Performance of ground source residential heat pumps

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Systems description

Monitoring of 2 vapor compression heat pumps in 2 single-family houses during 2 years.

R22 direct expansion systems with ground source and house floor sink. Small electrical heaters in bathroom and bedrooms (table 1).

	Pump #1	Pump #2
Evaporator depth (m)	0.6	0.6
Evaporator surface area (m^2)	75	125
Condenser length (m)	250	377
Condenser surface area (m^2)	75	85
House heat loss flow rate @ -10 °C (W)	7070	9620

Table 1: systems description

Performance measurement and computation methods

Values to be monitored: heat flow (Φ_{COND}), compressor electrical power (Po_{ELCOMP}), COP.

Measurements: pressures (P), temperatures (T) and volumetric flow rate of refrigerant (q_V), compressor and electrical heaters power (Po_{ELCOMP}, $Po_{ELBEDROOMS}$, $Po_{ELBATHROOM}$), ground, indoor and outdoor temperatures (T) (figures 1 and 2).

Measurements are performed every second, averaged over one minute and stored in a data logger for further analysis. Measurement uncertainty is about 5%.

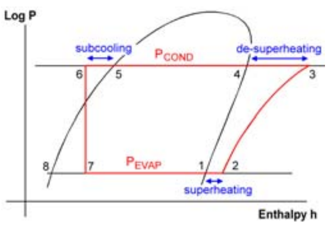

Figure 1: refrigerant cycle

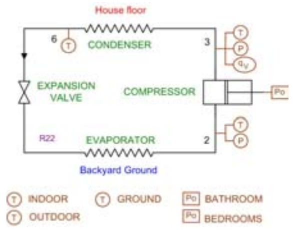

Figure 2: measurements

Heat flow rate (Φ_{COND}) and COP are computed as:

$$\Phi_{COND} = q_V\, \rho(T_3, P_3)\, [h(T_3, P_3)-h(T_6, P_3)]$$

$$COP = \Phi_{COND} / Po_{ELCOMP}$$

Further calculations are performed to obtain:

- daily values: total heat (Q_{DAY}), total electrical consumption of the compressor (E_{DAY}) and average COP (COP_{DAY}).

- annual values (September to May): total heat (Q_{YEAR}), total electrical consumption of the compressor (E_{YEAR}) and seasonal COP (SCOP)

Results

COP daily performance results are presented in figures 3 and 4.

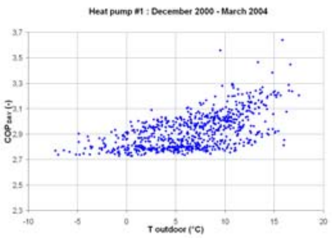

Figure 3: daily COP values for heat pump #1

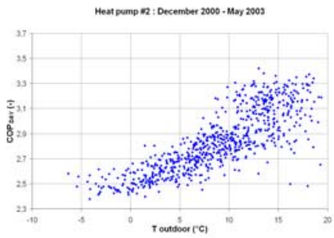

Figure 4: daily COP values for heat pump #2

Annual results are presented for three (pump #1) and two heating seasons (pump #2) (table 2).

For a comparison of different years, the total amount of degree-days (15/15) is also given.

Heat pump running costs are based on average Belgian market prices: 0.16 Eur/kWh (peak) and 0.08 Eur/kWh (off-peak) for electricity.

As a comparison, running costs for the same amount of heat using electrical heaters, fuel oil and natural gas burners are also presented, based on burner efficiencies of 0.9 and on Belgian fuel market prices: 0.043 Eur/kWh (fuel oil) and 0.035 Eur/kWh (natural gas).

	Pump #1			Pump #2	
Period	Feb2001-Jan2002	Feb2002-Jan2003	Feb2003-Jan2004	Feb2001-Jan2002	Feb2002-Jan2003
E_{YEAR} (kWh)	3806	3445	3689	7084	6655
Q_{YEAR} (kWh)	11270	9938	10331	19076	18426
Degree-days (-)	1955	1863	2116	1955	1863
SCOP (-)	2.96	2.88	2.80	2.69	2.77
Off-peak perc. (%)	63	63	63	46	46
Cost HP (Eur)	417	378	404	873	820
Cost Gas (Eur)	438	386	402	742	717
Cost Fuel Oil (Eur)	539	476	494	913	882
Cost Elec (Eur)	1235	1089	1132	2350	2270

Table 2: annual performance

Pump 1 has a SCOP of about 2.9 while pump #2 has a lower value of about 2.7. This difference can be explained by the fact that the floor was a tiling floor for pump #1 and a parquet floor for pump #2. The use of parquet floor leads to a higher condensation temperature.

The differences in the costs are due to the differences in the off-peak percentages and the heat demand of the houses. Both pumps ran about 2700 hours per year (30% of the time).

Ground source heat pump behavior

For a given heat pump system, the thermodynamic cycle is well-defined and changes slowly with time. The two most important values, which change over one year, are T_{EVAP} and T_{COND}. The performance of the heat pump depends only on these temperatures and is usually published in tables or charts (figure 5).

T_{EVAP} is linked to the ground temperature T_{GROUND} and T_{COND} is linked to the floor temperature T_{FLOOR} through the performance of the heat exchangers. Moreover T_{FLOOR} is related to T_{INDOOR} and T_{GROUND} is related to weather conditions (mainly $T_{OUTDOOR}$). If the LMTD across the heat exchangers can be assumed constant, we obtain behavior curves depending on T_{GROUND} and T_{INDOOR} similar to those depending on T_{EVAP} and T_{COND} (figure 6).

T_{INDOOR} is usually kept around 20 °C.

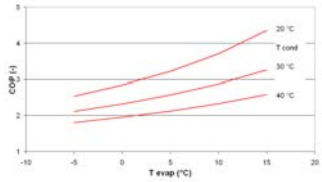

Figure 5: COP versus T_{EVAP} and T_{COND} for a typical heat pump

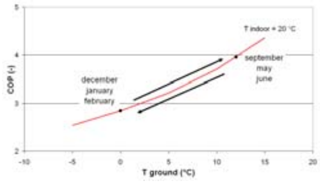

Figure 6: COP versus T_{EVAP} and T_{COND} for a typical ground source heat pump

Results analysis

Figure 7 presents measured COP_{DAY} values and computed ones for heat pump #1 from Sept 2001 to May 2002 as a function of day-average T_{EVAP} and T_{COND}.

The dispersion of the points during winter, when the temperature of the ground is stable (◊) is due to the variation of the condensation temperature even with constant indoor temperature. This variation is related to the duration of one heating cycle of the heat pump: when the pump is running, the floor becomes warmer because of the thermal inertia of the concrete in the floor.

Thermal inertia causes T_{COND} to increase and COP to decrease but allows the storage of heat during the night, when electricity is cheaper. A balance must be found between energy performance (COP) and economical performance (running costs).

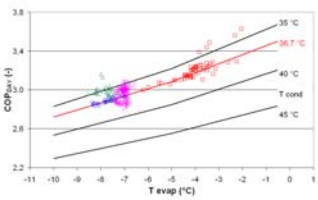

Figure 7: computed and measured COP_{DAY} versus T_{EVAP} and T_{COND} (□: autumn; ○: early winter; ◊: winter; Δ: spring)

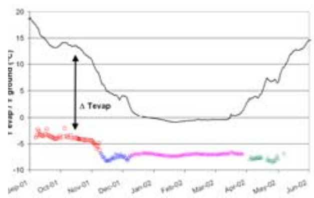

Figure 8: T_{EVAP} (□: autumn; ○: early winter; ◊: winter; Δ: spring) and T_{GROUND} (-) over one year

T_{EVAP} is related to T_{GROUND} through the quality of the heat exchanger in the ground. Experimental values show that the LMTD in this heat exchanger is not constant over the year (figure 8).

Complex heat transfer phenomena occur in the ground:

-compact soil in autumn due to rain during summer and autumn (heat transfer increase)

-ground partially frozen in winter (good heat transfer)

-melting of ice creating “voids” in the soil during spring (bad heat transfer).

T_{COND} is correlated with the running percentage of the heat pump over one day due to the heating up of the floor with the duration of one heating cycle (figure 9).

This running percentage is also correlated with the thermal losses of the house, proportional to the difference between $T_{OUTDOOR}$ and T_{INDOOR} (figure 10).

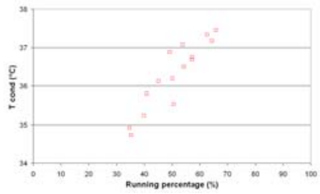

Figure 9: T_{COND} versus running percentage of the heat pump for a constant T_{EVAP}

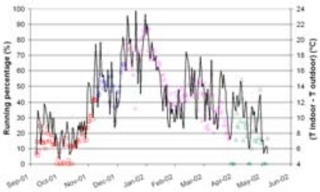

Figure 10: Running percentage of the heat pump (□: autumn; ○: early winter; ◊: winter; Δ: spring) and heat demand over one year (-)

Conclusions

Q_{YEAR} depends on the thermal losses of the house and can be evaluated with thermal building software like TRNSYS. E_{YEAR} can then be computed if COP values are known. These last values depend on T_{EVAP} and T_{COND} and can be evaluated only by modeling the heat transfer in the heat exchangers.

This modeling is quite complex for the ground as well as for the floor.