# Indoor Environment and Energy Consumption of an Elementary School in a Subtropical Region

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**ABSTRACT**

Indoor thermal environment and air quality in an elementary school were measured and examined for the basic data of net Zero Energy Buildings (ZEBs) and the adaptation to the impacts of climate change. The target school is located in Okinawa, a subtropical archipelagic region with hot and humid climate in Japan. The school is equipped with air conditioners (ACs) that are sometimes operated without natural ventilation. The measurement results are as follows: (1) The ACs were operated when the daily average air temperature was over 22 C. (2) The ACs in the class rooms were controlled by the teachers individually. The preset temperature was sometimes too low. (3) Direct solar radiation penetrated the class rooms, which increased the heat load. (4) The higher point in the class rooms was the higher temperature when AC was working. (5) The $CO_2$ concentrations in the class rooms were kept under 1000ppm by heat exchange ventilation systems.

## INTRODUCTION

Comfortable indoor thermal environment achieved by ACs often conflicts with energy saving and indoor air quality if the ACs are operated without ventilation. Energy saving is one of the most important factors to design and use buildings from the viewpoint of reducing $CO_2$ emission by electric energy generation and relieving climate change. The characteristics of energy consumption and generation in a building are needed to achieve a ZEB that is a goal of energy saving buildings (METI, Japan, 2015).

On the other hand, indoor thermal comfort of buildings is also a very important factor. Especially, AC's cooling operation is an essential function to keep the indoor air comfortable in hot and humid summer. Climate change drives outdoor air temperature higher, which causes heat stroke not only outside but also inside (EPA, CDC, USA, 2016). Air conditioning is regarded as a kind of adaptation to the impacts of climate change.

It is necessary to operate ACs and ventilation correctly to keep better thermal and air quality conditions and to save energy. Public facilities are regarded to be good targets of ZEBs, because the initial cost of ZEBs is generally higher than non-ZEBs. Largest floor area of public facilities is covered by educational facilities, especially elementary schools (MLIT, Japan, 2017). If these schools are designed as ZEBs, huge amount of energy and $CO_2$ emission can be saved.

However, the characteristics of energy consumption in a school are unique in comparison with office buildings, because of daily and annual schedules of class rooms. Especially, ACs are used for only cooling in subtropical zone, which is different from higher latitude zones. Main purpose of this research is to obtain the basic data of thermal environment and energy consumption in an elementary school in Okinawa to clarify these points through measurements of indoor thermal conditions, indoor air quality and energy consumption about 7months including summer.

## MEASUREMENT PROJECT

### Target elementary school

The target school has totally 27 classes in 6 grades and total number of students is 846. It is located in Naha city, the capital city of Okinawa with population of 320k, about 26.2deg. N. The location was developed from a former military base in 1997 and the school was opened in 2012. The school consists of 4 buildings and arranged with the playground as shown in Figure 1. The school lot is surrounded by a commercial area, a green park and low-rise residential houses.

The school buildings are 2- or 3-storied reinforced concrete buildings including a kindergarten, a kitchen for school lunch, a gymnasium and a swimming pool. The class rooms are arranged on one side of the buildings. The class rooms are not separated perfectly, but open to the common space without walls. Air conditioning areas on a floor are connected each other without a part of corridors and staircases. There are vertical ceiling windows in the class rooms on the top floor, but they are sealed with paper because of too bright and hot. Each class room has 2 AC units and a heat exchange ventilation system on the ceiling and they are controlled individually by the teacher in charge. These situations are shown in Figure 2-4.

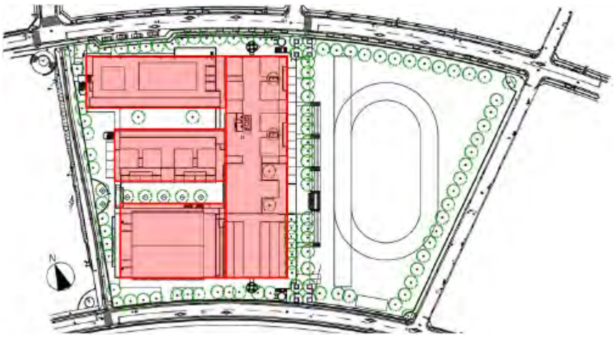

*Figure 1. Arrangement of school buildings*

*Figure 2. Class room and common open space*

*Figure 3. Vertical ceiling windows*

*Figure 4. Two AC units and a ventilator on the ceiling*

### Measurement points, items and instruments

Table 1 shows the measurement points and items. The items are grouped into 4 categories: Temperature and Relative Humidity, $CO_2$ Concentration, Electric Power Consumption and Gas Consumption. The measurement points of thermal environment and $CO_2$ concentrations were mainly set in class rooms on 2nd and 3rd floor. Gas was consumed in GHPs as heat source of ACs.

Temperature, relative humidity, $CO_2$ concentration, and gas consumption were measured by small package type data loggers with sensors. These instruments can record 16,000 data. Electric power consumptions were measured by cramp type sensors.

### Measurement schedule

The measurement was started on 28 June 2019 and ended on 5 February 2020, totally 223days including 7 months fully from July to January. All the measurement data were recorded at 10-minute interval and collected about 1.5-month intervals.

*Table 1. Measurement points and items*

| Measurement Point (Height from floor, mm) | Measurement Item |
|---|---|
| Outside of a bldg. (2300) | Air Temp., Rel. Humidity |
| Entrance Hall (2300) | Air Temp., Rel. Humidity |
| Gymnasium (2200) | Air Temp., Rel. Humidity |
| 2nd F. Class Room (1100) | Air Temp., Rel. Humidity |
| 2nd F. CR AC Outlet (2800) | Air Temp., Rel. Humidity |
| 2nd F. Common Space (2500) | Air Temp., Rel. Humidity |
| 2nd F. Outside Corridor (2500) | Air Temperature |
| 3rd F. Class Room (1100) | Air Temp., Rel. Humidity |
| 3rd F. CR AC Outlet (2800) | Air Temp., Rel. Humidity |
| 3rd F. Common Space (2500) | Air Temp., Rel. Humidity |
| 3rd F. Class Room (100) | Air Temperature |
| 3rd F. Class Room (2800) | Ceiling Temperature |
| 3rd F. Outside Corridor (2500) | Air Temperature |
| 3rd F. Class Room (2000) | $CO_2$ Concentration |
| 2nd F. Class Room (2000) | $CO_2$ Concentration |
| Electric Power Lead-in Meter | Total Electric Power |
| Rooftop Electric Cubicle A | East Bldg. Lighting, etc. |
| Rooftop Electric Cubicle B | Kindergarten, Kitchen, etc. |
| Rooftop Electric Cubicle C | Pump, GHP, EV, Motor, etc. |
| Rooftop Electric Cubicle D | Kitchen, Kindergarten |
| 2nd F. Power Distribution Panel | 2nd F. Power Outlet, AC, etc. |
| 3rd F. Power Distribution Panel | 3rd F. Power Outlet, AC, etc. |
| East Bldg. Gas Meter | Gas Heat Pump (GHP) |
| Kitchen Gas Meter 1 | GHP for School Bldgs. |
| Kitchen Gas Meter 2 | GHP for Gymnasium |

## MEASUREMENT RESULTS

### Daily average thermal environment

Dairy average air temperature and relative humidity at outdoor and indoor measurement points except class rooms are shown in Figure 5. The outdoor temperature is almost lowest in winter, but not highest in summer. The gymnasium temperature is highest and the open space temperature of 2nd floor is lowest in summer except summer vacation term. The outdoor relative humidity is always higher than indoor humidity data. These results indicate the effect of ACs on indoor air.

Daily average air temperatures at all measurement points in the class rooms are shown in Figure 6. Low temperatures of AC outlets indicate the operation of ACs. Weekly changes are very clear, but sometimes ACs were working on weekends without classes.

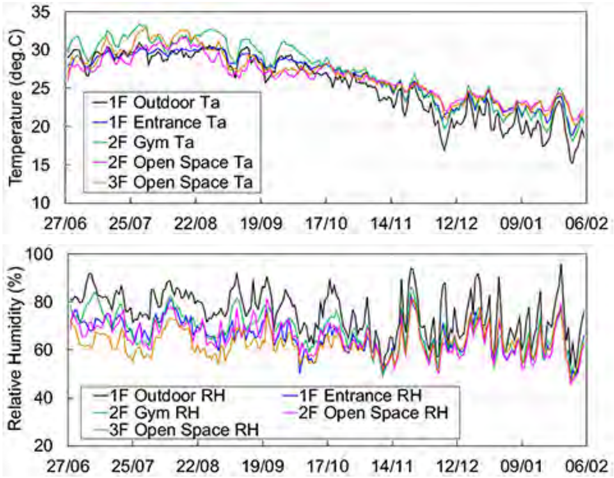


*Figure 5. Thermal environment of the school*

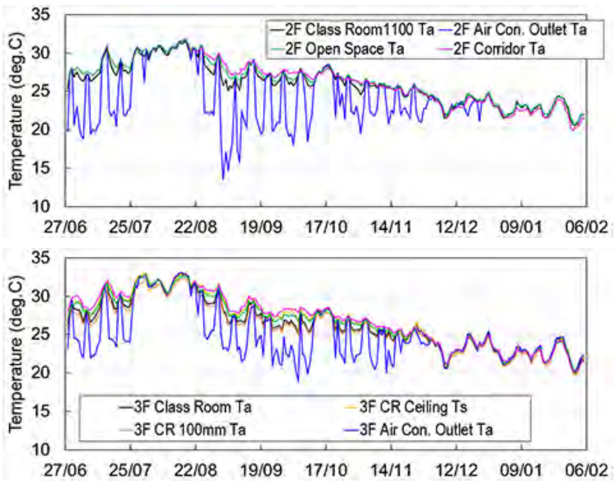


*Figure 6. Temperatures in the class rooms*

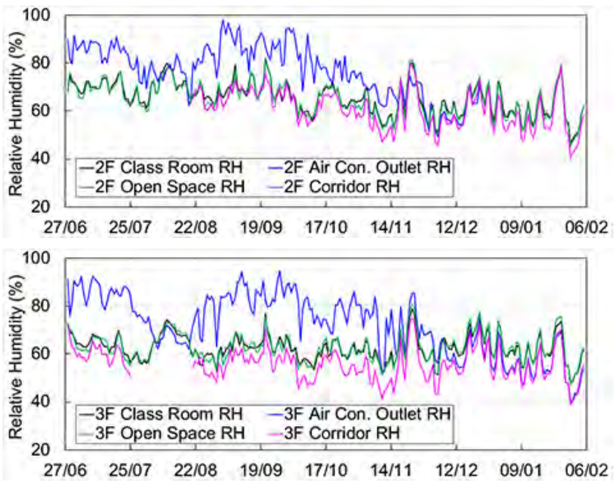


*Figure 7. Relative humidity in the class rooms*

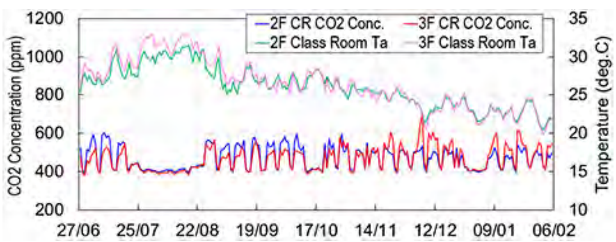


*Figure 8. CO2 concentration and air temperature*

The cooling terms last until November and December on 3rd and 2nd floor, respectively. The AC outlet temperature is sometimes below 20 deg. C, and the room temperature is nearly 25 deg. C on 2nd floor. The lowest temperature in the measurement term is about 20 deg. C on 1 Feb.

Daily average relative humidity data in the class rooms are shown in Figure 7. Humidity data of AC outlets are very high when ACs were working. Humidity data at the corridor are always lower than inside data, though it is located outside of AC area. The difference between inside and outside on 3rd floor is clearer than 2nd floor. It is regarded as the effect of heat from the roof.

### Daily average CO2 concentration

Dairy average CO2 concentrations in two class rooms with the daily average air temperatures are shown in Figure 8. CO2 concentrations on 2nd and 3rd floor are almost the same level, about 400ppm, in the summer vacation term. It is the same level of the atmosphere, which means these class rooms were well ventilated in the summer vacation term.

CO2 concentration on 2nd floor is higher than 3rd floor when ACs were working, though they reverse in winter. Especially, CO2 concentrations on 3rd floor are clearly higher than 2nd floor when the air temperatures were below 23 deg. C. This difference between 2nd and 3rd floor in winter is regarded to be caused by lack of ventilation. The occupants on the top floor may feel colder than lower floors because of cold radiation from the ceiling in winter.

### Daily electric energy consumption

Daily electric energy consumptions in the elementary school are shown in Figure 9. It does not include the energy consumed in the kindergarten and the kitchen. Most of the electric energy is used for lighting that includes power outlets. GHP means electric energy for gas heat pumps as the heat source of ACs. GHP needs electric energy mainly to drive the pumps and the fans, not for the heat source itself.

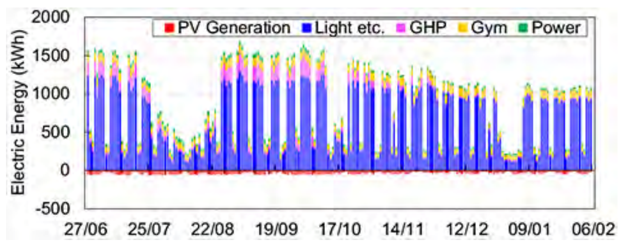


*Figure 9. Daily electric energy consumption*

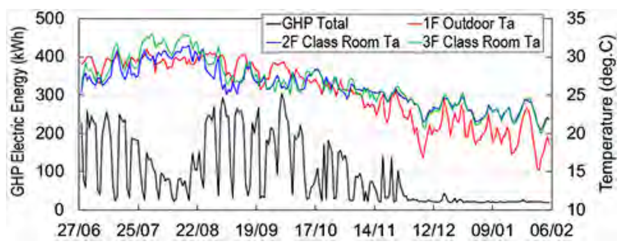


*Figure 10. Electric energy for GHP and air temp.*

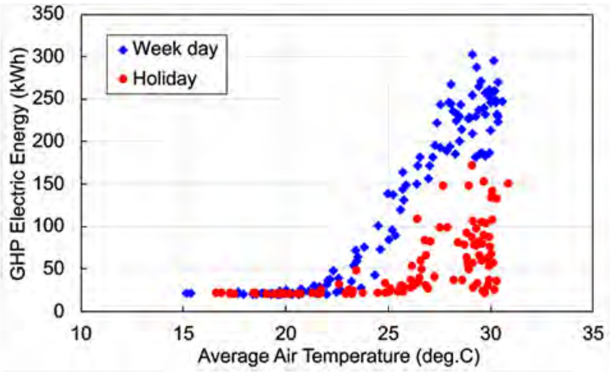


*Figure 11. GHP electric energy and outdoor air temp.*

### GHP energy and air temperature

Electric energy for GHP and outdoor and indoor air temperatures are shown in Figure 10. The electric energy for GHP data is clearly fluctuating weekly and seasonally along with the temperatures except the summer vacation term. The GHP energy was almost zero when the daily average outdoor air temperature was lower than about 22 or 23 deg. C.

Correlation between the GHP electric energy the daily average outdoor air temperature is shown in Figure 11. The GHP electric energy sharply changes when the daily average outdoor temperature is over 22 deg. C. The GHP energy on holidays may be used for the teachers' work and sometimes unexpected operation of ACs as shown in Figure 6 and 10.

### Gas energy for GHP

Gas consumptions were measured by pulse counters of which 1 pulse is equal to $1m^3$ of gas. Relation between daily gas pulse count and GHP electric energy is shown in Figure 12, and theses correlation is shown in Figure 13. The GHP electric energy consumed without the gas pulse is regarded to be used for the maintenances, monitors and controllers, not for the gas engines.

The lower heat value of the gas is $39.7MJ/m^3N$ that is equal to $11kWh/m^3N$. The practical heat value is roughly estimated to be the same value, though it is not normal condition. If 1kWh of GHP electric energy is consumed, $2.27m^3$ of gas is used for GHP. That amount of energy is almost the same value as 2.27x11kwh, nearly 25kWh. Total energy for ACs is estimated as 26 times as large as GHP electric energy including the electric energy.

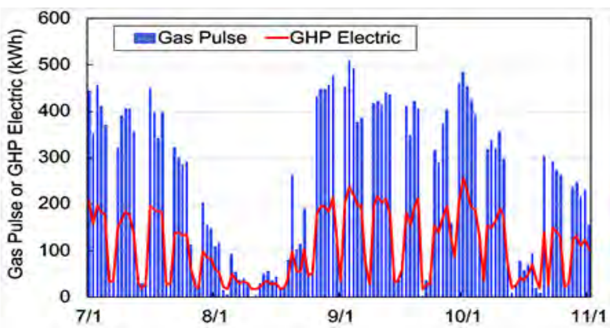


*Figure 12. Gas pulses and GHP electric energy*

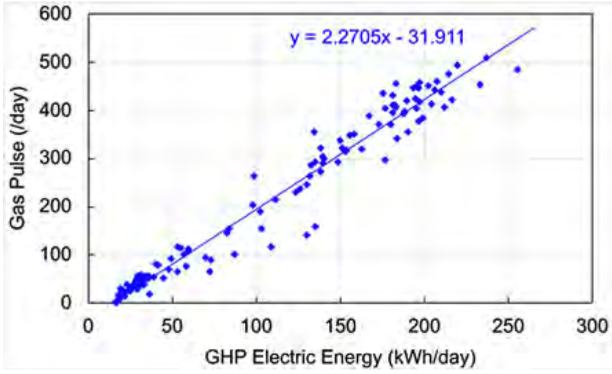


*Figure 13. Gas pulses and GHP electric energy*

### Solar power generation

This school is equipped with photovoltaic panels (PVs) on the rooftop as shown in Figure 14. The solar system consists of 2 sets of solar battery arrays. Each solar battery array consists of 55 VPs, and the rated power of one PV is 92.5W. Total rated power of the solar system is about 10kW.

Fluctuations of global solar radiation, outputs of 2 PV arrays and total output of PVs are shown in Figure 15. Difference between the outputs of 2 PV arrays is almost negligible. Global solar radiation data used here are obtained from Okinawa Meteorological Observatory that is located about 3km south. Theoretical PV energy can be calculated from the solar radiation data.

Correlation between the theoretical and the measured PV energy is shown in Figure 16. The theoretical PV output is calculated from the solar radiation data and the rated performance of the PVs. They correlate well and the practical output is about 82.5% of theoretical energy. Although these PV arrays are surrounded by tall buildings and arranged in parallel to the building sides and not facing to due south, the performance ratio of 82.5% is relatively high efficiency.

*Figure 14. PV arrays on the rooftop*

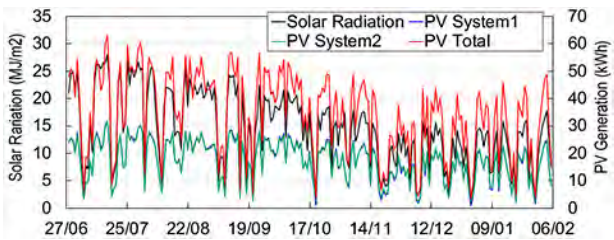


*Figure 15. Global solar radiation and PV outputs*

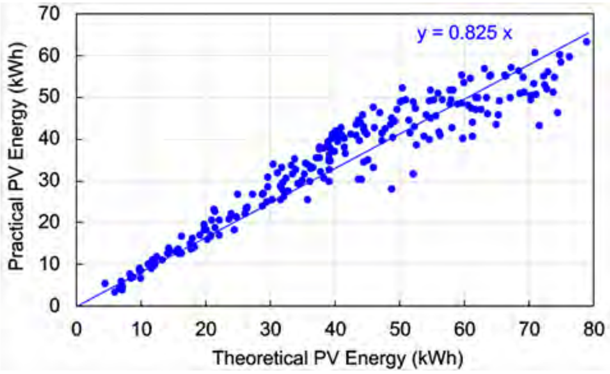


*Figure 16. Theoretical and practical PV energy*

**Environment and energy in summer**

The summer vacation started on 27 Jul. and ended on 25 Aug. in 2019. A week from 26 Aug. just after the summer vacation is selected as a typical summer term, since the weather conditions were unstable in July.

Temperature fluctuations in the non-air conditioning area in the elementary school are shown in Figure 17, and those in the air conditioning areas are shown in Figure 18. These data in the figures are instantaneous values measured at intervals of 10 minutes.

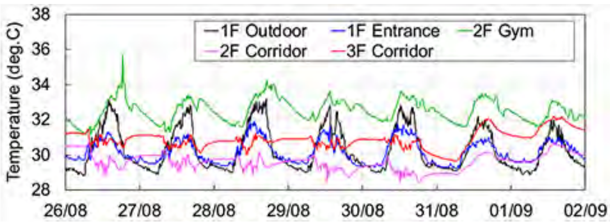


*Figure 17. Temperatures of non-AC area in summer*

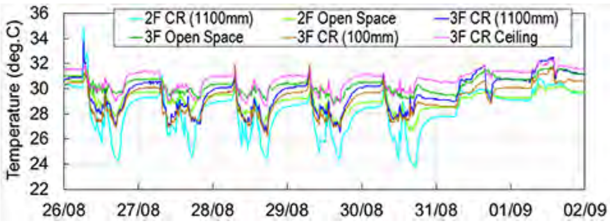


*Figure 18. Temperatures of AC area in summer*


*Figure 19. Temperature and electric power in summer*

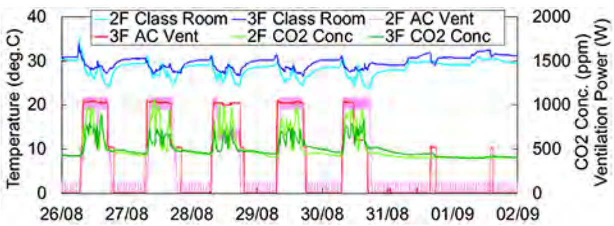


*Figure 20. Air quality and ventilation in summer*

Temperature in the gymnasium was highest and higher than outdoor temperature. The roof of the gymnasium is made of corrugated thin plates of steel with thin heat insulation boards, which is regarded as a cause of this high temperature.

The corridor on the 2nd floor was cooled as well as air conditioning areas in the daytime. The corridor on the 3rd floor was rather higher temperature like other non-air conditioning points, while it was not cooled in the nighttime. RC structure with huge heat capacity affects this high temperature in the nighttime.

The indoor temperatures on the 2nd floor were generally cooler than those on the 3rd floor. Especially, the temperature difference was over 2 deg. C at the center of the class rooms. The ACs in the class rooms were controlled by the class teachers, which is regarded as a cause of the temperature difference.

The indoor temperatures changed suddenly just before air conditioning in the morning. It is regarded as an impact of direct solar radiation from the east windows. These phenomena were not observed in winter as shown in Figure 22. It causes higher cooling load and larger energy consumption.

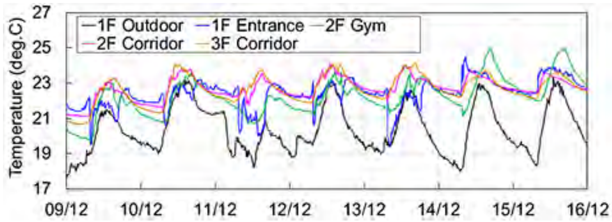


*Figure 21. Temperatures of non-AC area in winter*

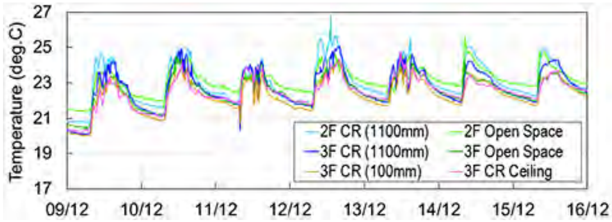


*Figure 22. Temperatures of AC area in winter*


*Figure 23. Temperature and electric power in winter*

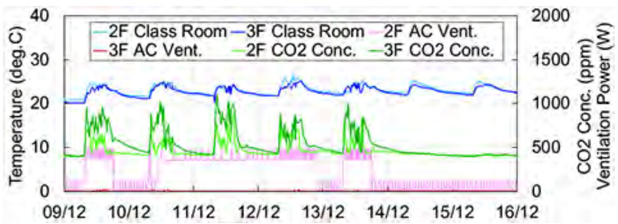


*Figure 24. Air quality and ventilation in winter*

Fluctuations of the AC outlets temperatures, the GHP electric power, temperature and electric power in the gymnasium are shown in Figure 19. The AC outlet temperature on 2nd floor was below 15 deg. C, nearly 10 at lowest. If the outlet air blows directly on students, it must be too cool for their health.

The temperature in the gymnasium is always very high, about 32-33 deg. C. It must be too hot for physical education and exercises. Small amount of the GHP energy was consumed when the ACs were not working, which was already mentioned before about Figure 13. The gymnasium electric energy was used mainly for lighting and ventilation not for the ACs.

Fluctuations of $CO_2$ concentrations, electric power for the ventilation system and the room air temperatures are shown in Figure 20. $CO_2$ concentration on the 2nd floor was higher than that on the 3rd floor, while the air temperature on the 2nd floor was always lower. The higher $CO_2$ concentration and the lower room temperature indicated that the class room on the 2nd floor was tightly closed and strongly air-conditioned.

The highest $CO_2$ concentration was under 1000ppm that was recommended level as indoor air quality. The $CO_2$ concentration data indicated that the total heat exchanging ventilation systems in these class rooms and the architectural design and features could keep appropriate air quality under air-conditioning.

Electric power for ventilation on the 2nd floor is always vibrating in a range of about 100W, though that on 3rd floor is rather stable. The cause of this vibration is unknown. The ventilation systems were operated only two levels with the ACs definitely.

**Environment and energy in winter**

A week from 9 to 16 Dec. was selected as a typical winter week from the weather conditions, though it is difficult to define real winter season in the subtropical zone. Figure 21-24 show the same contents of data for winter as shown in Figure 17-20 for summer.

The outdoor temperature was always lower than other points in winter. The gymnasium temperature changed widely, from the lowest in the nighttime to the highest in the daytime on the weekend. Thermal performance of the gymnasium roof is regarded as a main reason of this temperature change. The entrance temperature was almost the same level as the outdoor temperature in the daytime, which showed that the entrance hall was open and exposed to outdoor air.

The corridor temperatures on the 2nd and the 3rd floor were almost the same level. However, the class room temperature on the 2nd floor was higher than that on the 3rd floor in the daytime. Especially, the ACs on the 2nd floor were operated occasionally on 12 Dec. as shown in Figure 23. The ceiling temperature on the 3rd floor was lowest in the class room. It is regarded as a thermal impact of the rooftop, which is the reverse case of summer. Sudden changes of the temperatures on 11 Dec. were caused by unstable weather.

The gymnasium electric energy was the same level as the summer case, which means the ventilation and the lighting systems in the gymnasium were used all year round. Small amount of the GHP electric power was found even in winter, though the ACs were not used.

The $CO_2$ concentration on 3rd floor was always higher than that on the 2nd floor and occasionally it was over 1000ppm. The ventilation power in Figure 24 indicates that the mechanical ventilation system on the 3rd floor was not operated, while that on 2nd floor was operated by half level. The cooler thermal conditions on the 3rd floor led air tightness without mechanical ventilation. The ventilation on the 2nd floor in the nighttime on 11 and 12 Dec. is regarded as a mis-operation.

**Vertical distribution of temperature**

The measurement points for temperature in the class room on the 3rd floor are located at 100mm, 1100mm and 2800mm from the floor. The highest point is the ceiling, Vertical distributions of temperature can be obtained from these data.

The data in the actual class hours were used to make the vertical distributions of temperature, because the class hours were calmer than other time. One typical week in each month and the summer vacation term was selected for the average data. Monthly average data at 3points were obtained from all the data in the class hours of one typical week in each month.

The vertical distributions of temperature in the class room on 3rd floor in each month are shown in Figure 25. The highest temperatures were recorded in the summer vacation. These distribution in the summer vacation was almost uniform vertically with a lower temperature at the lowest point.

The air conditioning months are Jul., Aug., Sep., Oct. and Nov. The higher temperature is observed at the higher point in the air conditioning months. These are typical temperature distributions in air-conditioned rooms.

The shapes of vertical distribution changed in Dec. and Jan. Especially, the temperature at the highest point was lower than that at the middle point. Solar radiation on the rooftop, heat capacity of the roof material and the cooled air by the ACs are regarded as causes of these distribution shapes.

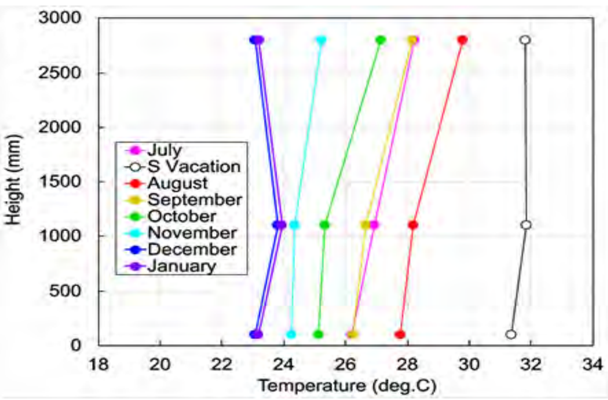


*Figure 25. Vertical distributions of temperature*

**Discussion**

Thermal environment and $CO_2$ concentration of indoor air and related energy consumption were measured and examined in this research for basic data to design Zero Energy Buildings (ZEBs). The target building is an elementary school that is located in a subtropical zone, which is a unique point of this research. Several weak points of the air conditioning system and ventilation system, architectural design and materials were found from the view point of energy consumption.

However, ideal or standard criteria of indoor thermal conditions for elementary schools are not clear, and standard energy consumption in elementary schools is not clear, either. It is impossible to estimate the energy consumption level exactly only from this research. If actual reactions of students and teachers of the school to the thermal situations were observed, ideal and/or standard thermal conditions would be clear and it would be possible to estimate energy consumption and saving level. It is next step to apply the thermal comfort index to the data obtained in this research.

## CONCLUSIONS

Characteristic results obtained in this research are as follows: (1) The ACs in the class rooms were controlled independently by the teachers. (2) The ACs started to be used when the daily average outdoor temperature was over 22 deg. C. (3) The ACs were working even on weekends sometimes. (4) The outlet air temperature from the ACs was sometimes set too low. (5) The heat exchanging mechanical ventilation system worked well to keep $CO_2$ concentration in the class room under 1000ppm. (6) Solar radiation on windows and roofs clearly affected on the indoor thermal environment.

The results of this research are effective for the design of ZEBs. They indicate that there are two points to save energy and to complete ZEBs. One is the architectural design and construction materials, and the other is appropriate building equipment, especially ventilation, air conditioning and lighting systems.

It is an essential factor in subtropical zones to control solar radiation on buildings. Orientation of windows, solar protection devices and heat capacity of materials should be considered to reduce cooling load in summer. These facts are already very general things for energy saving buildings in higher latitude zones. Practical design to apply these facts to low latitude areas is one step to ZEBs in subtropical zones.

Important points to save building equipment energy are to select appropriate performance equipment and to operate it correctly. Air conditioning system, lighting and ventilation system are essential for buildings. Not only the performance of them, but also the operation of them is very effective to reduce energy consumption. However, the operation depends upon the building owners or users. Practical manuals or guidelines are required for the correct operation.

## ACKNOWLEDGMENTS

The data used in this paper were obtained in a funded research of "Strategic Innovation Program for Energy Conservation Technologies" organized by New Energy and Industrial Technology Development Organization, Japan (NEDO).

## REMARKS

The word "ZEB" used in this paper means a practical net Zero Energy Building when it actually operated. It does not mean the same meaning of the "ZEB" that is defined by Ministry of Economy, Trade and Industry, Japan (METI) and its related committees, ZEB roadmap committee and ZEB roadmap follow-up committee.

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