Basic Study on Evaluation Methods of Energy Consumption of Buildings

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ABSTRACT

The extended degree-day method (EDD method) is a simplified seasonal heat load calculation method. In considering heat load components such as solar radiation, internal heat generations and outdoor-indoor temperature difference, this method has a good prediction and a widespread application, not only for prediction of energy requirements in air-conditioning systems, but also for evaluation of thermal performance of building envelopes. In this paper, the concepts and some improvements of the EDD method are to be introduced, and furthermore, a calculation example is given to describe the procedure.

INTRODUCTION

The energy conservation of buildings involves two separate aspects: one is to improve the thermal performance of exterior envelopes of buildings, the other is to make efficient use of building mechanical equipment.

In Japan, "The Law Concerning Rationalization of Energy Use (Energy Conservation Law)" was established in 1979 to conserve energy. According to the law, building owners have an obligation to minimizing heat loss through the building envelopes and to use their equipment efficiently.

Two guidelines were set in the law. PAL, for evaluating the thermal performance of envelopes, and CEC, for the efficiency of air-conditioning systems. PAL is the abbreviation for "Perimeter Annual Load," which estimate the annual heat load of perimeter zones which are indoor space measured 5 m from the surfaces of the envelopes, and is defined as follows:

$$\text{PAL} = \frac{\text{Perimeter annual load [Mcal/annual]}}{\text{Floor area of perimeter zone [m}^2\text{]}} \qquad (1)$$

Guideline: PAL < 80 (for office buildings)
PAL < 100 (for commercial buildings)

CEC is the abbreviation for "Coefficient of Energy Consumption for Air-conditioning," which is expressed by Eq.2.

$$\text{CEC} = \frac{\text{Annual energy consumption}}{\text{Annual air-conditioning load}} \qquad (2)$$

Guideline: CEC < 1.6 (for office buildings)
CEC < 1.8 (for commercial buildings)

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Here, the denominator of Eq.2 involves all the heating and cooling loads, but the numerator not only consider heating and cooling loads, but also consider other kinds of energy consumption in an air-conditioning system, such as electric consumption of fans, duct heat loss, and so on. So it applies a standard for evaluation of equipment efficiency. CEC is not the main focus of study in this paper, therefore, it will not be described in more detail.

Two calculation methods were recommended for determination of PAL in the law. One is the extended degree-day method (EDD method), which is a simplified method developed by one of the authors (Matsuo et al. 1979), and the other is HASP/ACLD/8001 (HASP method), a program method which is a precise computer method based on hourly response factors (Matsuo et al. 1980).

The objective of this paper is to describe the concepts and calculation procedures of the EDD method.

CONCEPTS AND EQUATIONS OF EDD METHOD

Development of the Degree-day Method

The degree-day method (DD method), as a simplified method, has been used to estimate the annual fuel cost for heating in buildings and the capacity of equipment in some cold countries. But with increased energy consumption in buildings, more accurate simplified heat load calculation methods have become necessary and a lot of attempts have been made to develop the DD method to a perfect heat load calculation method such as Kusuda (1981), Parken and Kelly (1981), and Sherman (1988) did.

The study of accurate degree-day calculation procedures was developed for evaluating the effects of internal heat gains, which separate occupancy period into occupied and unoccupied (Kusuda 1981). A calculation example of commercial and industrial buildings was also provided for comparison of the degree-day method and the MBLTBM method (Parken and Kelly 1981).

Another significant development was the study about infiltration degree-days (IDD). This method introduced infiltration for quantifying climatic conditions (Sherman 1988).

In Japan, almost all air-conditioning systems run at intermittent operations. Therefore, more attempts have been made to raise the prediction accuracy to reflect the effects of the running schedule of air-conditioning systems, as the EDD method did.

Concepts and Equations of EDD Method

According to steady-state heat transfer, the sensible heat load in a space can be expressed as follows:

$$q_H = (K_T^* + 0.3\,VA_F)(\theta_d - \theta_o) - \eta_T I_S + (\varepsilon/\alpha_o)K_T^* I_l - GA_F \qquad (3)$$

where

q_H = heating load [kcal/°C h]
A_F = floor area [m^2]
η_T = general solar transmittance of envelopes, if the envelope is opaque, the coefficient is expressed as $(\varepsilon/\alpha_o)K_T^*$ [m^2]
α_o = outside film coefficient where α_o=20 [kcal/m^{2}h]
ε = long-wave emissivity of outside surface of exterior where ε=0.9 [-]
K_T^* = general overall heat transfer coefficient of envelope [kcal/°C h]
θ_d = indoor design temperature [°C]
θ_o = outdoor temperature [°C]
I_S = solar radiation incident to outside surface of windows or walls [kcal/m^{2}h]
I_l = long-wave radiation transmission through window glass to outdoor [kcal/m^{2}h]
G = internal heat gain [kcal/m^{2}h]
V = infiltration and ventilation [m^3/m^{2}h]

The following new parameters are added to Eq.3.

$$K_T = K_T^* + 0.3VA_F$$
$$\theta_{ref} = \theta_d - \Delta\theta$$
$$\Delta\theta = GA_F/K_T k$$
$$\rho = \eta_T/K_T$$
$$\varepsilon/\alpha_o = 0.9 / 20 = 0.045$$

$$\sigma = K_T^*/K_T \doteqdot 1$$

Eq.3 can be represented as the following:

$$q_H = K_T\{\theta_{ref} - \theta_o - \rho I_S + 0.045\sigma I_l\} \quad (4)$$

where

θ_{ref} = reference temperature [°C]

ρ = general ratio of solar transmittance to heat transmission coefficient [h C/kcal].

The terms within {} of Eq.4 have a temperature dimension, thus they can be considered as the sol-air temperature, then substituting θ_o, I_S, and I_l with values of their daily average and accumulating them when it is at a plus for one year, extended heating degree-day (EHD) are obtained as follows.

$$EHD = \Sigma\{\theta_{ref} - \theta_o - \rho I_S + 0.045 I_l\} \quad \text{for } \theta_{ref} > \theta_o \quad (5)$$

Carrying out the same procedure for cooling load, extended cooling degree-days (ECD) can also be obtained:

$$ECD = \Sigma\{\theta_o - \theta_{ref} + \rho I_S - 0.045 I_l\} \quad \text{for } \theta_o > \theta_{ref} \quad (6)$$

Since there are four parameters in EHD and ECD, the EDD method incorporates effects of local climatic conditions, outdoor-indoor temperature differences, internal heat gain, solar radiation, long-wave radiation, infiltrations, and ventilation.

The values of EHD and ECD can be calculated with the standard weather data (SHASEJ 1973) of major cities in Japan at nine orientations: horizontal, south, southwest, west, northwest, north, northeast, east and southeast. For example, Figure 1 shows the values of EHD and ECD in Sapporo (AIJ 1981).

If an air-conditioning system is supposed to be running continuously (24 hours a day), the seasonal cooling load (SCL) and seasonal heating load (SHL) can be obtained as follows:

$$SCL=0.024K_T\ ECD\ [\text{Mcal/annual}] \quad (7)$$
$$SHL=0.024K_T\ EHD\ [\text{Mcal/annual}] \quad (8)$$

Here, the number 0.024 is the product of the numbers of hours a day and thermal unit per million calories.

Correction Coefficient for Intermittent Running

In order to make the EDD method applicable to intermittent running, a kind of correctional coefficient was called as an intermittent running correction coefficient and written for K, and was introduced to correct the effects of running time.

$$K = \frac{\text{accurate seasonal heat load}}{0.024\ K_T\ EDD} \quad (9)$$

where

EDD = value of EHD when heating or ECD when cooling.

To determine the coefficient K, HASP/ACLD/8001 is applied to support the calculation of accurate heat load in the numerator of Eq.9. However, the seasonal heat load depends on many factors, such as window area ratio, shading device, insulation thickness, occupancy, and illumination. The following statistical works and techniques are used to quantify the values of K:

(1) Some factors and their levels are selected in a wide range according to practical view points, which are shown in Table 1.
(2) Then these factors and levels are combined into 81 numbers of numerical experiments, which are laid out at the orthogonal array $L_{80}(3^{40})$ by utilizing the "design of experi ment" techniques.
(3) The results of the numerical experiments on the EDD method and the HASP method are analyzed by statistic techniques to obtain K.

Some assumptions or idealizations about the calculating conditions are made for statistical analysis:

(1) The linear regression equation is preset for fitting a straight line by the least squares estimate:

$$Y = KX \tag{10}$$

where

Y = accurate heat load considering intermittent running of air-conditioning calculated by HASP/ACLD

X = predicted heat load without considering intermittent running of air-conditioning calculated by EDD

K = regression coefficient called as intermittent correction coefficient.

(2) Two kinds of typical buildings, office and commercial, were selected, and some conditions about the buildings called as standard conditions, are presupposed according to investigations. They are,
Air-conditioning schedule:
Office : 8:00~17:00 for weekdays, 8:00~13:00 for Saturday.
Commercial : 8:00~18:00 for weekdays.

(3) Indoor design temperature in running time:
Cooling: 26°C,
Heating: 22°C for office and 20°C for commercial.

Two regression coefficients, K_C for seasonal cooling load and k_H for seasonal heating load, had been obtained in all of the major cities of Japan (IBEC, 1980,1984). The regression of such example is shown in Figure 2.

With intermittent coefficients, the seasonal heating and cooling load calculation formulas (Equation 8 and 9) are expressed as:

$$SHL=0.024\ K_H\ K_T\ EHD\ [\mathrm{Mcal/annual}] \tag{11}$$
$$SCL=0.024\ K_C\ K_T\ ECD\ [\mathrm{Mcal/annual}] \tag{12}$$

where

K_H = heating intermittent correction coefficient

K_C = cooling intermittent correction coefficient.

For example, Figure 3 illustrates the correspondence of both annual energy consumption (AIJ 1981), x axis for prediction results by Eq.11 and Eq.12, and y axis for precise results based on the precise computer program HASP/ACLD. This shows that the EDD method has a good prediction.

IMPROVEMENT OF EDD METHOD

The improvement and development of the EDD method has been studied in two ways: the average solar transmission coefficient to estimate the effect of blind operation, and the time correction coefficient to consider the unstandardized running time of air-conditioning systems (Wen 1989).

Mean Solar Transmission Coefficient

It was known by Wen(1989) that the operation of a window blind, which was not considered in previous EDD methods, is an important factor for calculation of solar radiation heat gain through window glass. As a development, the average solar transmission coefficient, η_a, which is defined by Eq.13, is proposed to reflect the effect of blind operation.

$$\eta_a=\eta_0+(\eta_C-\eta_0)\gamma \tag{13}$$
$$\gamma =\Sigma \beta_m I_m)/(\Sigma I_m) \tag{14}$$
$$I_n=(\Sigma I_n)/365 \tag{15}$$

where

η_a = average solar transmission coefficient [m2]
γ = ratio of solar heat gain which includes the effect of blind operation, [-].
η_C = solar transmission coefficient which considers blinds fully closed [m^2]
η_0 = solar transmission coefficient which considers blinds fully opened [m^2]
β = shade ratio which is defined as the ratio of area covered by a blind to area of the window [-]
I = hourly annual average of solar incidence through window glass into room [$kcal/m^2h$]
m = subscript of the hour sequential number, where m = 1,2,...,24
n = subscript of the day sequential number, where n = 1,2,...,365.

The average solar heat gain ratio, η_a concerns two components: the ratio of solar transmission coefficient η_C and η_0, which can be obtained by (IBEC, 1980,1984), and the ratio of solar heat gain, γ, which is dependent upon the incidence intensity of solar radiation.

To determine γ, a typical blind operation, which is referred from the HASP method (Matsuo et al. 1980), is supposed to represent the shade ratio β, and the standard weather data (SHASEJ, 1973) are used to calculate the hourly average solar heat gain, I_m, which is dependent on latitude and orientation in Eq.14. With these assumptions, a typical solar heat gain ratio, γ, can be obtained, which is called as the standard solar gain ratio and written for γ_S. Table 2 shows the values.

Time Correction Coefficient

With the introduction of time correction coefficients, the intermittent correction coefficients should be separated into two different parts: K_G for correction of local climactic conditions, and K_T for correction of running time of air-conditioning systems, so regression Eq.10 would be replaced by the following:

$$Y = K_T K_G X \tag{16}$$

where
K_T = time correction coefficients which reflect the effects of running time of air-conditioning
K_G = regional correction coefficients which reflect the effects of climatic conditions.

If K_T is considered as the ratio of unstandardized operation to standard operation, it can be expressed by Eq.17:

$$K_T = K_{uns}/K_S \tag{17}$$

where
K_{uns} = regression coefficient in the case in which an air-conditioning system runs at an unstandardized set time schedule
K_S = regression coefficient in the case in which an air-conditioning system runs at a standard set time schedule.

Here, the standard and unstandardized running are defined with the starting and stopping times of the air-conditioning system as the followings:
Standard running : 8:00~17:00 (10 hours running)
Unstandardized running: 11:00~14:00 (4 hours running)
9:00~16:00 (8 hours running)
Note: Other cases are on the analogy of them.

Both the time coefficients, K_{TH} for heating and K_{TC} for cooling, were determined by statistical calculation, as shown in Figure 4. According to the curves, it is clear that both the time coefficients are only the functions of running and that they are not dependent on region. If the air-conditioning system runs at the standard schedule, K_T should be given the value 1, but if the air-conditioning system runs at any schedule other than the standard, the heating or cooling load must be corrected by time correction coefficient K_{TH} or K_{TC}.

With the introduction of a time correction coefficient, of course, a new series of region correction coefficients are determined and shown in Table 3.

Comparison of Methods

Some comparison of prediction accuracy and its adaptability is performed between the improved EDD method and the previous EDD method. The results show that the improved method has some advantages over the previous one.

Upgrade of Prediction Accuracy. The prediction accuracy was studied by comparing the standard error (which was expressed as the difference between prediction values by the EDD method and precise values by the HASP method in Eq.18).

$$D_S=\sqrt{\Sigma(EDD_i - HASP_i)^2/N} \tag{18}$$

where

D_S = standard error [Mcal/m^{2}annual]
EDD = the prediction heating or cooling load result by the EDD method [Mcal/m^2 annual]
HASP = the precise heating or cooling load result by HASP/ACLD method {Mcal/m^{2}annual]
N = the numbers of numeral experiments, here N=81
i = the subscription of number of experiments.

The heat load results according to 81 numbers of numeral experiments were used for error analysis, and the comparison results are shown in Table 4, which shows that these improvements made the EDD method a better predictor than the previous one.

Extension of Adaptability. Since the previous EDD method was developed for any special conditions, such as the usage of buildings and the operation schedules of air-conditioning systems, its adaptability had be limited. However, Because these improvements were carried out in a wide assumptive condition, it was able to give the EDD method a wider application, not only to predict annual heat load of energy conservation standards, but also to analyze the thermal performance of building envelopes for optimum design of saving buildings energy.

EXAMPLE OF CALCULATION

In this section, the calculation procedures of the EDD method shall be presented through a practical example.

Calculation Model

A one-column span of a typical office building and the plan is selected, which is shown in Figure 5, and various specifications about the model building are shown as follows:

Location: Sapporo
Running time : 8:00~17:00, 10 hours running
Indoor design temperature: 22°C for heating, 26°C for cooling
Floor area: 30 m^2, Orientation : south
Exterior wall: A=7.8 m^2, K=0.65 [kcal/°C h], η=0.65*0.045=0.029
Blind: light colored and standard operation
Window: A=7.8 m^2, K=5.13 [kcal/°C h], γ_S=0.20, η_0=0.84
η_C=0.55, η_a=0.84+(0.55-0.84)*0.02=0.78
Internal heat gain: 10 [kcal/m^{2}h].

Calculation Steps and Results

Step 1. Total heat transfer coefficient, ΣKA, of envelopes:
Exterior wall $K_W A_W$: 0.65*7.8 = 5.1
Glass window $K_G K_G$: 5.13*7.8 = 40
+) Infiltration: supposed to be zero

ΣKA = 45.1

Step 2. Solar transmittance of envelopes:
Exterior wall $\eta_W A_W$ = 0.029*7.8 = 0.234
+) Glass window $\eta_{aG} A_G$ =0.78*7.8 = 6.084

$\Sigma \eta_T A$ = 6.3

Step 3. Reference temperature θ_{ref}:

$\Delta\theta = G*A / \Sigma KA = 10*30/45.1 = 6.65$

Heating: $\theta_{ref} = 22 - 6.65 = 15.35$

Cooling: $\theta_{ref} = 26 - 6.65 = 19.35$

Step 4. The general ratio of solar heat gain/heat transmission coefficient:

$\rho = \Sigma \eta A / \Sigma KA = 6.3 / 45.1 = 0.41$

Step 5. The values of EHD and ECD:

EHD = 180, ECD = 2500

(The values were determined by using θ_{ref} and ρ according to Figure 1).

Step 6. Correction coefficients:

$K_{TH} = 1.0$, $K_{TC} = 1.0$ (from Figure 4)

$K_{GH} = 0.85$, $K_{GC} = 0.87$ (from Table 3)

Step 7. Seasonal heat loads:

Heating load: $SHL = 0.024 * \Sigma KA*K_{TH}*K_{GH}*EHD$
$= 0.024*45.1*1.0*0.85*180$
$= 166$

Cooling load: $SCL = 0.024 * \Sigma KA*K_{TC}*K_{GC}*ECD$
$= 0.024*45.1*1.0*0.87*2500$
$= 2354$

Step 8. PAL value:

$PAL = (SHL+SCL)/A_F = 2520/30 = 84$

The data referred from IBEC (1980,1984) were not notified.

CONCLUSION

As a perfect and simplified heat load calculation method, the EDD method has been used in Japan for predicting the seasonal cooling and heating load, and for estimating the thermal performances of building envelopes. As a study objective, the EDD method is expected to be developed and to play a more important role in the evaluation of energy consumption and other thermal analysis fields.

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TABLE 1
Factors and Levels

NO	Factors	Level 1	Level 2	Level 3	Appendixes
1	Ratio of area of window	0	30	60	[%]
2	Orientation	S	SW	W	NW,N,NE,E,SE
3	Insulation thickness	0	25	50	Material: glass wool.
4	Varieties of glass	Absorbent +ordinary	Absorbent	Ordinary	Glass thickness: 6 mm.
5	Shading device	without	Over hang	Box type	
6	Blind	Without	lighter-colored	Middle-colored	
7	Occupancy	0.1	0.2	0.3	[People/m^2]
8	Illumination	10	20	30	[W/m^2]
9	Heat structure	Light (0 mm)	Middle (150 mm)	Heavy (300 mm)	Determined by the thickness of concrate.
10	Ventilation	2	4	6	[m^3/m^2 h]

TABLE 2
Typical Solar Gain Ratio, γ_S

region	S	SW	W	NW	N	NE	E	SE
SAPPORO	0.30	0.20	0.20	0.21	0.21	0.23	0.23	0.43
TOKYO	0.20	0.20	0.20	0.20	0.20	0.22	0.22	0.21
KAGOSIMA	0.20	0.49	0.33	0.21	0.20	0.22	0.22	0.42

TABLE 3
Standard Region Correction Coefficients, K_G

Region	Office		Commercial	
	K_{GC}	K_{GH}	K_{GC}	K_{GH}
SAPPORO	0.82	0.88	0.98	0.82
TOKYO	0.87	0.85	0.93	0.75
KAGOSIMA	0.86	0.89	0.93	0.73

TABLE 4
Comparison of Prediction Accuracy [Mcal/m^2annual]

Load	Method	Region		
		SAPPORO	TOKYO	KAGOSIMA
Cooling	Previous	6.77	8.38	9.77
	Improved	5.87	7.35	8.81
Heating	Previous	7.35	4.56	3.67
	Improved	6.47	4.04	2.86

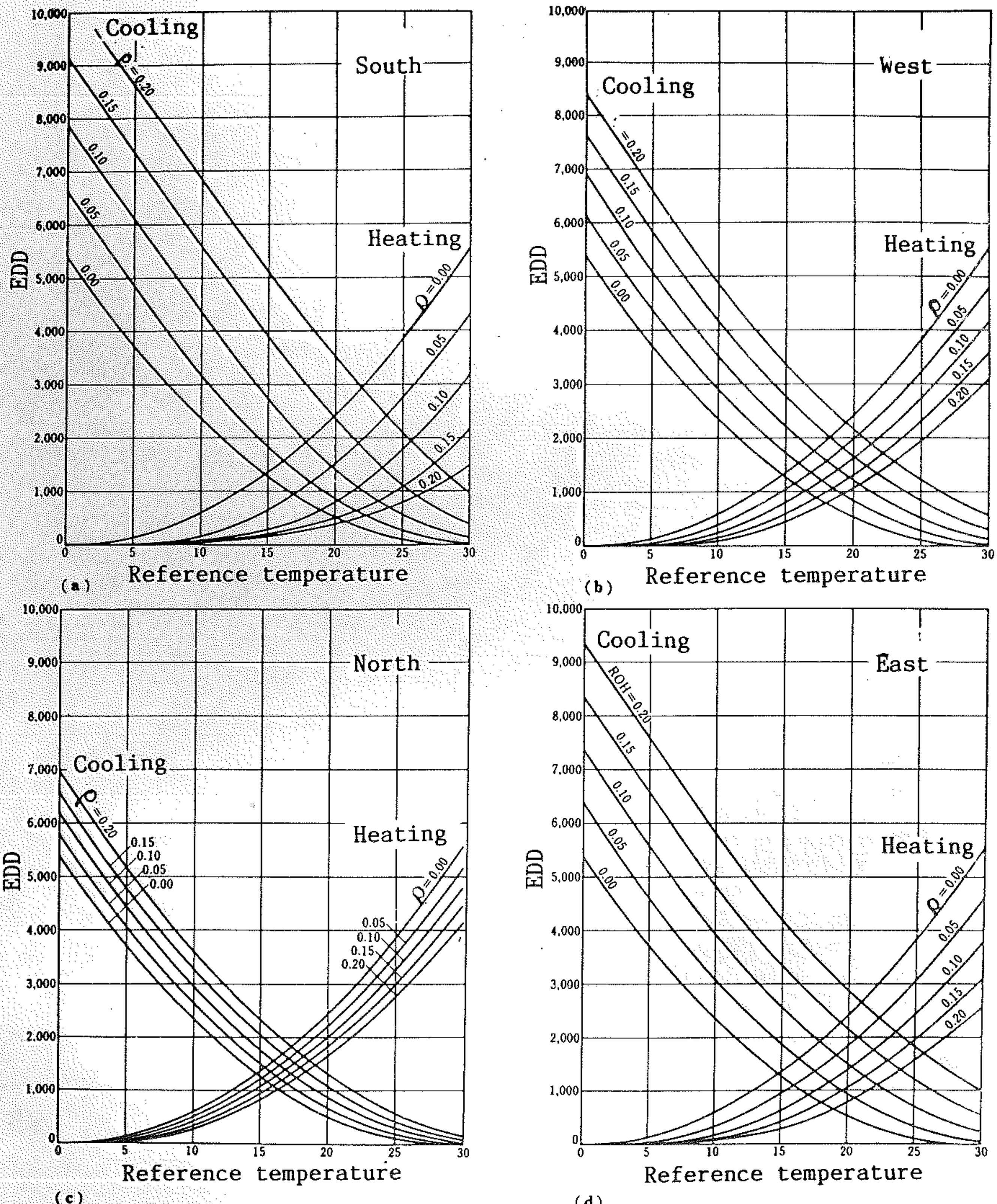

Figure 1. Extended degree-days at Sapporo

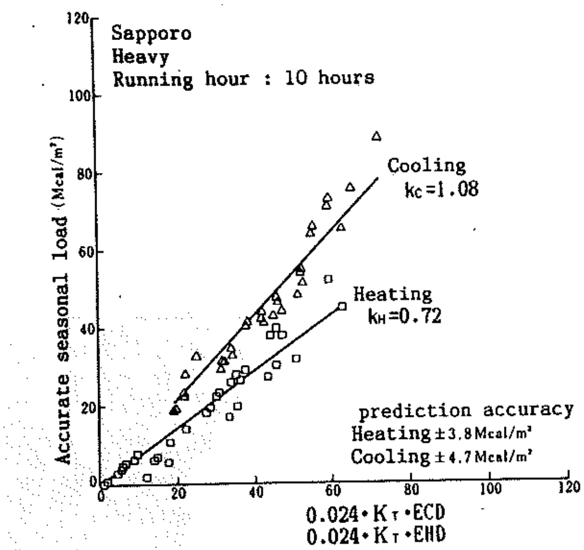

Figure 2. *Regression coefficient of EDD calculation result with accurate result*

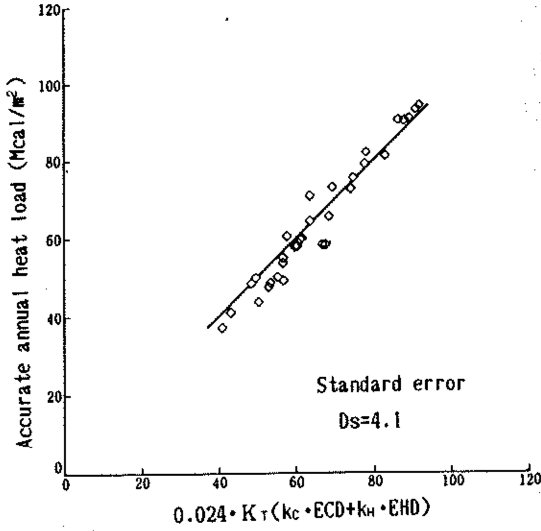

Figure 3. *Comparison of EDD calculation result with accurate result*

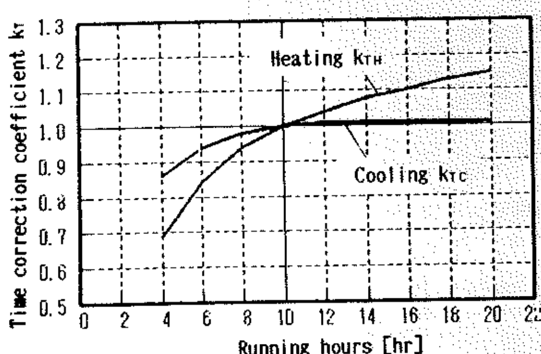

Figure 4. *Time correction coefficient for intermittent running*

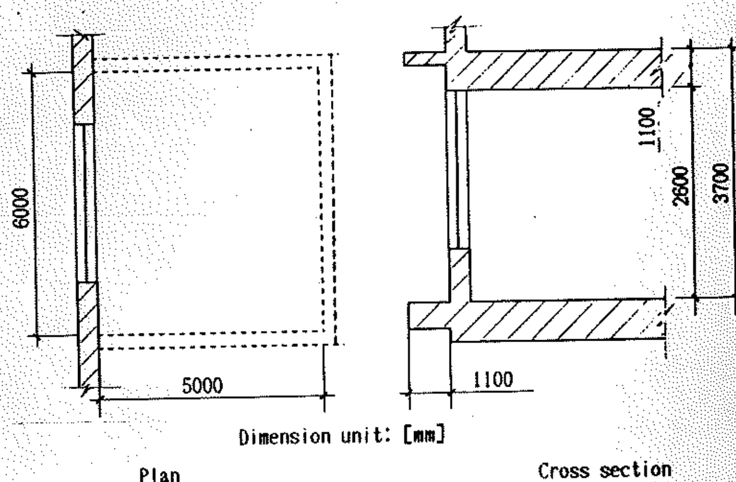

Figure 5. *Calculation model room*