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Economic Evaluation of the Passive Solar-house Heating System Using the All-glass Evacuated Solar Collector Tubes and the Pebble Bed Heat Storage

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Abstract

The economics of a passive solar heating system (PSHS) with the pebble bed heat storage was evaluated, and the applications of the PSHS were analyzed, in this study. The results are as follows: The heating load, solar heat gain, and stored heat/year of the PSHS in the solar house model were found to be 10,778MJ, 3,438MJ, and 11,682MJ, respectively. The yearly energy expenses of the PSHS and the alternative heating system (conventional coal heating system, CCHS), which uses coal, were found to be USD 1.60/year and USD 60.90/year, respectively, and the yearly expenses of the PSHS were found to be 38 times less than those of the alternative heating system (CCHS). If it will be supposed that the life cycle of the passive solar heating system, according to the results of the LCC analysis in the two systems, is 40 years, the total expenses for the life cycle of the PSHS and the CCHS will be USD 1,431.50 and USD 2,740.00, respectively. The period for the investment payback of the PSHS is six years.

Keywords : Life cycle cost, Passive solar system, Pebble bed heat storage, All-glass evacuated solar collector tube

I. Introduction

Since recently, due to the unstable oil prices and the destruction of the environment owing to the inordinate use of fossil energy, the interest in alternative fuels has been increasing (Jang, 2005). Since the late 1970s, China has been conducting many studies on solar energy. It is now supplying developed solar energy, but only to the hot water system field (Jang, 2005). Actually, solar energy is not sufficiently supplied to residences for heating purposes.

When it comes to putting solar energy to practical use, it is important to guarantee higher efficiency than to guarantee the availability of the energy, using conventional fossil energy. Although the solar-heating system requires numerous initial fixed capital investments, it allows one to make up for such expenses with the fuel cost saved every year from the use of solar energy (Zhai, 2005 & Badescu etc., 2005). Life cycle cost analysis was used to evaluate

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the efficiency of the solar heating system. This calculation was conducted during the life year of the solar heating system, and then all kinds of factors were predicted (Oh, 2005, Yoo, 2003, Lu, 1995, and Li, 1993).

This study was conducted to identify the basic materials that are needed for the development of an economical passive solar heating system by evaluating the efficiency of such system using the natural heat circulation pebble bed heat storage type passive solar heating system.

II. Pebble Bed Heat Storage Type Passive Solar Heating System

The pebble bed heat storage type passive solar heating system is composed of a solar heat collecting part and a heat storage part. The solar heat collecting part is made up of the glass-evacuated tube solar collector, and the heat storage part is made up of the pebble bed, the circulation pipes, the expanding water container, drain tap valve, and drainage valve

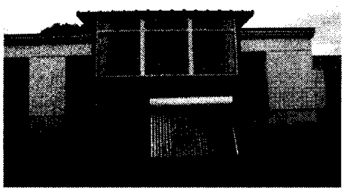


Fig. 1 House model for experiment

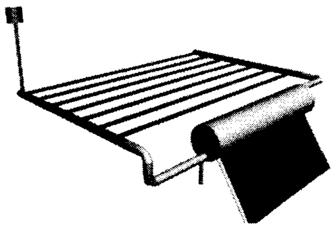
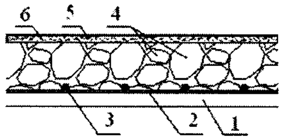


Fig. 2 Natural hot water circulation system



1. Structural body 2. Heat-retaining materials 3. Coils for heat circulation 4. River pebbles 5. Cement mortar 6. Floor paper

Fig. 3 Sectional view of the pebble bed heat storage

are attached to the circulation pipe. Fig. 1 shows the model house where the pebble bed heat storage type passive solar heating system was installed. The of area of model house is $10.4m^2$ and the height of model house is 2.6m. The solar collector element is consist of the all glass evacuated solar collector tubes and a heat tan, the area of the collector tubes is $7.2m^2$. Fig. 2 shows the natural hot water circulation system, and Fig. 3 shows the sectional view of the system's heat storage part.

III. Analysis of Life Cycle Cost

1. Overview of Life Cycle Cost

Life cycle cost (LCC) is the tool that was designed to evaluate the efficiency of a heating system considering the expenses generated during the whole life of a building related to planning, design, construction, use, and disuse. To evaluate LCC, it is necessary to calculate all the items that belong to the expenses, applying the same value (Yoo, 2003 & Oh, 2005).

Several calculation methods are used to evaluate the LCC, including the present-worth method, which calculates the LCC by applying the value at the time that the facilities investment is being made; the annual-worth method, which calculates the LCC by applying the expenses during the one-year operation period; and the closing price method, which calculates the LCC by applying the value at the time that the year of use ends. In this study, the efficiencies of the solar-heating system with the natural circulation pebble bed heat storage type passive solar heating system (PSHS) and of the conventional coal heating system (CCHS) were compared and evaluated using the present-worth method.

2. Analysis Procedure

The analysis procedure that was conducted in this study is shown in the Fig. 4.

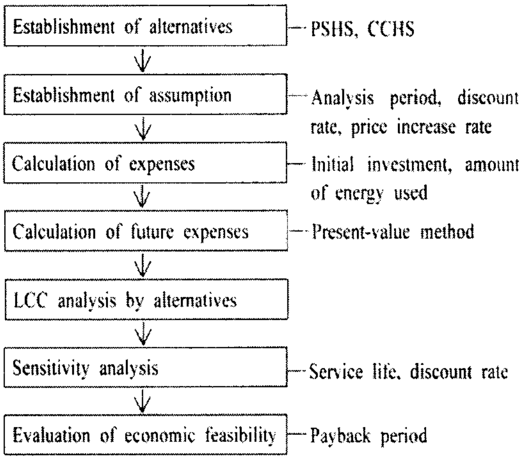


Fig. 4 LCC analysis procedure

3. Establishment of Assumption

The interest rate being used in this study — the average interest for a fixed deposit (4.73%) — that the Commercial Bank of China applied in the recent 10 years was applied [10].

The consumer price index, which is generally used to calculate the price increase rate, was used. The price increase rate that was applied in this study (1.10%) came from the materials that the Commercial Bank of China announced in the recent three years. To adjust the expenses that were generated at different times so that they could be compared based on the same period that was used for the standards, the discount rate was applied. The term, however, that was used as a general term was the real interest rate. The real interest rate can be calculated using formula (1).

$$i = \left(\frac{1 + \frac{i'}{100}}{1 + \frac{j}{100}} - 1 \right) \times 100(\%) \quad (1)$$

where i is the real interest rate,% i is the interest rate,% and j is the price increase rate, %.

The real interest rate calculated using the interest and price increase rates announced by the Commercial Bank of China is 3.59%.

4. Calculation of Expenses

Table 1 shows the standards for the calculation of the LCC expenses that were used in this study, and Table 2 shows the items that were actually applied.

Table 1 Standard for the calculation of the LCC

Items	Applications
Initial investment expenses	Material costs, labor costs, other expenses, security costs
Maintenance and management expenses	Operation expenses, replacement expenses
Energy expenses	Heating expanses

Table 2 LCC applications

Segment		PSHS(USD)	CCHS(USD)
Initial investment expenses		453.30	28.40
Maintenance and management expenses	Operation expenses	Assuming of 1% of the initial investment expenses	
	Replacement cycle	15 years	2~3 years

Table 3 Conditions for expenses integration and sensitivity analysis

Segment	Applications	Contents
Expenses integration	Present-value method	-Nonrecurring cost: one-time-occurrence cost in the n year $P_F = F\frac{1}{(1+d)^n}$ -Recurring cost: equal-occurrence cost every year $P_A = A\frac{(1+d)^n - 1}{d(1+d)^n}$ where, P_F is the sum of the present-value of nonrecurring cost, USD; P_A is the sum of the present-value of recurring cost, USD; F is the future price, USD, A is the yearly equal-price-occurrence cost, USD. d is the real discount rate, %; n is the analysis period, year.
		-Calculation of total life cycle cost by elements $LCC = \sum_{i=1}^{j} NPVi$ where, i is the initial construction costs, repair and replacement expenses, operation and management expenses, USD; N is the life period of system, year; P is the expense of present-value conversion, USD; V is the marketing discount rate, (%).
Sensitivity analysis	Discount rate of service life	As the indices in the LCC analysis are only estimates, wrong predictions may affect the results of the analysis.

5. Conditions for Expenses Integration and Sensitivity Analysis

Table 3 shows the conditions for the expenses integration and sensitivity analysis.

6. Comprehensive Analysis

The system that was used for the LCC evaluation in this study was the hot water circulation pebble bed heat storage type passive solar heating system.

The amount of energy that was heat-stored in the pebble bed using the system (PSHS) developed in this study was 79.9MJ/day.

Fig. 5 shows the yearly heating load of the house model with the pebble bed heat storage, the amount of heat that was obtained by the all-glass evacuated solar collector tubes, and the amount of heat that was stored in the pebble bed, which was found to be 10,778MJ, 3,438MJ, and 11,682MJ, respectively. Because the pebble bed was designed to cover the heating load during 3 days considering a continuous cloudy day, the stored energy in the pebble bed was much than that of solar heat gain.

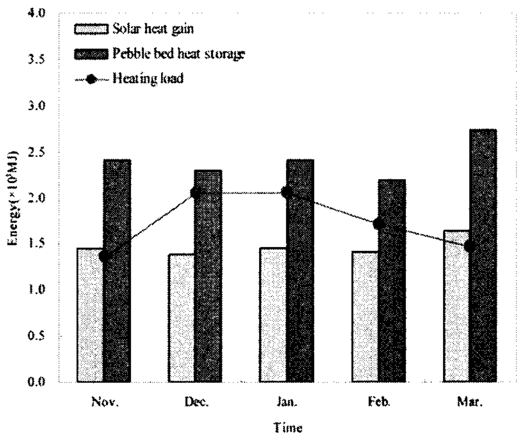


Fig. 5 Amount of yearly energy use

Table 4 shows the yearly energy cost of the PSHS developed in this study and that of the alternative energy system (CCHS). The cost of the developed system (PSHS) reached USD 1.60/year, and the cost of the coal system reached USD 60.90/year.

The results of the LCC analysis of the hot

Table 4 Yearly energy cost

	PSHS (USD)	CCHS (USD)
Cost	1.60	60.90

Table 5 Results of the LCC

	PSHS (USD)	CCHS (USD)
Initial investment expenses	454.30	28.40
Total energy expenses	64.10	2,498.70
Repair and replacement expenses	908.60	212.70
Maintenance and management expenses	4.50	0.10
Total life cycle cost	1,431.50	2,740.00

*Notes: For the initial investment expenses for coal, the approximation was applied. As it was assumed, when calculating the initial investment expenses for coal, that the heating system that uses coal is the same as that which was developed in this study, it was supposed that the labor or cement expenses are also the same. Assume that the repair and replacement expenses will reach 100% of the initial investment expenses. Assume that the maintenance and management expenses will reach 1% of the initial investment expenses.

water circulation pebble heat storage type passive solar heating system that was developed in this study, and of the alternative system, which uses coal, are shown in Table 5.

Table 5 shows the results by the item where the LCC was applied. As shown in these tables, the yearly expenses for the initial investment and for the repair and replacement of the system that was developed in this study reached more than those of the alternative system but amounted to 38 times less than the total expenses for the energy consumed. Fig. 6 shows the LCC-accumulated results of the two systems. As shown in Table 5, if the life cycle resulting from the analysis of the LCCs of the two systems is 40 years, the cost of the total life cycles of the developed system and the coal system are USD 1,431.50 and USD 2,740.00, respectively. Furthermore, the payback period of the system that was developed in this study

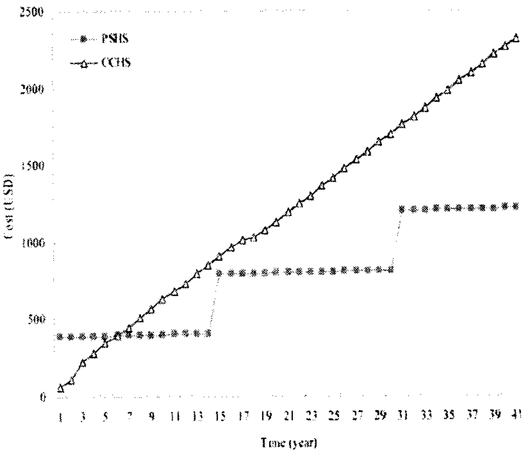


Fig. 6 LCC-accumulated distribution

was found to be approximately 6 years.

In the LCC analysis, if the discount rate, service life, and other values are wrongly estimated, the results may be affected. Thus, a sensitivity analysis was conducted, and the reliability of the results obtained from the LCC analysis was checked. In addition, the change in the expenses if the real discount rate will be changed to 2~6% and the service life to 2~60 year for the alternative was analyzed, using the results of the sensitivity analysis. As a result, the change in the discount rate and service life were found not to have affected the change in the order of each alternative within the scope, based on the estimates. The reliability of the LCC analysis was thus confirmed.

IV. Conclusions

The contents related to the efficiencies of the natural hot water circulation pebble bed heat storage type passive solar heating system (PSHS) and of the conventional coal heating system (CCHS) are summarized as follows.

1. The yearly heating load, the amount of heat that was obtained by the all-glass evacuated

solar collector tubes and the amount of heat that was stored in the pebble bed storage were found to be 10,778MJ, 3,438MJ, and 11,682MJ, respectively.

2. The yearly cost of the developed system (PSHS) and that of the conventional coal heating system (CCHS) reached USD 1.60/year and USD 60.90/year, respectively. If the life cycle is 40 years, the energy consumption cost of the system that was developed in this study is expected to reach an amount 38 times less that of the system, using alternative energy.

3. If the life cycle is 40 years, the cost of the total life cycles of the system (PSHS) that was developed in this study, and of the conventional coal heating system (CCHS), are expected to be USD 1,431.50 and USD 2,740.00, respectively. Furthermore, the payback period of the system (PSHS) that was developed in this study was found to be approximately 6 years.

4. The change in the expenses if the real discount rate will be changed to 2~6% and the service life to 2~60 year for the alternative, based on the results obtained from the discount rate and sensitivity analysis, was analyzed. Since the change in the discount rate and the service life did not affect the change in the order of each alternative within the scope, based on the estimates, the reliability of the LCC analysis was confirmed.

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