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The Transient Conjugate Heat Transfer Analysis in Multi-zone of an Apartment House by using Crank-Nicolson Finite Difference Method (FDM)

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ABSTRACT

Purpose: This study was conducted for the purpose of accurate energy analysis of apartment house which is composed of multi-zones such as a bedrooms, a livingroom, and a kitchen. Those of multi-zonal spaces have different indoor thermal environment requirements depending on space usage. For the analysis of this study was selected the 74m^2 type unit, which has the largest amount of supply in residential needs. The orientation of the apartment house unit was divided into the southeast and southwest directions, and the annual heating energy demand was calculated and compared. **Method:** A multi-zone heat transfer is done in dynamic and a very complex, such as conduction, convection, radiation and the solar radiation in a various building elements. In this paper, the Crank-Nicolson FDM scheme and the ISO 13790 algorithm were employed to analyze a complex and transient heat transfer in the multi-zone of apartment house. **Result:** The results of the analysis are as follows; the total amount of annual energy requirement for the apartment house unit which oriented in the southwest is 756 *kWh*. and equivalent to 10.2*kWh*/m^2. When the required amount of primary energy was converted equivalent to electricity by unit floor area, it was 28.1 kWh/m^2. On the other hand, the total amount of annual energy requirement for a unit oriented in the southeast direction is 1,037 *kWh* and 14.0 *kWh* /m^2. The result of conversion (electricity) to primary energy is 38.5 kWh/m^2. This result indicates that the energy demand is about 27% higher than the southwest.

KEYWORD

Multi-Zone of an Apartment House
Transient Conjugate Heat Transfer
Crank-Nicolson Finite Difference Method(FDM)

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1. Preface

1.1. Background and Purpose of Study

It is in the trend that the domestic laws and regulations on Building Energy Consumption are being strengthened at higher levels of the Guidelines on Building Energy Consumption in Europe. [1]. Accordingly, more sophisticated energy analysis methods are required during the building design stage. And an analysis of building energy consumption shall be conducted by using an equation of higher degree accompanied with a wide range of calculations for various kinds of heat transfer elements, such as, a heat transfer process between architectural elements of a housing space consisting of a multi-zone for which the requirements and conditions for the solar irradiation and heat environment including the regional temperature and moisture based on the weather data primarily. It was a dilemma to enhance the reliability of an analysis of building energy. But, much development has been made by developing an algorithm under which the results from an analysis are matched to the actual conditions. In this study, an analysis of building energy was conducted while there were complexly considered the behaviors of conduction, convection, radiation, ventilation and solar irradiation which are made on a ceiling, a roof, a wall, a window and a door of an apartment house by using an algorithm adopting the Crank-Nicolson FDM in order to find out a transient conjugate heat transfer mechanism that is created inside or outside of a room of a residential area while having been considered the thermal characteristics of each residential zone of a residential building. This study is intended to analyze exquisitely a transient conjugate heat transfer phenomenon caused by some complicated heat transfer processes in a multi-zone which required various kinds of thermal performances like an apartment house and to establish an analysis process with which an energy performance can be forecasted accurately.

1.2. Scope and Method of Study

In this study, first, there shall be reviewed the Crank-Nicolson FDM and ISO 13790 that are optimized for an analysis of a transient conjugate heat transfer as well as the domestic and foreign laws and regulations related to building energy consumption. Second, for analyzing a transient conjugate heat transfer at a multi-zone of a residential space like an apartment house, the 74m^2*Type* of houses as the universal unit house scale whose no. of supplied units is very high and which are universally used among the apartment houses was

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selected as the analysis object. In addition, a transient conjugate heat transfer analysis scheme and process which satisfies various conditions for thermal analyses, such as, conditions for solar irradiation have been established by dividing some multi-zones into the ones toward the southern east and the ones toward the southern west. Third, after establishing the boundary conditions and organizing many complicated mutual thermal nodes and networks, such as, heating, supplied energy, heat transfer through structures and irradiation, etc., for buildings are organized regarding to heating loads during a winter season when the energy consumption is the highest, an analysis model is made based on the results from the works. And after deducing the results form the final analysis, it was evaluated whether some energy can be saved or not regarding to the mechanical loads that are actually designed.

2. Contemplation on Analysis Theories and Processes

2.1. Contemplation on Analysis Theories and Criteria

when building energy consumption is designed, the provisions in accordance with the Operating Guidelines defined by the Government and the relevant laws and regulations shall be reflected for saving the energy consumption of the public, commercial and residential buildings and for enhancing the efficiency. This is intended to reduce some environmental problems and greenhouse gas and to save building energy consumption. When Building Energy Consumption is designed, the reviews and the feasibilities shall be examined depending on the evaluation methods, criteria and purposes, etc., and then a design shall be implemented while being considered such factors.

The Crank-Nicolson FDM is a numerical analysis which enhances the accuracy of an approximate solution depending on the density of some finite grids which are created in a geometric zone as a numerical analysis method which a differential equation is transformed into a matrix equation by using the changes of locations of natural phenomena between dots which are neighboring each other after some finite no. of dots are created within the geometric zone. [2][3][12].

ISO 13790 gives some theoretical grounding and relevant data required for calculating thermal transfer, thermal equilibrium and acquisition of irradiation through windows as a standardized calculation method for heating and cooling energy used at buildings. [4]~[9],[10],[11],[13]. The international standards for analyzing Building Energy Consumption and evaluating the performances like ISO 13790 measure the building performance based on some energy equations and is mainly intended to secure the transparency and reliability of the resultive values by using the objective building data. In this study, it is intended to deduce the analysis results by using 'CAPSOL' as a dynamic energy analysis simulation tool for analyzing some heat in order to secure the accuracy of the analysis of the target structures mentioned above.

2.2. Analysis Process

Fig. 1 shows the basic scheme for analyzing the multi-zone energy of apartment buildings subject to the analysis while being considered the adjustments of indoor temperatures, thermal flow within the structures of a building and conditions for irradiation and the radiation generated from building elements. This is, it shows a concept diagram of an analysis of some mutual complex heat transfer phenomena between the spaces for each purpose constituting a multi-zone after establishing mutual complicated thermal nodes and networks of the following elements defined as follows, that is, heating (θ_{th}), cooling(θ_{tc}), supplied energy(Q_C), heat transfer by a structure(Q_M) and solar irradiation through a wall(S) as the thermal features of a residential area. The basic scheme of a multi-zone transient conjugate heat transfer analysis is to organize the heat transfer network by transforming the heat capacity required for a wall facing directly the outside air, an indoor boundary wall, a heated space and a non-heated space into each thermal resistance and thermal capacitors. The thermal network consists of many nodes having different heat characteristics. Each temperature is calculated by using the boundary conditions that are defined in a certain node and the time intervals of heat flow between nodes are calculated based on the time stages. In the schematic diagram in *Fig. 1,* a wall including the floor, the ceiling and windows are indicated with its resistance (R) and capacitor (C_m) and the non-heated space inside a wall is analyzed by applying a thermal resistance (A) created by radiation and a thermal resistance for convection which reacts in parallel or an equivalent thermal resistance (B). The boundary conditions which are applied to the network of thermal resistances and thermal capacitors are indicated at specific temperatures (θ_1 & θ_2) which are applied to each zone node. Each zone whose thermal requirements are different is distinguished by walls. Since the indoor zones (I & IV) have some volume, they are indicated with a Zone Capacitor (C_z), but the external zones (E & ES) have no volumes. The external zone of a specific part of the southern area which faces the external air directly is set as a Solar Zone (ES). Among the heat flows of the surface caused by a convection current and some infrared light inside the internal zone, the combination zone (I) is formed by the heat resistance created by the combination of a convection current and infrared radiation (R_{CR}) and the isolated zone is formed based on the elements for each convection heat resistance (R_C) and each view factor or is formed by a view factor based on infrared radiation heat resistance. The heat flow (V) of a heat storage medium is generated in both directions in the indoor zone due to the natural and mechanical ventilations.

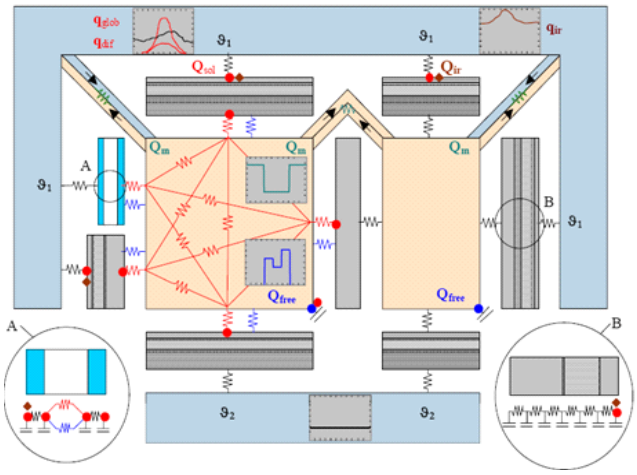

Fig. 1 The scheme of energy analysis of multi-zonal space

3. An Analysis of Transient Conjugal Heat Transfer in a Multi-zone of an Apartment House

3.1. Overview of Analysis

In this study, in order to satisfy the evaluation method of energy consumption required in the energy saving design standards for buildings, the weather factors were reflected as well as the thermal requirements and the architectural elements of a housing space in accordance with the international standard, 'ISO 13790' based on the Building Energy Performance Manual of EU, 'EPBD(*Energy Performance, Building Directives*)', the building energy performance evaluation standards of Germany, 'DIN V 18599' and by using the Crank-Nicolson FDM-based algorithm [10]. In addition, in order to calculate the energy demand of each unit house of an apartment building which is subject to this Study, the climate data in Seoul Region (Global Solar Irradiation, Diffuse Irradiation and Temperature Data), walls, windows, doors and zones and indoor & outdoor surface heat resistances were applied. The object of this Study is 74m^2*Type* which is a general unit house size among apartment houses and the floor plan and the sectional plan are shown in Figure 2 & 3. The heating device operating zones of a house designated for analyzing the building energy consumption are the living room, the Main Bedroom, the bed room 1 and the bed room II. An appropriate indoor temperature was set at 20℃. And the system is set in order that the indoor heating system starts to be operated if the indoor temperature in the relevant zone drops below 20℃. The heat transmittance for the performance for each part of a building shall follow the design criteria for the central region[10] and the boundary conditions for the indoor & outdoor surface heat transfer resistances are shown in *Table* 1.

As the weather data, the one of Seoul Region among the Meteonorm Weather DB was adopted. The physical characteristics of main materials constituting the structures of a building are shown in *Table* 2.

The specification of the grade 1 of the materials used for the windows facing outdoor air directly are *5mm+12mm+5mm*, ε=0.03. The directions of each unit house are conditioned to the southern east and the southern west and the living room, the Main Bedroom, the bedroom #1 and the bedroom #2 of each house were compared to be analyzed.

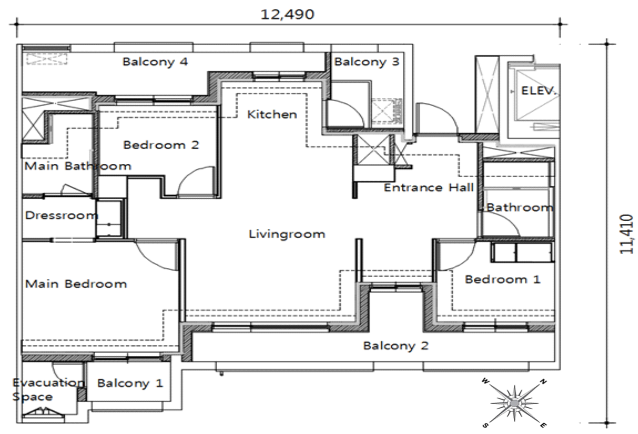

Fig. 5 Plan of Apartment Housing 74㎡ Type Multi-zonal Unit

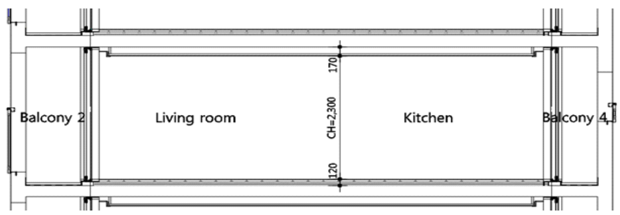

Fig. 6 .Section of Apartment Housing 74㎡ Type Unit

Table 3 Physical Properties of Internal & External Surface Resistance

Surface Resistance / Building Elements	Internal Surface Resistance (㎡K/W)	External Surface Resistance(㎡K/W)	
		Indirect	Direct
Living room external wall	0.11	0.11	0.043
Floor of Apartment House	0.086	-	-

3.2. Boundary Conditions

Table 4. Boundary Conditions of Multi-zone Building Elements

Building Elements	Material	Thickness (*mm*)	Thermal Conductivity (W/mK)	Thermal Resistance (㎡/wK)
Wall	Cement Mortar	2	1.4	0.014
	Brickwork	190	0.6	0.38
	Poly-Urethane	65	0.02	3.25
	Gypsum	10	0.18	0.056
Floor Roof	Cement Mortar	4	1.4	0.029
	Cellular Concrete	40	0.105	0.38
	Buffer Material	30	0.810	0.037
	Concrete	210	1.65	0.15

3.3. Analysis Modeling

For analyzing building energy consumption, each wall, window and door, etc., of each unit house (74m^2 Type) of an apartment building were modeled and each is composed of several multi-zones depending on the practicality and the indoor and outdoor boundary conditions were entered. The weather data for a year in Seoul Region was used and other various kinds of conditions, such as, the capacity of each device and a heating device operating time, etc., for each multi-zone were used for modeling as shown in *Fig. 4*.

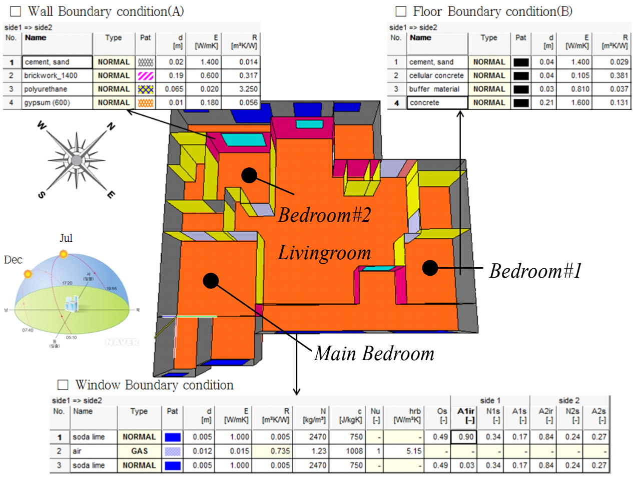

Fig. 4 Multi-zonal Modelling of Unit & Boundary Conditions

4. Results from an Analysis of Transient Conjugate Heat Transfer in a Multi-zone of an Apartment House

4.1. Analysis of Solar Irradiation and Temperatures

Fig 5~8 show the changing trend of the solar irradiation and surface temperatures on the southern wall side and the northern one owing to the arrangement of 74m^2 Type unit houses toward the southern west and the southern east during the period from November to March. Moreover, in order to comprehend the solar irradiation which flows onto the wall side and the surface temperatures during the same period of winter, the average irradiation value and the average surface temperature during the winter season (November to March) were checked. Fig. 5 &6 below show the results of the distribution of solar irradiation flowing onto wall bodies of the southern and northern walls due to the arrangements of 74m^2 Type unit houses toward the southern west and the surface temperatures. The data on solar irradiation and surface temperatures is composed of the average inflow solar irradiation and the average surface temperature for each month during the period of November, December, January, February and March.

1) In case of the wall side facing the south, it was found that the average monthly inflow irradiation is 68W/m^2 in November, 54W/m^2 in December, 63W/m^2 in January, 84W/m^2 in February and 94W/m^2 in March. In case of the wall side facing the north, it was found that the distribution is 33W/m^2 in November, 25W/m^2 in December, 30W/m^2 in January, 46W/m^2 in February and 69W/m^2 in March. In case of the south wall surface, the inflow solar irradiation is around 44% (the south wall surface: 363W/m^2 and the north wall surface: 203W/m^2) compared to the north wall surface depending on the movement of the sun.

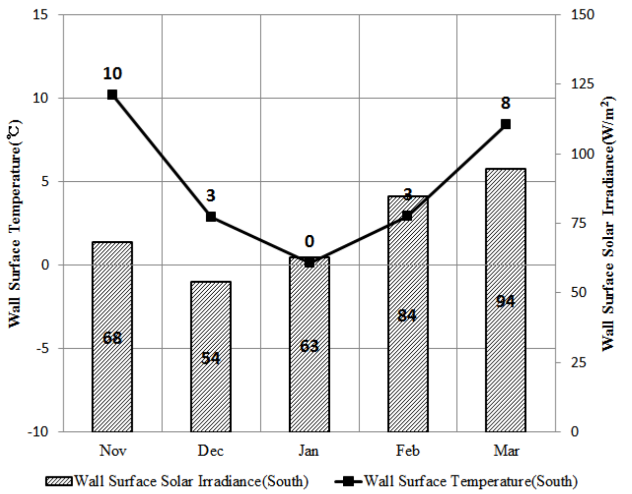

Fig. 5 Wall Surface Irradiance & Temperature(South-West South Wall)

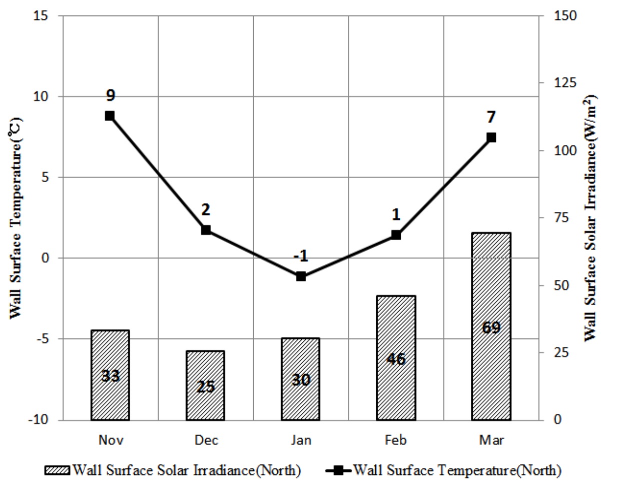

Fig. 6 Wall Surface Irradiance & Temperature(South-West North Wall)

2) As far as the distribution of the monthly average surface temperature as shown in *Fig. 8*, in case of the wall side facing the south, it was found that it is 10℃ in November, 3℃ in December, 0℃ in January, 3℃ in February and 8℃ in March. On the other hand, in case of the wall side facing the north, it was found that the average temperature is 9℃ in November, 2℃ in December, -1℃ in January, 1℃ in February and 7℃ in March.

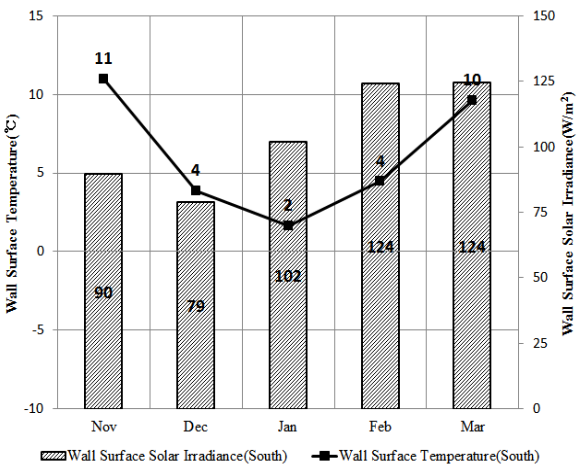

Fig. 7 Wall Surface Irradiance & Temperature(South-East South Wall)

And the Fig. 7 &8 show the distributions of the monthly average inflow solar irradiation that flows onto the wall surfaces facing the south and north in winter and the monthly average surface temperature during the period of November to March owing to the arrangement of the 74m^2 Type unit houses.

1) In case of the wall side facing the south, it was found that the monthly average inflow solar irradiation is 90W/m^2 in November, 79W/m^2 in December, 102W/m^2 in January, 124W/m^2 in February and 124W/m^2 in March. In case of the wall side facing the north, it was found that the monthly average inflow solar irradiation is 28W/m^2 in November, 23W/m^2 in December, 25W/m^2 in January, 35W/m^2 in February and 52W/m^2 in March. In case of the south wall surface, it was found that the inflow solar irradiation is around 69% compared to the north wall surface (South Wall Surface: 519W/m^2 and North Wall Surface: 163W/m^2) compared to the north wall surface depending on the movement of the sun. According to the analysis data by each direction, generally, the vertical surface solar irradiation and the sunshine duration are the highest in the southern west. [13]

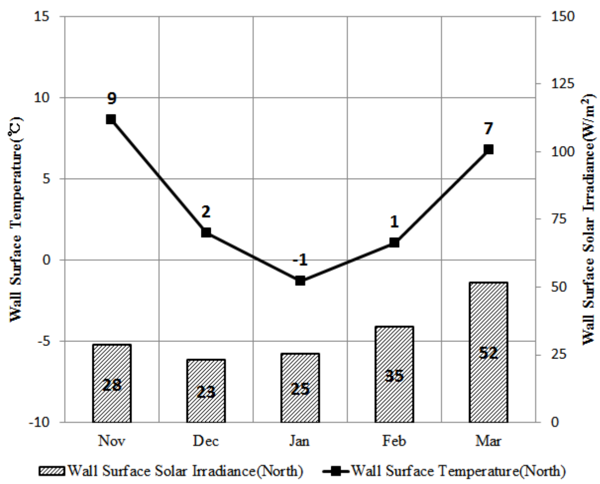

Fig. 8 Wall Surface Irradiance & Temperature(South-East North Wall)

2)As far as the monthly average surface temperature, in case of the south wall surface, it was found that it is 11℃ in November, 4℃ in December, 2℃ in January, 4℃ in February and 10℃ in March. In case of the north wall surface, it was found that the average temperature is 9℃ in November, 2℃ in December, -1℃ in January, 1℃ in February and 7℃ in March. So, it was found that the average temperatures of the north wall side were lower than those of the south one.

4.2. Analysis of Heating Energy

Fig 9~12 show the yearly heating device operating hours owing to the arrangement of the reference floor of the 74m^2 Type unit houses in the directions of the southern west and the southern east and the residential zoning by utilizing the weather data in Seoul Region. It can be seen that the heating device operating hours for each zone are different depending on a direction. In case of the southern east type, since the heating device operating hours are longer compared to the southern west type, it is judged that the main apartment building must be arranged toward the southern west in order to save energy and costs.

1) It was found that the heating device operating hours for a living room in the model arranged toward the southern west were 348*h out of* 8,760*h* in total from November to early April. As the results of an analysis of the southern east arranged model, it was found that the operating hours were 479*h* from November to the middle of April. Thus, it was analyzed that the southern west-arranged model is beneficial for saving some heating energy by around 27% compared to the southern east one.

2) In case of the main bedrooms arranged toward the southern west and the southern east, the yearly average heating hours were 253*h and* 265*h* respectively. So, it was found that the yearly average heating hours for the southern east one is higher by around 4.7% compared to those for the southern west one.

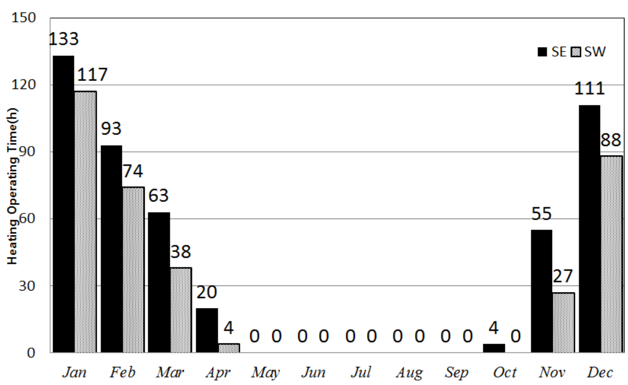

Fig.9 Annual Total Heating Hour of Livingroom

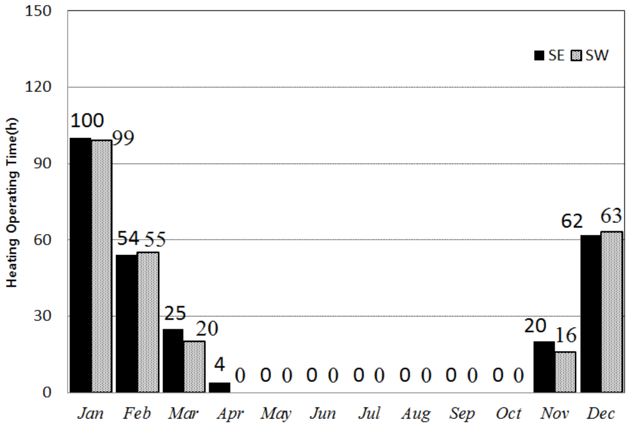

Fig. 10 Annual Total Heating Hour of Main Bedroom

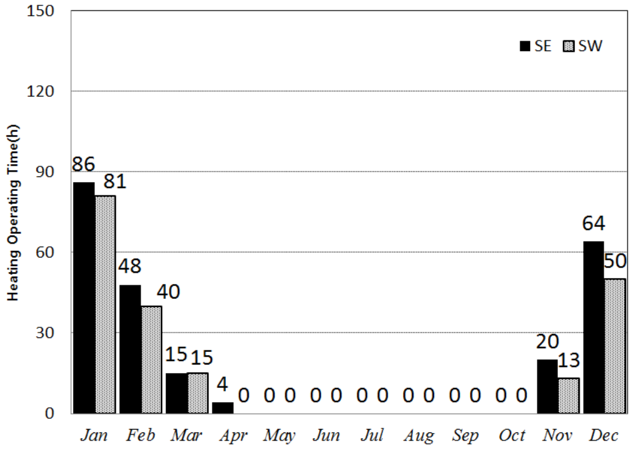

Fig. 11 Annual Total Heating Hour of Bedroom#1

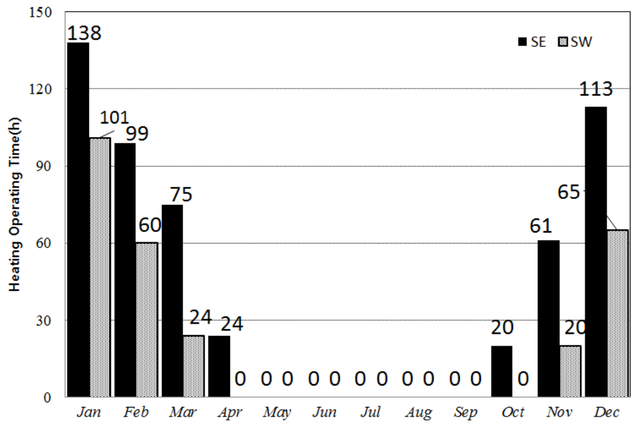

Fig. 12 Annual Total Heating Hour of Bedroom#2

3) In case of the bedroom 1, it was found that the yearly average heating hours for the southern west type and the southern east type was 199*h*/237*h*. In case of the bedroom 2, those of each type was 270*h*/530*h*. Thus, there is a deviation between both. The reason is because the location of the bedroom is directed toward the north as shown in Fig. 2, 'Floor Plan' and not much solar irradiation is shone. In addition, the southern west directed one receives much solar irradiation and radiation energy in the morning, but the southern east one receives much solar irradiation relatively in the afternoon, so the radiation energy is small relatively in the morning. So, it can be analyzed that such results were generated. Since the energy consumption volumes are different depending on the direction of each building, it is necessary to design optimally in order to save some energy while those facts are considered during the construction planning and designing stages.

4.3. Evaluation of the Required and Demanded Quantities of Building Energy

Fig. 13 shows the yearly average demanded quantity of energy that is calculated for the multi-zone unit of a 74m^2 Type apartment house. Taking a look at the results of the models having the southern west and east directed living rooms, it was found that the required quantity of energy for the southern west directed one is lower than that for the southern east one. The yearly required quantity of energy for the southern west one 756*kWh* , *that is,* 10.2kWh/m^2. In case that it was converted as the primary energy (electricity) per unit area(㎡), the required quantity of the primary energy was 28.1kWh/m^2. On the other hand, the yearly average required quantity of energy for the southern east directed unit house was 1,037*kWh*, that is, 14.0kWh/m^2. In case that it was converted as the primary energy (electricity), the required quantity of the primary energy was 38.5kWh/m^2. So, it was analyzed that it was higher by around 27% compared to that for the southern west type. As the results form the analysis, it was found that the energy consumption and heating load for each unit house can be saved depending on the planning and arrangements of apartment houses. Currently, the regulations on the heat isolation performances of the public buildings and commercial buildings, etc., as well as apartment buildings are being strengthened and the arrangement of the main building of the residential building complex is suggested with the recommended criteria. [10] Thus, if the regulations on the arrangement of the main building are strengthened, it can play a role for saving building energy.

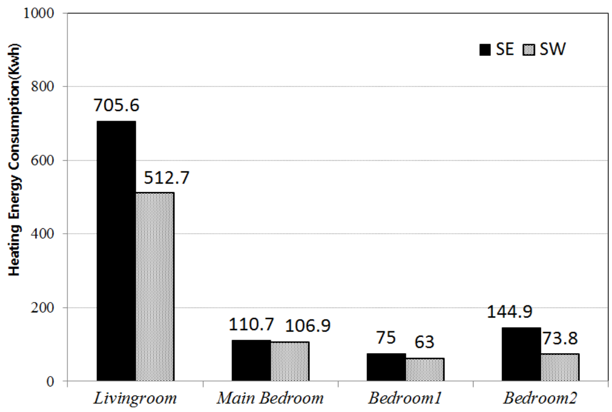

Fig. 13 Predicted Annual Heating Energy Demands(kWh)

4.4. Possibility of Energy Saving Depending on Mechanical Loads

The capacity of a heating boiler adopted for the domestic apartment houses is generally 18.6*kW*(16,000*kcal*). In this study, the mechanical performance of boilers which are generally used were reflected. In order to analyze the mechanical load of a 74m^2 Type of unit house, the same capacity of boiler was adopted. As the results from the analysis, it was calculated that the energy consumption was 10.2*kW* in case that the main building is arranged toward the southern west and 14.0*kW* in case of toward the southern east. As the results from an analysis of mechanical loads, there was some difference between the energy consumptions for the main building toward the southern west and the southern east. In case of the southern west oriented house receiving much solar radiation energy relatively, the load rate becomes lower for the boiler capacity, it is possible to reflect some allowance rate onto the calculation of a mechanical load. Accordingly, it can be expected that the mechanical capacity and the design adoption cost of a heating equipment, etc., can be reduced and the utilization level of an air-conditioning plant room can be enhanced thanks to the minimization of the area for installing a device.

5. Conclusion

In this study, in order to analyze the transient conjugate heat transfer phenomenon with some solar irradiation through wall bodies and windows when the 74m^2Type unit houses that are supplied a lot and are universally used among the apartment houses are arranged toward the southern west and the southern east, a dynamic energy analysis model was created by adopting the Crank-Nicolson FDM and ISO 13790 algorithm. Based on the model, the following analysis results were deduced.

(1) As the results from the analysis of the monthly average inflow solar irradiation and wall surface temperatures regarding to the southern-west and southern-east directed unit houses during November to March, in case of the southern −west arrangement of apartment houses, the monthly average inflow solar irradiation was 68W/m^2 in November , 54W/m^2 in December, 63W/m^2 in January, 84W/m^2 in February and 94W/m^2 in March. On the other hand, in case of the wall surface facing north, it was 33W/m^2in November, 25W/m^2in December, 30W/m^2in January, 46W/m^2in February and 69W/m^2 in March. These prove the results that general southern west oriented vertical surface receives the most solar irradiation and has the most sunshine duration. In addition, it was found that the monthly average surface temperatures were 10℃ in November, 3℃ in December, 0℃ in January, 3℃ in February and 8℃ in March. In case of the wall facing the north, it was 9℃ in November, 2℃ in December, -1℃ in January, 1℃ in February and 7℃ in March. In case of the southern east oriented unit houses, it was found that the monthly average inflow solar irradiation was 90W/m^2 in November, 79W/m^2 in December, 102W/m^2 in January, 124W/m^2 in February and 124W/m^2 in March. In addition, in case of the wall surface facing the north, it was found that it was 28W/m^2 in November, 23W/m^2 in December, 25W/m^2 in January, 35W/m^2 in February and 52W/m^2 in March. As far as the monthly average surface temperatures are concerned, in case of the south wall surface, it was 1 1℃ in November, 4℃ in December, 2℃ in January, 4℃ in February and 10℃ in March. In case of the north wall surface, it was 9℃ in November, 2℃ in December, -1℃ in January, 1℃ in February and 7℃ in March.

(2) In the model unit house facing the southern west, it was found that the heating device operating hours was 348h among 8,760h in total during the period from November to April. In the model facing the southern east, it was 479*h* during the same period. In case of the main bedroom, the yearly average heating device operating hours were 253*h and* 265*h respectively*. In case of the Bedroom #1 types, the yearly average heating device operating hours were 199*h and* 237*h* respectively for the southern west and east types. In case of the bedroom # 2types, it was 270*h and* 530*h respectively for the both types of unit houses*. As the results from the analysis, it was found that the heating device operating hours for each zone was different due to the effect of solar irradiation depending on each direction. Accordingly, it is judged that it is beneficial to build an apartment building to face the southern west rather than the southern east in order to save some energy and to reduce the costs.

(3) As the results from an analysis of the yearly required and demanded quantities of energy, in case of the unit houses facing the southern west, the yearly average required quantity of energy was low. The yearly average required quantity of energy for the unit houses facing the southern west was 756*kWh*, and if it is converted into the unit area, it was 10.2*kWh*/m^2, the demanded quantity of primary energy was 28.1kWh/m^2. On the other hand, the yearly average required quantity of energy for the unit houses facing the southern east was 1,037*kWh*, that is, 14.0*kWh*/m^2. And it was found that the demanded quantity of primary energy for such type of houses was 38.5kWh/m^2 which was higher than that for the southern west types by around 27%.

Acknowledgements

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