

ENERGY SAVINGS OF APARTMENT HOUSES BY NATURAL VENTILATION

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1. Introduction

In the hot season, natural ventilation is generally used to cool buildings. Wind takes away the heat from buildings, which is from the solar radiation and generated heat from equipment such as lights, and also removes sensible and latent heat from human bodies, improving the thermal sensation. The utilization of natural ventilation is influenced by many factors such as the daily living schedule of occupants, weather condition of a region, surrounding environments and building design. The purpose of this paper is to analyze quantitatively the energy saving effects by cross-ventilation, relating to the arrangement of apartment buildings and the location of them.

There have been several studies on the natural ventilation of dwellings. The authors have investigated the ventilation and the indoor thermal environment of apartment building from the viewpoint of energy savings^{1)~4)}. Recently, the natural ventilation of dwellings for the purpose of saving energy is also studied actively in Europe and the United States, and some computations and experiments are reported, such as the papers of Chandra et al.⁵⁾ and Kammerud et al.⁶⁾.

The contents of this paper are as follows :

- (1) The wind pressure coefficient is required to calculate the ventilation rate. Therefore, the wind tunnel tests are done to obtain the relation between the wind pressure coefficient and the wind direction or the building volume ratio.
- (2) The ASHRAE's SET*, the Standard New Effective Temperature⁷⁾, is used for the evaluation of thermal comfort. Psychological experiments on comfort sensation are carried out to obtain the relation between the human comfort and the SET* in a naturally ventilated environment.
- (3) The thermal performance of a ventilated dwelling unit and an unventilated one is simulated by the program called "PSSP" (Passive System Simulation Program)^{8)~11)}. Energy savings of natural ventilation are estimated in terms of heat extraction for the cooling of dwelling units. Sapporo, Tokyo and Kagoshima are selected to examine the energy saving effects regionally.

Nomenclature

BV : building volume ratio which means the ratio of total floor area to lot, %
C : wind pressure coefficient
F : stories of an apartment building
G : ventilation rate, m³/h
s : area of an opening, m²
Sr : cross-sectional area of a room, m²
u : indoor air flow speed, m/s

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V : wind speed, m/s

V_{∞} : free-stream speed in the windtunnel, m/s

Z : height from the plane of the wind tunnel, mm

θ : orientation of a building from the south, degree

Subscript W, L : windward and leeward, respectively.

2. Wind Tunnel Tests

The wind tunnel tests are carried out to obtain the wind pressure coefficients of windward and leeward wall surfaces, relating to the building volume ratio, BV , stories of building, F , and wind direction. The arrangements of model buildings are shown in Table 1. The models are scaled in 1/400.

The building volume ratios are changed with the longitudinal interval, D . Two kinds of model height are tested at the building volume ratio of 50 %. The wind tunnel used in the tests has a cross-sectional area of 1.5 m by 1.5 m, with a test length of 4.6 m. The free-stream speed V_{∞} is about 8 m/s. The models in the wind tunnel can be seen in Fig. 1. To produce a wind speed profile similar to that of the natural wind in the urban area, a screen is fixed at the outlet of the wind tunnel¹²⁾. The wind speed profile of 3 m downstream from the outlet is shown in Fig. 2. The influence of the models on the mean wind speed is reduced above a height of 0.25 m which is equivalent to 100 m in field scale. Therefore, the wind speed at a height of 0.25 m is used as the reference speed. To avoid the blocking effect, the model blockage is limited up to 5 %¹³⁾.

The relation between the wind pressure coefficient and the building volume ratio, BV , is shown in Fig. 3. As BV increases from 0 % to 25 %, the absolute values of the wind pressure coefficient decrease significantly, while they decrease slowly in the case that BV is over 25 %.

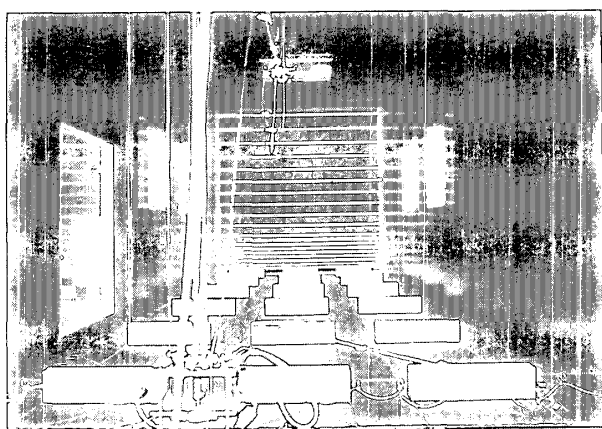


Fig.1 Outline of the wind tunnel tests

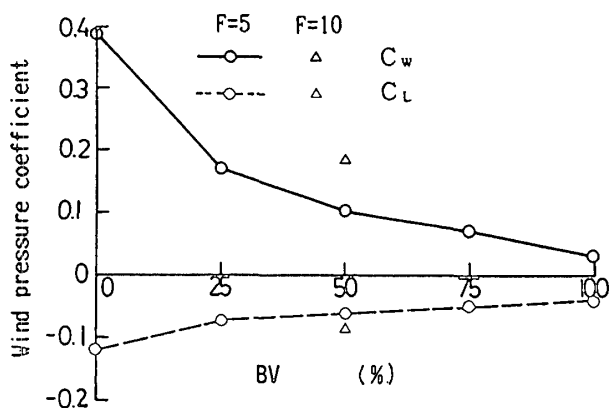


Fig.3 Relation between the wind pressure coefficients and the building volume ratio (wind direction= 0°)

Table 1 Arrangements of buildings

F (stories)	BV (%)	D (m)	H (m)	θ ($^{\circ}$)
5	0	—	15	0
5	25	123	15	0
5	50	57	15	0
5	75	34	15	0
5	100	23	15	0
5	50	57	15	45
10	50	123	30	0

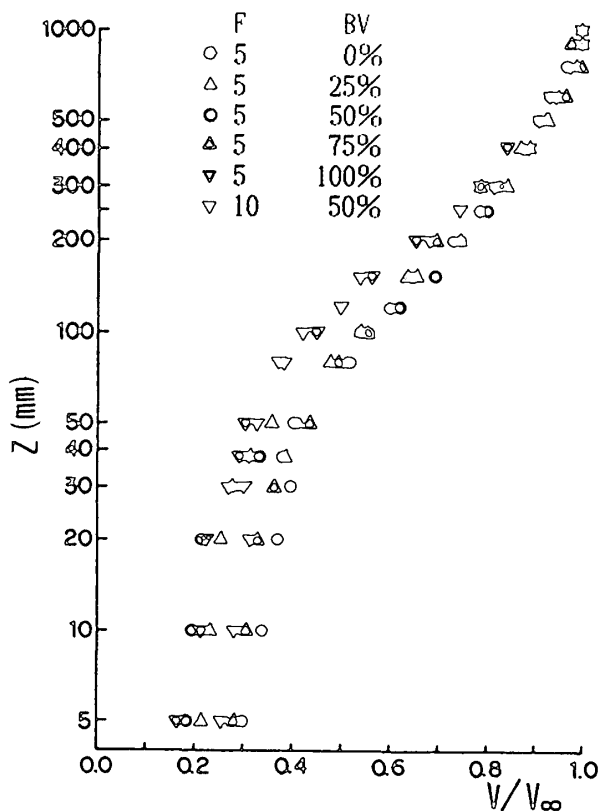
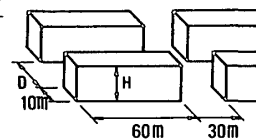


Fig.2 Profiles of mean wind speed at 3 m downstream from the outlet in the wind tunnel

Fig. 4 shows the change of the wind pressure coefficient to the wind direction at BV of 50 %. The pressure difference between the windward and the leeward changes little if the wind direction is below 60° , but it decreases evidently over 60° .

All of the wind pressure coefficients mentioned above are the average values of the measurement points on the windward or leeward walls of the model building.

3. Psychological Experiments on Thermal Comfort Sensation

The indoor thermal environment must be evaluated inclusively by air temperature, humidity, radiative temperature and air flow speed. The SET^* , the Standard New Effective Temperature is adopted as the overall index

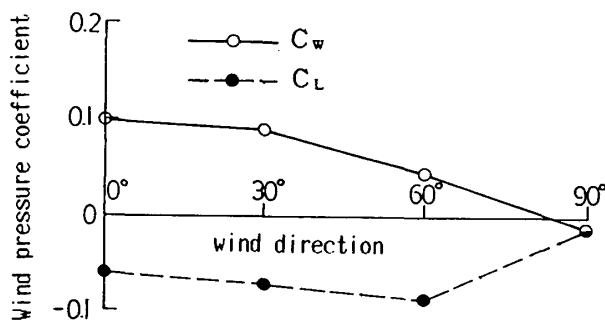


Fig. 4 Relation between wind pressure coefficient and wind direction ($BV=50\%$, $F=5$)

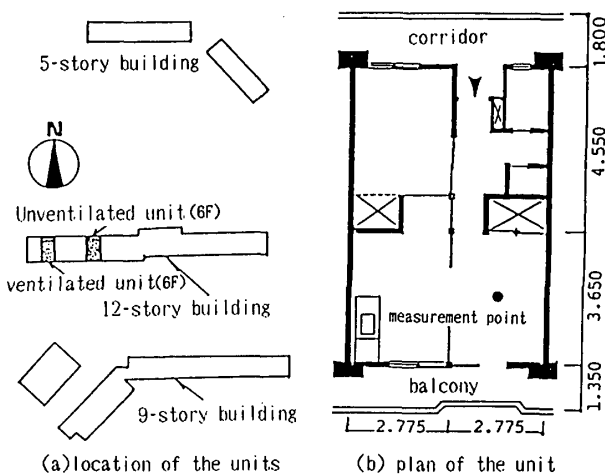


Fig. 5 Location and plan of dwelling units for the psychological experiments

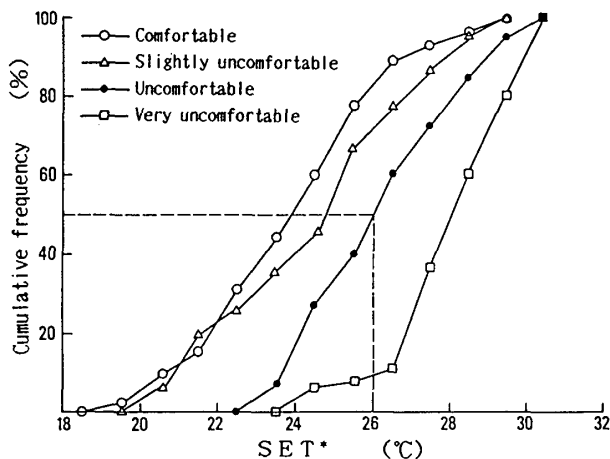


Fig. 6 Cumulative frequencies of the SET^* for comfort sensation votes

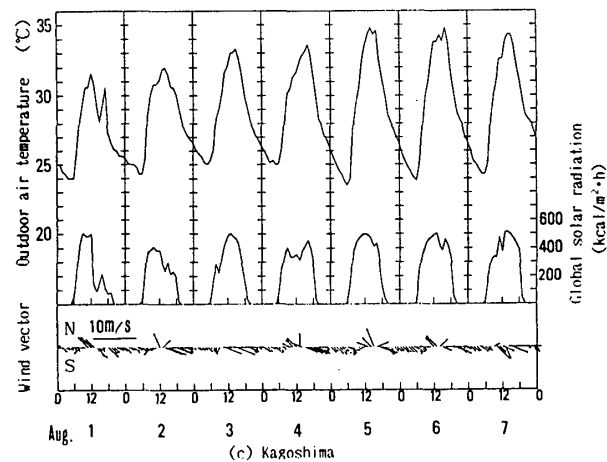
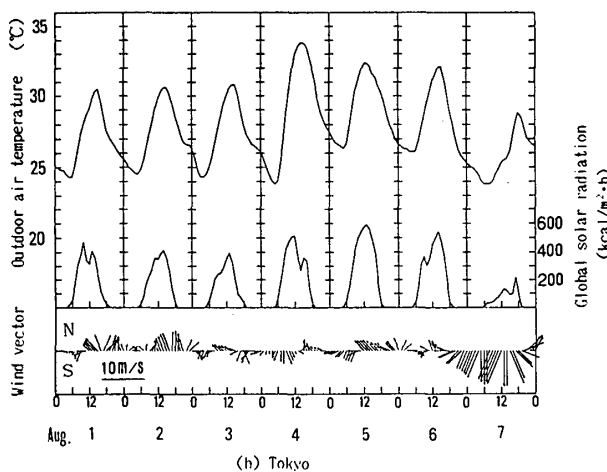
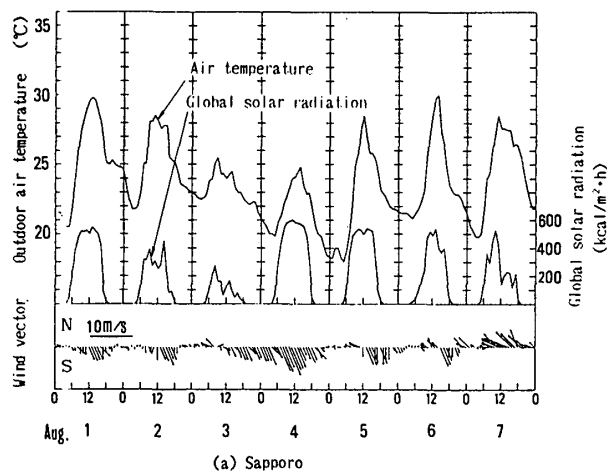


Fig. 7 The Standard Weather Data of calculation term

of the thermal sensation here. The SET* includes all the environmental and human thermal elements, therefore it can be adapted to any conditions.

In order to make clear the relation between the comfort sensation and the SET*, the psychological experiments are conducted in the naturally ventilated dwelling unit on the 6th floor of the 12-story building as shown in Fig. 5¹⁴⁾. There are some studies on the thermal sensation on the artificially ventilated condition¹⁵⁾, however it is difficult to make a turbulent air flow of which turbulent scale and frequency range widely as natural wind. On the other hand, there are few studies on the naturally ventilated condition. Therefore, the experiments in the naturally ventilated room are done. The experiments are composed of 32 runs in total, using 4 males and 4 females subjects in college age. In a run of the experiment, a subject clothed in 0.3 clo is sedentary in 90 minutes, facing to the windward in a ventilated room after 30 minute rest in an unventilated room. The subjects' votes of comfort sensation are voted on 4-category scale by pushing vote buttons. At the same time, air temperature, relative humidity, globe temperature and wind speed are recorded.

The cumulative frequency distributions of the SET* for the 4 levels of comfort sensation are depicted in Fig. 6. In a viewpoint of energy savings, the median of the SET* of a category "uncomfortable" is assumed as the tolerable limit of the indoor thermal environment. That value of the SET* is 26°C.

4. Energy Saving Effects of Cross-ventilation

To discuss the utilization of natural ventilation regionally, Sapporo, Tokyo and Kagoshima are selected. The Standard Weather Data¹⁶⁾ of the above mentioned cities through Aug. 1-7, considered to be typical summer days, are shown in Fig. 7. Fig. 8 shows the wind roses and the wind speed frequency distributions in this term. In Tokyo, the wind direction at night is different from that in the daytime, which is considered to be the influence of the land and sea breeze.

The PSSP is used to predict the indoor thermal environment. It can calculate dry-bulb temperature, mean radiant temperature, relative humidity, ventilation rate and air-conditioning load. The simulated results by the PSSP are

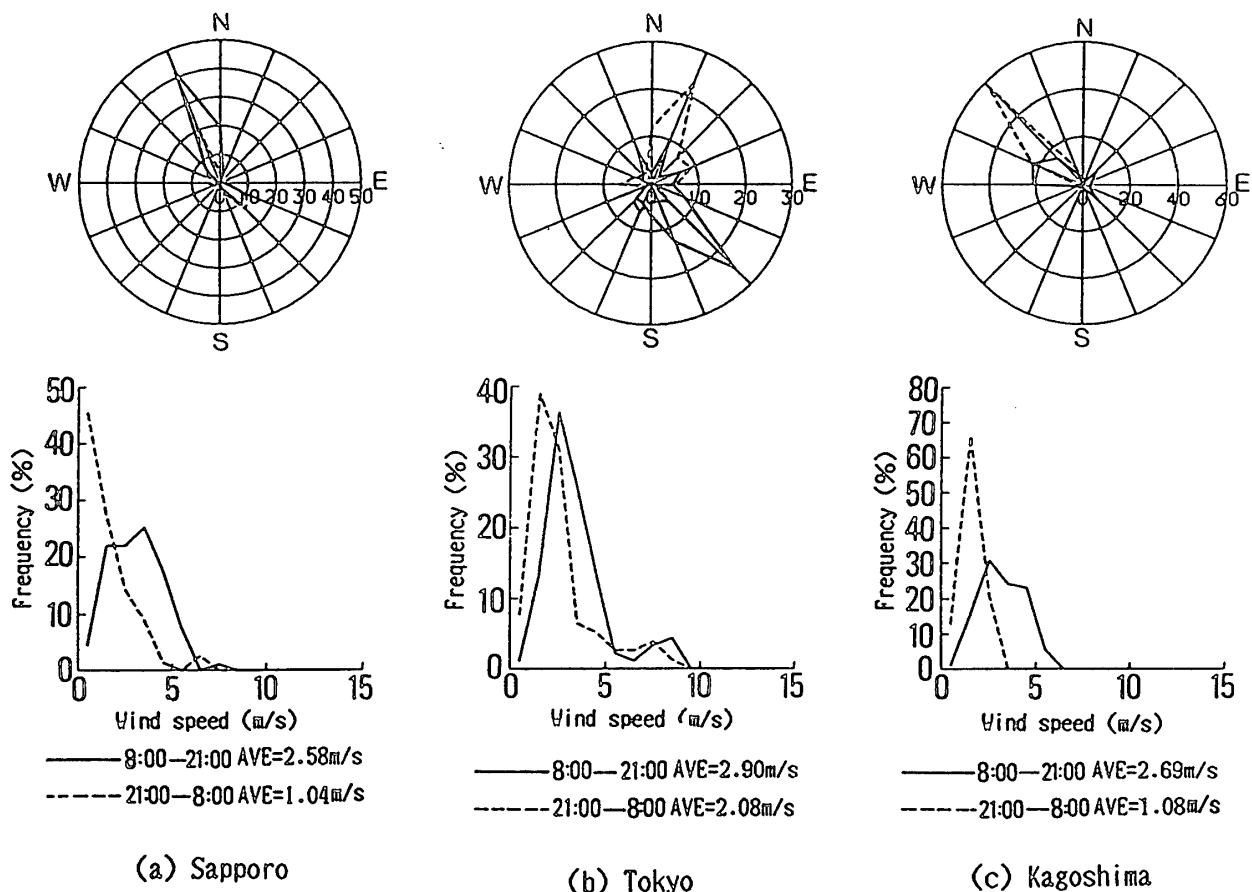


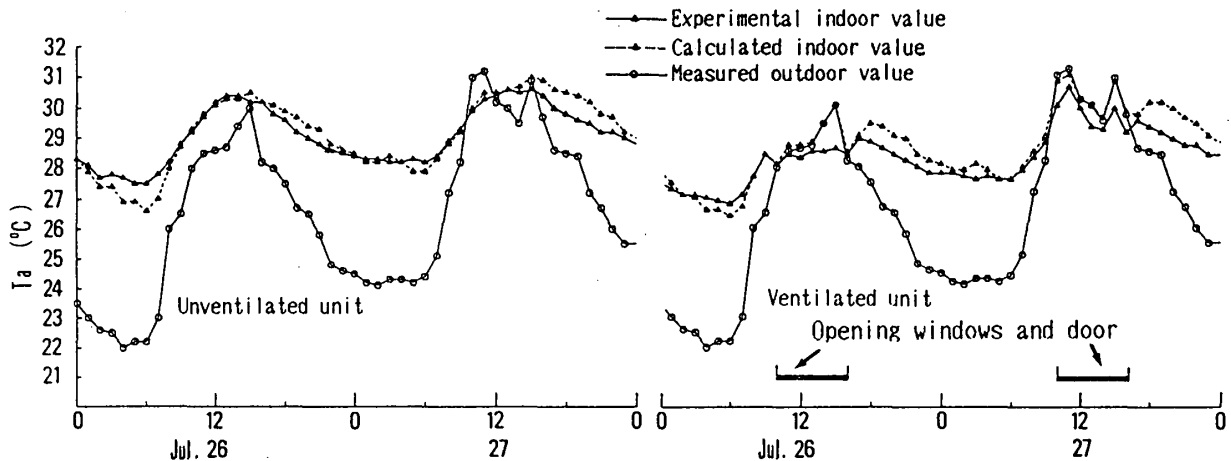
Fig.8 Wind roses and wind speed frequencies of the Standard Weather Data (1~7, August)

compared with the measured results as shown in Fig. 9 (a), (b) and (c). These data are measured and simulated in the dwelling units shown in Fig. 5. The simulated values agree with the measured ones fairly well.

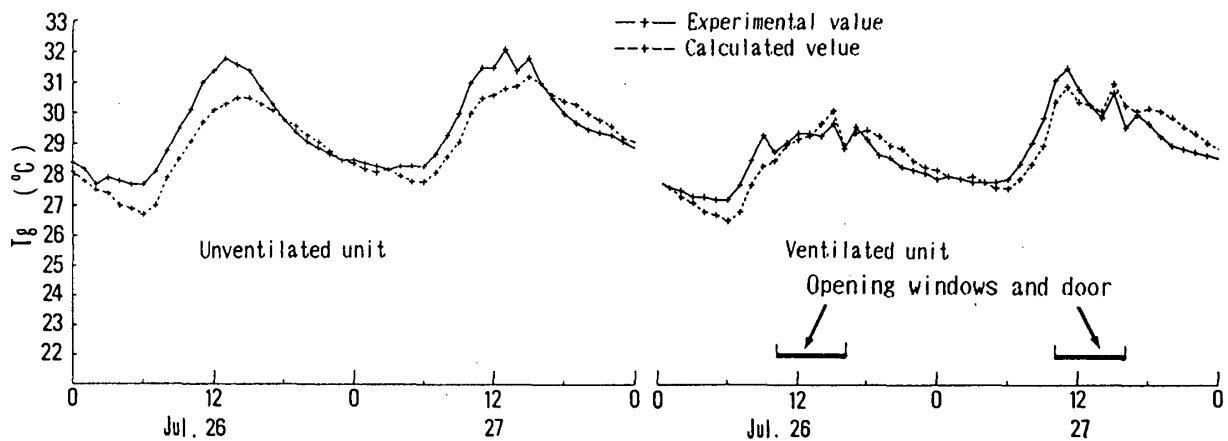
The amount of ventilation per hour, G is calculated by the PSSP. Considering the air flow distribution in a ventilated unit¹⁷⁾, the air flow speed in the middle part of the room, u , is calculated by

$$u = 2 * G / (3600 * S r) \quad (\text{m/s}).$$

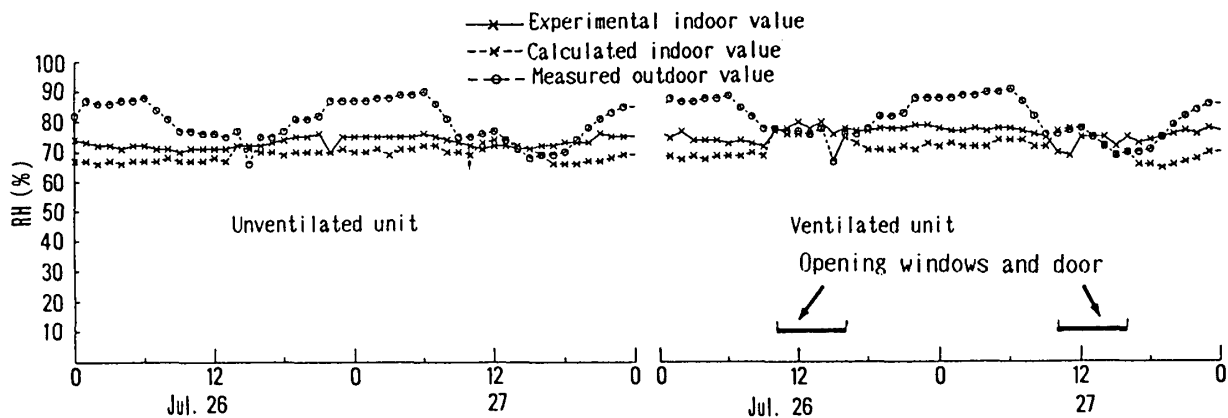
The dwelling unit shown in Fig. 10 is selected to examine the energy saving effects of natural ventilation in summer by the thermal performance simulations. It is supposed to be on the 3rd floor of a 5-story apartment building



(a) indoor and outdoor air temperature



(b) globe temperature



(c) relative humidity

Fig. 9 Comparisons of calculated indoor air temperature, globe temperature and relative humidity with experimental ones

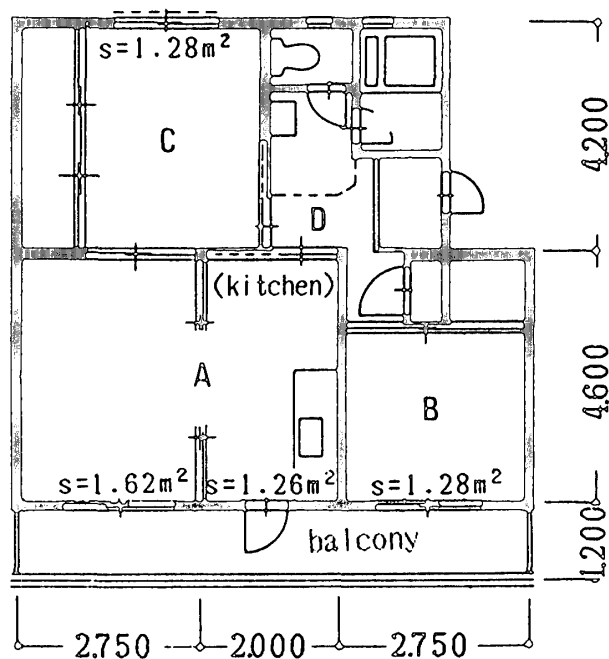


Fig. 10 Plan of the dwelling unit for energy saving simulations

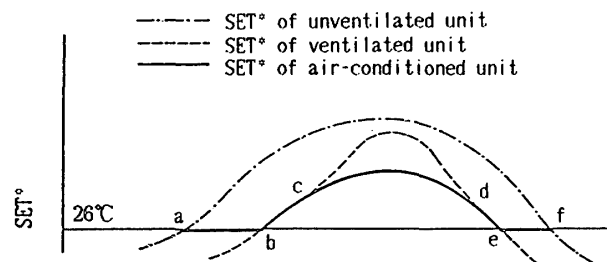


Fig. 11 Procedure to control the air-conditioner by the SET*

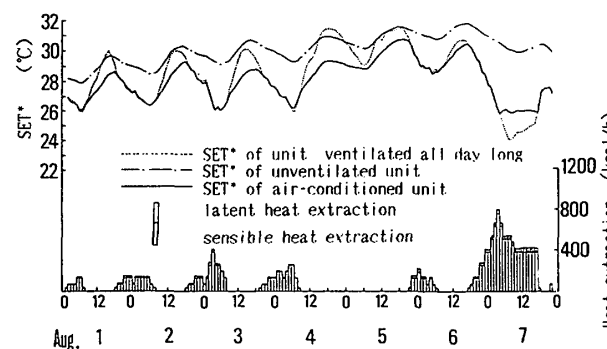


Fig. 12 Fluctuation of the SET*s in Room A and heat extraction of air-conditioned Room A (Tokyo. $BV=50\%$, $\theta=0^\circ$, $F=5$)

or the 6th floor of a 10-story one. The floor area of the unit is about 62 m^2 , and the unit is divided into 4 rooms. The unit consists of 20 cm concrete walls, wooden partitions, normal pane windows, interior doors (wooden doors, or Fusuma in Japanese) and exterior steel doors. Only Room A which is a living room and kitchen is equipped with a room air-conditioner, and its outlet air is supposed to be maintained constantly 15°C of temperature and 90 % of relative humidity. In the case that natural ventilation is utilized, the windows, the exterior door at the balcony and the Fusuma doors are opened. On the contrary, all of the windows and doors are closed in the case of the unventilated unit. To simplify the analysis, there are no curtains or blinds at the windows and no generated heat from occupants, equipment and lights.

The procedure to control the air-conditioner of the unventilated unit is shown in Fig. 11. The basic concept to estimate the energy saving effects by natural ventilation is to acquire the heat extraction of the Room A in the unventilated unit whose air conditioner keeps its SET* as same as that of the room A in the naturally ventilated unit (b~c and d~e in Fig. 11). But it seems to be unnecessary to cool extremely the unventilated unit to agree both the SET*s, if the SET* of the ventilated unit is below a certain degree (a~b and e~f in Fig. 11). Therefore, 26°C of the SET* is adopted as the tolerable limit which is shown in Chapter 3. On the other hand, it is also unnecessary to warm the unventilated unit in the case that the SET* is lower than that of the ventilated unit (c~d in Fig. 11).

All of the simulations mentioned below are carried out during the first 7 days of August. The clothing and the activity level in the SET* calculation is supposed to be 0.4 clo and 1.2 met respectively, and the wind pressure coefficients shown in Chapter 2 are applied to the simulations. Fig. 12 shows the SET*s of 3 different units and the heat extraction in Tokyo at the building volume ratio of 50 %. As the openings of the ventilated unit are opened all day long, its SET* is generally lower and more variable than that of the unventilated unit where the air leakage through cracks on the windows and doors is taken into account. As for the air-conditioned unit, its SET* fluctuation is different from both the ventilated and unventilated, and its heat extraction is large in the night but almost zero in the daytime because of the night cool heat storage.

The daily average amount of heat extraction in the unventilated and air-conditioned unit is offered as the value defining the energy savings by the utilization of natural ventilation. The relation between the energy savings and the building volume ratio, at the 3rd floor of the 5-story apartment building facing to the south, is shown as to 3 cities in Fig. 13. In Sapporo, the SET* of the unventilated unit is often lower than 26°C , the value of energy savings is

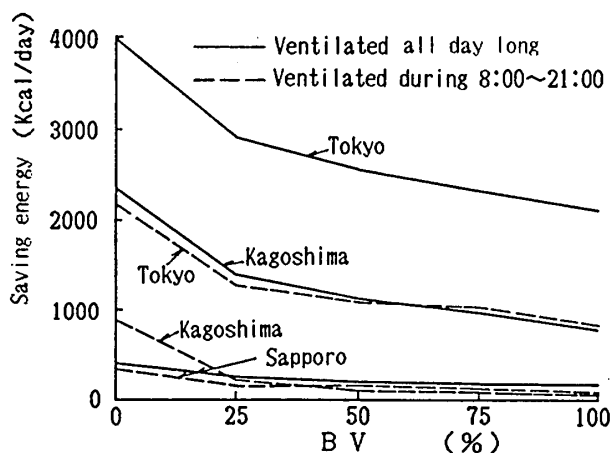


Fig. 13 Influence of the building volume ratio and the ventilating pattern on energy savings ($F=5$, $\theta=0^\circ$)

consequently very small. Though Kagoshima is hotter than Tokyo in the concerned duration shown previously in Fig. 7, Kagoshima is less energy saving than Tokyo by natural ventilation. This is because the outdoor air is so hot and the outdoor wind from the south is so weak in Kagoshima that the SET* of the ventilated unit is relatively high and the SET* difference between the ventilated and unventilated is small in comparison with Tokyo. Fig. 13 also indicates that the ventilation all day long is more effective than ventilation only during the daytime.

Next, the influence of the building orientation on the energy savings is investigated. The energy savings of 3 kinds of orientation at the building volume ratio of 50 % are shown in Fig. 14. If the building volume ratio is the same, the higher building will have larger effects of energy savings because of the increase of the wind pressure as shown in Fig. 3. The energy savings of the units oriented to 45°E or 45°W are large in comparison with that of the unit oriented to the south. There are few differences of the SET*s among the ventilated units but as for the unventilated, the SET*s in the units oriented to 45°E or 45°W are higher than that in the unit oriented to the south as shown in Fig. 15.

5. Conclusions

This study indicates quantitatively the effects of wind-induced cross-ventilation on energy savings in summer. The main results are as follows :

- 1) The regional characteristics of climate affect the energy savings by natural ventilation.
- 2) The energy saving effects of natural ventilation all day long are larger than that of natural ventilation only during the daytime.
- 3) The saving energy by natural ventilation decreases according to the increase of the building volume ratio.
- 4) A 10-story building has larger effects of energy saving by natural ventilation than a 5-story building. Though the energy savings by natural ventilation of the buildings oriented to 45°E or 45°W are larger than that of the building oriented to the south, the SET*s in ventilated rooms change little by the orientation of buildings.

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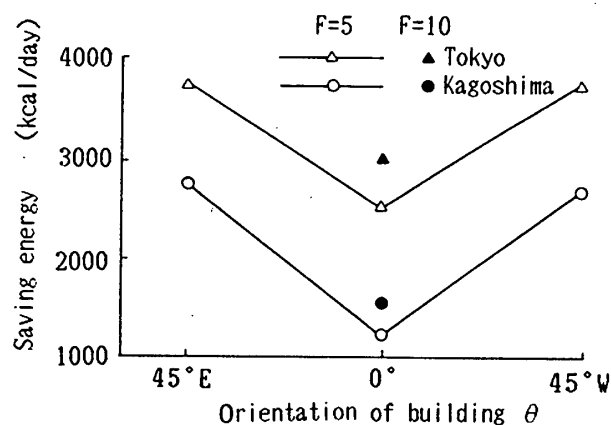


Fig. 14 Influence of building orientation on energy savings ($BV=50\%$)

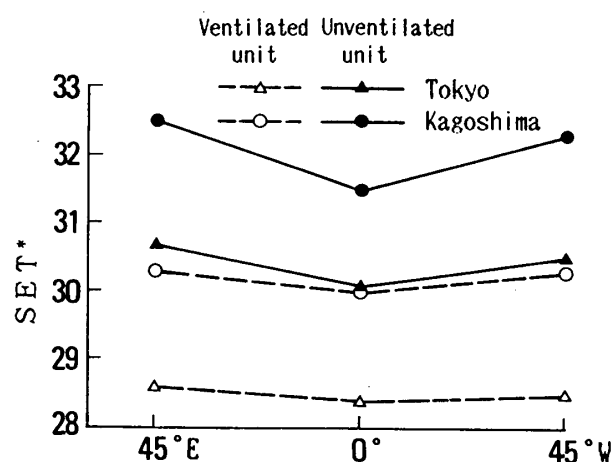


Fig. 15 Influence of building orientation on the average SET*s ($BV=50\%$, $F=5$)

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住宅における通風の省エネルギー効果に関する研究（梗概）

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1. 緒 言

夏季の気候が蒸暑な日本の住宅では、自然通風は古くから広く利用されてきた対暑方法である。しかし、時間的に変動の激しい自然風がもたらす気流感と清涼感それに伴う快適感など、人体に対する温熱効果を考慮に入れて、通風の省エネルギー効果を算定した例はいまだ少ないようである。

本稿は、集合住宅を対象として通風の省エネルギー効果を定量的に解析し、住棟の形状と配列、地域の気候特性および生活方式（窓の開閉）との関係を明らかにしようとするものである。まず壁面の風圧係数に関する風洞模型実験を行い、換気・通風量および室温などの算定に使用する。次に通風時の温熱感覚に関し、被験者を用いた申告実験を行い、室内熱環境のレベルを設定する。

以上の結果を用いて室内熱環境の解析を行い、気候特性を考慮した通風の省エネルギー量と住棟配置との関係を求める。

2. 風洞模型実験

室内の換気・通風量は住棟の形状、容積率および方位などに左右される。これら住棟配置計画上の諸要素と住棟の風上および風下壁面の風圧係数との関係を調べるために縮尺 1/400 の模型を規則的に配列した住棟群について風洞実験を行う。住棟配列の条件を Table 1 のごとく設定する。住棟前後の間隔 D を変化させて容積率を定める。実験の状況および模型配置の状態を Fig. 1 に示す。風洞の吹き出し口には、自然風との相似を考慮し、高さ方向に間隔の異なるスクリーンを設置する。スク

リーンの直後から模型を設置した際の下流約 3 m の位置における平均風速垂直分布を Fig. 2 に示す。 $Z=250$ mm 以上の高さで平均風速に対する模型配列の影響は小さくなる。したがって実際の高さ 100 m に相当するこの高さの風速を基準として壁面の風圧係数を算出する。

風向が住棟の主壁面に直角な場合の風圧係数と容積率との関係を Fig. 3 に示す。風圧係数の値は妻側を除く中間階の平均である。容積率が 0 %（独立住棟）から 25 % に上がると、風圧係数の絶対値は著しく低下するが、それ以後の容積率の増加に対する風圧係数の絶対値の低下は緩やかである。容積率 50 % において階数を 5 階から 10 階にした場合、風圧係数が大きくなる。容積率が 50 % の 5 階建住棟の場合の風向と風圧係数との関係を Fig. 4 に示す。風向が住棟の法線と成す角度が 60° 以下のときには風上と風下壁面の風圧係数の差 ($C_w - C_L$) は風向によってあまり変化しないが、それ以上の風向に対しては、風圧係数差の低下が顕著である。

3. 通風時の温熱感覚に関する被験者の申告実験

熱環境要素および着衣、代謝量、発汗などの人体側の条件を考慮している ASHRAE の標準新有効温度 SET* を、熱環境の指標として採用する。

夏季における通風による人体の温熱感覚と標準新有効温度 SET* との関係を明らかにするため、青年男女各 4 名の被験者により、8 月上旬に各人 4 回、計 32 回の申告実験を行う。実験住戸は片廊下式 12 階建住棟の 6 階にある (Fig. 5(a), (b) 参照)。被験者はまず非通風の状態で 30 分間の椅座安静状態を経た後、窓を開放して正面から風を受ける状態で通風環境に 90 分間暴露する。この間、室内の熱環境要素と同時に被験者の温熱感覚の変化を申告スイッチを用いて記録する。快適感に関する標準新有効温度 SET* の累積頻度分布を Fig. 6 に示す。最適な熱環境の形成より省エネルギー効果に重点をおき、通風室内の快適感の限界を「不快」申告の累積

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頻度が50%となる点と仮定すれば、Fig.6からそのSET*の値は26°Cとなる。

4. 通風による省エネルギー効果

通風の省エネルギー効果は地域の気候特性により大きく左右される。ここでは、札幌、東京および鹿児島県の3都市を対象地域とする。各都市の標準気象データから最も代表的な夏季の気象条件とみなされる8月1～7日の1週間を選ぶ。その期間の気温、水平面全日射量、風向および風速をFig.7に示す。また、風配および風速の頻度分布をFig.8に示す。

室内における気温、湿度、グローブ温度および気流速度を多数室の室間相互換気および室内放射伝熱を考慮したPSSPにより予測する。Fig.5(a)に示す12階建のRC造の6階に近接する2つの住戸を選び、一方を通風、他方を非通風の状態とし、Fig.5(b)に示す測定点の室内空気温度、グローブ温度および室内相対湿度を計算し、実測値と比較する。その結果をFig.9(a),(b)および(c)に示す。室内温度で約1°C、グローブ温度で約1.5°C以内の誤差であり、よく一致するものと考えられる。

通風による省エネルギー効果のシミュレーションの対象とする住戸のプランをFig.10に示す。住棟が5階建の場合は3階、10階建の場合は6階にあるものとする。住戸をDKを含めたA室、B室、C室およびD室に区分し、非通風住戸のA室のSET*を通風住戸のA室のSET*に等しくするために必要な非通風室Aの冷房エネルギー量を求めて通風の省エネルギー効果を検討する。通風時は、A,BおよびC室の外壁面の開口および各室間の間仕切りが開放される。非通風時には外壁面の開口および各室間の間仕切りは閉鎖される。開口には、カーテンやブラインドは取り付けられておらず、室内の発熱もないものとする。

非通風A室のSET*制御による冷房の設定方法をFig.11に示す。あらかじめ通風A室の自然室温時のSET*を求めておき、非通風A室のSET*がそれと等しくなるように非通風住戸Aを冷房する(b～c, d～e)。ただし、Fig.6に示す申告実験結果から通風A室のSET*が26°C以下となった場合には、非通風A室はSET*が26°Cで冷房される(a～b, e～f)。また、非通風A室の非空調時におけるSET*が通風A室より低くなくても再熱は行わない(c～d)。なお、冷房は吹き出し温度15°C、吹き出し湿度90%と仮定する。このようにして求められる冷房のエネルギー量を8月1日～7日の1週間にわたって積算し、その日平均値を通風の省

エネルギー量とする。

実際の生活パターンを考慮し、通風住戸における開口部の開閉は、日中(8:00～21:00)開放・夜間閉鎖と、夜間も含めて開放する全日開放の2つのパターンとする。

東京における住棟配列の容積率50%の全日開放した通風住戸、冷房しない非通風住戸、冷房する非通風住戸のSET*の計算値と冷房エネルギー量の経時変化をFig.12に示す。通風住戸のSET*は非通風住戸に比較して全体に低く、また時間的な変動が激しい。冷房する非通風住戸のSET*も通風住戸のSET*と同じではない。冷房のエネルギー量は夜間に大きい。

札幌、東京および鹿児島県における通風の省エネルギー量と容積率との関係をFig.13に示す。札幌では非通風住戸においてもSET*がほとんどの時間帯において26°C以下であり、通風の省エネルギー効果は小さい。鹿児島県では風の特性が通風に対して不利な状態であるため通風の省エネルギー効果は東京に比較して小さい。また、Fig.13から、開口を夜間も開放した全日通風の省エネルギー効果が日中開放、夜間閉鎖の場合に比較して大きいことがわかる。

Fig.14は東京および鹿児島県における容積率が50%の場合において、住棟の方位および高さを変化させた場合の省エネルギー量の変化を示している。住棟の高層にすることによってFig.3に示す風圧係数の変化により通風の効果が大きくなる。また、Fig.15に示すSET*の住棟の方位による違いにより、住棟の方位が傾いた場合の省エネルギー量が大きく表れる。

5. 結 論

(1) 地域の気候特性が通風の省エネルギー効果に及ぼす影響は大きい。札幌ではその効果はほとんど認められない。しかし、東京では開口部を全日開放した場合2000～4000 kcal/dayの省エネルギー量に達する。

(2) 全日通風の省エネルギー効果は日中のみの通風に比較して大きい。

(3) 通風の省エネルギー効果は住棟配置の容積率の増大とともに低下する。

(4) 東京および鹿児島県では、住棟を高層化することによって通風の省エネルギー効果が大きくなる。また、住棟の方位が45°傾いている場合、通風の省エネルギー量が大きくなるが、通風室のSET*は方位によって大きな違いはない。