Simulation Study for the Advanced Solar Hot Water Heating Systems

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Abstract

The simulation is very important as a design tool for the solar thermal systems. Solar hot water system is expected to reduce the hot water heating load which shares more than 47% of primary energy in the residential buildings in Japan. In this study, the possibility of the advanced solar hot water heating system is examined by the simulation. A compact solar hot water heating systems with the small solar collector area and well insulated small heat storage tanks are considered. The solar heating system with smaller collector area is expected to be introduced for the building with small area of the roof or to share the installation area with PV array. The simulation result shows that the solar contribution was increased by improving the insulation of the heat storage tank. The solar contributions with the collector of 4 m^2 and the heat storage tank of 150 litters using the vacuum insulation in Sapporo, Morioka, Sendai, Tokyo and Kagoshima are 0.40, 0.41, 0.46, 0.52 and 0.61, respectively. It was found that the smaller but high performance solar DHW systems are possible with the vacuum insulation for the heat storage tank.

1. Introduction

More than 35% of the purchased energy consumption is used for domestic hot water (DHW) heating in the Japanese housing sector. Therefore, it is important to reduce the energy consumption used for the hot water heating. Reduction of the energy consumption by solar DHW heating system is expected in the housing sector. However, installation area and cost issues make difficult to introduce. In this study, the possibility was examined to reduce the solar collector area and the volume of heat storage tank by improving the insulation of the heat storage tank.

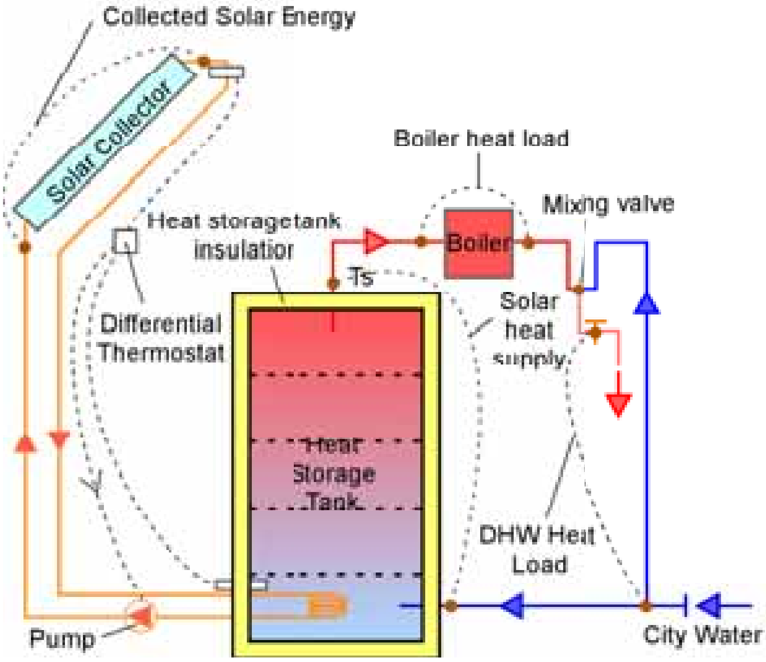


Fig.1. Solar DHW heating system.

2. Solar hot water system

Fig.1 shows the system diagram of the solar domestic hot water heating system model [5]. Solar hot water heating system is composed of solar collector, heat storage tank, the auxiliary heat source, heat exchanger and pump. The solar collector is a flat plate type with selective absorption surface and one glass pane. The collector performance factors expressed by the two values, $b_0 = (K_c/K_o)(\tau a) = 0.75$ and $b_1 = K_c = 0.5$ where, K_c is the overall thermal transmittance from the fluid in pipes to the ambient of solar collector [W/m^2K], K_o is the overall heat loss coefficient of solar collector [W/m^2K] and τa is the product of glass transmittance and absorber plate absorptance [-].The effectiveness of the built-in heat exchanger in the tank is assumed to be 0.3. The input electric power of the collector circulation pump is 35 W.

The collector tilted angle and the azimuth are 35 degrees and 0 degrees (due south), respectively. The climatic condition is Tokyo (35 degrees N, 140 degrees E)

The typical system component is the collector with area $6m^2$ and the storage tank of 300 litters.

Table 1. Simulation method.

		Solar collector area							
		2 [m^2]		3 [m^2]		4 [m^2]		6 [m^2]	
Heat storage tank volume	100 [litter]	Case1-1	Case5-1	Case2-1	Case6-1	Case3-1	Case7-1	Case4-1	Case8-1
	150 [litter]	Case1-2	Case5-2	Case2-2	Case6-2	Case3-2	Case7-2	Case4-2	Case8-2
	100 [litter]	Case1-3	Case5-3	Case2-3	Case6-3	Case3-3	Case7-3	Case4-3	Case8-3
	300 [litter]	Case1-4	Case5-4	Case2-4	Case6-4	Case3-4	Case7-4	Case4-4	Case8-4
Pump flow rate [kg/s]		0.03		0.05		0.07		0.10	
Parameter of solar collector		$b_o=(K_c/K_o)(\tau a)=0.75$ $b_1=K_c=0.5$ K_c : Overall thermal transmittance of solar collector [W/m^2K] K_o : Overall heat loss coefficient of solar collector [W/m^2K] τa : Product of glass transmittance and absorber plate absorptance [-]							

		Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8
Heat storage tank volume [litter]		100	150	200	300	100	150	200	300
Diameter (D) [m]		0.41	0.54	0.45	0.63	0.41	0.54	0.45	0.63
Height (H) [m]		0.77	0.89	0.94	0.97	0.77	0.89	0.94	0.97
Insulating material		Glass wool 16K insulation				Vacuum insulation			
Thermal conductivity [W/mK]		0.045				0.002			
Thickness [m]		0.05				0.05			
Heat loss coefficient from tank [W/K]	top, bottom	0.104	0.128	0.184	0.251	0.005	0.006	0.009	0.012
	side	1.734	2.366	2.682	3.411	0.084	0.114	0.13	0.165

Table 2. Domestic hot water supply temperature.

	0:01 - 20:00	20:01 - 24:00
Boiler temperature set point [deg. C]	37.0	44.0
Tap water temperature set point [deg. C]	35.0	42.0

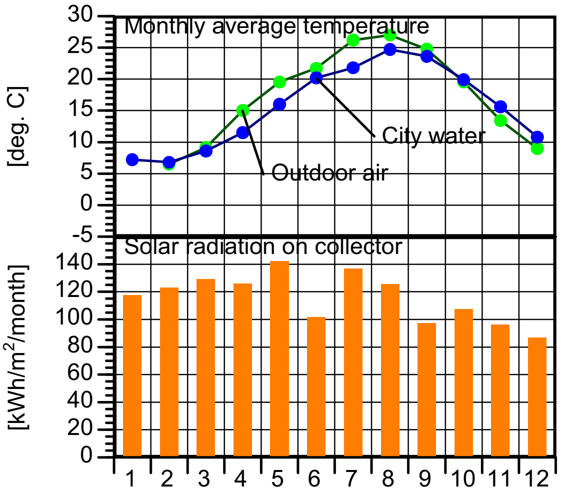


Fig. 2. Weather data in Tokyo (35 degree N).

3. Simulation models

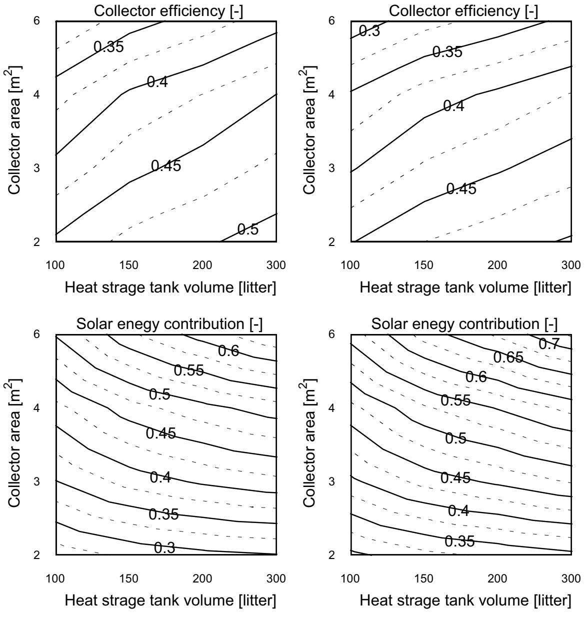
The simulation tool EESLISM [5] was used. Table1 shows the simulation cases examined in this study. The collector areas were assumed four cases, 2, 3, 4 and 6 m^2. The pump flow rates through the heat collection path were changed from the collector area. The heat storage tank volumes were assumed four cases, 100, 150, 200 and 300 litters. The insulation was two cases of the glass wool 16K and vacuum insulation. The thermal conductivities are 0.045W/mK, 0.002W/mK, respectively. The heat loss coefficients from the heat storage tanks are

Fig. 3. Comparison of yearly performance for the combinations of collector area and tank volume.

Table 3. Comparison of yearly performance for the combinations of collector area 6 m^2 and tank volume 300 litters.

Heat storage tank insulating	Glass wool 16K															
Case	Case1-1	Case1-2	Case1-3	Case1-4	Case2-1	Case2-2	Case2-3	Case2-4	Case3-1	Case3-2	Case3-3	Case3-4	Case4-1	Case4-2	Case4-3	Case4-4
Solar collector area [m^2]	2				3				4				6			
Heat storage tank volume [littes]	100	150	200	300	100	150	200	300	100	150	200	300	100	150	200	300
(A) Solar radiation on collector [kWh/year]	2777	2777	2777	2777	4167	4167	4167	4167	5556	5556	5556	5556	8334	8334	8334	8334
(B) Collected solar energy [kWh/year]	1263	1340	1380	1421	1698	1843	1922	2007	2033	2246	2365	2503	2494	2823	3016	3253
(B) / (A) Collector efficiency [-]	0.455	0.483	0.497	0.512	0.407	0.442	0.461	0.482	0.366	0.404	0.426	0.450	0.299	0.339	0.362	0.390
(C) Solar heat supply [kWh/year]	967	1048	1093	1116	1293	1429	1509	1564	1536	1719	1830	1921	1857	2112	2269	2421
(D) Boiler heat load [kWh/year]	2757	2687	2647	2626	2415	2289	2222	2176	2154	1986	1892	1818	1835	1588	1440	1307
(C) +(D) DHW heating load [kWh/year]	3724	3735	3739	3742	3708	3718	3730	3740	3690	3705	3722	3739	3692	3700	3709	3728
(C) / (C) + (D) Solar contribution [-]	0.260	0.280	0.292	0.298	0.349	0.384	0.404	0.418	0.416	0.464	0.492	0.514	0.503	0.571	0.612	0.649

Heat storage tank insulating	Vacuum insulation															
Case	Case5-1	Case5-2	Case5-3	Case5-4	Case6-1	Case6-2	Case6-3	Case6-4	Case7-1	Case7-2	Case7-3	Case7-4	Case8-1	Case8-2	Case8-3	Case8-4
Solar collector area [m^2]	2				3				4				6			
Heat storage tank volume [littes]	100	150	200	300	100	150	200	300	100	150	200	300	100	150	200	300
(A) Solar radiation on collector [kWh/year]	2777	2777	2777	2777	4167	4167	4167	4167	5556	5556	5556	5556	8334	8334	8334	8334
(B) Collected solar energy [kWh/year]	1246	1320	1360	1398	1656	1789	1863	1940	1961	2148	2254	2372	2362	2630	2788	2976
(B) / (A) Collector efficiency [-]	0.449	0.475	0.490	0.503	0.397	0.429	0.447	0.466	0.353	0.387	0.406	0.427	0.283	0.316	0.335	0.357
(C) Solar heat supply [kWh/year]	1089	1183	1233	1283	1456	1612	1697	1786	1726	1932	2052	2180	2081	2358	2525	2719
(D) Boiler heat load [kWh/year]	2625	2546	2502	2458	2238	2106	2029	1955	1968	1773	1666	1556	1621	1342	1186	1008
(C) +(D) DHW heating load [kWh/year]	3714	3729	3735	3741	3694	3717	3726	3741	3694	3705	3718	3737	3702	3701	3711	3726
(C) / (C) + (D) Solar contribution [-]	0.293	0.317	0.330	0.343	0.394	0.434	0.455	0.477	0.467	0.521	0.552	0.583	0.562	0.637	0.680	0.730



Case1 to 4 (Glass wool 16K) Case5 to 8 (Vaccume insulation)

Tokyo (35 degree N)

Fig. 4. Simulation results of yearly performance by the collector area and the tank volume in Tokyo.

shown in Table 1. The heat storage tank was divided into five layers in this simulation. Table 2 shows the domestic hot water supply temperature. The amount of hot water use depends on seasons and differs from day to day using the random number and daily hot water use profile used in the previous study. They are 370 litters/day from January to June and from October to December and 230 litters/day from July to September [6]. The temperature of DHW is assumed to be 35.0 degrees C from 0:01 to 20:00 and 42.0 degrees C from 20:01 to 24:00. The temperature of boiler outlet is assumed 2 degrees C higher than the set point hot water temperature of DHW supply considering the pipe heat loss. The ambient temperature of DHW pipe heat loss was assumed 22.0 degrees C. The standard weather data prepared as the Expanded AMeDAS Weather Data [7] and the supplied city

Table 4. Comparison of yearly performance for the combinations of collector area and tank volume.

			Sapporo	Morioka	Sendai	Tokyo	Kagoshima
Latitude		[degrees N]	43.04	39.70	38.27	35.68	31.56
Longitude		[degrees E]	141.21	141.15	140.87	139.77	130.56
Annual average outdoor air temperature		[deg. C]	8.72	10.42	12.60	16.51	18.51
Annual average city water temperature		[deg. C]	9.65	10.33	12.11	15.56	18.38
Annual total horizontal radiation		[kWh/m^2/year]	1178.69	1159.09	1213.98	1241.96	1419.4
Collector tilt angle		[degrees]	43.04	39.70	38.27	35.68	31.56
Solar collector area		[m^2]	6				
Heat storage tank volume		[littes]	300				
Solar radiation on collector		[kWh/year]	7954	7691	8181	8334	9122
Case4-4	Collected solar energy	[kWh/year]	3087	3054	3231	3253	3376
	Collector efficiency	[-]	0.388	0.397	0.395	0.390	0.370
	Solar heat supply	[kWh/year]	2321	2332	2454	2421	2392
	Boiler heat load	[kWh/year]	2254	2136	1758	1307	903
	DHW heating load	[kWh/year]	4575	4468	4212	3728	3294
	Solar contribution	[-]	0.507	0.522	0.583	0.649	0.726
Case8-4	Collected solar energy	[kWh/year]	2889 (- 198)	2866 (- 188)	3020 (- 210)	2976 (- 277)	2942 (- 434)
	Collector efficiency	[-]	0.363 (- 0.025)	0.373 (- 0.024)	0.369 (- 0.026)	0.357 (- 0.033)	0.323 (- 0.048)
	Solar heat supply	[kWh/year]	2664 (+ 343)	2656 (+ 324)	2787 (+ 332)	2719 (+ 298)	2631 (+ 239)
	Boiler heat load	[kWh/year]	1907 (- 347)	1808 (- 328)	1421 (- 337)	1008 (- 300)	671 (- 231)
	DHW heating load	[kWh/year]	4571	4464	4207	3726	3302
	Solar contribution	[-]	0.583 (+ 0.076)	0.595 (+ 0.073)	0.662 (+ 0.080)	0.730 (+ 0.080)	0.797 (+ 0.071)

water temperature data prepared by the Solar System Development Association in Japan were used in this simulation. The time increment of simulation is 10 minutes.

4. Simulation results

4.1. Case1 to Case4 (Glass wool 16K insulation)

Fig. 2 shows the monthly average weather data and city water temperature in Tokyo. Fig. 3 and Table3 show the annual simulation results in Tokyo. Fig. 4 shows the simulation results of yearly performance by the collector area and the heat storage tank volume in Tokyo. The collector efficiency increases with the larger tank volume for the same collector area. However, the collector efficiency decreases with the larger collector area. The maximum of collector efficiency is 0.5 in Case1-4 (2 m^2 300 litter) and minimum of collector efficiency is 0.3 in Case4-1 (6m^2 100 litter). The solar contribution increases with larger collector area and tank volume. The cases more than 0.6 of the solar contribution are Case4-3 (6 m^2 200 litter) and Case4-4 (6 m^2 300 litter).

4.2. Case5 to Case8 (Vacuum insulation)

Cases 5 to 8 were assumed the vacuumed insulation for the heat storage tanks. The collector efficiency is 0.35 in Case8-4 (6 m^2 300 litter). It is slightly lower than 0.39 in Case4-4 (6 m^2 300 litter) used the glass wool insulation. The solar contribution is increased by using the vacuum insulation for the heat storage tank in all cases. The maximum of increase is 0.08 in the case of $6m^2$ collector area and 300 litter tank volume. The solar contribution is 0.73 for the Case8-4 (6 m^2 300 litter). The cases more than 0.6 of the solar contribution are Case4-2 (6 m^2 150 litter), Case4-3 (6 m^2 200 litter) and Case4-4 (6 m^2 300 litter).

Using the vacuum insulation the solar DHW system showed better performance than the system with the glass wool insulated tank. For Case7-2, 4 m^2 collector and 150 litters tank, the solar contribution is 0.52. Therefore, the solar DHW systems become small by using the vacuum insulation for the heat storage tank.

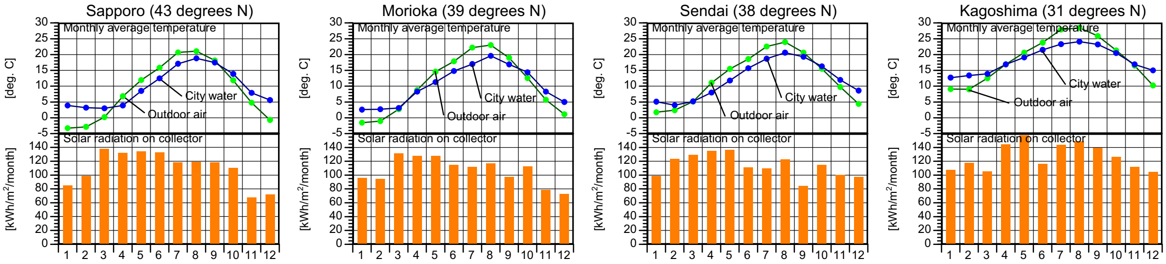
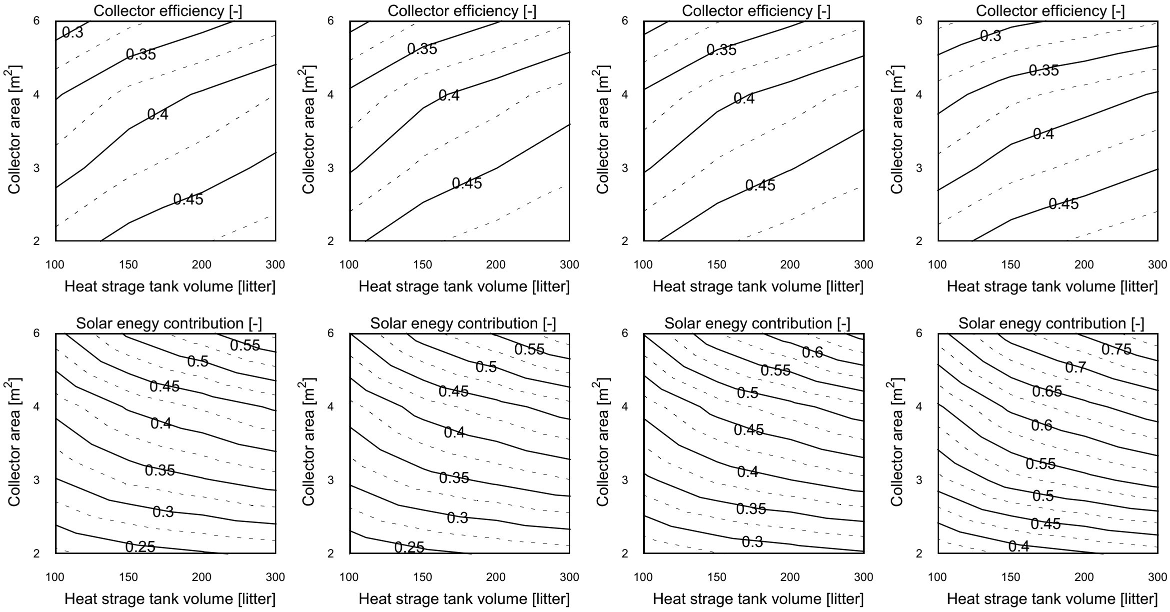


Fig. 5. Outdoor air and city water monthly average temperature and solar radiation on collector in four cities.



Sapporo (43 degrees N) Morioka (39 degrees N) Sendai (38 degrees N) Kagoshima (31 degrees N)

Fig. 6. Simulation results of yearly performance by the collector area and the heat stprage tank volume in four cities.

Table 5. The examplc cases more than 0.5 of solar contribution with vacuum insulation.

	Sapporo	Morioka	Sendai	Tokyo	Kagoshima
Case	8-2	8-2	7-4	7-2	6-2
Solar collector area [m^2]	6	6	4	4	3
Heat storage tank volume [littes]	150	150	300	150	150
Solar contribution [-]	0.506	0.515	0.520	0.521	0.515

5. Comparison of yearly performance in five cities

The previous chapter shows that the solar DHW systems with vacuum insulation have possibilities of downsizing in Tokyo. In this chapter, results of Sapporo (43 degrees N, 141 degree E), Morioka (39 degrees N, 141 degree E), Sendai (38 degrees N, 141 degree E) and Kagoshima (31 degrees N, 131 degree E) were compared. The collector tilted angles are assumed to be equal to the each latitude. The solar DHW system is the same system model with the vacuum insulated heat storage tank cases in Tokyo.

Table 4 shows the simulation result of Case4-4 (6 m^2 300 litter) and Case8-4 (6 m^2 300 litter) in five cities. In Sapporo and Morioka, the average monthly outdoor air temperatures are lower than 0 degrees C in winter. As the city water temperatures are low. DHW heating load of Sapporo and Morioka in the north areas in Japan are large. Kagoshima is the warmest region among five cities. The outdoor air and city water temperatures are higher than other cities. Therefore, DHW heating load is the lowest in five cities. The collector efficiencies become lower for the south areas. However, the difference is not seen by region. The half of DHW load is contributed in every city. However, the solar contribution is lower than 0.6 even the most high performance case Case4-4 (6 m^2 300 litter) with the glass wool for the heat storage tank in Sapporo, Morioka and Sendai. However, the solar contributions are increased by average 0.075 in all cities by using the vacuum insulation. The solar contributions in five cities are 0.583, 0.595, 0.662, 0.730 and 0.797, respectively in Case 8-8 with 6 m^2 collector and 300 litters tank. When the vacuum insulation is used for the heat storage tank, the solar contribution in Case8-4 (6 m^2 300 litter) is more than 0.6 expect for Sapporo and Morioka. In Kagoshima, the solar energy was contributed 0.8 of DHW load in Case8-4 (6 m^2 300 litter).

Fig. 5 shows the monthly average weather data and city water temperature in four cities. Fig. 6 shows the collector efficiency and the solar contribution in four cities. The vacuum insulation for the heat storage tank is able to reduce the solar collector area and the volume of heat storage tank in the five cities. The combinations of the solar systems to achieve more than 0.5 of the solar contributions are shown in Table 5. The smaller and high performance solar DHW systems are possible with the vacuum insulation for the heat storage tank.

6. Conclusion

In order to find the compact and high performance solar DHW system, the simulation was carried out and the results of the yearly performance of the collector efficiency and the solar contribution were examined.

1) The comparison of the total system performance of the solar DHW heating system with the glass wool insulation and the vacuum insulation for the heat storage tank for the 32 combination of the collector area and the heat storage tank volume in Tokyo and four other cities, Sapporo, Morioka, Sendai and Kagoshima were carried out.

2) The simulation results show that the vacuum insulation was increased the solar contribution. The solar contributions with the collector of 4 m^2 and the heat storage tank of 150 litters using the vacuum insulation in Sapporo, Morioka, Sendai, Tokyo and Kagoshima are 0.40, 0.41, 0.46, 0.52 and 0.61, respectively.

3) The combinations of the solar systems to achieve more than 0.5 of the solar contributions in Sapporo, Morioka, Sendai, Tokyo and Kagoshima are 0.506 in Case8-2 (6 m^2 150 litter), 0.515 in Case8-2 (6 m^2 150 litter), 0.502 in Case8-1 (6 m^2 100 litter) and 0.520 in Case7-4 (4 m^2 300 litter), 0.521 in Case7-2 (4 m^2 150 litter) and 0.515 in Case6-2 (3 m^2 150 litter), respectively.

4) The smaller and high performance solar DHW systems are possible with the vacuum insulation for the heat storage tank.

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