H-061 Productivity, Clothing, Energy Conservation and Indoor Environment in 28°C Office (Abstract of the Final Report)

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[Abstract] Since offices provide spaces for the productive activities of the workers, the cost effectiveness including their performance should be taken into account, as well as the possible outcome on the conservation of energy. In this project, the relationship between indoor environment and the performance of the office workers was examined through investigation of thermal environment and indoor air quality of offices and through several subjective experiments. The results of the subjective experiments and field study showed a possibility to prevent the decrement of performance in the office with modified preset temperature by taking measures to increase satisfaction of the occupants: such as increase of air velocity, allowing lighter clothes, and providing personal control of their environment. The result from the field survey in an office with higher grade of environmental control technologies showed less decrease of productivity per 1°C than the previous studies. The freedom of control could compensate the deteriorative effect. Elevated temperature can affect the perceived air quality as well as thermal sensation of the occupants. The detail data on a wide variety of clothing thermal resistance with air movement were collected with the Thermal manikin measurement. With these data, thermal effect of different cooling devices was simulated using human thermoregulation model. The results from experiments were used to develop a model for estimating relative work performance from thermal satisfaction and a model for estimating work performance from Predicted Percentage of Dissatisfied (PPD), which can be calculated from a given thermal condition. With the relationships, raised preset temperature in office and possible thermal improvement methods to be introduced in the office were evaluated in terms of both the economical effect and energy conservation.

1. Introduction

The Kyoto Protocol has been effective since February of 2005; Japan has the responsibility to reduce the emission of the Greenhouse effect gas by 6% of the amount emitted in 1990. Starting from summer of 2005, the Japanese government recommended keeping an office temperature setting of 28°C with no-ties and no-jackets fashion for workers, known as COOL BIZ campaign.

However, the effect of the campaign has not examined thoroughly. Since offices provide spaces for productive activities of workers, the cost effectiveness including their performance should be taken into account, as well as the possible outcome on the conservation of energy.

2. Research Objectives

In this research project, the relationship between indoor environment and the performance of the office workers was examined through investigation of thermal environment and indoor air quality. With the relationship, the mitigation of the indoor temperature settings in office was evaluated in terms of both the economical effect and energy conservation. Also, the possible environmental control systems and/or methods were studied to optimize the application of temperature setting of 28°C. Scheme of this research project is shown in Figure 1.

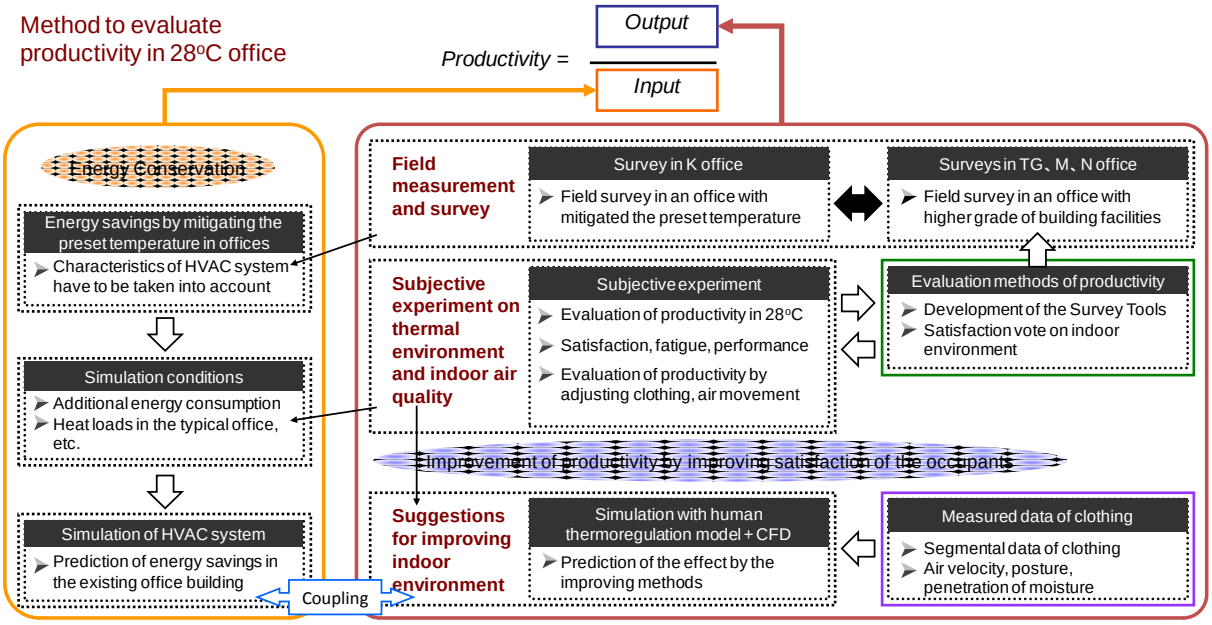


Figure 1. Scheme of this research project to integrate sub topics

3. Research method and results

1) Productivity and economical effects

The Survey Tools for Indoor Environmental Quality and Productivity was developed in FY2006 to acquire and store the data via the internet. The survey tools from the previous year were upgraded in FY2007. The abilities required for the works in different types of office were obtained.

A field survey was conducted to investigate thermal environment in an office with elevated temperature setting. Due to the design of the HVAC (Heating, Ventilating and Air Conditioning) system and distribution of heat sources in the room, uneven distribution of temperature was observed causing some part of the office to be higher than 30°C during the day. The decrease of heat load attributed to raising preset temperature caused the hunting phenomenon in the supply air temperature. From this observation, tuning HVAC system may be necessary in some of the existing office buildings to run elevated temperature setting with proper function of the system. From the questionnaire survey, more than 70% of workers were thermally dissatisfied in July and August in

this office. The self-estimated performance and the level of fatigue were correlated stronger with thermal satisfaction vote by the occupants than air temperature and the standard new effective temperature.

A subjective experiment was conducted in FY2006 testing the effect of thermal environment and ventilation rate. Relationships were obtained that the level of fatigue is less and performance is higher when the subjects were more satisfied with indoor environment, thermal environment and indoor air quality. Another subjective experiment was conducted in FY2008 to test the effect of thermal discomfort on performance by exposing the subjects in 25.5°C, 28.5°C and 31.5°C. The similar relationships were obtained also in this experiment, confirming that the level of fatigue and thermal satisfaction are the keys to evaluate the effect of thermal environment on performance.

A subjective experiment was conducted in FY2007 to investigate the effect of the improvement of thermal satisfaction on productivity. The operative temperature was set at 25.5°C and 28.5°C to simulate office with normal and elevated temperature settings. In the higher temperature conditions, lighter clothing and individually-controllable cooling devices were introduced to improve thermal satisfaction of the subjects. The cooling devices were desk fan, mesh office chair and fan-mounted shirt. With higher freedom of individual control in the 28.5°C conditions, the subjects voted as satisfied as in the 25.5°C conditions. From the relationship obtained, higher performance and lower level of fatigue were obtained when subjects voted more thermally satisfied. The cooling effect of introducing the cooling devices was also evaluated by thermal manikin measurement.

The effect of 28°C office thermal environment on human was simulated with human thermoregulation model and was expressed in terms of Predicted Percentage of Dissatisfied (PPD), which is a well known and widely-used index of thermal comfort. The use of cooling devices introduced in the subjective experiment lowered PPD.

The energy consumption of HVAC system was simulated in the typical office building model to evaluate the effect of raising cooling preset temperature during summer. Raising preset temperature from 25°C to 28°C was estimated to reduce the energy use by 79.0MJ/(m^2*COOL BIZ-period).

2) The study on clothing

In FY2006, the $R_{cle\mathrm{i}}$ values for 49 garments and 97 ensembles were obtained. I_{cle} for the overall body ranged from 0.02 clo to 0.24 clo for the garments and from 0.13 clo to 0.60 clo for the ensembles. The $R_{cle\mathrm{i}}$ values for the ensembles ($R_{cle\mathrm{i}.en}$) against the sum of components' $R_{cle\mathrm{i}}$ ($\Sigma R_{cle\mathrm{i}.gr}$), for nine segments were plotted to observe the correlation. In each segment, $R_{cle\mathrm{i}.en}$ tends to be slightly less than $\Sigma R_{cle\mathrm{i}.gr}$. The common regression for all the body segments, $R_{cle\mathrm{i}.en} = 0.784 \cdot \Sigma R_{cle\mathrm{i}.gr}$, was proposed for estimating the $R_{cle\mathrm{i}}$ for the ensembles ($R_{cle\mathrm{i}.en}$) from the sum of components' $R_{cle\mathrm{i}}$ ($\Sigma R_{cle\mathrm{i}.gr}$).

In FY2007, the effects of air velocity on effective clothing insulation were investigated by the use of thermal manikin. The values of the local effective thermal insulation provided by clothing, $R_{cle.i}$, were obtained for eight areas. $R_{cle.i}$ is the hypothetical thermal resistance expressing the effect

of the addition/removal of clothing. The ratio standardized by the $R_{cle.i}$ under the still air condition (v = 0.26 m/s), $C_{orr.Rcle.i}$, had a correlation with air velocity v, together with the approximated local relationships between them ($C_{orr.Rcle.i} = a_{.i} \cdot (b + v)^{m.i}$). $C_{orr.Rcle.i}$ decreased largely for the area with a long representative radius. $C_{orr.Rcle.i}$ had a linear relationship with the ratio of convective heat transfer coefficient standardized by $h_{c.i.cal}$ under the still air condition, ($h_{c.i}/h_{c.i.cal}$). The common formula, $C_{orr.Rcle.i} = -0.156 \cdot (h_{c.i}/h_{c.i.cal}) + 1.156$, was obtained for the eight body areas. The decrease in the effective thermal insulation provided by the clothing was expressed by air velocity or by the ratio of the convective heat transfer coefficient standardized by the value under still air condition. By using these relations, the local heat balance could be evaluated, considering the decreases in the clothing thermal resistance caused by air flow.

In FY2008, both dry heat resistance and wet heat resistance of two clothing ensembles for men were measured by the use of sweating thermal manikin. The co-relationship between effective dry heat resistance and effective wet heat resistance was found. The effective wet heat resistance became bigger in comparison with the dry heat resistance. The local sweat rates were measured on 14 areas of human skin by the use of the evaporimeter at 28°C, 34°C, and 37°C. The sweating on forehead, back, thigh, and foot were higher than the other area. This result might be a good information to choose the clothing form, clothing material properties, i.e., wet resistance and air permeability.

3) Personal ventilation and energy conservation

As a practical example of 28°C office buildings without losing comfort of occupants or workers, a field survey was conducted in an office that installed Task/Ambient Conditioning system in FY2006. Three levels of the use of Task conditioning system were tested for comparison. The vitality vote of male subjects was higher when Task conditioning system was turned on.

A field survey was conducted in FY2007 in another office with higher grade of environmental control technologies which include under floor air-conditioning system for occupied zone. From the results of subjective questionnaire (28 males and 2 females), workplace productivity was estimated higher than the value of typical office without new environmental control technologies. In this office, the setting temperature of HVAC was about 25°C. Then in FY2008, more detailed field measurements were done in the same new office following previous year to investigate occupants' behavior and possibility of practical use. The decrease of productivity was estimated and it was 0.5% per 1°C of rising temperature. This value was less than the previous studies. The freedom of control could compensate the deteriorative effect, and it is possible to be compensated by several environment control design applied to the office. Set point could be increased up to 27°C in this office.

4) Field study on thermal environment and indoor air quality

The impact of the room temperature on subjects' recollection of watched video program was studied in FY 2006 in two experimental types, i.e., the experiment under warm condition (29°C), neutral condition (25°C) and cool condition (22°C). After watching 30 minutes video program,

subjects answered the questionnaire, which asked the contents of the video program. It was found that there was significant difference in the percentage of correct answer in the difficult questions of the memory test among experimental types. The percentage of correct answer under the cool condition was more than that under the warm condition. The evaluation for the indoor environment and subjects' internal condition by subjects under the warm condition was worse than that under the cool condition. The arousal level and concentration ability under the warm condition could be decreased especially during the latter half of the experiment.

The impact of the air pollution caused by human bioeffluents on the occupants' perceived air quality was studied in FY 2007 in three different thermal conditions, i.e., warm condition (28°C), neutral condition (25°C), and cool condition (23°C). Fifty subjects occupied a room for 75 minutes. Fatty acid VOCs, which could be one ingredient of bioeffluents, were identified and quantified in the room air. The concentrations of the fatty acid VOCs in the warm condition were higher than those in the neutral/cool condition.

Double environmental annoyances, i.e., rather high room temperature of 28°C and traffic noise were set up for subjective experiment. These annoyances could have adverse effect on both perceived air quality and task performance. Ten subjects were exposed to four different conditions, i.e., i) room temperature of 25°C without traffic noise, ii) 25°C with traffic noise, iii) 28°C without noise and iv) 28°C with noise. They conducted three tasks (calculation, sheet spreading, and comprehension) under each condition. In a result of calculation, the occupants' performance under condition with traffic noise was higher than that without noise. And the performance under 25°C condition was higher than that under 28°C condition. In sheet spreading, the performance without noise was higher than that with noise. And the performance under 28°C condition was higher than that under 25°C condition. These results could be explained with arousal theory.

A field survey on productivity and thermal/air environment in a real office was conducted in FY 2008 with the method which had been developed in this study. Although the set-point temperature during cooling period in this office was 25°C, the set-point was elevated to 28°C in the end of July for two weeks for investigating the effect of temperature on productivity in a real office. The real office workers participated in this task test as subjects and evaluated thermal/air environment. As results of this study, it was found that the higher the temperature, the slower the task speed for both simple task and complex task. While the higher the temperature, the lower the task accuracy for simple task, the significant effect of temperature on task accuracy was not observed for complex task. The awakening of the indoor environmental quality might be related to task speed, while the sleepiness/boredom by the environment might be related to accuracy.

The experiments were conducted in a room size chamber where the indoor air was contaminated by human bioeffluents in order to investigate the relationship between odour intensity and VOCs concentrations. High correlation was observed in the relationship between the odor intensity and concentrations of decanal and nonanal.

5) Integrating research results

As an important basic concept for evaluating the indoor thermal environment and energy

conservation, the definition of 28°C should be clear. The temperature can be defined in several ways including return temperature to air conditioning system, preset temperature at the operation of air conditioning system or temperature of a thermostat in office, and temperature of occupant zone. Both advantages and disadvantages of the definitions were discussed.

The methods of integrating the achievements from the sub topics to optimize the office environment of 28°C in summer were developed (Figure 1).

The results from three experiments performed in sub topic (1) were used to develop a model for estimating relative work performance from thermal satisfaction and a model for estimating work performance from PPD. With these models, work performance can be predicted from a given thermal environment; mitigation of thermal environment can be evaluated at any rate, which allows stepwise adoption of COOL BIZ.

Productivity of COOL BIZ, including the effect of introducing cooling items, is illustrated in Figure 2. The estimations cover only the summer season from June 1 to September 30, which is referred to as "COOLBIZ-period". From normal cooling setting of 25°C with suit, raising air temperature to 28°C with light clothing would reduce the running cost of HVAC by 68.5Yen/(m^2·COOL BIZ-period) but would suffer the cost for decreasing work performance by 7640Yen/(m^2·COOL BIZ-period). Introducing the cooling items would reduce the running cost only by 9.0Yen/(m^2·COOL BIZ-period) and would also enjoy benefit for increasing work performance by 3800Yen/(m^2·COOL BIZ-period). The estimations were only shown as an example and other situation can also be evaluated.

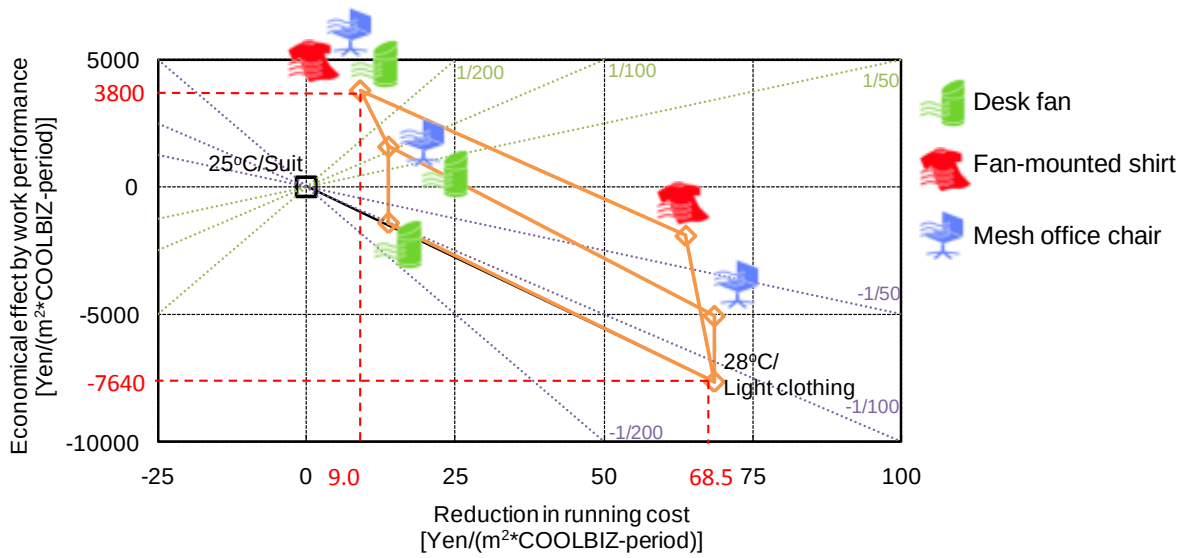


Figure 2. Productivity of COOL BIZ

4. Discussion

1) Based on the guideline of working indoor environment, keeping the air temperature between 17 and 28°C is recommended. The results from this research project revealed that it is important how the workers actually perceive the indoor environment. Based on the guideline and on the results of this project, the recommended definition of 28°C is to keep air temperature of occupant zone at 28°C, instead of the preset temperature of the HVAC system. The other

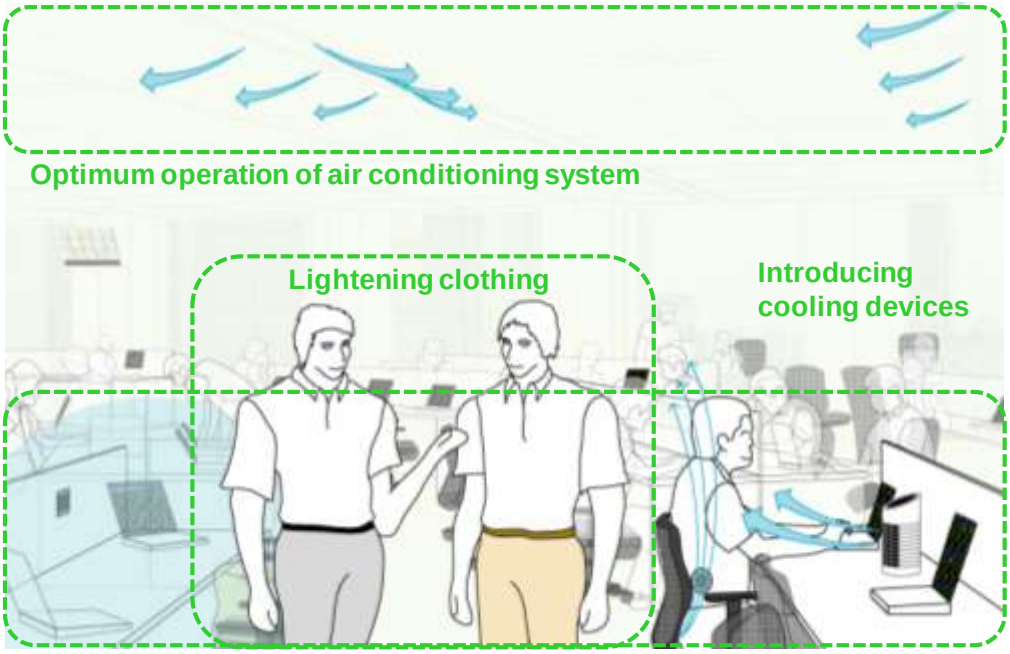
factors of thermal environment (radiant temperature, relative humidity, air velocity, and clothing insulation) should not be restricted but should be left open as alternative parameters to adjust suitably to the situation of office.

2) Detailed measured data of clothing insulation by body segments obtained in this project were useful in the simulation of human thermoregulation model to integrate the research results and provide the evaluation of productivity of COOL BIZ as shown in Figure 2. The data can also be applied in the other research projects as the detailed data of clothing insulation being scarcely available in the world.
3) Though the COOL BIZ campaign has been widely recognized, there is still doubt underneath in feeling thermally comfortable and keeping productive by just taking out jackets and ties to raise indoor temperature up to 28°C. Based on scientific studies, this project achieved to propose improvement measures of thermal environment and to provide information of possible troubles for raising indoor temperature.
4) The consumption of energy can be reduced by raising indoor temperature during cooling season above the normal setting. Company owner can consider an appropriate temperature setting for the activities and other parameters in his office just by lightening the workers' clothing, for example. It should also be noted from the results in this project that some types of performance were not being affected by the elevated temperature. More flexible scheme and stepwise adoption of COOL BIZ should be considered and publicized to be accepted by foreign countries that are most likely having much cooler preset temperature than in Japan. It will also be useful for persuading domestic companies.

5. Conclusions

1) The definition of 28°C was proposed. Possible troubles were pointed out that can be caused by raising preset temperature for cooling without appropriate measures to maintain thermal environment for occupants.
2) The effect of introducing improvement measures of thermal environment for the elevated preset temperature in existing office was evaluated.
3) Detailed data on clothing insulation for each body segment were obtained by thermal manikin measurement. The data included air permeability and wet resistance of clothing. These data were used to evaluate thermal environment with different types of clothing by human thermoregulation model.
4) The effect of thermal environment developed by different types of air conditioning system on the workers was evaluated from a field survey in an office with high grade of environmental control technologies.
5) Under moderately hot environment (27.5°C), the increase of air pollution by human bioeffluents was observed and the possibility of affecting perceived air quality was pointed out.
6) Deterioration of work performance in terms of speed of execution was observed in the elevated temperature conditions; however, the effect on concentration to work was not clearly observed for more complex tasks.

7) A model to evaluate productivity for office thermal environment was developed, and the economical effects based on work performance and the energy conservation for adopting COOL BIZ were evaluated using the model.



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1) G. Iwashita: Influence of Moderate Temperature on Performance and Long Time Memory of Video Program Contents - The Impact of the Room Temperature on Occupant Productivity (Part 2) -, Journal of Environmental Engineering, Transactions of Architectural Institute of Japan, No.628, pp.815-821, 2008.6 (Japanese)
2) M. Haneda, N. Nishihara and S. Tanabe: Subjective experiment for the effect of thermal environment and ventilation rate on productivity, Journal of Environmental Engineering, Transactions of Architectural Institute of Japan, No.638, pp.507-515, 2009.4 (Japanese)
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3) S. Tanabe and N. Nishihara: Indoor environmental quality and productivity, Journal of Architecture and Building Science, No.1564, 22-23, 2007.7 (Japanese)
4) S. Tanabe and N. Nishihara: Relation between health, fatigue and knowledge-creating environment, IBEC, Vol.28(5), 23-28, 2008.1 (Japanese)

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Conference paper

37 national conference papers in Japanese