiling, and no transmitted solar heat gain. Therefore its fluctuation of the room air temperature is similar to that of the outdoor air, but somewhat higher in the daytime with a time lag of an hour. On the other hand, the maximum air temperature in the room space of Model B on Sept. 14 is 28°C, lower than that in Model A (32°C) and that of the outdoor air (31.5°C) by about 4°C. This indicates the passive cooling effect of the combination of earth cooling and ventilation.

The air temperature mentioned in the previous paragraph was measured in the central part of the room space, point ③ in Fig. 3. There were two other measuring points of air temperature in the room space, point ② (14 cm above the floor) and point ④ (14 cm below the ceiling) as shown in Fig. 3. Figure 8 shows the correlation of the air temperature among these three points. As the room space in Model A is a closed space, temperature stratification is produced by free convection. In Model A, therefore, the temperature difference between point ② and point ④ is about 1°C when the temperature of point ③ is 30°C. In Model B, on the other hand, notable temperature difference among these measuring points cannot be found because of the forced ventilation.

As to the fluctuations of relative humidity of the room spaces shown in Fig. 7, Model A has more moderate one than Model B. Since the room space in Model A is air-tightened to some extent, its relative humidity should be varied more drastically in accordance with the variation of the air temperature. Thus the room space in Model A seems to have an ability of moisture adjustment. To clarify this phenomenon, the fluctuations of absolute humidity of the room spaces are shown in Fig. 9. In Model A, the value of absolute humidity is not constant but varied. It is high in the daytime and low at night in accordance with the variation of the air temperature. This indicates absorption and emission of moisture on porous materials. To the contrary, the fluctuation of absolute humidity in Model B is similar to that of outdoor air because the outdoor air is introduced into the room space through the crawl space. In the daytime, the values of absolute humidity in the room space of Model A is about one and a half time as large as those of Model B.

In the daytime, as shown in Fig. 7 and Fig. 9, the room space in Model B has lower air temperature than the outdoors, but almost the same absolute humidity as the outdoors. Consequently the relative humidity of the room

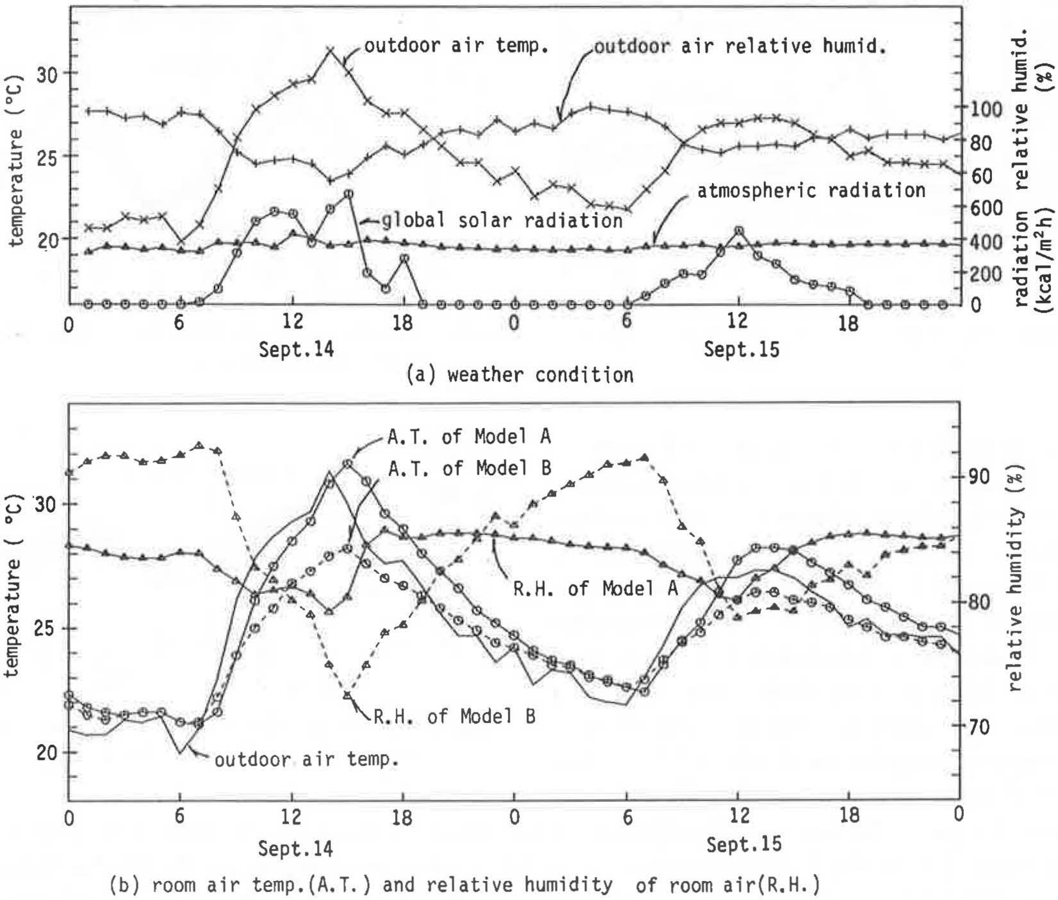


Fig. 7 Results of Experiment No. 1, all the openings in Model A are closed and Model B is the passive cooling house.

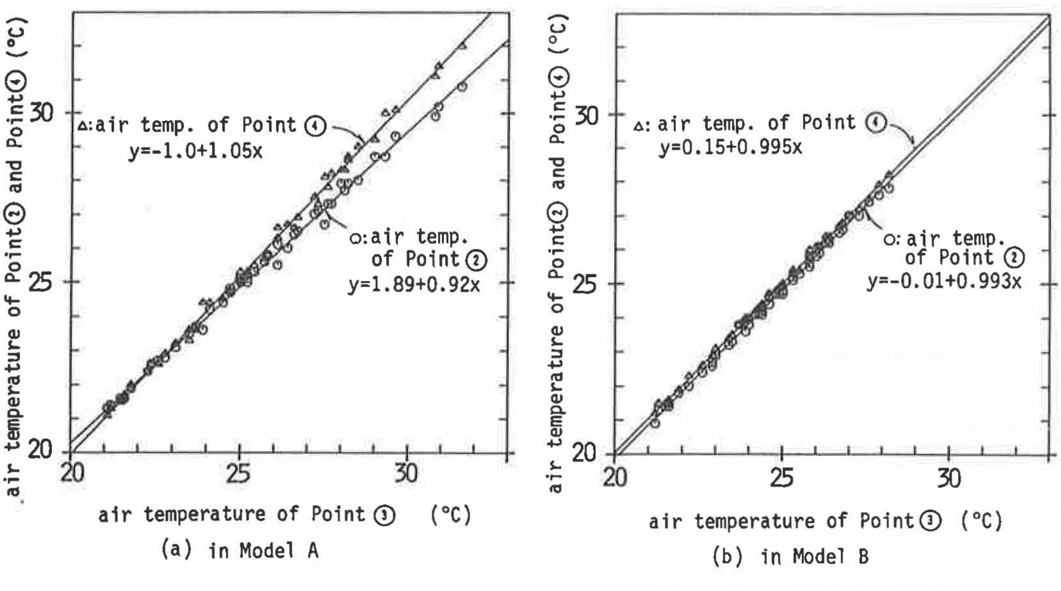


Fig. 8 Correlations of air temperatures measured at different heights in Experiment No. 1.

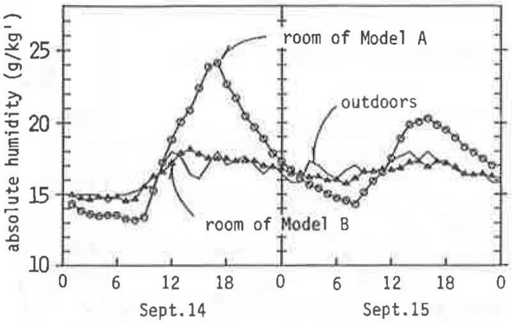


Fig. 9 Fluctuations of absolute humidity in Experiment No. 1.

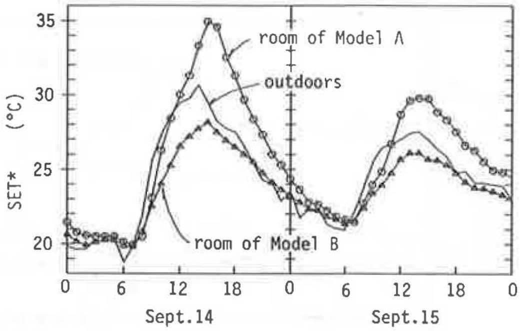


Fig. 10 Fluctuations of the Standard Effective Temperature, SET*, in Experiment No. 1.

space in Model B is higher than that of the outdoors. Considering this fact, we have to estimate the validity of the cooling effects including the increase of relative humidity. Thus the Standard Effective Temperature[8),9)], SET*, is used for the evaluation of thermal environment in the experimental houses. The SET*s calculated by obtained data of Experiment No. 1 are shown in Fig. 10. In Fig. 10, assumed values of the SET* in the outdoors are added for reference. The following assumption is adopted to calculate the SET* ; a clothing level of 0.3 clo, a metabolic rate of 1.1 Met and airflow speed of 0.2 m/s. The mean radiant temperature of the outdoors is supposed to be equal to the outdoor air temperature. The SET* in Model B is less than 28°C, and close to the room air temperature. The SET* in Model A, on the other hand, is 35°C at the maximum, surpassing the room air temperature. Therefore we conclude that the passive cooling system is effective from the viewpoint of human thermal sensation, though it increases more or less indoor relative humidity.

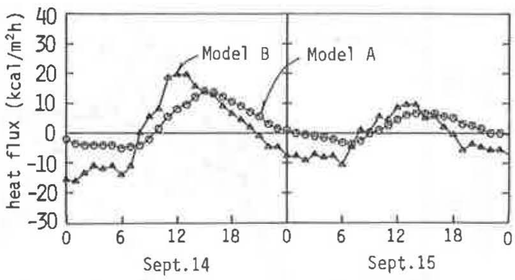


Fig. 11 Fluctuations of heat flux at the ground surface in the crawl space in Experiment No. 1.

Figure 11 shows the heat flux at the ground surface in the crawl space measured with a heat flow meter. The plus value means a heat flow from the ground surface toward the soil. In the midday, the heat flux in Model B indicates the maximum value ; for example, it is 20 kcal/m²h in Sept. 14. The outdoor air induced to the crawl space heats the soil, in other words the soil cools the air in the crawl space. This is the earth cooling effect.

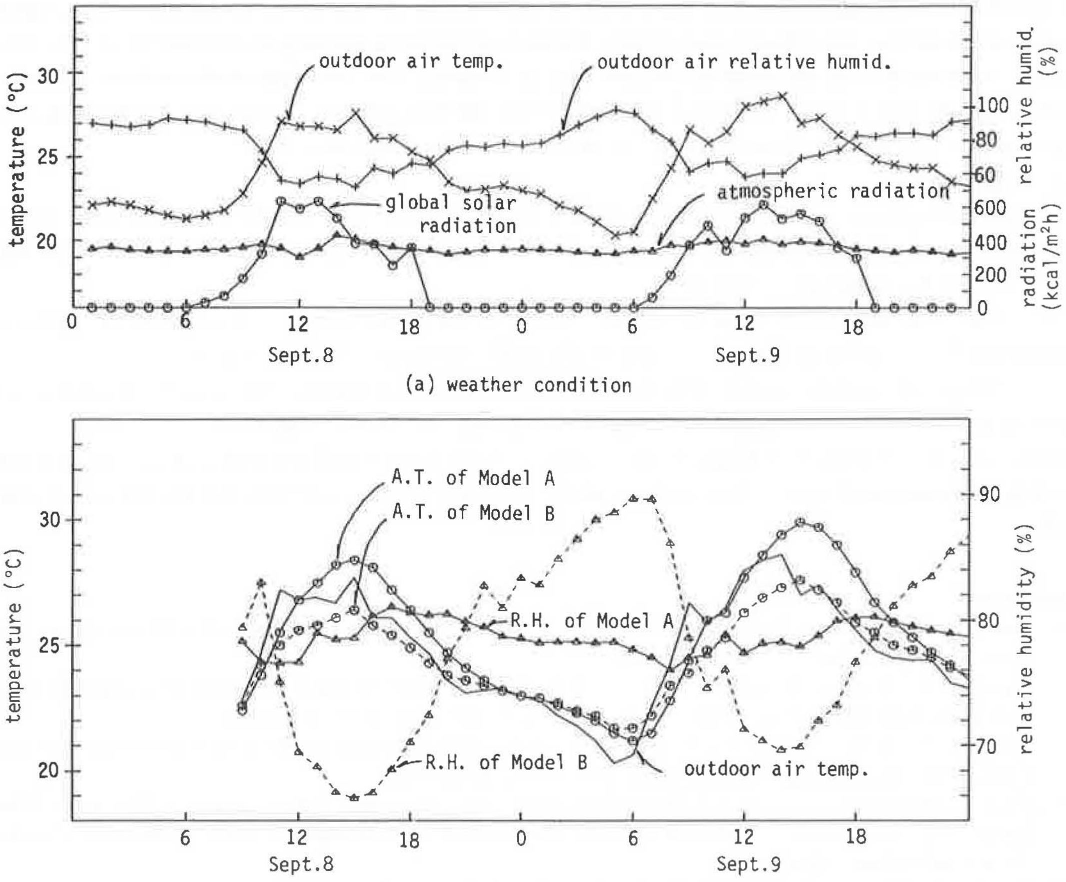
3.2 Results of Experiment No. 2

In this experiment, the openings of the crawl space and the attic space, four all of them, in Model A were opened. The experimental results from 8th to 9th of September in 1987 are shown in Fig. 12. The outdoor air temperature in both the days is rather low as summer weather condition. The air temperature in the room space in Model B, to which the passive cooling system is applied, is lower in the daytime than that of the outdoor. As to Model A, no remarkable tendency of the room air temperature can be found in comparison with that of Experiment No. 1. The reason is that the heat insulation layer on the ceiling reduces the influence of heat conduction from attic space to the room space.

4. Simulation of Combined Effect of Earth Cooling and Ventiation

We have shown some experimental results to estimate the combined effect of earth cooling and ventilation. Field experiments are affected by weather condition. In fact, it was rainy summer in 1987 especially in August. Therefore we apply a simulation method to examine the passive cooling effect of earth cooling and ventilation in mid summer.

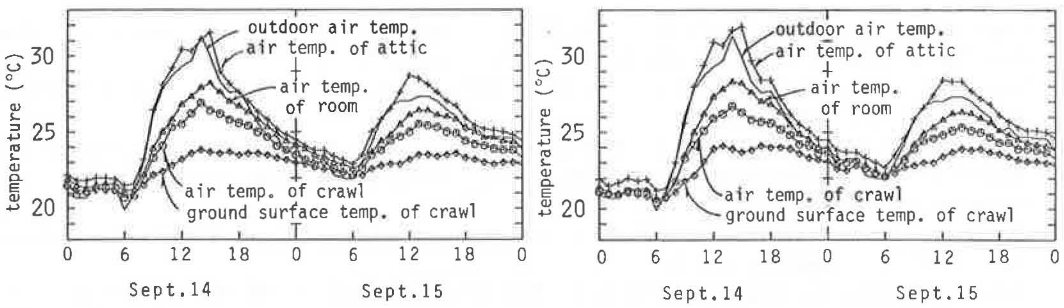
The thermal performance of Model B in Experiment No. 1 is simulated by using PSSP/MV 1[10)~12)]. The PSSP/MV 1 is a computer simulation program to calculate thermal performance of multi-room buildings, and transformed to applying to these simulations (see Appendix). The observed weather condition in concerning duration and the soil temperature measured at 40 cm depth are used as the given limitation.



(a) weather condition

(b) room air temp.(A.T.) and relative humidity of room air(R.H.)

Fig. 12 Results of Experiment No. 2, the openings in the crawl and the attic space of Model A are opened and Model B is the passive cooling house.



(a) experimental results of temperatures in Model B (b) calculated results of temperatures in Model B

Fig. 13 Comparison of temperatures in the passive cooling house, Model B.

The measured temperatures and the calculated ones of Model B in Experiment No. 1 are shown in Fig. 13. The differences between the measured values and the calculated ones are slight and almost within 1°C. We can conclude from these results that the simulation precisely describes the thermal performance of Model B.

Passive cooling capacity of the method which we propose can be defined as the cooled amount of the outdoor air passing through the crawl space. In Experiment No. 1, this passive cooling capacity was about 10 kcal/m²h as all-day-long average value and about 19 kcal/m²h as daytime (from 8 a. m. to 7 p. m.) one by the simulation results mentioned before. As Experiment No. 1 was carried out in the middle of September, this passive cooling capacity would not indicate the same values in mid-summer. Therefore a simulation assuming mid-summer (from lst to 7 th of August) is executed using the Standard Weather Data in Fukuoka. The simulation results indicate the passive cooling capacity of 16 kcal/m^{2}h as all-day-long average value and 31 kcal/m^{2}h as daytime one, and these values are approximately one and a half times as large as those obtained in Experiment No. 1.

5. Conclusions

We examined a passive cooling system for dwellings to utilize combined effect of earth cooling and ventilation. Its effect was discussed by field experiments of model houses and thermal performance simulations. The main conclusions of this study are as follows :

(1) The room air temperature in the passive cooling system in the daytime is lower than the outdoor air temperature by 4°C at the maximum according to the field experiments of model houses.

(2) The passive cooling capacity of the passive cooling system is estimated as 31 kcal/m^{2}h a unit area of crawl space in the daytime of mid summer according to the thermal performance simulation.

There are some remained problems in this system ; feasibility for actual dwellings, utilization of natural ventilation, promotion of earth cooling ability, reduction of humidity. These problems will be examined in further studies.

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Appendix

A heat balance equation at an inside wall surface is expressed according to Eq. 38 in reference 10) as

$$\left(\alpha_{c,J,n}+a_{J,J}+\sum_{k=1}^{Jn}\beta_{J,k,n}\alpha_{r,J,k,n}\right)T_{J,n}-\sum_{k=1}^{Jn}\beta_{J,k,n}\alpha_{r,J,k,n}T_{k,n}-\alpha_{c,J,n}T_{i,n}-a_{J,0}T_{J',n}=D_{J,n-1}-NSR_{J,n}-AL_{J,n} \quad \cdots\cdots (1)$$

A heat balance equation at the ground surface in the crawl space is shown transforming Eq. (1) to

$$\left(\alpha_{c,J,n}+a_{J,J}+\sum_{k=1}^{Jn}\beta_{J,k,n}\alpha_{r,J,k,n}\right)T_{J,n}-\sum_{k=1}^{Jn}\beta_{J,k,n}\alpha_{r,J,k,n}T_{k,n}-\alpha_{c,J,n}T_{i,n}-a_{J,0}T_{J',n}+LE_{J,n}=D_{J,n-1}-NSR_{J,n}-AL_{J,n} \quad \cdots\cdots (2)$$

Where, $LE_{J,n}$ denotes latent heat at the ground surface. The latent heat is expressed with Lewis's Law for evaporative heat exchange and using an evaporation ratio, $k_{J,n}$, as

$$LE_{J,n}=k_{J,n}\alpha_{c,J,n}/C_{J,n}(X_{s,J,n}-X_{i,n})L_{J,n}=k_{J,n}\alpha_{c,J,n}/C_{J,n}(b_nT_{J,n}+c_n-X_{0,n})L_{J,n} \quad (3)$$

where, $C_{J,n}$ is used for denoting specific heat of moist air; $X_{s,J,n}$ for saturated absolute humidity at temperature of $T_{J,n}$, $X_{i,n}$ for absolute humidity in a space (crawl space), $L_{J,n}$ for heat of evaporation or condensation of water, $X_{0,n}$ for absolute humidity of the outdoor air. Saturated absolute humidity, $X_{s,J,n}$, is approximated as a linear function of $T_{J,n}$. Its gradient, b_n, is the slope of the tangent which touches the saturated absolute humidity curve at temperature of $T_{J,n-1}$. The evaporation ratio, $k_{J,n}$, at the ground surface in the crawl space is assumed as a constant value of 0.5.

In the crawl space of Model B, convective heat transfer in a turbulent flow are assumed. As the crawl space has a rectangular section, the convective heat transfer coefficient, $\alpha_{c,J,n}$, in it is obtained by using following equations[13),14)].

$$S_t=C_f/2\,P_r^{-2/3} \quad (4)$$

$$C_f=[2\log(R/k_s)+1.68]^{-2}/4 \quad (5)$$

Where, S_t is used for denoting Stanton number; P_r for Prandtl number, C_f for a friction coefficent, R for a hydraulic radius, k_s for roughness of the ground surface. According to Eq. (4) and (5), the convective heat transfer coefficient is about 14 kcal/m²h°C when the ventilation rate is 150 m³/h.

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住宅における地盤冷熱と換気の併用によるパッシブクーリング効果（梗概）

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1. 緒　言

地盤をパッシブクーリングに利用する場合，2つの要素を考える必要がある。地盤の冷熱源としての特性とその冷熱の輸送方法である。地下室，半地下室などは接地床や接地壁で地盤とその冷熱を利用する室が直接に連結している。一方，クールチューブの場合は，冷熱源である地盤と冷熱を利用する室が分離している。

地盤をパッシブクーリングの冷熱源として利用するため，筆者等は建物床下の地盤の熱特性をシミュレーションにより検討し，建物床下の地盤は日射遮へいと水分蒸発により建物内で最も低温となる部位であることを指摘した。また，冷熱の輸送方法としてこの部位に外気を接触させて冷却した後，室内に導入すれば換気を併用したパッシブクーリング手法となることも提案した。本論文は前述の予測に基づいて2棟の試験家屋を製作し，1棟を地盤冷熱利用棟として比較実験および室温変動シミュレーションにより地盤冷熱と換気の併用によるパッシブクーリング効果を検討したものである。

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2. 試験家屋の概要

2.1　試験家屋の構造

同一仕様の2棟の試験家屋を九州大学筑紫キャンパス（福岡県春日市）内に建設した。試験家屋の外観を Fig.1 に示す。試験家屋は床下，居室，小屋裏の3スペースで構成されている。試験家屋の居室平面を Fig.2，家屋断面と各種測定点を Fig.3 に示す。試験家屋の外壁は厚さ 11 mm の白色ペイント塗装合板で居室側を 30 mm のフォームポリスチレンで断熱している。屋根は茶色ペイント塗装の 0.6 mm 厚亜鉛鉄板であり，下地は厚さ 6 mm の合板である。また，床は 11 mm，天井は 6 mm の厚さの合板で，天井には 50 mm のフォームポリスチレンを設置した。居室南北面には窓，床下および小

屋裏の南北面にも換気口がある。また，床には床下と居室，天井には居室と小屋裏を結ぶ換気口がある。すべての窓および換気口は密閉閉鎖することが可能であり，今回の解析では窓は常時閉鎖している。空気温度，表面温度および地中温度は T 熱電対，湿度は高分子素子湿度計で測定した。日射量，外気温，外気露点温度，大気放射量，風向および風速などの気象条件は試験家屋に隣接した5階建物の屋上で測定した。

2.2 試験家屋の同一性比較実験

すべての開口を閉鎖した状態で2棟の試験家屋の室温変動および気密性能の同一性を実験的に確認した。Fig. 4 に地中 80 cm の温度，床下地表面温度および床下，居室中央，小屋裏の空気温度を比較して示す。2棟における違いはほとんどない。2棟の試験家屋の気密性能を加圧法によって測定した。室内外の差圧とすき間からの空気漏洩量の関係を Fig. 5 に示す。圧力差 0.5～10 mmAq では，2棟の気密性能はよく一致している。

2.3 地盤冷熱利用棟

2棟の試験家屋はそれぞれA棟，B棟と呼び，同一性比較実験後，B棟を地盤冷熱利用棟に改造した。Fig. 6 に示すように，B棟では外気を床下地盤面と接触させて冷却し，その冷気を居室に導入した後，小屋裏を経て排気する。換気の駆動力として今回の解析では天井換気口に小型換気扇（30 W）を設置したが，自然換気を用いた実験も今後予定している。換気扇運転時の換気量は 150 m^3/h である。

3. 地盤冷熱と換気の併用による効果に関する比較実験

3.1 実験 No. 1

地盤冷熱と換気を併用したB棟とすべての換気口を閉鎖したA棟の比較実験を1987年9月14～15日に行った。Fig. 7(a) に実験時の気象条件を，Fig. 7(b) に実験結果を示す。密閉したA棟の居室空気温度は外気温とほぼ同じ傾向を示すが，1時間程度の時間遅れがある。一方，B棟の居室空気温度は14日の最大値で28°Cであり，外気の最大値32°Cに比べて4°C低い。この温度低下が地盤冷熱と換気の併用効果と考えられる。

居室内空気温度分布を，居室中央部，下部および上部の空気温度相関図として Fig. 8 に示す。A棟の室内空気温度は，居室下部が最も低く，居室上部が最も高い。その差は居室中央部の空気温度が30°Cの時に1°C程度である。一方，B棟では強制換気のため，垂直温度分布はない。

また，Fig. 7 に示す居室の相対湿度の変動が，密閉されているA棟では穏やかである。居室温度の上昇に伴って相対湿度は減少すべきであるが，その傾向は顕著でない。Fig. 9 によれば，A棟の居室の絶対温度の変動は昼間に増大しており，空気温度の変動に対応している。この原因は壁面での吸放湿の影響が考えられる。昼間のA棟の絶対湿度はB棟のそれの約1.5倍である。

Fig. 7, Fig. 9 に示すように，昼間のB棟居室の空気温度は外気温度より低く，絶対湿度は外気とほぼ等しいから，昼間のB棟居室の相対湿度は外気の相対湿度より高くなる。昼間に絶対湿度が増加する本パッシブクーリング方式は，湿度の体感に与える影響を含めて表する必要がある。Fig. 10 によれば居室の SET* 最高値がB棟では28°Cであり，ほぼ居室空気温度と同じであるが，A棟では35°Cであり，居室空気温度を上回っている。この結果から本方式は室内の相対湿度が多少増加しても十分有効であると考えられる。

Fig. 11 に床下地盤面における熱流の実測値を示す。B棟では日中に地盤表面から地中への熱流が 20 kcal/m^2h あり，この数値が地盤の冷却力を示すものと考えられる。

3.2 実験 No. 2

A棟の床下および小屋裏換気口を開放してB棟と比較する。外気温度がかなり低下し，夏季の実測とは呼びにくいが，実験 No. 1 と同様にB棟の居室空気温度は日中，外気よりも低下した（Fig. 12 参照）。

4. 地盤冷熱と換気の併用効果のシミュレーション

地盤冷熱利用棟の室温変動シミュレーションを PSSP/MV 1 を一部改造して行った（Appendix 参照）。実験 No. 1 時の気象条件を用いたシミュレーション結果と実測結果を Fig. 13 に示す。地表面温度，床下空気温度，居室空気温度および小屋裏空気温度の実測値と計算値は1°C以内の精度で一致した。

地盤冷熱と換気を併用する本方式の冷却力は床下に導入された外気の温度低下から求められる。実験 No. 1 のシミュレーション結果からこの冷却力を求めれば，床下単位面積当たり日平均で約 10 kcal/m^2h，昼間（8時～19時）のみの平均では約 19 kcal/m^2h であった。しかし，実験 No. 1 は9月14日～15日に行われており，この冷却力がそのまま盛夏時のものとは考えにくい。そこで，福岡市の8月1日～7日の1週間の標準気象データを用いて，地盤冷熱と換気による冷却力を計算した結果，日平均では約 16 kcal/m^2h，昼間平均では 31 kcal/m^2h となった。

5. 結　語

2棟の試験家屋の屋外比較実験，同試験家屋の室温変動シミュレーションにより，地盤冷熱と換気を併用したパッシブクーリング手法の有効性を検討した。本研究の主な結論は次のごとくである。

1） 試験家屋の実験結果によれば地盤冷熱と併用したパッシブクーリング方式により，室温を外気より最大4°C低下できる。

2） 室温変動シミュレーションによれば，同方式の冷却力は，盛夏時の昼間で 31 kcal/m^2h である。