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Energy Simulation of a Heat Pump System with Thermal Storage according to Control Strategies

Young Soo Chang, Byung Ha Kang
Kookmin University, School of Mechanical Engineering
77 Jeongneung-ro, Seongbuk-gu, Seoul 136-761, Korea
yschang@kookmin.ac.kr; bhkang@kookmin.ac.kr

Choong-Sub Lee
Kookmin University, Graduate School School of Mechanical Engineering
77 Jeongneung-ro, Seongbuk-gu, Seoul 136-761, Korea
cndtjq88@naver.com

Abstract **–**A comparative analysis was performed on the energy consumption and cost of heat pump system with thermal storage for various control strategies according to cooling and heating load variations. Simulation models of heat pump and thermal storage are developed to obtain energy consumption for cooling and heating of a building in Seoul during summer and winter season. Energy simulation has been conducted for the zone control as well as existing control strategies such as heat pump priority and thermal storage priority. Power consumption and energy cost has been evaluated based on electricity pricing in Korea. When the cooling and heating loads increase, the heat pump priority method is more effective. Whereas, when the low cooling and heating loads are demanded, the thermal storage priority method is more economical than heat pump priority method. Zone control strategy is found to be comparable to the heat pump priority method for large loads, while it is also economic for small loads compared to the heat pump and heat storage priorities control strategies.

Keywords**:** heat pump, thermal storage, heat pump priority, thermal storage priority, zone control

1. Introduction

Recent energy issue has been caused by increasing energy demands, shortages of energy resources and environmental problem. Especially, building sectors occupies considerable energy consumption and CO_2 emission. In order to reduce energy consumption and improve energy performance of air conditioning system in building, lots of studies have been conducted. Heat pump system with thermal storage as shown in Fig. 1 is one of the promising technologies and can be operated under various control strategies according to electricity pricing and cooling or heating load variation. The most widely used conventional methods are heat pump priority and storage priority strategies.

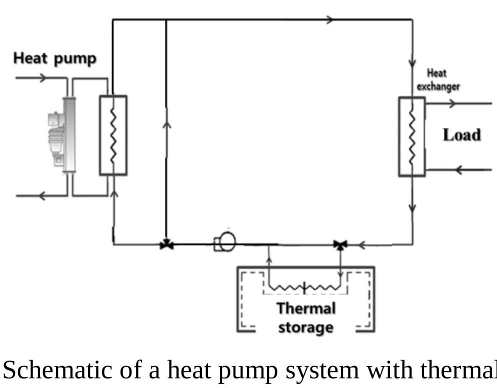


Fig. 1. Schematic of a heat pump system with thermal storage

In the heat pump priority method, heat pump maintains rated operation and thermal storage is responsible for the remainder of load. This method can keep the high efficiency by minimizing the part load operation of heat pump. But, according to the load decrease, the utilization ratio of thermal storage is gradually reduced. In the thermal storage priority method, thermal storage is responsible for base of the cooling or heating load, and heat pump is in charge of the rest. Thus, regardless of changes in load, maximum utilization of the thermal storage is possible. However, due to part load operation of the heat pump in daytime, the operation efficiency decreases. A zone control strategy was proposed considering load variations (Lee et al.). When load is lower than rated capacity of thermal storage, thermal storage only operates coping with load, and when load is between rated capacity of thermal storage and optimum capacity of heat pump, heat pump only operates according to load variation. Thermal storage and heat pump operate concurrently as load exceeds the optimum capacity of heat pump.

In this study, physical models of heat-pump and thermal storage have been presented, and the performance simulations have been conducted for the heat pump priority, thermal storage priority, and zone control strategies. A comparative analysis was carried out on energy consumption and operation costs considering electricity pricing in Korea.

2. Simulation Models

In this study, simulation models of heat pump and thermal storage system are developed, and energy consumptions of heat pump system are obtained considering cooling and heating load variations of building in Seoul. Meteorological data provided by the Solar Energy Society of Korea has been used for the simulation. And cooling and heating loads are calculated using an energy simulation tool TRNSYS. The building is an office building consisted of 10^{th} floor and located in Seoul, Korea. Details of the simulation have been designed based on the existing study (Seok et al.).

Heat pump model used in this study is a static model and consists of sub-components that are compressor, condenser, and evaporator. In the compressor model, discharge temperature is calculated regarding polytropic process and refrigerant mass flow rate is obtained by volumetric efficiency, compressor frequency, and refrigerant inlet density.

$$\frac{T_{dis}}{T_{suc}} = \left(\frac{P_{dis}}{P_{suc}}\right)^{\frac{n-1}{n}}, \; R_p = \frac{P_{dis}}{P_{suc}} \tag{1}$$

$$\dot{m}_{comp} = \eta_v \cdot \rho_i \cdot V_d \cdot RPS \tag{2}$$

Condenser and evaporator are modelled by *UA* and LMTD at three-zone and two-zone according to the refrigerant phase, respectively. Mean temperature difference at condenser is calculated as in Eq. 3.

$$\frac{1}{\Delta T_{c,m}} = \frac{\dot{Q}_{c,sh}}{\dot{Q}_c}\frac{1}{\Delta T_{c,sh}} + \frac{\dot{Q}_{c,sat}}{\dot{Q}_c}\frac{1}{\Delta T_{c,sat}} + \frac{\dot{Q}_{c,sc}}{\dot{Q}_c}\frac{1}{\Delta T_{c,sc}} \tag{3}$$

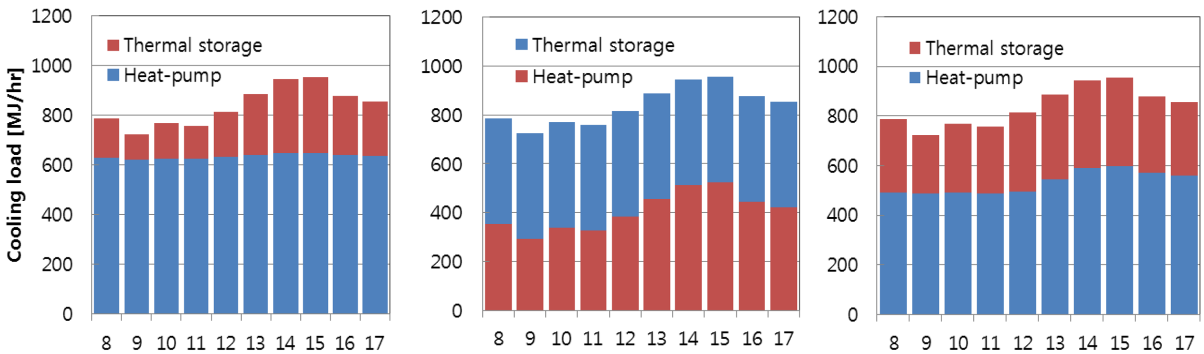
Thermal storage is a capsule type storage tank. This model has some assumptions that a tank is divided into some virtual layers and each layer has same number of capsules. Governing equations are obtained from energy conservation as shown in Eq. 4 and 5 (Lee et al.).

$$\rho_b V_b C_{p,b}\frac{dT_b}{dt} = U_c n A_c (T_w - T_o) + \dot{m}_b C_{p,b}(T_i - T_o) \tag{4}$$

$$h_{fg}\frac{dM_{PCM}}{dt} = \dot{m}_b C_{p,b}(T_i - T_o) \tag{5}$$

3. Results

In response to the hourly cooling load, performance simulation of heat pump and thermal storage has been conducted for various control strategies. Fig. 1 shows load sharing results of heat pump and thermal storage according to cooling load variations in a day in July when average cooling load is 80% of design cooling load. In heat pump priority strategy, heat pump operates almost in a rated condition, and comprises a large portion of cooling load, while storage usage ratio is low. On the other hand, in thermal storage priority strategy, most of the stored energy in thermal storage is consumed, and part load operation ratio of heat pump becomes greater with decrease in cooling load. Zone control strategy describe load sharing in-between heat pump and thermal storage priority strategies. Heat pump operates in a better performance condition than thermal storage priority method, and a larger amount of stored energy in the thermal storage can be utilized than heat pump priority method.



(a) Heat pump priority (b) thermal storage priority (c) zone control

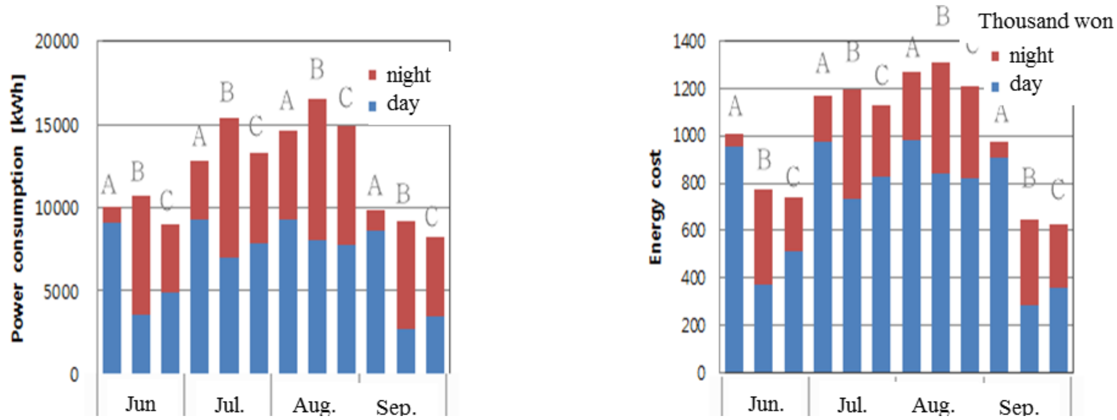
Fig. 2. Load sharing of heat pump and thermal storage according to control strategies

Fig. 2 shows the monthly energy consumptions and operation costs for each method. At the low load condition in June and September, the energy consumption differences according to control methods are relatively small; however the differences of operation cost seem to become bigger. This comes from load sharing of heat pump and thermal storage and electricity pricing. The electric rates are much lower in the night time than in the day time in Korea to promote electricity levelling. At the high load condition in July and August, heat pump priority consumes less energy than the thermal storage priority. However, the energy cost differences get reduced. It is due to the relatively cheaper electricity cost in the night than the cost in the daytime.

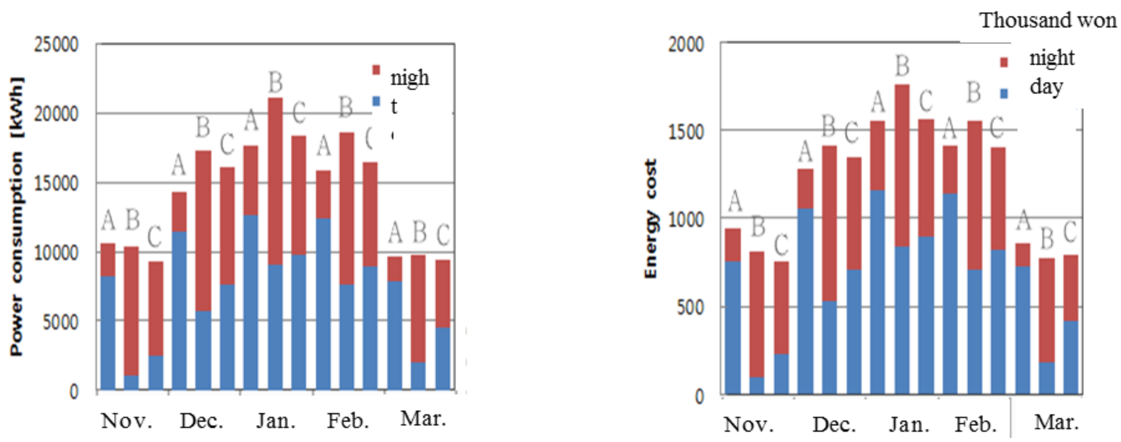
When the large building load occurs, the heat pump priority method is more effective. Whereas, when the low building load is demanded, the storage priority method is more economical than heat pump priority method for energy costs. As explained in Fig. 2, zone control strategy resides in-between heat pump and thermal storage priority strategies, and has advantages over two conventional control methods. Heat pump operates in a better performance condition than thermal storage priority method, and stored energy in the thermal storage is utilized more than heat pump priority method. Zone control strategy shows the lowest energy cost as well as power consumption during cooling and heating season. This means that zone control strategy, depending on the various building loads, will be effective for energy saving aspect.

4. Conclusion

This study has been conducted for the optimal control of heat pump system with thermal storage. Physical models of the heat pump and thermal storage have been developed. And also, in response to the cooling and heating load, energy simulation for the heat pump priority, thermal storage priority, and zone control strategies were performed. For conventional control methods, when large cooling or heating load occurs, heat pump priority shows less energy consumption and operating cost. Whereas, when the low cooling or heating load is demand, thermal storage priority method is more effective. Zone control strategy is found to be comparable to the heat pump priority method for large loads, while it is also economic for small loads compared to the heat pump and heat storage priorities control strategies.



(a) Cooling season



(b) Heating season

Fig. 3. Energy simulation results during cooling period(A : heat pump priority; B : thermal storage priority; C : zone control)

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