Study on the Installation of Thermal Storage System in Residential Houses

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Abstract
In recent years, residential houses have become more airtight and better insulated, and some, along with the IT revolution have been equipped with SOHO applications. This leads to a decrease in the heating load, while increasing electricity consumption in the daytime. On the other hand, electricity demand has increased in the summer, while the load rate of equipment in electricity plants has been decreased. Here a new thermal storage air conditioning system, using direct heat exchange, is proposed for a residential house, while its possibility and availability have been studied according to the prediction of energy consumption, which demonstrates the effectiveness of the thermal storage system for residential houses.

Keywords: Thermal Storage; Ice Storage; Heat Exchange Mode; Residential Houses

1. Introduction
With the advancement of technology, the performance of airtightness and insulation of residential houses has been improved, while the IT revolution and SOHO (Small Office and Home Office) have been popularized for domestic application. All these lead to a decrease of the heating load and increase of the cooling load. Thus the difference of peak and off-peak domestic electricity demand will increase, especially in the summer.

On the other hand, the load rate of equipment in electricity plants has decreased in recent years. From the point of view of energy conservation and prevention of the green house effect, action should be taken to shift the electricity peak.

In this paper ice storage together with an all-air system is proposed for a residential house, whose efficiency in economy and energy conservation is evaluated. Considering the hot water load, the hot water storage system is also adopted.

2. Characteristics of future residential houses and air conditioning load
Figure 1 shows the features of future residential houses, whose air conditioning load characteristic is listed as follows:
(1) The increase of cooling load and daytime electricity consumption due to SOHO applications and intelligent equipment, and decrease of the heating load due to better airtightness and insulation results in unbalanced heating and cooling demand.
(2) Unbalanced heating and cooling demand leads to inefficiency in air conditioning and increases running costs.
(3) According to the requirements of the healthy house,
fresh air is drawn into rooms by the ventilation system to produce a good living and working space.

The authors consider that the thermal storage system is available to solve the above problems, and it can shift the peak load, reduce the size of machine (refrigerator) and running costs. Thermal storage systems have often been used in office buildings, but have few installations in homes. Here a new thermal storage system is proposed for residential houses.

3. Proposition of thermal storage system for residential houses

3.1 Direct heat exchange method for Ice storage

In existing ice storage systems the two-step heat exchange method is adopted as shown in figure 2. The one step works between refrigerant and water or refrigeration brines, and the other works between water and air. So one pump and one air handling unit are necessary, which leads to more space for equipment, and limits the popularization of ice storage systems in homes.

In this paper, a simplified device (direct heat exchange between ice and air) is presented. Figure 3 shows the characteristic of the direct heat exchange method; air exchanges heat with ice made in the tank directly. The operating method can be simplified due to this method, and as a result the ice storage system can be introduced into residential houses. The merits of direct heat exchange are as follows:

1. The system is simplified because no pump is necessary;
2. Both heat exchange loss and transportation power are low;
3. Space saving and low noise.

3.2 Thermal storage system for residential houses

3.2.1 Outline of thermal storage system for residential houses

Figure 4 shows sketch of the thermal storage system for a residential house. The heat pump is the center in this system, which can remove heat from storage during the summer, while the waste heat can be charged in the hot water tank before the tank becomes full, otherwise, the waste heat will be released into the outside air.

While in the winter, the heat pump adds heat to storage. The thermal storage tank is also used as an air handling unit, in which ice storage occurs during summer and hot water storage during winter. Direct heat exchange occurs between air (mixing of fresh air and return air) and the tubes inside the tank, the conditioned air is then supplied to the rooms by fan. As the temperature difference between supply air and room air is relatively high, induced airflow is created through a small fan inside the room unit.

Hot water is stored in the water tank, which not only meets the needs of kitchen and bathroom all the year, but can also be used for floor heating in winter.
3.2.2 Constitution of the thermal storage air handling unit

Figure 5 shows that the thermal storage air handling unit consists mainly of a mixing chamber, thermal storage tank, water humidifier, and fan. The thermal storage part is constituted of an inner pipe and external copper tube. Refrigerant circulates inside the inner pipe, and water in the tube becomes ice at midnight. In the daytime mixed air passes through the tubes containing ice and direct heat exchange occurs between air and ice, thus conditioned air is created.

The hot water humidifier is only used during the winter to ensure the necessary humidity inside the rooms.

3.2.3 Characteristics of the proposed system

Besides the benefits of the common thermal storage system, such as reducing the equipment size, savings in capital and energy costs, the above system has the following characteristics:

(1) The thermal storage tank is combined with the air handling unit, which reduces the space requirement for equipment, thus making the thermal storage system possible for houses;

(2) Hot water can be guaranteed the whole year round and can also be used for floor heating in winter. Waste heat is used during summer for heating water, which leads to better energy efficiency.

(3) Outdoor air can be ensured as an all-air system is used, thus meeting occupancy health requirements.

4. Outline of case study

The above thermal storage system is proposed for the Steel Perfect Recycle House (SPRH) in Kitakyushu, and the details of this house are listed below.

4.1 General situations of SPRH

The plan view of SPRH is shown as figure 6. The two-story house with a floor area of 174.6m² has a steel frame and is accommodation for a two-person family. The first floor is designed as a future home, including a SOHO room, a reception room and a machine room, etc. The second floor is a conventional living space, including a living room, a bedroom, a bathroom, etc. Based on the SOHO functions, the life schedule (Figure 7) changes correspondingly, as people can work or meet with friends at home during daytime.

4.2 Calculation of air conditioning load

The setting values and calculation value of the air conditioning load is listed in table 1, according to the time-dependent schedule (Figure 7), the total peak load of cooling and heating are 13.4kW and 14.7kW respectively. Simulation for the air conditioning load is based on the SMASH program, and the annual heating load is 14777MJ, while the annual cooling load is 33441MJ, which is much greater than the heating load. The heating and cooling load of SPRH and other residential houses is shown in figure 8. It can be seen that cooling load of SPRH is higher than common homes because the SOHO applications generate more heat inside rooms. Figure 9 shows the detailed cooling load on August 4 in summer, obviously, the cooling load in the daytime is much larger than that at night. On the other hand, the peak heating load in winter is 278MJ/d, which is 31% lower than the peak cooling load in summer.

4.3 Calculation of the hot water load

According to people living in SPRH, hot water demand can be decided. Assuming that the temperature difference between city water and hot water is 45°C, hot water for one person is 150kg/d, the hot water load
Q can be calculated by Equation 1:

\[ Q = \rho V C_p \Delta t \]  

(1)

here \( \rho \): Density of water  
\( V \): Volume of water  
\( C_p \): Specific heat  
\( \Delta t \): Temperature difference

By calculation, the hot water load is 56.5MJ/d and the peak load rate reaches 2.3kW, e.g., 45kg hot water.

4.4 Setting of the thermal storage air conditioning system

Assuming that ice storage capacity \( Q_{isc} \) is 50% of the peak cooling load during daytime, heat loss of ice storage \( k_{st} \) 5%, sensible heat temperature difference 7°C, Ice Packing Factor (IPF) 0.95, the volume of ice storage tank \( V_{ist} \) can be calculated by Equation 2.

\[ V_{ist} = \frac{Q_{isc} \times (1 + k_{st}) \times 4.1868}{1000 \times \Delta t + 80 \times 920 \times 0.95} = 0.6 \text{ m}^3 \]  

(2)

In winter the ice storage tank acts as an auxiliary hot water tank. Assuming that heat storage capability \( Q_{hsc} \) is 50% of the peak day heating load, heat loss \( k_{st} \) 5%, sensible heat temperature difference 20°C, the volume of hot water tank can be calculated as the following (Equation 3).

\[ V_{hwt} = \frac{Q_{hsc} \times (1 + k_{st}) \times 4.1868}{1000 \times \Delta t + 80 \times 920 \times 0.95} - V_{ist} = 0.96 \text{ m}^3 \]  

(3)

Table 2. details the capability of the proposed system.

4.5 Setting of the conventional system.

The conventional system is composed of room air conditioners and an electric water heater. Heating and cooling are realized by the air conditioners, while the water heater uses night electricity to supply hot water. Table 3 shows the composition of the proposed system and conventional system respectively for SPRH.

\[ \text{Table 1} \]

Air conditioning load of SPRH

| Setting Values | SOHO      | Reception Room | Living Room | Bedroom |
|----------------|-----------|----------------|-------------|---------|
| Indoor temperature (C/H) | 26/20°C  | 26/20°C | 26/20°C | 26/20°C |
| Indoor humidity | 50% | 50% | 50% | 50% |
| Heat generation from equipment | 1 kW     | 0.12 kW | 0.12 kW | 0.12 kW |
| Lighting heat | 0.12 kW | 0.12 kW | 0.12 kW | 0.12 kW |
| Heat generation rate in Night* | 30%      | 0%     | 0%     | 0%     |
| Human heat release | 0.12 kW | 0.12 kW | 0.12 kW | 0.12 kW |
| Shielding rate | 0.27 | 0.27 | 0.27 | 0.9 |
| Room volume | 38.9 m³ | 38.9 m³ | 70 m³ | 31.1 m³ |
| Cooling load | 4.2 kW | 6.0 kW | 6.4 kW | 2.6 kW |
| Heating load | 3.8 kW | 5.6 kW | 14.7 kW | 8.6 kW |

Note: C/H, Heating/cooling; Heating generation rate in Night is the ratio of the peak value; Here assumes that there are 3 computers, 1 duplicating machine and other office equipment in SOHO.

\[ \text{Table 2} \]

Capability of proposed Thermal storage system

| Ice Storage | Hot water storage |
|-------------|-------------------|
| Summer      | Winter            |
| Volume (m³) | 0.6               | 0.96               |
| IPF         | 0.95              | -                  |
| \( \Delta t \) (C) | 10       | 25                 | 25 |
| Storage capability (MJ) | 193.2      | 62.8               | 100.5 |
| Output (MJ) | 190.7             | 59.7               | 95.5 |

Note: effective output at heat loss as 5%.

\[ \text{Table 3} \]

Composition of proposed plan and conventional plan for SPRH

| Proposed Plan | Input (kW) | Output (kW) |
|---------------|------------|-------------|
| Heat pump     | 3.15 (c)   | 6.16 (c)    |
| Heat pump     | 3.0 (h)    | 9.0 (h)     |
| Auxiliary     | -          | -           |
| Total         | 4.25       | -           |

Conventional plan

| Room air conditioner S40 (for SOHO) | Room air conditioner S28 (2 for living room, 2 for reception room) | Room air conditioner S25 (for bedroom) | Electric water heater |
|------------------------------------|---------------------------------------------------------------|----------------------------------------|-----------------------|
| 1.14 (c)                           | 0.97×4 (c)                                                   | 0.925 (c)                              | 2.4                   |
| 1.84 (h)                           | 3.8×4 (h)                                                   | 1.02 (c)                               | 200L                 |
|                                    | 1.14×4 (h)                                                  |                                        |                       |

Note: Room air conditioner data from specification of DAIKIN; Water heater from TOTO; h:heating; c: cooling.
5. Prospect evaluation

5.1 Comparison of electricity consumption

According to equivalent operation time under full load conditions, annual electricity consumption can be calculated. Figure 10 shows annual electricity consumption of the proposed and conventional systems. Annual electricity consumption of the ice storage air conditioning system is 23% lower than that of conventional system. It also demonstrates the midnight electricity utilization ratio (including air conditioning and hot water supply) of the two systems, midnight electricity of the proposed system is 73.8% of the total, while the conventional system is only 47.9%.

5.2 Electricity cost

Electricity cost relates greatly to the electricity contract mode. Regarding the proposed system, 78% of the daytime electricity consumption has been transferred to midnight (22:00~8:00). According to the night 10 plan of KYUSHU Electricity Corporation, the time-dependent energy cost is a major economic incentive for the use of thermal storage.

Energy cost for the conventional system depends on the consumption amount based on plan C, while table 4 lists the detailed electricity contract modes for the two systems. The comparison of energy cost is shown in Figure 11, and the proposed plan can be reduced by nearly 40%.

5.3 Comparison of annual cost

Initial cost and annual cost of the proposed system and conventional system is listed in table 5. Lifetime of the proposed system is supposed as 15 years and the conventional system as 10 years.

5.4 Impact on the environment

As is known, CO$_2$ is emitted together with electricity consumption. Here, CO$_2$ emission caused by electricity consumption is 0.131kg-C/kWh from 22:00 to 8:00 of the next day, which is 10% lower than that emitted in the daytime. From figure 12, it can been seen that CO$_2$ emission of the proposed system is 25% lower, thus it has less environmental impact.
6. Conclusions
In this paper the thermal storage air conditioning system using the direct heat exchange method is proposed for a residential house. Energy consumption, annual cost and impact on the environment by the proposed system and the conventional one are evaluated and compared. Energy cost of the proposed system is 23% lower. Although the two plans have about the same annual cost, the proposed system has little impact on the environment with less CO₂ emission, and can guarantee the supply of outdoor air to maintain good indoor air quality. While the thermal storage system is not widely used in houses so far, it shows promise for the future.

Further study will be continued, and the real performance of the proposed thermal storage system will be verified through simulation and experiment.

Acknowledgment
The authors would like to thank the Japan Society for the Promotion of Science (JSPS) for supporting this research. They also acknowledge the kind instructions of Mr. K. Oyabu of the Indoor Air Institute, Okayama, from the beginning of the conception of this new thermal storage system, and express deep appreciation to those who gave their generous help in the Perfect Recycle House project.

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