Performance measurement and modeling of air source residential heat pumps

POLYTECH.MONS

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System description

Monitoring of 1 vapor compression heat pump in a single-family house during 1 year.

Uses R407C with static air evaporator (20 m² finned tubes) and plate condenser.

Heating through a water loop in the floor. No electrical heaters, a second compressor switches on when $T_{OUTDOOR}$ is below -5 °C.

Performance measurement and computation methods

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

Measurements: pressures (P), temperatures (T) and volumetric flow rate of refrigerant (q_{VREF}), temperatures (T) and volumetric flow rate of water (q_{VW}), compressor and auxiliary water pump electrical power (Po_{ELCOMP}, Po_{ELAUX}), indoor and outdoor temperatures (T) (figures 1 and 2).

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

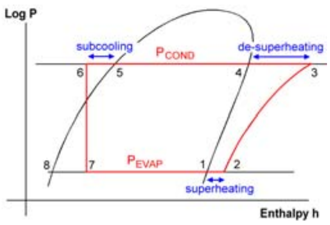

Figure 1: refrigerant cycle

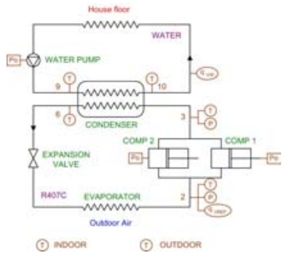

Figure 2: measurements

Heat flow rate (Φ_{COND}) and COP (compressor or heat pump) are computed as:

$\Phi_{COND} = q_{VREF}\ \rho(T_2, P_2)\ [h(T_3, P_3)-h(T_6, P_3)] = q_{VW}\ c_{PW}\ (T_{10} - T_9)$

$COP_{COMP} = \Phi_{COND} / Po_{ELCOMP}$

$COP_{HP} = \Phi_{COND} / (Po_{ELCOMP} + Po_{ELAUX})$

Further calculations are performed to obtain:

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

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

Results

COP daily performance results are presented in figure 3. Annual results for one heating season are presented in table 1.

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).

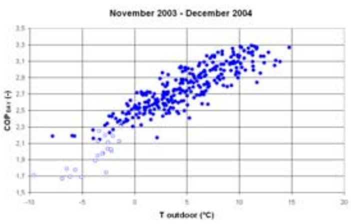

Figure 3: daily COP values(●: one compressor; ○: two compressors)

Nov 2003 – Oct 2004	
E_{YEAR} (kWh)	6453
Q_{YEAR} (kWh)	16737
Degree-days (-)	1955
SCOP (-)	2.59
Off-peak perc. (%)	78
Cost HP (Eur)	630
Cost Gas (Eur)	651
Cost Fuel Oil (Eur)	801
Cost Elec (Eur)	1634

Table 1: annual performance

Daily performance modeling

For a heat pump system, the thermodynamic cycle is well-defined (figure 1). Its characteristics, determined from measurements, are:

superheating (ΔT_{SH}), subcooling (ΔT_{SC}), iso-s efficiency (η_{ISOS}) and electrical efficiency (η_{EL}) of the compressor, pressures (P_{EVAP} and P_{COND}).

With these parameters, it is possible to calculate density (ρ), entropy (s) and enthalpy (h) values and therefore Φ_{COND} and Po_{ELCOMP}.

For the computation of daily values Q_{DAY} and E_{DAY}, four sets of parameters are needed:

- Set 1: ΔT_{SH}, ΔT_{SC}, η_{ISOS} and η_{EL} (cycle parameters)
- Set 2: P_{EVAP} and P_{COND} (source-related parameters)
- Set 3: q_{VREF} (compressor characteristics)
- Set 4: running time of the heat pump over one day τ_{DAY}

Sets 1-3 are averaged to define a day-average cycle and day-average parameters, in order to compute Q_{DAY} and E_{DAY}:

$Q_{DAY} = \tau_{DAY}\ q_{VREF}\ \rho_2\ (h_6 - h_3)$

$E_{DAY} = \tau_{DAY}\ [q_{VREF}\ \rho_2\ (h_3 - h_2)]/\eta_{EL}$

The day-average cycle replaces all the running cycles of the heat pump. Its duration is the sum of all cycle durations over one day. Q_{DAY} and E_{DAY} values computed with day-average parameters are compared with measured ones in figures 4 and 5.

The average error on Q_{DAY} is 1.1% and on E_{DAY} is 1.6%, lower than measurement uncertainty.

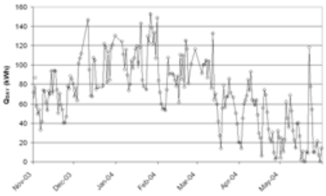

Figure 4: Q_{DAY} measurements (◊) and computed values with day-average cycle (-)

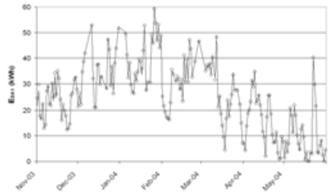

Figure 5: E_{DAY} measurements (◊) and computed values with day-average cycle (-)

Annual performance modeling

Cycle parameters (set 1) change slowly with time and are quite constant during a whole year. Day-average cycle parameters (set 1) for each day of a whole year can be computed by three methods:

- model 1: uses measured day-average parameters (see above)

- model 2: correlates measured day-average parameters with P_{EVAP} over one year and uses the correlation. P_{COND} is not used because it has few variations over the year

- model 3: averages measured cycle parameters over one year and assumes them constant.

Models 1-3 use measured day-average P_{EVAP}, P_{COND}, q_{VREF} and τ_{DAY} to compute Q_{YEAR}, E_{YEAR} and SCOP for the period Nov 2003 to May 2004 (table 2).

	Q_{YEAR} (kWh)	Error Q_{YEAR} (%)	E_{YEAR} (kWh)	Error E_{YEAR} (%)	SCOP (-)	Error SCOP (%)
Meas.	13092	/	4683	/	2.80	/
Model 1	13061	-0.2	4671	-0.3	2.80	0.0
Model 2	12968	-1.0	4713	+0.6	2.75	-1.6
Model 3	12910	-1.4	4588	-2.0	2.81	+0.7

Table 2: annual performance – measurements and models

Model 3 gives accurate predicted results for Q_{YEAR}, E_{YEAR} and SCOP, with errors lower than measurement uncertainty.

This last model needs daily values for P_{EVAP}, P_{CCOND}, q_{VREF} and τ_{DAY}:

- q_{VREF} can be obtained from compressor characteristics. It depends mainly on the compression ratio: $q_{VREF} = q_{VREF}\ (P_{COND}/P_{EVAP})$ and is usually available

- τ_{DAY} depends on the thermal losses of the house and can be evaluated efficiently with software like TRNSYS. As a consequence, τ_{DAY} should be correlated to $T_{OUTDOOR}$

- P_{EVAP} (T_{EVAP}) is correlated to the heat transfer in the evaporator, and therefore to $T_{OUTDOOR}$

- P_{COND} (T_{COND}) is correlated to the heat transfer in the condenser, and therefore to T_{FLOOR}

A simple model (model 4) was created, which correlates P_{EVAP} and τ_{DAY} to $T_{OUTDOOR}$ (figures 6 and 7). P_{COND} was correlated with P_{EVAP} because the temperatures of the source and of the sink are related via the running time of the heat pump: low $T_{OUTDOOR}$ yields high heat demand and therefore a warmer floor.

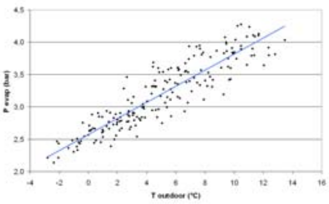

Figure 6: correlation between P_{EVAP} and $T_{OUTDOOR}$ for one year measurements

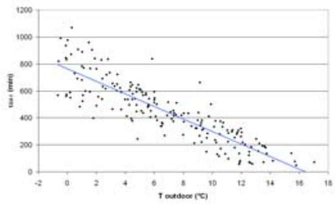

Figure 7: correlation between τ_{DAY} and $T_{OUTDOOR}$ for one year measurements

With these correlations and the compressor characteristics, we computed all day-average values using constant parameters obtained in model 3. Results are given in figures 8 and 9 for daily performance and in table 3 for annual performance.

	Q_{YEAR} (kWh)	Error Q_{YEAR} (%)	E_{YEAR} (kWh)	Error E_{YEAR} (%)	SCOP (-)	Error SCOP (%)
Meas.	13092	/	4683	/	2.80	/
Model 4	13741	+5.0	4887	+4.3	2.81	+0.6

Table 3: annual performance – measurements and model 4

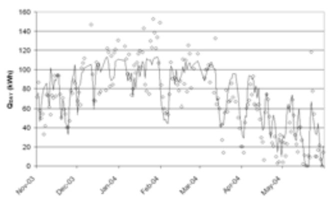

Figure 8: Q_{DAY} measurements (◊) and computed values with model 4 (-)

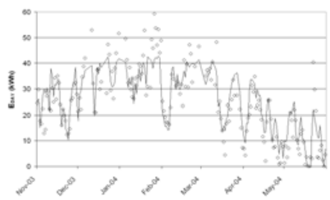

Figure 9: E_{DAY} measurements (◊) and computed values with model 4 (-)

Model 4 gives poor daily results but is quite accurate for annual results. The overestimation for the annual values is mainly due to overestimation of q_{VREF} with the compressor characteristics.

Conclusions

In order to compute annual performance, four sets of parameters are needed:

- set 1 and set 3 can be obtained by a few measurements or by processing manufacturer data

- set 2 and set 4 can be obtained with two methods: computation of thermal behavior of the heat exchangers and of the house, or by experimental correlations.