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Verification of Thermal Load Simulation Program against ASHRAE Standard 140

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ABSTRACT

Modern design practice of buildings is to evaluate the energy performance and sustainability, often using simulation methods. Certified environmental performance evaluation methods such as LEED, a green building certification program in the US, are commonly used as reference. This paper provides an outline of “HVAC Simulation Program for Office Spaces”, a simulation program developed by Kajima Technical Research Institute (KaTRI) as well as test results demonstrating the accuracy of its predictions of thermal loads based on ASHRAE Standard 140. Most of the test cases given in Standard 140 have been calculated using the program and the accuracy was shown to meet requirements.

Contents

Ⅰ. Introduction

In evaluating the energy performance and sustainability of buildings, recent practice by designers and those using authorized environmental performance evaluation methods such as LEED, a green building certification program in the US, is to make use of simulation results. A simulation program used for this purpose must be objectively evaluated. A procedure for testing building energy simulation programs has been published and is being used worldwide: ASHRAE Standard 140 “*Standard Method of Test for the Evaluation of Building Energy Analysis Computer Program”* (ANSI/ASHRAE 2011 and Judkoff and Neymark 2013). This paper presents test results obtained using our simulation program “HVAC Simulation Program for Office Spaces” based on this standard.

Ⅱ. HVAC Simulation Program for Office Spaces

1. General Description

“HVAC Simulation Program for Office Spaces” is the program developed by Kajima Technical Research Institute (KaTRI) to evaluate both cooling/heating loads and the indoor thermal environment in office spaces. Here, the indoor thermal environment includes not only indoor air temperature and humidity but also vertical temperature distribution and the radiative thermal environment. This program is a very effective tool for rationally determining the specifications for various architectural elements such as windows as well as heating, ventilating and air-conditioning (HVAC) equipment.

The program incorporates a macroscopic model for predicting vertical temperature distribution. The unique characteristics of this model are that it can predict vertical temperature distribution while calculating thermal loads over the long term, such as for annual evaluations. This vertical temperature distribution model was described and verified by Togari et al. (1993), Arai et al. (1994) and Takemasa et al. (1996). The software also includes “window models” that evaluate the thermal performance of windows. These window models can predict the temperature of each window element, so can evaluate not only cooling/heating loads but also the radiative thermal environment near the window. These characteristics strongly contribute to the rational design of window and facade systems considering the thermal load aspect as well as the indoor thermal environment for occupants near the

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1) Architectural Design Division

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windows.

The following sections provide a summarized outline of the software.

2. Outline of Models Incorporated in the Program

As noted above, the HVAC Simulation Program for Office Spaces incorporates a simplified model for predicting vertical temperature distribution and window models.

(1) Macroscopic model for predicting vertical temperature distribution

It is well known that, in an interior space, the vertical temperature distribution is liable to be large compared with the horizontal distribution, which tends to be uniform. Togari et al. (1993) proposed a macroscopic model for predicting vertical temperature distribution by dividing a space vertically into zones (see Fig.1).

The model consists of three parts. The first is the "wall current surface model" for evaluating the descending (or ascending) air current that flows along vertical surfaces (shown as ① in Fig.1). The second is the "primary airstream evaluation model," which handles the airstreams discharged from outlets as non-isothermal free jets to evaluate their influence on vertical temperature distribution (② in Fig.1). The last is the "heat transfer factor C_B" for evaluating the heat transfer caused by the temperature difference between vertically adjacent zones (③ in Fig. 1). In terms of the heat flows on the wall surface, heat radiation and convection are treated separately in this program. Heat flows due to the thermal storage and heat conduction of a wall are assessed using a one-dimensional unsteady-state heat conduction calculation based on the forward finite difference method. Convective heat transfer with the adjacent zone is calculated using convective heat transfer coefficients. An airflow balance equation and a heat balance equation in each zone are solved to predict the air temperature in each zone. Similarly, a vapor balance equation in each zone is solved to predict the humidity in each zone. The ability of this model to accurately predict vertical temperature distributions was verified by comparing its predictions with experiments in a climate test chamber (Togari et al. 1993 and Arai et al. 1994) and with a 3-story atrium with a skylight (Takemasa et al. 1996). It was confirmed that the model can simulate the measured results well under both heating and cooling conditions. This model is particularly useful for the design of large spaces, where vertical temperature distributions tend to be large.

(2) Window models

The recent trend in building design is to focus on appearance as well as on ensuring good views and a good light environment. The result is that window areas have tended to increase. Windows are a fundamental weak point in thermal terms, and thorough consideration of their design is required in order to achieve a proper balance between energy conservation and a good indoor thermal environment. Good thermal performance is needed for office windows in particular and efforts to properly evaluate the thermal performance of windows are necessary to achieve this.

The authors propose streamlined models (called "window models") capable of evaluating the thermal performance of a window in terms of both thermal loads and the thermal environment near the window. The thermal environment is determined by considering the basic airflows around various window systems (Takemasa et al. 2013). The proposed models were constructed so that they could easily be incorporated into the above macroscopic model for predicting vertical temperature distribution in a cooled/heated space. A number of window models were constructed: for single glazing + blinds, low-e double-glazing + blinds, airflow windows (AFW), double-skin facades, etc.

The modelling of these window models was based on the following basic principles.

1. Nodes are placed at elements on the window (including some locations for air temperature) and the heat balance equation at each node is solved to calculate the temperature at each element. During this process, radiation and convection are treated separately.
2. The model must be capable of evaluating both the thermal load on the window surface and the thermal environment near the window.
3. The model should couple with a vertical temperature distribution prediction model for the room interior (Togari et al. 1993).
4. The model must also be capable of evaluating an exhaust system above or below the window.
5. The model must be applicable to a variety of window systems.

Fig.2 shows schematics of the window models for single glazed + blinds, low-e double-glazed + blinds, AFW, and

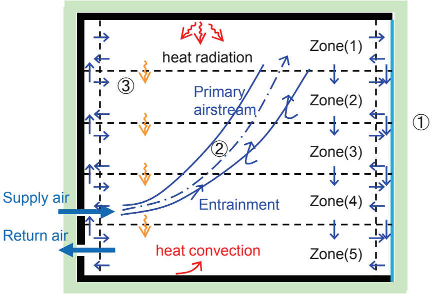
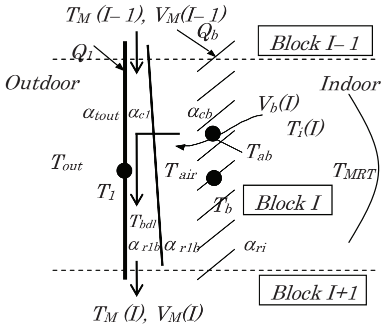
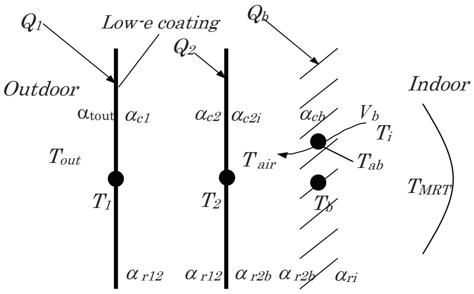


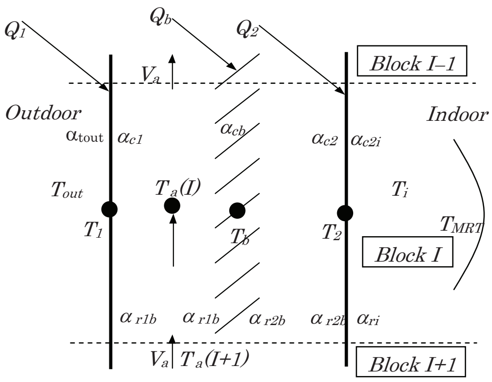
Fig.1　Schematic of the Model for Predicting Vertical Temperature Distribution



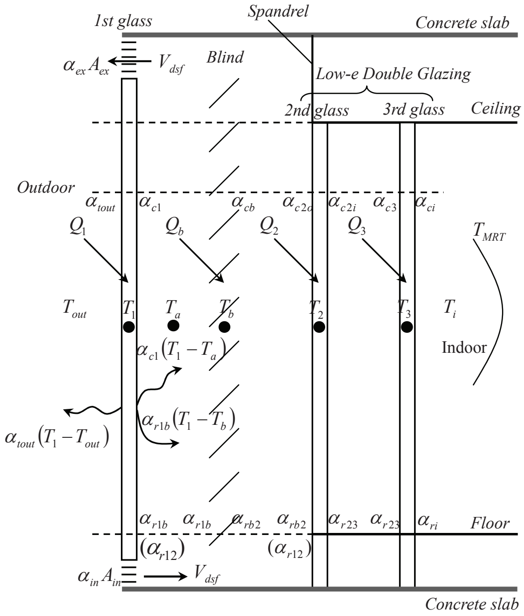
(1) Single Glazed + Blinds



(2) Double Glazed + Blinds



(3) Airflow Window



(4) Double-Skin Facade

Fig.2 Schematics of Windows Models

double-skin facades. The detailed modelling of these window systems is explained in a previous paper (Takemasa et al. 2013). Evaluation of the indoor thermal environment near the window includes the radiative thermal environment such as mean radiant temperature (MRT) and operative temperature (OT). The thermal environment near the window is affected by outdoor conditions, such as intense sunlight and cold drafts, which respectively create hot zones and cold zones or cold drafts.

The accuracy of the window models was verified by comparing calculated results with test and measured results (Takemasa et al. 2013). It was confirmed that the window models can reproduce the measured results well for various window systems.

(3) Calculation examples and other applications

Fig.3 to 5 show examples of calculation results for

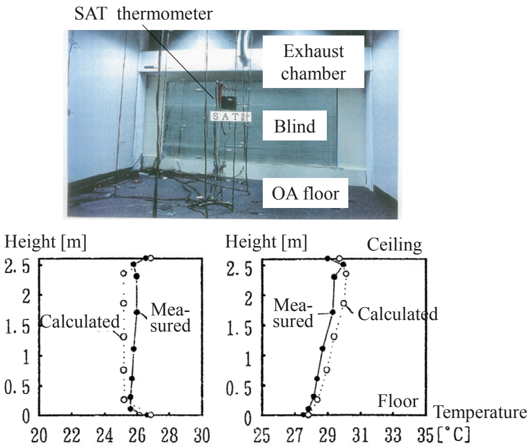


Fig.3 Examples of Vertical Temperature Distribution Prediction

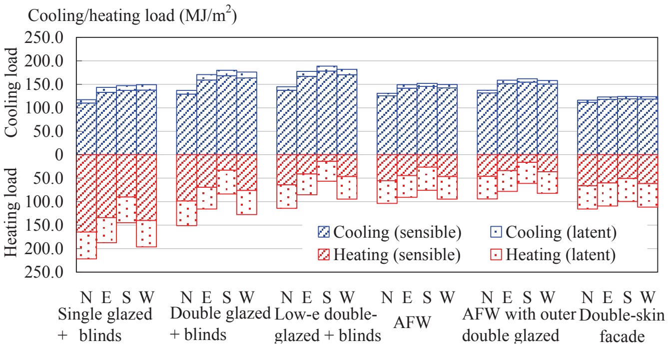


Fig.4 Examples of Cooling/Heating Load Calculation

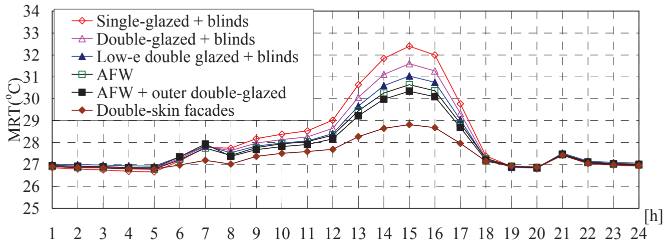


Fig.5 Examples of MRT Evaluation on South in Summer at 1m from the Window and 1.1m above the Floor

changes in vertical temperature distribution, monthly-accumulated cooling/heating loads, and the MRT near the window.

Other than the evaluation of vertical temperature distribution and thermal performance of windows, natural ventilation can be handled by combining the macroscopic model for predicting vertical temperature distribution with an airflow network model for evaluating the air change rates for natural ventilation (Takemasa et al. 2004). The airflow rates by natural ventilation are calculated with the ventilation circuit network driven by the pressure difference and temperature difference between adjacent zones and by wind pressure at outer openings　(Miura et al. 2012).

The macroscopic model can be also integrated with computational fluid dynamics (CFD) to evaluate airflow and temperature distributions in detail where necessary, at the same time handling the vertical temperature distribution, radiative heat transfer, wall heat conduction and HVAC controls and evaluating unsteady-state phenomena. A few examples of these are the evaluation of a ceiling chamber HVAC system using a hybrid model combining a macroscopic model with CFD (Takemasa et al., 2007), and detailed evaluation of the thermal environment and cooling loads for task and ambient air-conditioning systems using unsteady-state simulation that combines a macroscopic model with CFD (Katoh et al., 2008).

Ⅲ. Benchmark Test of ASHRAE Standard 140

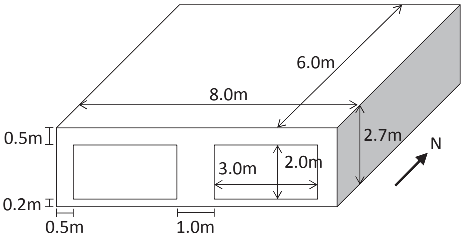
1. ASHRAE Standard 140

The National Renewable Energy Laboratory (NREL), in collaboration with the International Energy Agency (IEA), has developed a number of suites of building energy simulation tests (BESTESTs) for evaluating and diagnosing errors in software used for the energy analysis of commercial and residential buildings (Judkoff and Neymark 2013). ASHRAE Standard 140 adopts five BESTEST suites for testing a variety of building thermal fabric and mechanical HVAC system modeling features.

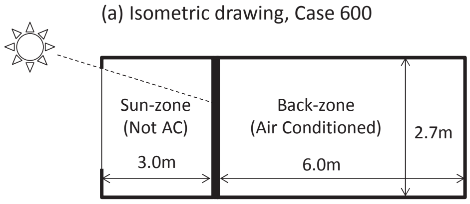
The building thermal fabric test cases verify the ability to model the thermal physics related to many typical building features. A series of buildings are specified that proceed from the thermally simple to the realistic approximately one parameter at a time. Table 1 and Fig.6 (a) show the basic building specification, which remains similar for all cases with minimal changes. There are 39 test cases

Table 1　Building Specification, Case 600

Weather Data	TMY, Denver (US)
Building Specification	Floor Area 48m^2, Ceiling Height 2.7m
Window	Clear, 2 Panes, 12m^2, South, U-Value 3.0W/m^{2}K, SHGC 0.789
Exterior Wall U-Value	Exterior Wall 0.56W/m^{2}K, Roof 0.33W/m^{2}K
Infiltration	0.5 ach
Internal Heat	200W (only sensible, radiative : convective = 6 : 4)
Air Conditioning	Heat = ON if temperature < 20°C; otherwise, Heat = OFF. Cool = ON if temperature > 27°C; otherwise, Cool = OFF.



(a) Isometric drawing, Case 600



(b) Section, Case 960

Fig.6　Buildings of Test Cases

Table 2　Test Cases List

Case No.	Setpoints H, C, V (°C)	Mass	Intgen (W)	Infil (can)	Opaque Surface				Glass (m^2)	Orient	Shade
					Int IR Emit	Ext IR Emit	Int SW Absorpt	Ext SW Absorpt			
195	20, 20	L	0	0	0.1	0.1	–	0.1	0	S	no
200	20, 20	L	0	0	0.1	0.1	–	0.1	0	S	no
210	20, 20	L	0	0	0.1	0.9	–	0.1	0	S	no
215	20, 20	L	0	0	0.9	0.1	–	0.1	0	S	no
220	20, 20	L	0	0	0.9	0.9	–	0.1	0	S	no
230	20, 20	L	0	1	0.9	0.9	–	0.1	0	S	no
240	20, 20	L	200	0	0.9	0.9	–	0.1	0	S	no
250	20, 20	L	0	0	0.9	0.9	–	0.9	0	S	no
270	20, 20	L	0	0	0.9	0.9	0.9	0.1	12	S	no
280	20, 20	L	0	0	0.9	0.9	0.1	0.1	12	S	no
290	20, 20	L	0	0	0.9	0.9	0.9	0.1	12	S	1.0 mH
300	20, 20	L	0	0	0.9	0.9	0.9	0.1	6, 6	E, W	no
310	20, 20	L	0	0	0.9	0.9	0.9	0.1	6, 6	E, W	1.0 mHV
320	20, 27	L	0	0	0.9	0.9	0.9	0.1	12	S	no
395	20,27	L	0	0	0.9	0.9	–	0.1	0	S	no
400	20,27	L	0	0	0.9	0.9	–	0.1	0	S	no
410	20,27	L	0	0.5	0.9	0.9	–	0.1	0	S	no
420	20,27	L	200	0.5	0.9	0.9	–	0.1	0	S	no
430	20,27	L	200	0.5	0.9	0.9	–	0.6	0	S	no
440	20,27	L	200	0.5	0.9	0.9	0.1	0.6	12	S	no
600	20,27	L	200	0.5	0.9	0.9	0.6	0.6	12	S	no
610	20,27	L	200	0.5	0.9	0.9	0.6	0.6	12	S	1.0 mH
620	20,27	L	200	0.5	0.9	0.9	0.6	0.6	6, 6	E, W	no
630	20,27	L	200	0.5	0.9	0.9	0.6	0.6	6, 6	E, W	1.0 mHV
640	SETBACK	L	200	0.5	0.9	0.9	0.6	0.6	12	S	no
650	27, V	L	200	0.5	0.9	0.9	0.6	0.6	12	S	no
800	20,27	H	200	0.5	0.9	0.9	NA	0.6	0	S	no
810	20,27	H	200	0.5	0.9	0.9	0.1	0.6	12	S	no
900	20,27	H	200	0.5	0.9	0.9	0.6	0.6	12	S	no
910	20,27	H	200	0.5	0.9	0.9	0.6	0.6	12	S	1.0 mH
920	20,27	H	200	0.5	0.9	0.9	0.6	0.6	6, 6	E, W	no
930	20,27	H	200	0.5	0.9	0.9	0.6	0.6	6, 6	E, W	1.0 mHV
940	SETBACK	H	200	0.5	0.9	0.9	0.6	0.6	12	S	no
950	27, V	H	200	0.5	0.9	0.9	0.6	0.6	12	S	no
960	2 Zones	See Figure 6. 960 tests passive solar/interzonal heat transfer.									
600FF	NONE	These cases, labeled FF (interior temperatures free-float), are exactly the same as the corresponding non-FF cases except there are no mechanical heating or cooling systems.									
900FF	NONE										
650FF	NONE, V										
950FF	NONE, V										

organized into a basic series and an in-depth series. Table 2 provides a list of the test cases. The basic series (Cases 600 through 650 and 900 through 960) is relatively realistic and was defined to test such features as thermal mass, direct solar gain through windows, window shading, window orientation, internal gains, sunspaces, night ventilation, and dead-band and setback thermostat control. The in-depth series of cases (195 through 440, 800 and 810) are more primitive and are designed to provide excitation of a particular heat transfer mechanism or path while suppressing signals from other mechanisms or paths.

2. Test Results

Fig.7 through 16 show the test results. Example results are provided for the tested programs in Informative Annex B8 of Standard 140, and the results of our program were compared to these. Our program is expressed by “HVAC-Office (KaTRI)” in the figures. The compared programs are ESP-RV8 (ESP), BLAST-3.0 level 193 v.1 (BLAST), DOE-2.1D14 (DOE2), SERIRES/SUNCODE 5.7 (SRE/SUN), SERIRES 1.2 (SERIRES), S3PAS, TRNSYS 13.1 (TRNSYS) and TASE. Cases 270 through 320, 440 and 810 were not calculated because our program does not directly input interior solar absorptance. For the all cases except free floating cases (Cases 600FF, 650FF, 900FF and 950FF), annual and peak heating/cooling loads are verified. For the free floating cases, interior temperature is verified. In addition, for the representative cases, hourly values for cooling/heating loads, temperature and solar radiation are verified. The figures show that the results for our program are in the range between the minimum and maximum of the other programs although cooling loads for Cases 600 through 650 and 900 through 960 tend to be a little large and the shading coefficient for the overhang for the south is estimated to be a little large. This confirms that our HVAC Simulation Program for Office Spaces is able to accurately predict cooling/heating loads in office spaces.

Ⅳ. Conclusions

This paper provides an outline of our simulation program “HVAC Simulation Program for Office Spaces” and gives test results based on ASHRAE Standard 140. This program can evaluate both cooling/heating loads and the indoor thermal environment. It offers short computation times and is very effective for the rational determination of specifications for various architectural elements and HVAC equipment. The accuracy of the program in predicting cooling/heating loads was verified by calculating most of the test cases given in Standard 140; the results show that the program offers sufficient accuracy compared to other programs described in previous publications.

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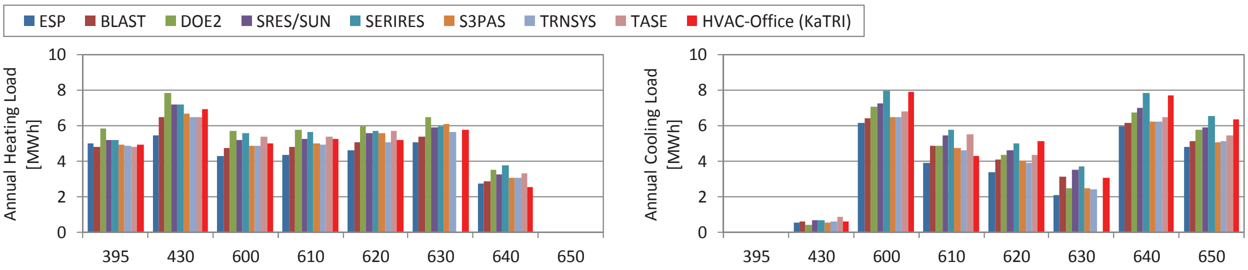
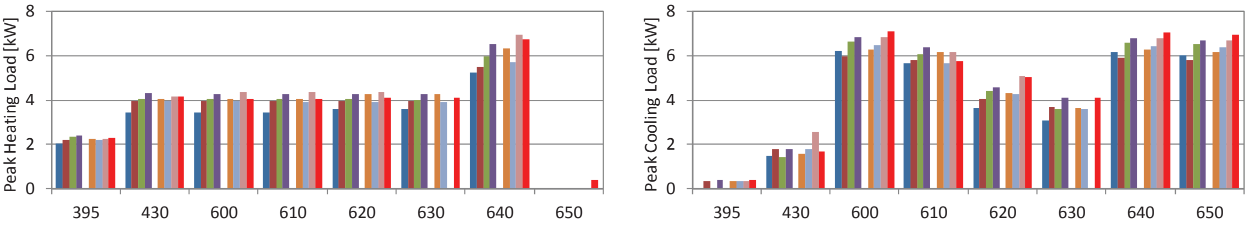
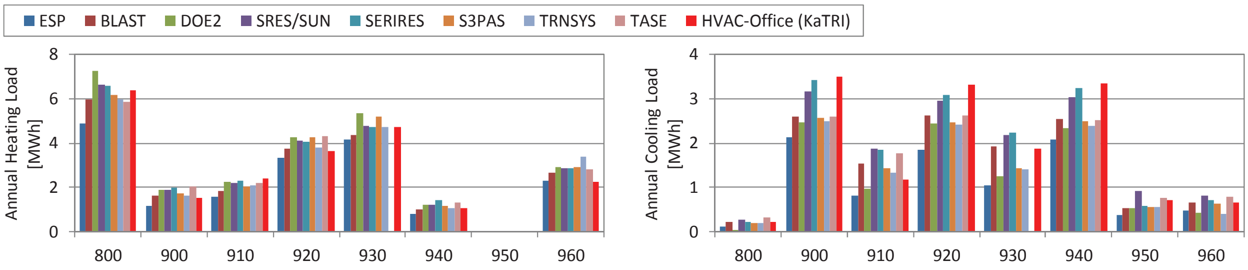


(a) Annual Heating Load　(b) Annual Cooling Load

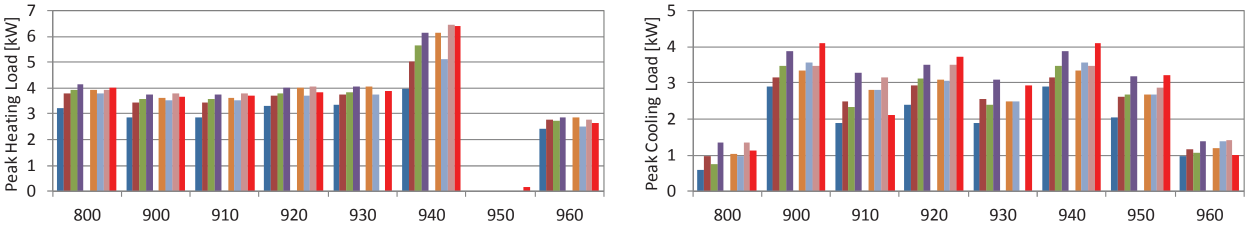


(c) Peak Heating Load　(d) Peak Cooling Load

Fig.7　Annual and Peak Loads of Low Mass Basic Tests

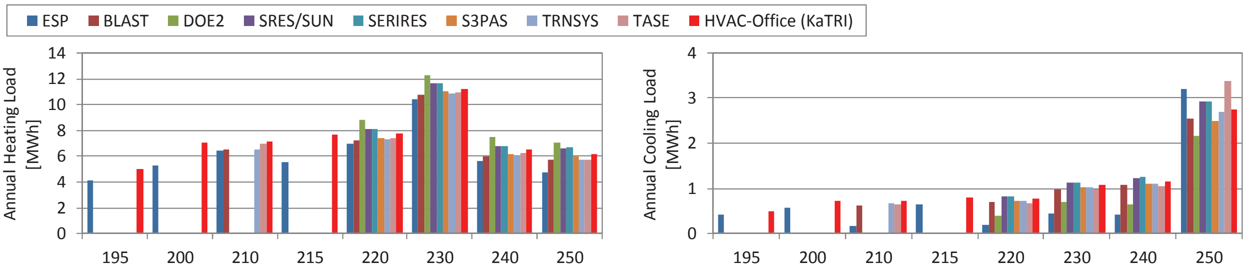


(a) Annual Heating Load　(b) Annual Cooling Load

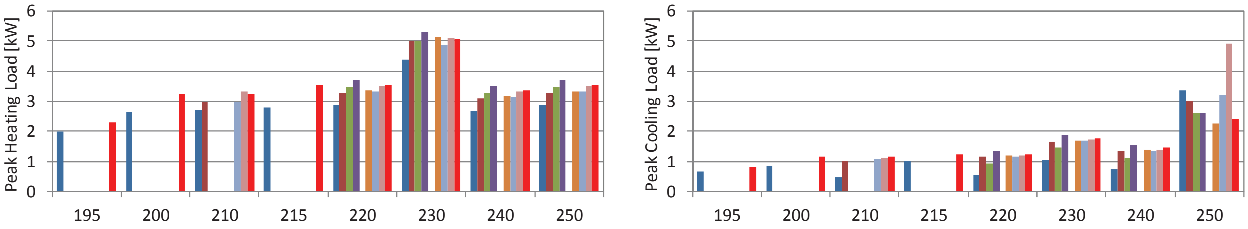


(c) Peak Heating Load　(d) Peak Cooling Load

Fig.8　Annual and Peak Loads of High Mass Basic Tests

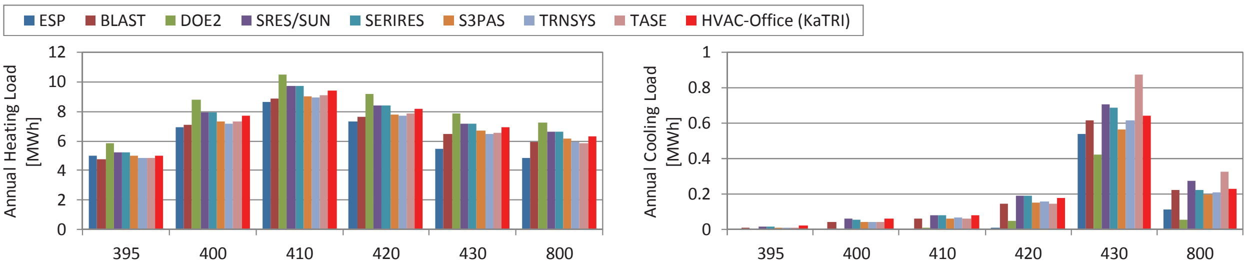


(a) Annual Heating Load　(b) Annual Cooling Load



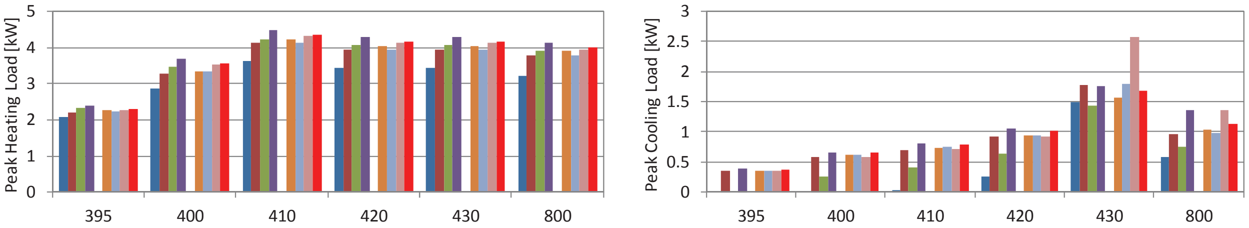
(c) Peak Heating Load　(d) Peak Cooling Load

Fig.9　Annual and Peak Loads of In-Depth Tests (Case 195 through 250)



(a) Annual Heating Load

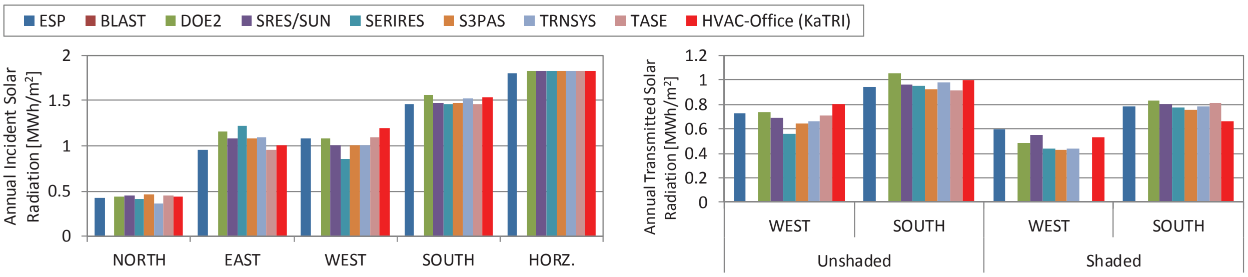
(b) Annual Cooling Load



(c) Peak Heating Load

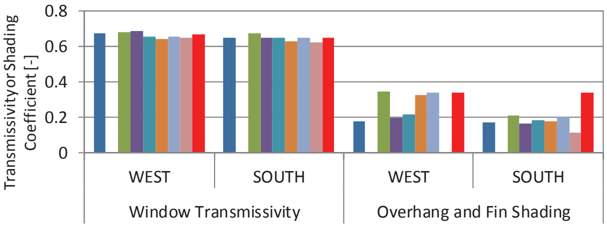
(d) Peak Cooling Load

Fig.10 Annual and Peak Loads of In-Depth Tests (Case 395 through 440, 800 and 810)



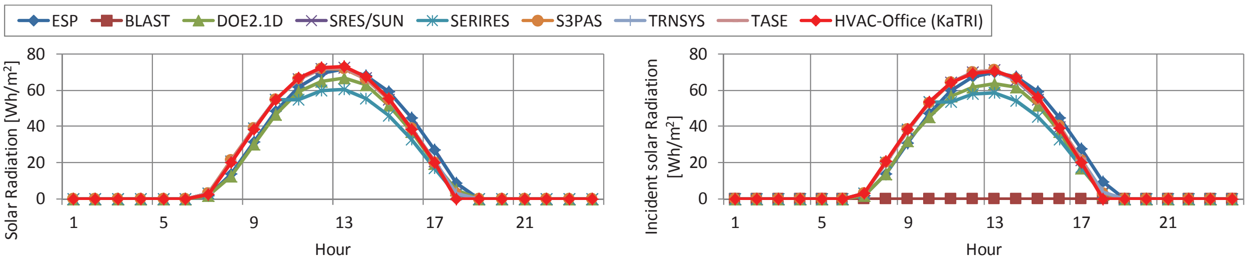
(a) Annual Incident Solar Radiation

(b) Annual Transmitted Solar Radiation



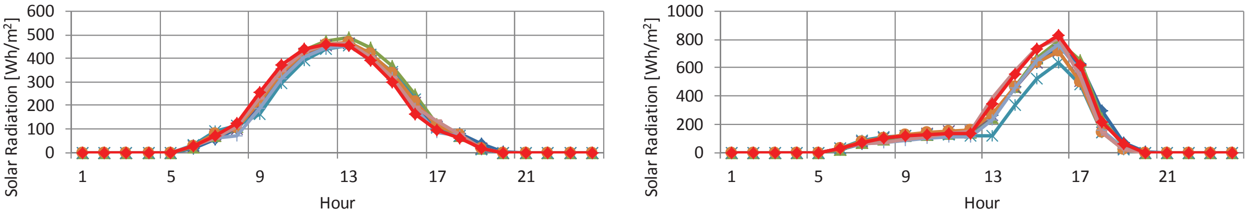
(c) Annual Transmissivity and Shading Coefficient

Fig.11 Annual Solar Radiation of Basic Tests (Cases 600 through 630)



(a) Cloudy Day Hourly Incident Solar South Facing Surface

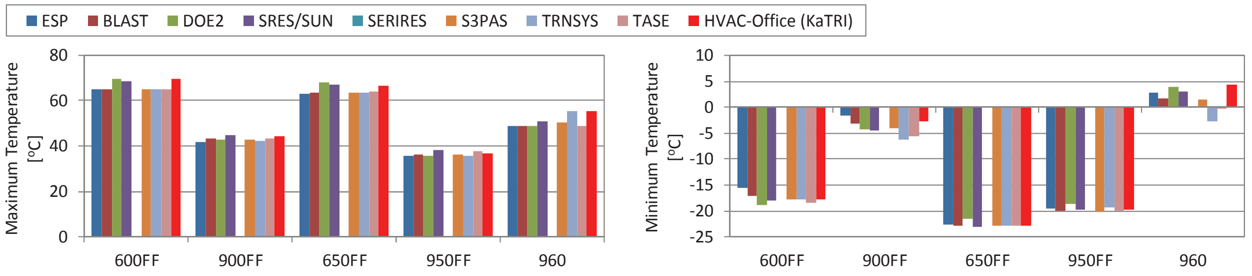
(b) Cloudy Day Hourly Incident Solar West Facing Surface



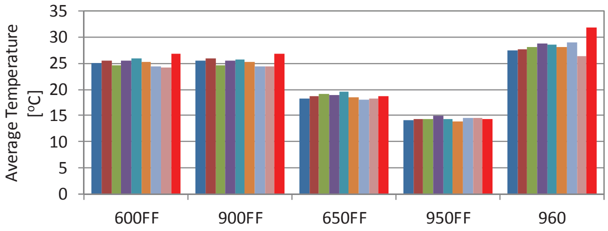
(c) Clear Day Hourly Incident Solar South Facing Surface

(d) Clear Day Hourly Incident Solar West Facing Surface

Fig.12 Hourly Solar Radiation of Basic Tests (Case 600 and 620)

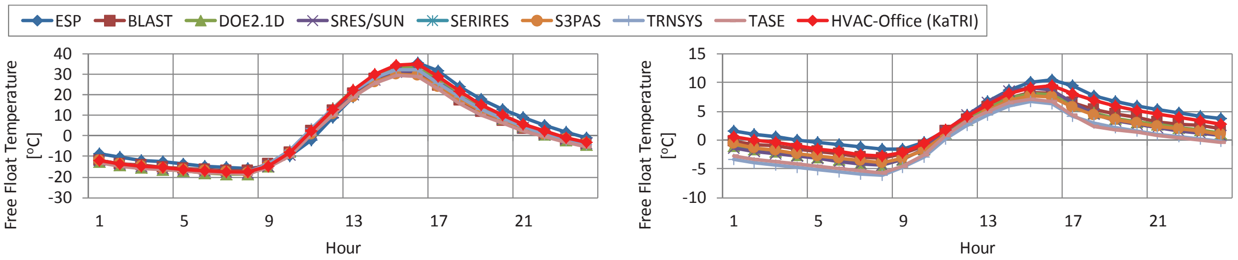


(a) Maximum Hourly Annual Temperature　　(b) Minimum Hourly Annual Temperature

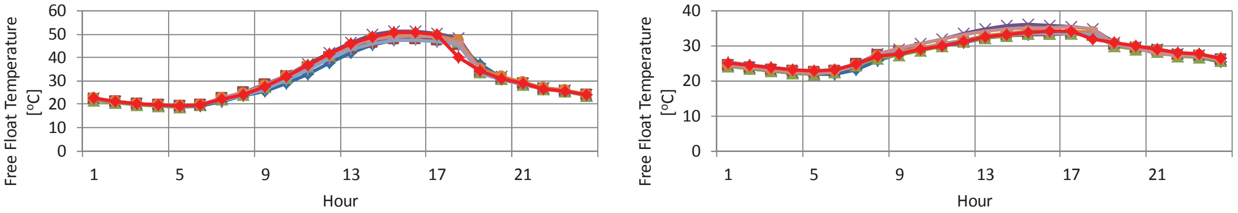


(c) Average Hourly Annual Temperature

Fig.13　Annual Interior Temperature of Free Float Tests

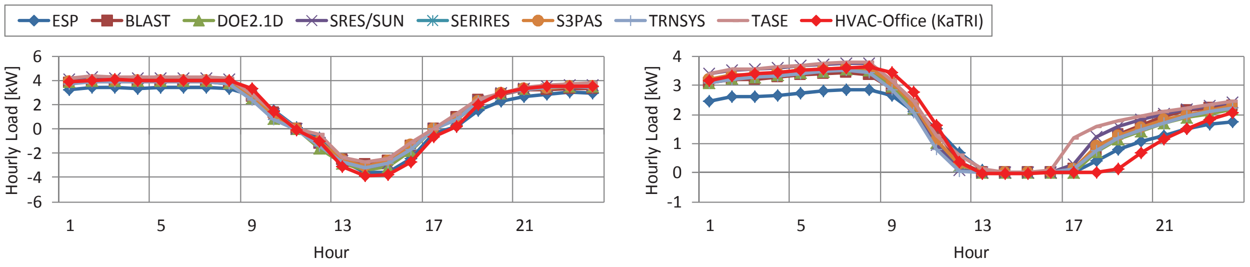


(a) Hourly Free Float Temperature, Clear Cold Day, Case 600FF　　(b) Hourly Free Float Temperature, Clear Cold Day, Case 900FF



(c) Hourly Free Float Temperature, Clear Hot Day, Case 650FF　　(d) Hourly Free Float Temperature, Clear Hot Day, Case 950FF

Fig.14　Hourly Interior Temperature of Free Float Tests



(a) Hourly Load, Clear Cold Day, Case 600 : Heating (+), Cooling (-)　　(b) Hourly Load, Clear Cold Day, Case 900 : Heating (+), Cooling (-)

Fig.15　Hourly Heating/Cooling Load of Basic Tests

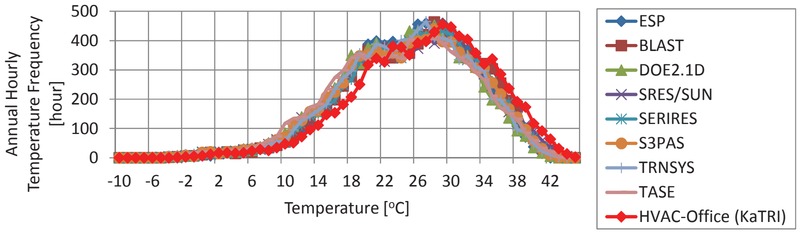


Fig.16　Annual Hourly Temperature Frequency of Case 900FF