SIMULATION AND EVALUATION OF LATENT HEAT THERMAL ENERGY STORAGE HEAT PUMP SYSTEMS

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PROJECT OUTLINE

Project Title: Simulation and Evaluation of Latent Heat TES-Heat Pump Systems

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Project Goals: Derive the relative value of TES for heat pump storage (heating and cooling) as a function of storage temperature, mode of storage (hotside or coldside), geographic locations, and utility time-of-use rate structures.

Computer models will be used to simulate the performance of a number of TES/heat pump configurations. Models will be based on existing performance data of heat pump components, available building thermal load computational procedures, and generalized TES subsystem design. Different electricity rate structures will be assumed for each site. Life-cycle costs for each site, configuration and rate structure will then be computed.

Project Status: The following six cities have been chosen as simulation sites: Boston, MA; Fort Worth, TX; Miami, FL; Nashville, TN; Phoenix, AZ; and Seattle, WA. These cities possess a wide range of climates and therefore offer the opportunity to evaluate the performance of various TES/Heat Pump configurations under a wide range of operating constraints.

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SUMMARY

A computer model is being developed for the purpose of evaluating the performance of a number of latent heat Thermal Energy Storage (TES)/Heat Pump systems for residential heating and cooling applications. The basis for this evaluation will be system annualized life cycle cost. Annual system performance will be determined at various simulation sites across the continental United States using manufacturers performance data for the basic heat pump components and the computed performance characteristics of a simplified TES subsystem design. The systems considered will be required to satisfy building heating and loads calculated using TRNSYS (Ref. 1) for different imposed electricity rate structures. Both the TES/Heat Pump system performance and the load simulation model will be driven by hourly weather data provided by Sandia National Laboratory (Ref. 2). By interfacing TES/Heat Pump performance with these thermal loads, optimum systems will be selected for each combination of site and rate structure considered.

INTRODUCTION

The combination of heat pump systems combined with thermal energy storage have the advantage of: 1) providing a means of substituting lower cost thermal energy during heating operation for that which is normally supplied by resistance heaters, 2) improving the efficiency of heat pump systems during both heating and cooling operation and 3) decreasing heat pump operating cost by allowing the heat pump to operate primarily during periods in which low cost electricity is provided under time-of-day (TOD) electricity rate structures. Although the focus of previous work has been aimed at heat pumps combined with sensible heat storage subsystems, the advantages associated with latent heat storage has precipitated research and development efforts considering latent heat TES/Heat Pump systems as well. Latent heat systems in general store more energy per unit volume than do sensible heat systems, allow for storage at constant temperature and do not require the internal heat exchanger needed by many sensible heat storage systems.

This analysis will consider six different TES/Heat Pump configurations. These proposed designs include: 1) direct TES/Heat Pump systems in which the

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storage subsystem is charged within the refrigeration cycle itself and discharged by direct heat exchange between indoor return air and storage material, 2) indirect systems that are both charged and discharged within the refrigeration cycle of the heat pump, 3) hybrid systems that act as direct systems during cooling operation and indirect systems during heating and 4) hybrid systems that act as indirect systems during both heating and cooling. The storage subsystem considered is of a rectangular design which provides for heat transfer between both storage material and refrigerant and storage material and air.

For each combination of simulation site and electricity rate structure, specific TES/Heat Pump configurations will be optimized to determine the combination of component sizes that minimizes life cycle costs. These individual optimized systems will then be ranked based on both life cycle cost and specific performance factor for the combination of simulation site and rate structure under consideration.

THERMAL LOAD CHARACTERIZATION

In order to properly evaluate the performance of each TES/Heat Pump system, they must be required to satisfy realistic heating and cooling loads. These thermal loads will be computed using the TRNSYS computer simulation. The methodology used in this model follows ASHRAE recommended procedures which utilize transfer functions for calculating conduction heat gains and losses. These heat gains/losses are then combined with other specified or computed, sensible and latent heat loads to determine the total hourly latent and sensible heat load for the house. The assumption made in this analysis is that the heating/cooling system will exactly satisfy these load requirements. The computation of these thermal loads requires that hourly (or any other increment of time) weather data be provided for the entire simulation period along with a general building design and construction characteristics.

Site Selection

The following six cities have been chosen as simulation sites: Boston, MA; Fort Worth, TX; Miami, FL; Nashville, TN; Phoenix, AZ; and Seattle, WA. These cities possess a wide range of climates and therefore offer the opportunity to evaluate the performance of various TES/Heat Pump configurations under a wide range of operating constraints.

The choice of sites has been based primarily on weather data provided through the SOLMET Typical Meteorological Year (TMY) weather tapes and work completed by the General Electric Corporation. The TMY data consists of hourly weather information for 26 cities across the United States for a "typical" year. This typical weather year was developed using data that had been collected over a number of years for each of the 26 sites. Using these weather data, the number of annual heating and cooling degree-days for each of the 26 sites was then computed.

Each of these sites was then identified as being within one of 12 climatic regions of the continental United States. These regions were defined by the General Electric Corporation (Ref. 3) in a study entitled "Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems." Simulation sites were then chosen based on location and the extremes in climatic conditions as given by the heating and cooling degree-days.

Building Design

The TRNSYS model requires only a general description of the design itself; however, detailed information dealing with the construction, orientation, and insulation levels of the building must be defined. The building design, orientation, and construction will be the same for each of the sites; however, insulation levels will be varied in order to characterize existing practices in various regions of the country.

The basic building design will consist of a rectangular, single story, 140 m^2 (1500 ft.^{2}) wood panel residence with a full basement. Although this design is not necessarily representative of that to be found at all of the simulation sites, it does offer a reasonable and justifiable approximation to the design that might exist at each site.

TES/HEAT PUMP SIMULATION

The approach to be utilized in modeling the TES/Heat Pump system is based on balancing mass and energy flows within the refrigeration cycle. The method to be used follows the same general procedures suggested by Oak Ridge National Laboratory (Ref. 4). This procedure is as follows:

1. assume values for the thermodynamic states at various points within the cycle;
2. find the flow balance conditions for these assumed thermodynamic states using compressor and capillary tube performance data;
3. for these flow balance conditions use evaporator and condenser performance data to arrive at new thermodynamic states; and
4. continue until agreement is reached.

Manufacturer's component performance data will be used for heat exchangers, compressor and expansion valves while a simple TES subsystem will be modeled in order to compute storage subsystem performance.

TES/Heat Pump Configurations

The six TES/Heat Pump configurations to be considered are classified depending upon the method used to discharge the TES subsystem. Direct systems are discharged by the transfer of heat between the storage material and the indoor air stream, while indirect systems are discharged by using the TES subsystem as a low temperature sink (cooling) or high temperature source (heating) for the heat pump. All six configurations involve charging the TES subsystem within the refrigeration cycle of the heat pump by using the storage subsystem as either an evaporator or condenser as appropriate.

Figures 1 and 2 show schematically two of the six configurations which are being considered. Figure 1 is a representation of an indirect system that stores thermal energy for use only in the heating mode. The system operates as a conventional heat pump during cooling. During the charging cycle the TES subsystem acts as a condenser, while at the same time storing energy by means of the change of phase of the storage material from solid to liquid. During discharge, the TES subsystem then behaves as an evaporator for the heat pump cycle and rejects heat to the refrigerant by means of the change of phase from liquid to solid. This system offers the advantage of providing a relatively high temperature source for the heat pump with the exact source temperature depending upon the melt temperature of the storage material. A direct system used for storage heating would be charged by maintaining the storage temperature at a level that could be used for direct heating (40-60°C).

Figure 2 is a schematic of an indirect TES/Heat Pump system used for cooling purposes. The system operates as a conventional heat pump during heating operation. During the cooling season the storage subsystem is charged by converting the storage material from a liquid to a solid by allowing the TES subsystem to act as an evaporator. The subsystem is then discharged by reversing this process. This system effectively increases the efficiency of the heat pump cycle by allowing the TES subsystem to act as a low temperature sink for the heat pump during discharge operation. A direct system used for storage cooling would be charged by maintaining the storage temperature at a level that could be used for direct cooling (-1-10°C). A complete list of the configurations to be considered is given in Table 1.

TES Subsystem

Three basic criteria for the selection of a TES subsystem are: 1) the subsystem must have the capability to transfer heat between the storage material and refrigerant (charging or indirect discharging), 2) the subsystem must possess the capability to transfer heat between the storage material and air (direct discharging) and 3) the subsystem must be able to treat the humidification problems associated with space cooling.

All of these criteria may be addressed using the designs shown in Figures 3 and 4. Rectangular volumes containing the storage material will be stacked in the storage subsystem. Sandwiched between these volumes will be refrigerant coils. Since these coils will not require the entire volume between the storage containments, air will be passed through these spaces to allow for direct discharge. A closed form solution for the resulting melting and solidification problem has been found by Edwards (Ref. 5) and will be used to develop performance curves for the storage subsystem. This procedure allows for a stepwise solution along the length of the subsystem for both the melt/freeze and the refrigerant (air) side heat transfer problems.

Although the parameters to be considered in developing performance curves have not as yet been determined, entering refrigerant (air) temperature, refrigerant (air) flow rate, thickness of the storage material, and length of the subsystem appear to be of prime importance in determining both the rate of heat transfer and the total storage capacity.

TES/Heat Pump System Performance

TES/Heat Pump system performance will be determined for each site by interfacing together the thermal loads computed using TRNSYS and the refrigeration cycle performance for each configuration. For each electricity rate structure system control strategies will be developed that will define the operating strategy for each configuration. The intent of these control strategies will be to minimize system life cycle cost by charging and discharging the TES subsystem at the most opportune times. For each combination of simulation site and rate structure considered, various TES/Heat Pump systems will be optimized to determine that combination of component sizes that minimizes life cycle costs. These optimized systems will then be ranked based on life cycle cost and specific performance factor for each combination of simulation site and rate structure considered.

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Table 1. TES/Heat Pump Configurations

Option	Melt Temperature (°C)	Heating Operation	Cooling Operation	Storage System Use
1	$40 \le T_m \le 60$	Heat Pump/ Direct Heating	Heat Pump	Direct space heating
2	$-1 \le T_m \le 40$	Heat Pump/ Indirect Heating	Heat Pump	High temperature source for heat pump during heating
3	$-1 \le T_m \le 10$	Heat Pump	Heat Pump/ Direct Cooling	Direct space cooling
4	$10 \le T_m \le 27$	Heat Pump	Heat Pump/ Indirect Cooling	Low temperature sink for heat pump during cooling
5	$-1 \le T_m \le 10$	Heat Pump/ Indirect Heating	Heat Pump/ Direct Cooling	High temperature source for heat pump during heating -- Direct Space cooling in cooling mode
6	$-1 \le T_m \le 27$	Heat Pump/ Indirect Heating	Heat Pump/ Indirect Cooling	High temperature source for heat pump during heating -- Low temperature sink for heat pump during cooling

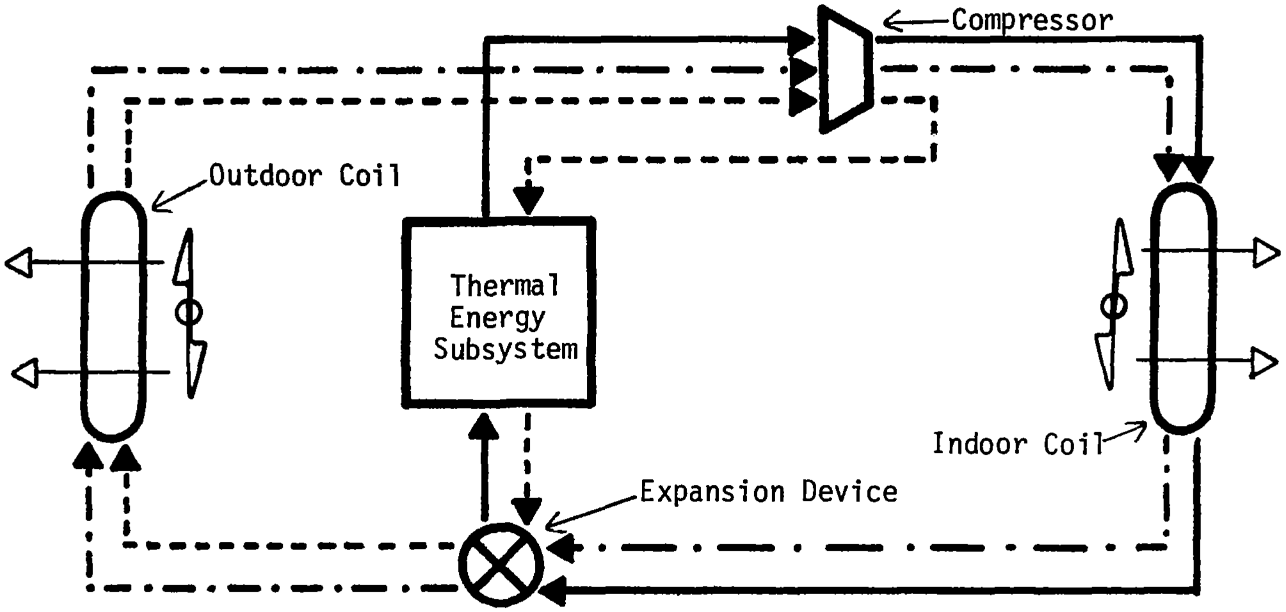

Figure 1. Indirect TES/Heat Pump Configuration (Storage Heating Only)

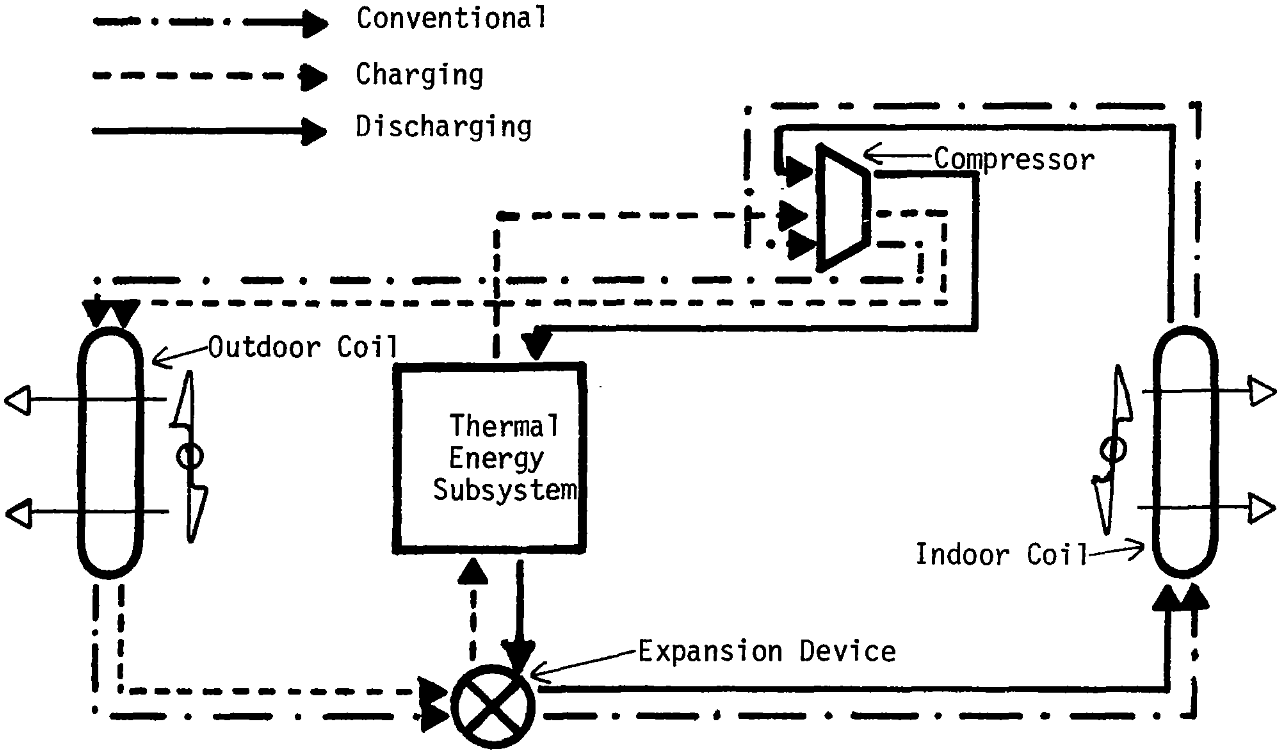

Figure 2. Indirect TES/Heat Pump Configuration (Storage Cooling Only)

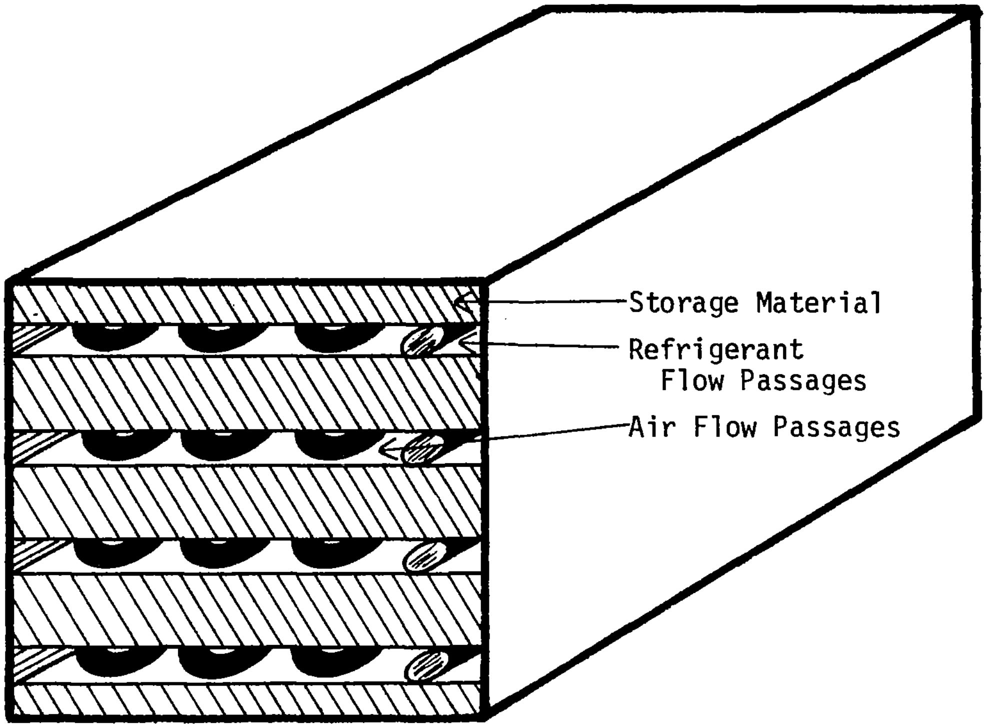

Figure 3. TES Subsystem Design

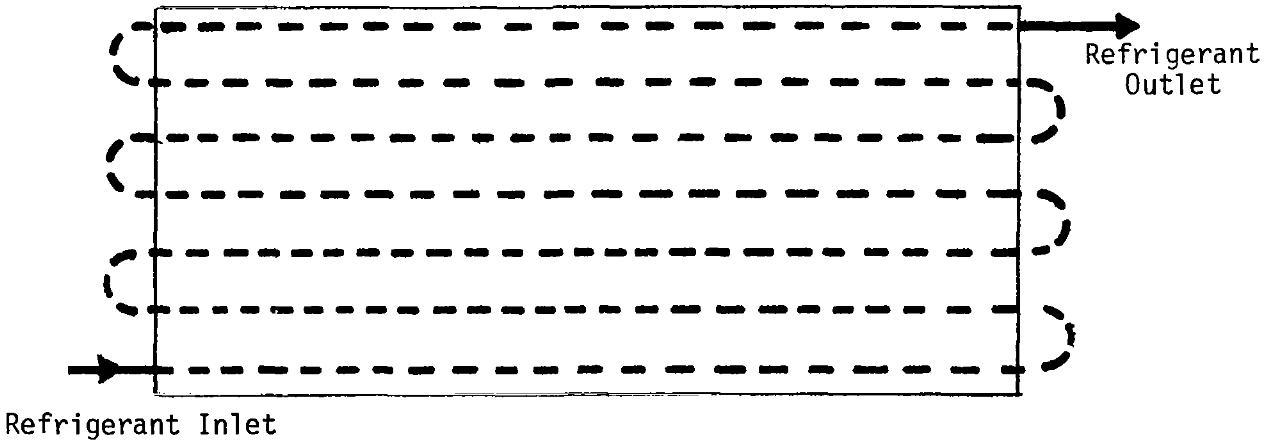

Figure 4. TES Subsystem Design (Top View)