Prediction of Energy Efficiency and Thermal Environment of Residential Buildings Utilizing PEFC-CGS Combined Floor Heating System

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ABSTRACT

The systematic numerical simulation program is developed to calculate the total energy efficiency of housing polymer electrolyte fuel cell co-generation system (PEFC-CGS) which is combined with hot water floor heating (HWFH). This simulation program can also predict actual building physics of heat transfer such as mutual radiant heat among interior surfaces and thermal strage relating with piping pitch of hot water and so on. The indoor temperature can be controlled by PMV (Predicted Mean Vote) to take account of thermal sensing affected radiant heat. As the results, it is clarified that the primary energy consumption is reduced up to 12% in winter because of the utilization of exhaust heat from PEFC-CGS and decreasing of indoor temperature for space heating by floor heating utility.

KEYWORDS

Residential building, Fuel cell, Co-generation system, Hot water floor heating, Thermal environment, Energy conservation

INTRODUCTION

The global warming is a big issue and has been challenged to address all over the world. In Japan, thermal insulation and airtight of residential buildings have been generalized for energy conservation and high efficiency instruments are now attracted a great deal of attention to conserve much energy. Above all, Housing Polymer Electrolyte Fuel Cell Co-generation system (PEFC-CGS) is expected as one of very promising energy saving appliances of distributed generation of electricity and heat for the next-genelation. However, its energy efficiency is not enough to determine because it is still under development for generalization. Thus, the numerical simulation program to demonstrate its performance is demanded.

Some of the research and technological development have been performed on the distributed generation system of electricity and heat such as PEFC-CGS. Ryu has investigated an availability of the distributed generation system by numerical simulation and clarified that the demand for electricity and heat influences its efficiency. The effect of energy conservation of this system is enhanced with increasing of thermal demand in the buildings (Ryu 2006). Then it is just conceivable that a combination of the distributed generation system and hot water floor heating (HWFH) improves energy conservation in winter. Tanaka has calculated an optimum facility capacity of its system incorporating a hot-water storage tank (Tanaka 2005). The total efficiency including building thermal performance is not clarified because the simulation program is simply developed with no consideration of building physics of heat transfer. Thus there is nothing of the program to predict the efficiency of PEFC-CGS based upon the dynamic simulation of the thermal environment and space conditioning load of buildings. A detailed thermal calculation of hot water floor heating and radiant heat from floor affecting thermal sensing should be also reflected in energy simulation.

In this paper, the energy efficiency of PEFC-CGS and the heating load of buildings are predicted and the primary energy consumption is calculated in detail. To consult much energy efficiency of PEFC-CGS with its optimal driving, a hot water floor heating utilizing exhaust heat from PEFC-CGS is combined as the radiation heating system. This paper outlined the numarical simulation program and the total enegy efficiency of PEFC-CGS and the heating load are predicted in proportion to the thermal performances of PEFC-CGS and buildings.

NUMERICAL SIMULATION

Figure 1 illustrates the distributed generation system of electricity and heat of PEFC-CGS combined with hot water floor heating. PEFC-CGS is composed of PEFC unit and hot water storage tank unit. PEFC unit generates electric power and the exhausted heat. Exhausted heat is stored into the hot

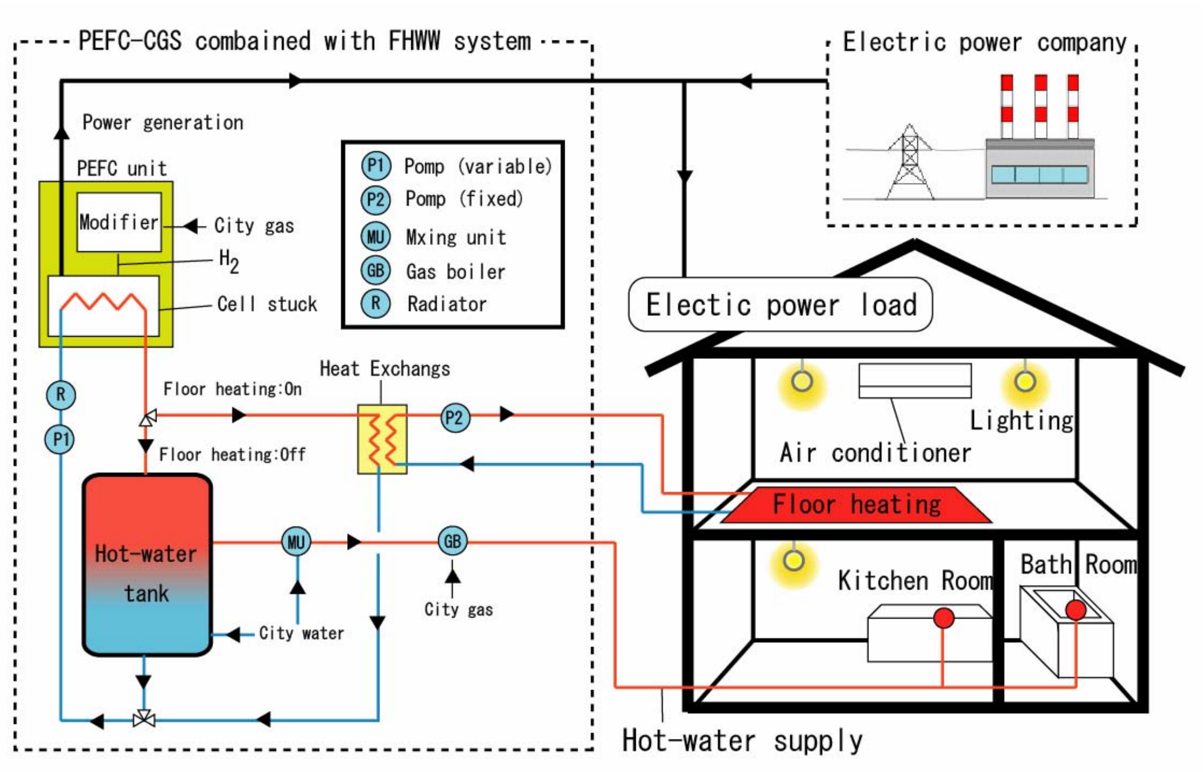


Figure 1 PEFC-CGS combined with the hot water floor heating

water storage tank through heat exchanger. The generated electricity by PEFC-CGS is used for home electric appliances. Then electricity from the electric power company is just supplied when the amount of generated electricity is insufficient.

The hot water is supplied from the hot water tank according as the demand in the buildings. To control a hot water temperature, it is adjusted in the mixing unit. In case that the temperature of hot water supply from storage tank is lower than the demanded temperature, a gas boiler with 80% efficiency is used as an auxiliary heater.

PEFC-CGS combined with the hot water floor heating is operated whole day in principle. The exhausted heat of PEFC-CGS is stored into the hot water storage tank in preference to the hot water floor heating. Thus the floor is just heated by excess heat while the hot water storage tank is filled completely at designated temperature. Hot water supply for floor heating is stopped and restarted in accordance with the temperature of the hot water storage tank. Circulating water is used for the hot water floor heating and is heated by heat exchange with circulating hot water passed through an exhaust heat recovery equipment of PEFC-CGS.

The numerical simulation program that reproduced this system has been developed. The algorism of the program is outlined as follows.

Table 1 Performances of PEFC-CGS in rated operating conditions

Power generation efficiency	31.5 [%]
Exhaust heat utilization efficiency	51.5 [%]
Power generation	1 [kW]
Exhausted heat	1.63 [kW]
Heat recovery water temparature	60 [degree C]
Hot water storage tank	200 [L]

PEFC-CGS

PEFC-CGS is modeled on the basis of the experimental results on the performance tests of its prototype in the Fukuoka research institute. Table 1 and Figures 2 to 4 shows the performances of PEFC-CGS. Equations (1) to (5) are the experimental formulas representing the performances of PEFC-CGS (Ayagaki 2007).

Figure 2 illustrates relations between the initial amounts of electricity and gas consumption and the time interval of stop and restart of PEFC-CGS. The longer the time interval is prolonged, the larger both of the electricity and gas are consumed in the early operation. Equations (1) and (2) are derived as regression formulas based on the Figure 2. E_p is the electricity consumption, G_p is the gas consumption and ST is the time interval.

$$\begin{cases} E_p = -0.6*10^{-7}*ST^2 + 0.1*10^{-3}*ST + 0.02 \quad (60\langle ST \le 900) & \dots(1) \\ G_v = 0.37*ST + 94.95 \quad (60\langle ST \le 900) & \cdots(2) \end{cases}$$

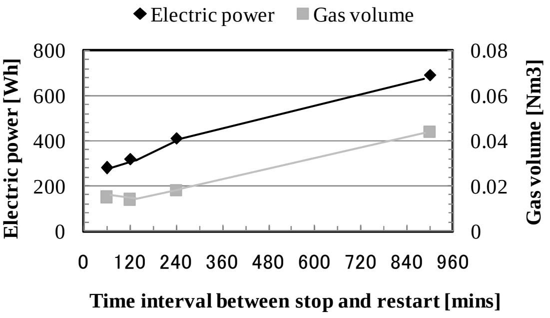


Figure 2 Initial amounts of electricity and gas consumption of PEFC-CGS

Figure 3 illustrates a relation between the time required for restart and the time interval of stop and restart of PEFC-CGS. The longer the time interval is prolonged beyond 240 minutes, the longer the time is necessary for restart. Equation (3) is derived as regression formulas based on the Figure 3. T_u is the time required for restart.

$$\begin{cases} t_u = -0.5*10^{-3}*ST^2 - 0.15*ST + 49.94 \quad (ST \le 208) \\ t_u = -0.4*10^{-2}*ST + 29.1 \quad (208\langle ST \le 909) & \cdots(3) \\ t_u = 0.2*10^{-3}*ST + 66.54 \quad (909\langle ST \le 5280) \end{cases}$$

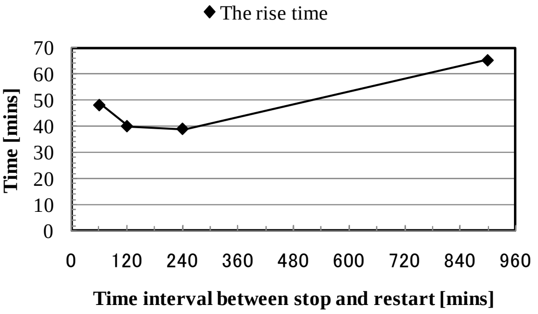


Figure 3 Time required for restart of PEFC-CGS

Figure 4 illustrates the part load efficiencies of power generation and exhaust heat utilization of PEFC-CGS. Even in the part load operation of 30%, the efficiencies of the power generation and exhaust heat utilization are 27% and 46%, respectively. Equations (4) and (5) are derived as regression formulas based on the Figure 4. GEP_r is the power generation efficiency and UEH_r is the exhaust heat utilization efficiency.

$$\begin{cases} GEP_r = -101.85*PL^4 + 295.57*PL^3 - \\ \qquad 324.96*PL^2 + 161.08*PL + 0.03 & \cdots(4) \\ UEH_r = -257.85*PL^4 + 692.08*PL^3 - \\ \qquad 680.4*PL^2 + 297.96*PL + 0.07 & \cdots(5) \end{cases}$$

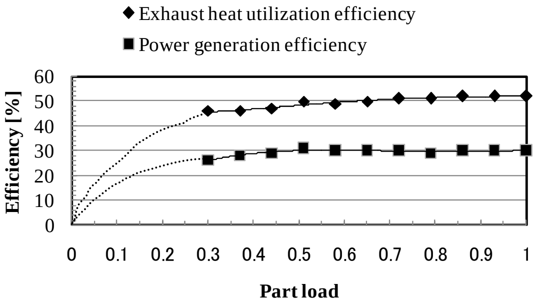


Figure 4 Part load efficiencies of power generation and exhaust heat utilization of PEFC-CGS

Energy simulation of buildings

The dynamic simulation software THERB incorporating with PEFC-CGS is used to estimate the thermal environment and space conditioning load in buildings. THERB can estimate temperature, humidity, sensible temperature, and heating/cooling load for multiple zone buildings and wall assemblies. The heat and moisture transfer models used in THERB such as conduction, convection, radiation and ventilation are based upon the detailed phenomena describing actual building physics, and can be applied to all forms of building design, structure or occupant schedules, etc (Ozaki 2005). All the phenomena are calculated without simplification of the heat and moisture transfer principles of any building component or element. The hot water floor heating is also incorporated by modeling a fin efficiency of hot water plumbing. Then, the indoor temperature can be controlled by predicted mean vote (PMV) to take account of actual thermal sensing (Fange P.O. 1972) , particularly an influence of radiant heat from floor.

Hot water storage tank and Heat exchanger

Numerical models of the thermal balance of the hot water storage tank and the heat exchanger are additionally developed and integrate with PEFC-CGS and the hot water floor heating. One-dimensional thermal stratification model is applied to the hot water storage tank considering a mixing heat loss with interlayer interaction by advection diffusion and conduction and a heat loss from the tank to exterior. The heat exchange is modeled by utilizeing the logarithmic mean temperature difference (Yokoyama 2005).

Input data

The standard weather condition of Fukuoka and the measured temperature of service water are used as the input data of the numerical simulation. The electric power loads excluding space conditioning and hot water supply load are estimated by the SCHEDULE ver.2.0 which is the software of the lifestyle formation of typical Japanese in each generation (SHASE 2000). Figure 5 shows the total electric power load used for home electric appliances and hot water supply load in a common Japanese family structured with four person including two children.

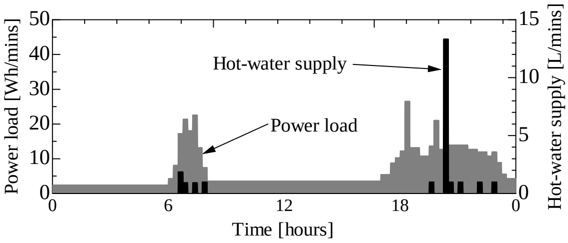


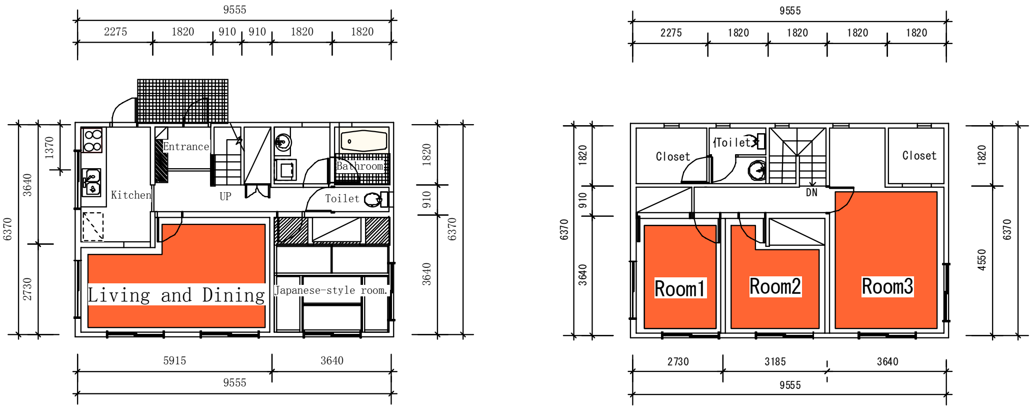
Figure 5 Electric power used for home electric appliances and hot-water supply

Calculation conditions

Table 2 shows the calculation conditions (Case 1 to 5). The differences of the calculation conditions are whether PEFC-CGS and the hot water floor heating (HWFH) are utilized. The heating load by the space-conditioning system is just calculated in Case 1 without both of PEFC-CGS and HWFH. The part-load operation and the full load operation (the rated operation) of PEFC-CGS is performed in Case 2 and 3. In addition to Case 2 and 3, HWFH is combined in Case 4 and 5. The part-load operation of PEFC-CGS responds following electricity demand as a rule. However, PEFC-CGS is stopped and restarted in accordance with the temperature of the hot water storage tank. It is stopped when the temperature of the hot water storage tank increases above 58 degrees Celsius and restarted when the temperature decreases below 50 degrees Celsius. The rated operation of PEFC-CGS is performed as the same conditions concerning the temperature of the hot water storage tank, while it trades the surplus electricity. In Case 4 and 5, PEFC-CGS is operated throughout the day. The exhausted heat of PEFC-CGS is stored into the hot water storage tank in preference to the hot water floor heating. The floor is heated by excess heat

Table 2 Calculation conditions

	PEFC-CGS	Operation statuses of PEFC-CGS	Floor heating
CASE1	None	None	None
CASE2	PEFC-CGS	Part load following electric requirements	None
CASE3		Rated	None
CASE4	PEFC-CGS combaine with HWFH	Part load following electric requirements	Operating
CASE5		Rated	Operating



(a) The first floor *(b) The second floor*

Figure 6 Building model

Table 3 Heating schedule and heating systems

Space	Conditioning schedule[hour]																								Conditioning
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	
Living and Dining							▨	▨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	▨	▨	▨	▨	▨	▨		above PMV -0.5
Room 1	▨	▨	▨	▨	▨	▨											🟦	🟦	▨	🟦	🟦	🟦	🟦	▨	Room air temperature 22 [degree C] (7:00-23:00) 18 [degree C] (23:00-7:00)
Room 2	▨	▨	▨	▨	▨	▨												🟦	🟦	▨	▨	▨	🟦	▨	
Room 3	▨	▨	▨	▨	▨	▨																🟦	🟦	▨	

▨ Space Conditioning
🟦 Floor Heating

Table 4 Corresponding value into primary energy

Primary energy	Electric Power	7:00-23：00	10.05[MJ/kWh]
		23:00-7:00	9.31[MJ/kWh]
	Gas		45.9[MJ/Nm^3]

while the temperature of the hot water storage tank is kept at designated temperature described above.

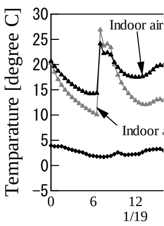


Figure 6 shows the building model. Table 3 shows the heating schedule and the heating system. The living and dining room and room 1 to room3 in Figure 6 are conditioned by PMV control (above minus 0.5). The space-conditioning system (COP=5.1) in each room is running while person is staying in the room. The hot water floor heating is operatied along the heating schedule in compatibility conditions as referred to above.

Table 4 shows corresponding value into primary energy of electricity.

RESULT AND ANALYSIS

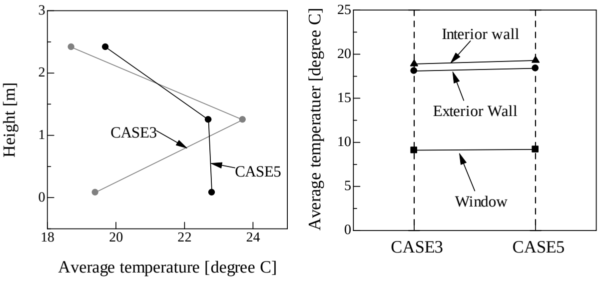
Thermal environment and heating load

Figure 7 shows the daily fluctuation of indoor air temperature and floor surface temperature. Figure 8 shows the vertical temperature distribution and the surface temperature in the living and dining room of Case 3 and Case5. The floor heating of living and dining is operated from 5:00 to 8:00 and from 12:00 to 21:00. Regardless of the heating system, the indoor thermal environment of living and dining room become comfortable while person is staying in there. However, there is big difference between indoor air temperature and floor surface temperature. The floor surface temparature in Case 5 is higher than Case 3 around 3 degrees Celsius. Wall and ceiling surface temparature in Case 5 also rises higher than Case 3 because of radiant heat from the heating floor. While, the indoor air temperature in Case 5 can be consequently decreased around 1.0 degree Celsius even if PMV is kept the same in Case 3 and Case 5. The differences of temperature and PMV between Case 3 and Case 5 become remarkable in the early morning.

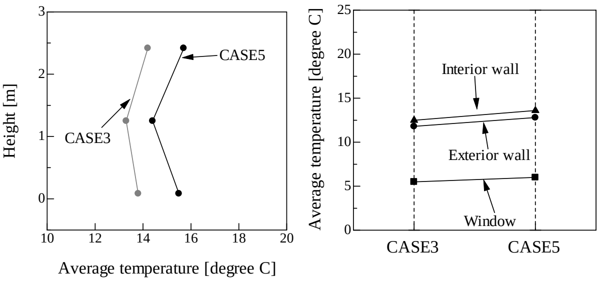
Figure 9 indicates the heating load of daily average in winter. The total heating load of PEFC-CGS combined with HWFH (Case 5) reduced around 8% less than the space-conditioning system (Case 1). Regarding the space-conditioning load, Case 4 and Case 5 are decreased 30% and 54% less than Case 1, respectively.

Operating situation and energy saving effect

Figure 10 illustrates operational status of PEFC-CGS and hot water supply, generating electricity, heating load and PMV in Case 2 to Case 5. Electric power load for conditioning of Case 4 and Case 5 utilizing the hot water floor heating is decreased less than Case 2 and Case 3. Although electricity is purchased in all cases, there is time zones that Case 3 and Case 5 of the rated operation of PEFC-CGS trade the surplus electricity.



(a) Mean temperature during 18:00 to 23:00



(b) Mean temperature during 23:00 to 7:00

Figure 8 Temperature distributions in the living and dining room

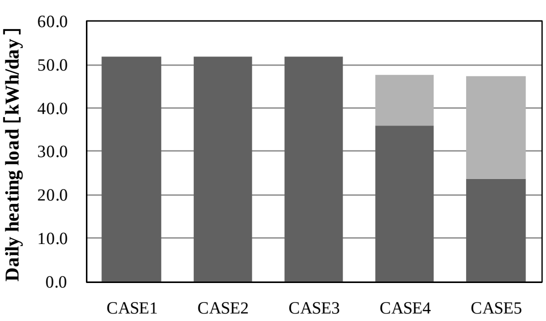


Figure 9 Average of daily heating load in winter

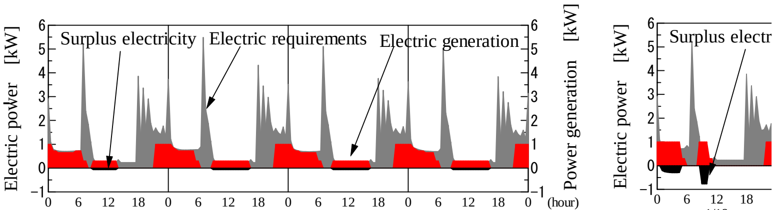


Table 5 explains the operating time, power generation efficiency, utilizable exhaust heat efficiency, energy availability and power contribution rate of PEFC-CGS. The energy availability and power contribution rate become larger by a combination with the hot water floor heating. Maximum values of them are 76.1% in Case 4 and 89.8% in Case 5, respectively.

Figure 11 illustrates the daily primary energy consumption in Case 1 to Case 5. Case 2 and Case 4 of the part-load operation of PEFC-CGS following electricity demand can decrease primary energy consumption less than Case 1 of the space-conditioning system without PEFC-CGS. Then, the energy consumption in Case 5 combined PEFC-CGS and the hot water floor heating becomes the lowest if PEFC gas is canceled surplus electricity out because electricity consumption for space conditioning is reduced and power contribution rate of PEFC-CGS is increased.

Table 5 Performance characteristic of PEFC-CGS

	Energy use efficiency of PEFC-CGS				
	Operating time	Power generation efficiency (1)	Exhaust heat utilization efficiency (2)	Energy availability ((1)+(2))	Power contribution rate
Unit	(hour/day)	(%)			
CASE1					
CASE2	14.2	24.6	38.5	63.1	42.4
CASE3	8.8	26.0	35.9	61.9	40.6
CASE4	24.0	27.8	48.2	76.1	76.3
CASE5	24.0	29.3	44.6	73.9	89.8

Power generation efficiency = (Total electric power load – purchased power + electric power selling※) / (Calorific value of gas consumed by PEFC)
Exhaust heat utilization efficiency = (Supplying heat load + Floor heating load – Calorific value of gas consumed by boiler) / (Calorific value of gas consumed by PEFC)
※Electric power selling was only considered when PEFC-CGS operation was rating.

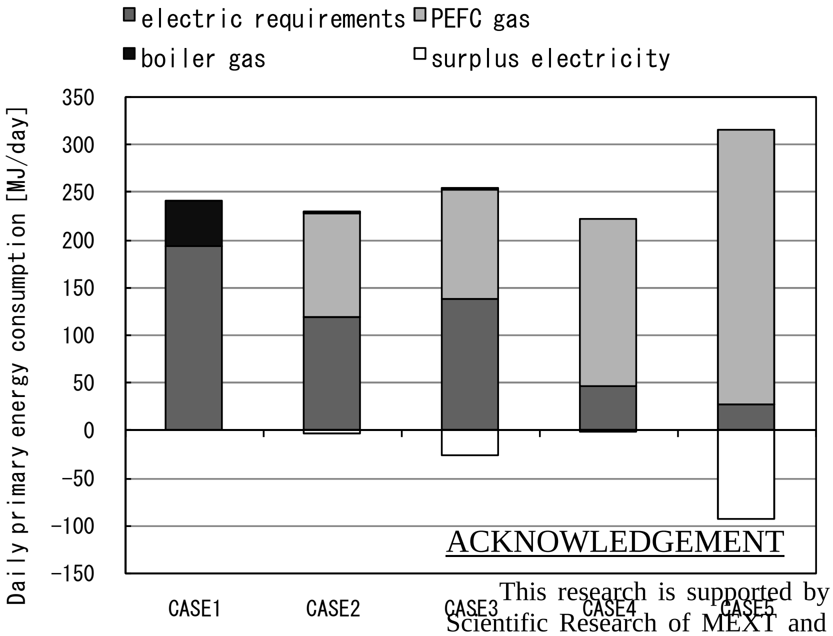


Figure 11 Daily primary energy consumption

CONCLUSION

In this paper, the total energy efficiency of housing polymer electrolyte fuel cell co-generation system (PEFC-CGS) which is combined with the hot water floor heating (HWFH) is systematically estimated by using the dynamic simulation software THERB based upon the detailed phenomena describing actual building physics. THERB can control thermal environment by predicted mean vote (PMV) to take account of thermal sensing. The total heating load of PEFC-CGS combined with HWFH reduced around 8% less than the space-conditioning system. Regarding the space-conditioning load, 54% is decreased because indoor temperature can be lowered in consideration of improvement of thermal comfort by radiant heat from the heating floor.

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