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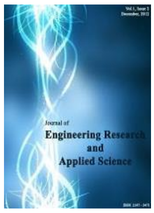

Performance of solar assisted parallel and series heat pump systems with energy storage for building heating

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Abstract
With rising energy costs and an increasing demand for renewable energy sources, thermal energy storage (TES) systems are becoming an interesting option. TES is a key component of any successful thermal system and a good TES should allow minimum thermal energy losses. The use of a latent heat storage system using phase change materials (PCMs) is an effective way of storing thermal energy. Latent heat storage enables high-energy storage density which reduces the footprint of the system and the cost. However, PCMs have very low thermal conductivities making them unsuitable for large-scale use without enhancing the effective thermal conductivity. On the other hand, solar energy systems and heat pumps are two promising means of reducing the consumption of fossil energy sources and potentially, the cost of delivered energy for refrigeration and air conditioning purposes. In this study, the performance of solar assisted parallel and series heat pump systems with latent heat energy storage for residential heating applications was investigated theoretically.
Keywords: Energy storage, solar assisted series and parallel heat pumps; residential heating.

1. Introduction

Heat pumps have a tremendous potential to bring renewable heating into houses. Because heat pumps are electricity-driven, there is a direct interaction with other energy demands within the built environment, such as PV panels. By using heat pumps in a flexible way, it is possible to better integrate these different electricity producing and consuming devices. This helps the energy supply to be more reliable, with a higher share of renewable input. On the other hand, the combination of a heat pump and solar energy system would appear to alleviate many of the disadvantages that each has when operating separately. During winter, the energy that could be collected by the solar system, but that would be too low in temperature to be useful for direct heating, may be used as a source for the heat pump. Because the solar collector storage system can supply energy at temperatures higher than the ambient outdoor air, the capacity and COP of the heat pump would increase over those for the heat pump alone, the peak auxiliary load requirement would be reduced, and the combined heating system would seem to operate more economically. The operation of the solar system at temperatures near or below room temperature would decrease the collector losses and allow more energy to be collected. The lower collection temperature might allow the use of collectors with one or no covers, and this would reduce the first cost from a conventional two-cover solar system. Finally, for those areas where warm temperatures occur during cloudy periods, the combined system might compensate for the reduced performance of the conventional solar system under cloudy conditions and the low capacity of the heat pump in cold weather [1-6].

2. Solar assisted heat pump system

Research and development in the solar-assisted heat pump (SAHP) field has been concerned with two basic types of systems: direct and indirect. In direct systems, refrigerant evaporator tubes are embodied in a solar collector, usually of the flat plate type. Research has shown that when the collector has no glass cover plates, the same collector surface can also function to extract heat from the outdoor air. The same surface may then be employed as a condenser, using outdoor air as a heat sink for cooling [7-12].

2.1. Parallel System

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As shown in Figure 1, the parallel system consists of a solar collector, a water-to-air heat exchanger, an air-sourced heat pump, a water-circulating pump, a storage tank, and other equipment. The parallel SAHP system is combining two main components: the solar system and the parallel heat pump system. In this system, the heat pump uses ambient air as an energy source while the water-to-air heat exchanger uses solar energy as a heat source, and they give their energies to the load one by one. Solar energy is used to meet as much of the heating requirement as possible. Thus, the total available energy of the system is the sum of the extracted energies from two different systems (the solar system and the heat pump).

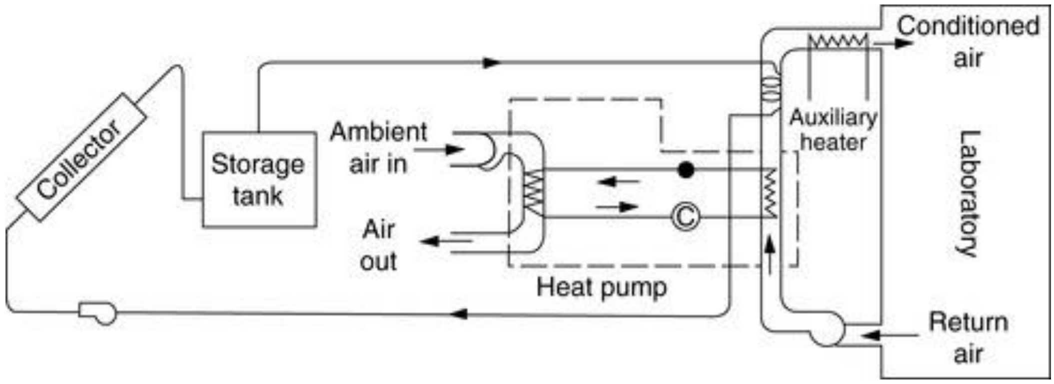

Figure 1. Parallel heat pump system.

2.2. Series System

Figure 2 shows a series SAHP system. The solar collector heats water, which is then stored in a tank. The tank provides heat directly to the house if the tank temperature is above 40°C, and the heat pump draws heat from the tank when the tank temperature is between 5 and 40°C. This system has the advantage that the tank can be operated at lower temperatures when required, allowing the collector to operate with high efficiency, and the tank heat storage capacity can be increased by the amount of sensible heat stored between 5 and 40°C. The disadvantage of the system is that when the tank temperature finally drops to 5°C, the heat pump cannot be used further without danger of freeze-up in the water tank. The system shown will not provide air conditioning because there is no way in which to exhaust the waste heat to outside air. It would be possible to provide air conditioning if there were another heat exchanger loop between the storage tank and outside air, but this would add to the cost of the heat exchanger and its associated circulating pump. A development effort is required on the heat pump in this system because residential heat pumps are not currently designed to operate efficiently with evaporator temperatures above 20°C, and this one would have to operate at up to 40°C.

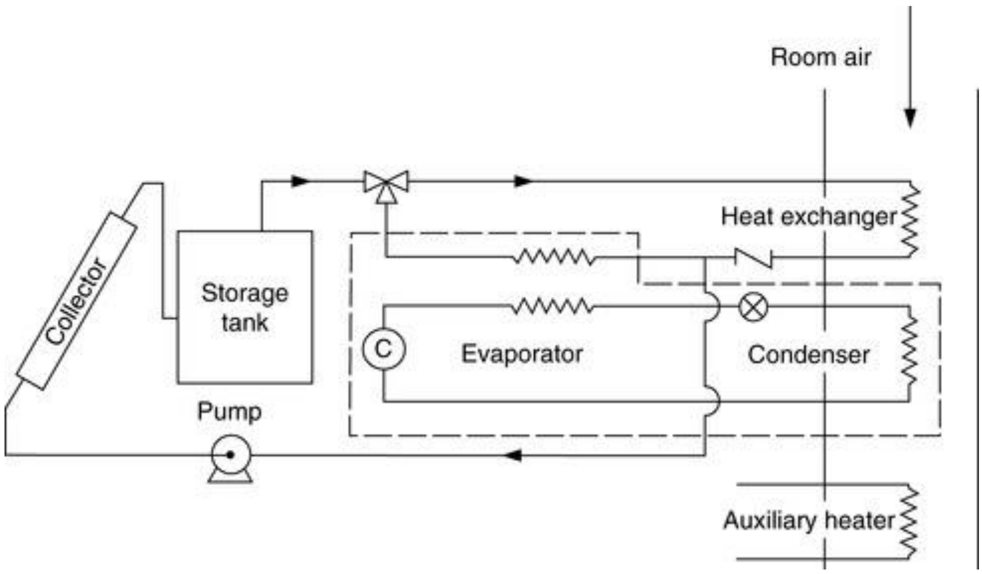

Figure 2. Series heat pump system.

2.4. Method of theoretical analysis

The complexity of the thermal analysis of solar-assisted heat-pump systems makes the use of computer simulations the only feasible method for determining the system dynamics and performance. These simulations were performed with the simulation program SOLSIM [13]. The solar system modeled is a conventional liquid-medium system. The collector parameters include F_R, b, $(\tau\alpha)_{eff}$ and $I_{s,ref}$. Insolation was chosen as a repeating, sinusoidally varying function, and, in this case, the time of sunrise, day length and peak insolation were specified. The heating load was specified as constant, given at each time. The storage capacity was specified and the storage was chosen as stratified according to the experimental results. Heat losses from the store are accounted for by specifying the overall thermal loss coefficient. The ambient temperature is modeled as a daily sinusoidal variation around an average ambient temperature. The SOLSIM required inputs are given in Table 1 [7].

Table 1. SOLSIM required inputs

Specific heat capacity of working fluid (J/kg.°C)	**4183**
Length of simulation (min)	900
Calculation interval (min)	15
Collector aperture area (m^2)	30
Value of $(\tau\alpha)_{eff}$	0.80
Value of a	0.0
Value of b	1.0
Value of F_R	0.9
Water mass flow rate at collectors (kg/min)	21.6
Value of $I_{s,ref}$ used in b (W/m^2)	800
Building heating load (J/h)	1.8x10^7
Water mass flow rate at load side (kg/min)	21.6
Thermal capacity of storage (J/K)	2.6x10^8
Initial temperature (K)	293
Minimum temperature to load (K)	293
Maximum allowed storage temperature (K)	312
Storage tank overall loss coefficient (W/m^2.°C)	0.250
Storage tank *L/D* ratio	2.46
Stratified latent heat storage (number of temperature layer)	3
Treated as sinusoidal around ambient average (K)	281
With a positive maximum swing (K)	12
Is a simple sine curve to be used ?	Yes
Maximum solar radiation (W/m^2)	800
Day length (sunrise-sunset) (min)	600
Time of sunrise (h)	07:00

The building used in the simulation is the laboratory, whose structural properties are given in Table 2. Table 3 gives the solar assisted series heat pump system parameters.

Table 2. Construction properties of the laboratory building

Window area (single glass, U = 4.8 W/m^2.°C)	**75 m^2**
Wall area (single brick, U = 1.6 W/m^2.°C)	60 m^2
Floor area (concrete, U = 2.5 W/m^2.°C)	75 m^2
Ceiling area (concrete & flat metal, U = 2.0 W/m^2.°C	75 m^2
Effective *UA* (kWh/°C)	0.800
Comfort temperature (°C)	22.0
Average degree days for heating season for Trabzon	1170
Average total heating load of the building for heating season (kJ)	3.64x10^7
Dimension of the building (m)	3.5 m x 6.0 m x 12.0 m
Volume of the building (m^3)	252 m^3

Table 3. Solar assisted series heat pump system parameters

Properties of solar collectors	
Number of glass covers	1
Thickness of glass cover	0.004 m
Refractive index	1.45
Collector plate absorptance	0.90
Collector emittance	0.85
Collector efficiency factor	0.85
Black and side losses	1.20 kJ/h.m^2.K
Mass flow rate	40 kg/h.m^2
Total collector area	30 m^2
Number of collectors	18
Heat pump information	
Capacity	5820 W
Compressor type	Hermetic
Evaporator type	Water-cooled shell and tube
Condenser type	Air-cooled copper tube
Evaporating temperature	7.2 ºC
Condensing temperature	54.4 ºC
Air mass flow rate in condenser	2420 m^3/h

The heat-pump's seasonal COP varies between the systems. The use of a solar source for the heat pump raises the seasonal COP over that of the conventional and parallel heat-pump systems. Table 4 shows theoretical performance of the solar-assisted parallel heat pump system for heating season. Table 5 also shows the theoretical performance of the solar-assisted series heat pump system for heating season.

Table 4. Theoretical performance of the solar-assisted parallel heat pump system for heating season

Months	**Number of working days of the SAPHPS**	**Heat Pump COP**	**Average outdoor Air temp. (ºC)**	**Solar Radiation (MJ/m^2.day)**	**Collector Efficiency (%)**	**Storage Efficiency (%)**	**Percent of heating load supplied by the SAPHPS (%)**
November	30	2.94	14.4	6.24	52	56	80
December	30	2.92	10.2	4.74	54	58	76
January	30	2.82	6.6	5.12	55	62	50
February	28	2.72	5.2	8.06	50	60	40
March	30	2.86	7.2	6.94	54	64	76
April	30	3.00	11.6	11.84	56	66	86
May	12	3.14	15.8	16.62	62	68	92

SAPHPS: Solar Assisted Parallel Heat Pump System

Table 5. The theoretical performance of the solar-assisted series heat pump system for heating season

Months	**Number of working days of the SASHPS**	**Heat Pump COP**	**Average outdoor Air temp. (ºC)**	**Solar Radiation (MJ/m^2.day)**	**Collector Efficiency (%)**	**Storage Efficiency (%)**	**Percent of Heating load Supplied by the SASHPS (%)**
November	21	4.44	14.4	6.24	62	62	62
December	14	4.34	10.2	4.74	62	64	46
January	16	4.30	6.6	5.12	64	66	50
February	20	4.24	5.2	8.06	66	66	52
March	22	4.34	7.2	6.94	68	68	66
April	24	4.60	11.6	11.84	70	68	72
May	10	4.80	15.8	16.62	68	67	82

SASHPS: Solar Assisted Series Heat Pump System ; COP: Coefficient of performance for heat pump

3. Conclusions

This study analyzed the performance of solar assisted series and parallel heat pump with energy storage for residential heating by using SOLSIM computer simulation program. In the theoretical study, over the heating season, the mean value of COP, the number of operating days per month, the percentage of building heating load met by the solar assisted systems, the average collector and storage efficiencies of the parallel and series heat pump systems have been deduce from obtained data and given in Table 4 and 5. The following conclusions were obtained:

- The parallel system saved 10120 kWh and the series system saved 9390 kWh net energy all per heating season for described laboratory building at Trabzon climatic conditions.
- The solar system is not suitable on its own for heating the laboratory building for given technical and climatic conditions, because the region has many cloudy days.
- It is also important to take into account pumping costs within the primary energy analysis, as increased pumping costs may reduce the financial advantages of a dual source system, particularly in mild climates.
- From the theoretical study, it was concluded that heat storage is an important component in moderate climatic conditions such as those encountered in Trabzon and for this purpose, $CaCI_2.6H_20$ can be used as the PCM in the energy storage tank. The PCM stores energy as latent heat at a nearly constant transition temperature (during charge and discharge), so it is preferable as an energy storage material to water or rock storage for the solar-assisted heat-pump systems in the region,
- Solar and heat pump systems is a combined technology that can take a market share in the segment of building heating and cooling since it carries some advantages: high renewable energy share, lower electricity demand, lower primary energy demand, lower CO_2 emission depending on the electricity mix feeding the heat pump. Market share of solar heat pump systems could reach 100 % of new houses in many countries where heat pump technology is well implanted and solar is mandatory for domestic hot water.
- Combining solar and heat pump technologies is relevant in several aspects: a high renewable fraction can be achieved and the safety of the solution makes it a good choice for many homeowners. The solar heat can help enhance the performance of the heat pump by raising the evaporation temperature. And the solar heat can be stored at low temperatures (0-80 °C) thus making good use of the collectors even during the cloudy days or at night. It is possible use of the latent heat of 2.0 m^3 of $CaCl_2.6H_2O$ melted/solidified around 32 ºC for heating applications.
- In the long term, solar heat pump could take a significant market share in all solar energy rich countries such as Turkey. Solutions including solar PV could develop and expand for net zero houses and positive energy houses. The components are mature; the combination of solar and heat pump needs however international R&D work to better understand the optimal configurations under several criteria. Solar and heat pump systems can be deployed for both small and large systems. There is no limitation of size in such a combination. Solar and heat pump combination offers many advantages for the developing market, such as.

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