PERFORMANCE OF GROUND SOURCE RESIDENTIAL HEAT PUMPS

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ABSTRACT

This paper presents the results of two-year monitoring of two ground-to-floor residential heat pumps, typical of the Belgian market, used for space heating in single-family houses. Both systems are common-type vapor compression heat pumps and use ground as cold source, house floor as hot sink and R22 as refrigerant. Firstly, we present the measurement method to obtain daily COP values from instantaneous measurements on the refrigerant. Secondly, annual energy consumption, seasonal COP and costs are presented for a three-year (heat pump #1) and two-year period (heat pump #2). Seasonal COP values from 2.69 to 2.96 are obtained. Finally, daily COP values are correlated to evaporation and condensation temperatures, and the daily running time of the heat pump is correlated to the day-average outdoor temperature. Condensation temperatures, which vary from 35 to 38 °C, are well explained by the daily running time of the heat pump. Evaporation temperatures, which vary from -2 to -9 °C, are related to the ground temperatures in a complex way, depending on the heat transfer processes in the ground.

Key Words: ***heat pump, experimental measurements, seasonal COP, ground source.***

1 INTRODUCTION

Heat pumps are energy-efficient heating systems because they pump heat from a costless source to a useful sink, using less energy for pumping than the amount of heat released. Their efficiency, called coefficient of performance (COP) is always greater than 1. From an energetic and environmental (CO_2 production) point of view, heat pump is the best choice. From an economical point of view, its interest depends on the COP values. These values are usually given by manufacturers for standard working conditions. The real values for a heat pump system (heat pump installed in a given house) for one heating season are therefore very different from the published ones. Moreover, the same machine installed in different houses will give different COP values, because of the interaction of the machine with house characterized by its own thermal features.

The scope of this project is the measurement and the modeling of the performance of heat pumps installed in single-family houses in Belgium. The project is devoted to a two-year monitoring of nine heat pumps used for space heating and two heat pumps used for sanitary water heating [Frère et al. 2004]. The measurements began in January 2001 and will be finished in December 2006. They are sponsored by Electrabel, the main electrical power producer and supplier in Belgium. To date, 6 surveys are finished, and this paper is devoted to the analysis of the working behavior of two ground-to-floor heat pumps.

2 PERFORMANCE MEASUREMENTS

2.1 Heat Pumps and Houses Description

Both heat pumps are vapor compression heat pumps and use ground as cold source, house floor as hot sink and R22 as refrigerant. Evaporation takes place in the ground and condensation in the floor. The evaporator is placed at a depth of 0.6 m in the backyard soil (75 m^2 surface area for heat pump #1 and 125 m^2 for heat pump #2) and the condenser is placed in the concrete floor of the house (250 m length for 75 m^2 surface area for heat pump #1 and 377 m length for 85 m^2 surface area for heat pump #2). Small electrical heaters are placed in the bathroom and bedrooms. The first system is placed in a house which has a heat loss flow of 7070 W. The second house has a heat loss flow of 9620 W. These flows are calculated for a minimum outdoor temperature of -10 °C and for an indoor temperature of 22 °C. The variation of the average outdoor temperature in Belgium over one year (2001) is given in Fig. 1.

Fig. 1. Average outdoor temperature in Belgium (year 2001).

The source is the ground of the backyard, which is a "static" source. Its temperature is quite stable and varies slowly. The temperature levels depend on the presence of a heat pump in the ground. Without a heat pump, the temperature at a depth of 60 cm varies from 20 °C during summer to 6 °C during winter (14 °C span) while with a heat pump, this variation is 20 °C, from 20 °C during summer down to 0 °C during winter.

The sink is the house floor, which is also a "static" sink. Its temperature varies as a function of the duration of the heating cycle. The maximum surface temperature is limited to 28 °C for physiological reasons. The floor has a high thermal inertia which allows storage of heat during the night.

2.2 Measurement Method

The most important value to be monitored is the COP, which is defined as the ratio of the heat flow delivered by the condenser (Φ_{COND}) and the electrical power used by the compressor (Po_{ELCOMP}). For that purpose, the following measurements are performed on the refrigerant, based on a Rankine cycle (Figure 2): evaporation and condensation pressures (P_2 and P_3), temperatures (T_2, T_3 and T_6), volumetric flow of refrigerant (q_V) and Po_{ELCOMP}.

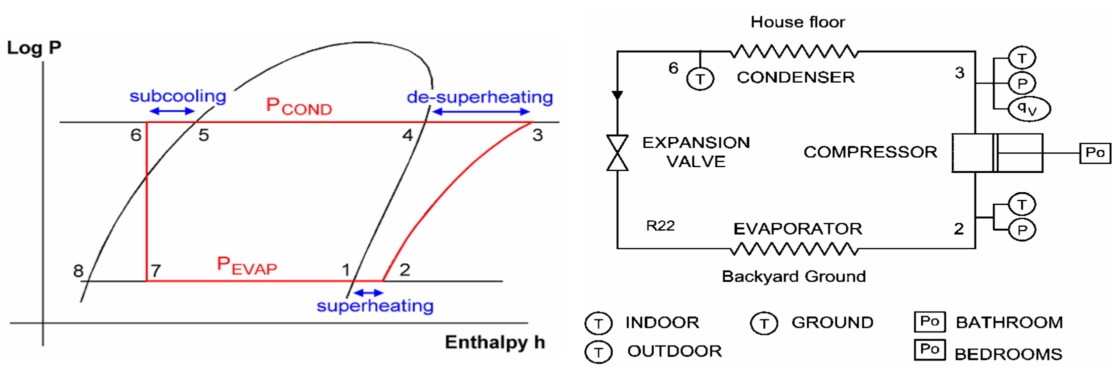

Fig. 2. Measurements performed on the heat pumps.

Other measurements are performed: electrical power of the electrical heaters located in the bathroom and in the bedrooms of the house ($Po_{EL\ BATHROOM}$ and $Po_{EL\ BEDROOMS}$), outdoor and indoor temperatures ($T_{OUTDOOR}$ and T_{INDOOR}) and ground temperature (T_{GROUND}).

All measurements are performed every second, then averaged over one minute and stored in a data logger for further analysis.

2.3 COP Calculation

The heat flow at the condenser (Φ_{COND}) and the instantaneous COP are computed as:

$$\Phi_{COND} = q_V\, \rho(T_3, P_3)\, [h(T_3, P_3) - h(T_6, P_3)] \qquad (1)$$

$$COP = \Phi_{COND} / Po_{ELCOMP} \qquad (2)$$

The saturation temperatures T_{EVAP} and T_{COND}, the superheating at the evaporator and the subcooling at the condenser can also be computed.

Further calculations are performed to obtain the total heat supplied by the heat pump over one day (Q_{DAY}), the total electrical consumption of the compressor (E_{DAY}) and the average COP over the day (COP_{DAY}). The sum of all daily values for one heating season (September to May) yields annual heat (Q_{YEAR}), electrical consumption (E_{YEAR}) and seasonal COP (SCOP) values.

3 RESULTS

3.1 Daily Performance Results

Measured COP values are shown on figures 3 and 4. Each point is a daily COP value (COP_{DAY}).

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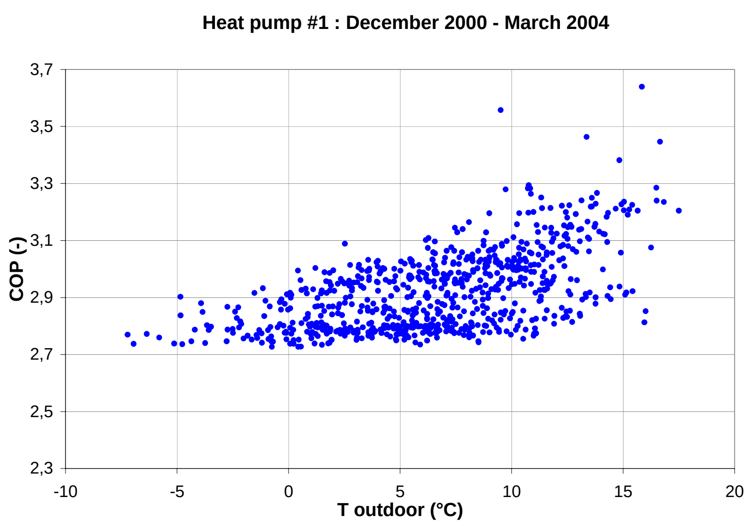

Fig. 3. Daily COP values for heat pump #1.

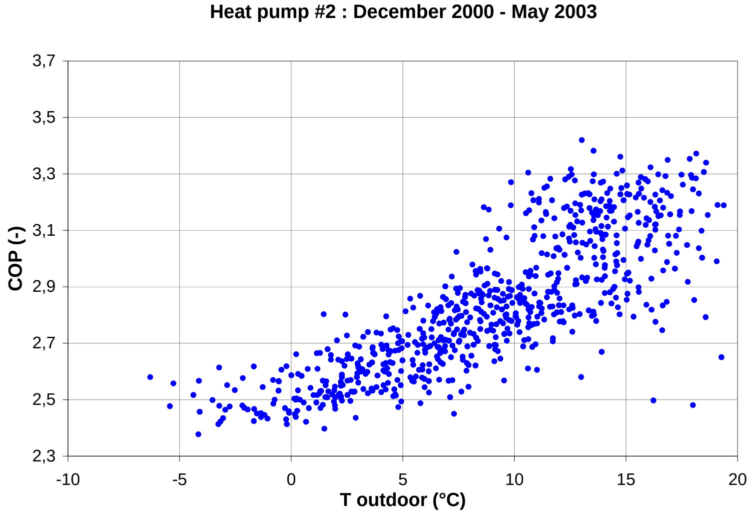

Fig. 4. Daily COP values for heat pump #2.

3.2 Annual Performance Results

Annual results for three (heat pump #1) and two heating seasons (heat pump #2) are presented in Table 1. In order to compare results for different years, the total amount of heating degree-days (15/15) is also given. Running costs depend on the moment of power consumption (peak or off-peak), the amount of off-peak electricity consumption is then given (off-peak percentage). The costs are based on average Belgian electricity market prices: 0.16 Eur/kWh (peak) and 0.08 Eur/kWh (off-peak). As a comparison, running costs for the same amount of released heat using electrical heaters, fuel oil and natural gas burners are also given. The last two costs are based on burner efficiencies of 0.9 and on Belgian fuel market prices (0.043 Eur/kWh for fuel oil, 0.035 Eur/kWh for natural gas).

Table 1. Measured annual performance.

	Heat pump #1			**Heat pump #2**	
Period	**Feb2001-Jan2002**	**Feb2002-Jan2003**	**Feb2003-Jan2004**	**Feb2001-Jan2002**	**Feb2002-Jan2003**
$\mathbf{E_{YEAR}}$ (kWh)	3806	3445	3689	7084	6655
$\mathbf{Q_{YEAR}}$ (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

We can see from Table 1 that heat pump #1 has a SCOP of about 2.9, while heat 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 parquet floor has a lower thermal conductivity and the condensation temperature is thus higher than the one of the tiling floor.

The costs are quite different, due to the differences in the off-peak percentage of the heat pumps (63% for pump #1 and 46% for pump #2) and the heat demand of the houses. Both heat pumps ran about 30% of the time (2700 h per year).

4 RESULTS ANALYSIS

4.1 Heat Pump Performance Behavior

For a given heat pump system, the thermodynamic cycle is well-defined (Fig. 2) and changes slowly with time. Usually, the superheating at the evaporator, the subcooling at the condenser and the efficiencies of the compressor can be assumed constant. 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:

$$\Phi_{COND} = f_1\ (T_{EVAP}, T_{COND}) \tag{3}$$

$$Po_{ELEC\ COMP} = f_2\ (T_{EVAP}, T_{COND}) \tag{4}$$

$$COP = f_3\ (T_{EVAP}, T_{COND}) \tag{5}$$

Equations (3) to (5) are usually published in tables or charts. Figure 5 presents the performance computed for a typical heat pump.

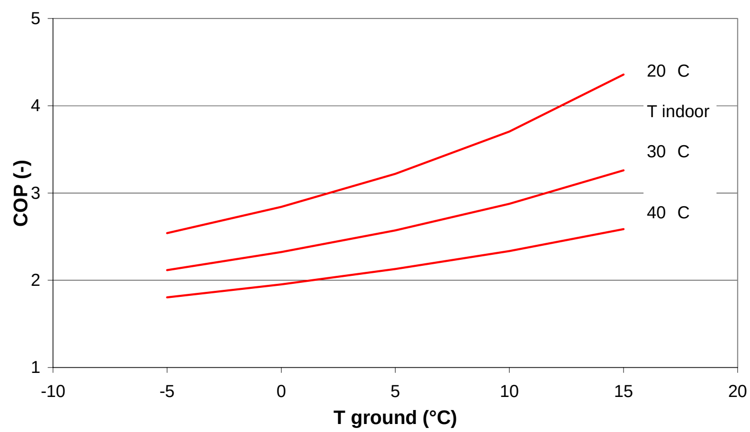

Fig. 5. computed COP versus T_{EVAP} and T_{COND} for a typical heat pump.

From Fig. 5, we can see that the COP decreases when the condensation temperature increases, as well as the evaporation temperature decreases. T_{EVAP} is linked to the ground temperature T_{GROUND} through the quality and performance of the heat exchanger in the ground and T_{COND} to the temperature of the floor T_{FLOOR} trough the quality and performance of the heat exchanger in the floor of the house. Therefore, for best operation, the ground temperature must be kept as high as possible and the floor temperature as low as possible. Moreover T_{FLOOR} is related to T_{INDOOR} and T_{GROUND} is related to the weather conditions (mainly $T_{OUTDOOR}$).

If we can assume the log mean temperature differences (LMTD) across the heat exchangers constant, we obtain heat pump behavior curves similar to those resulting from equations (3) to (5) with T_{INDOOR} and T_{GROUND} instead of T_{COND} and T_{EVAP}. As T_{INDOOR} is usually kept around 20 °C, we obtain one behavior curve depending on the temperature of the ground only. Figure 6 presents the performance of a typical ground-to-floor heat pump assuming constant LMTD values.

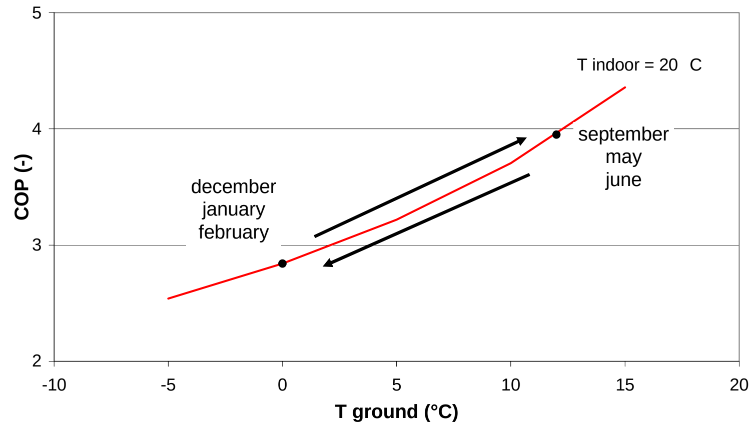

Fig. 6. Computed COP versus T_{GROUND} and T_{INDOOR} for a typical ground-to-floor heat pump.

From Fig. 6, we can see that the COP is high when the ground is warm (autumn, spring). This value is 30% lower during winter. The design of the heat pump (thermal power) must be realized for bad weather conditions, i.e. winter and for a cold ground. Concerning the SCOP, it will be close to the COP predicted for a cold ground because the heat pump runs mainly during winter.

4.2 Measurements 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}.

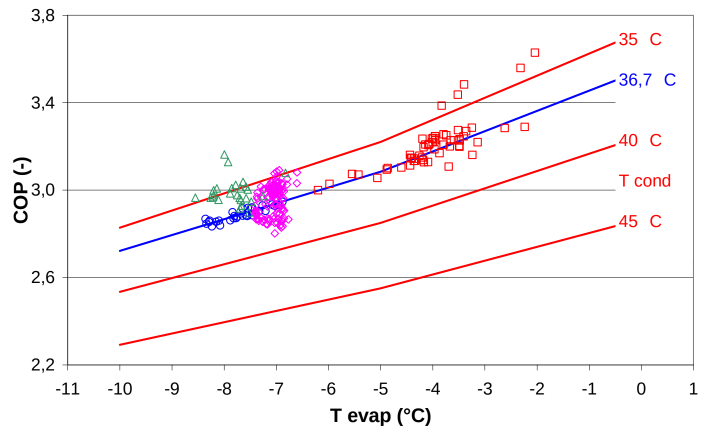

Fig. 7. Theoretical and measured COP versus T_{EVAP} and T_{COND}
(□: autumn; O: early winter; ◊: winter; Δ: spring).

It shows that T_{EVAP} varies from -2 °C to -9 °C and T_{COND} from 35 °C to 38 °C. The dispersion of the dots during winter, when the temperature of the ground is stable (◊) is due to the variation of the condensation temperature T_{COND} even with constant indoor temperature. This variation is related to the duration of the 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).

4.3 Evolution of T_{EVAP} and T_{COND}

T_{EVAP} is related to T_{GROUND} through the quality of the heat exchanger in the ground. The usual assumption is that the log-mean temperature difference across the exchanger is constant. Here, this difference is related to the difference between T_{GROUND} and T_{EVAP} (ΔT_{EVAP}). Experimental values show that ΔT_{EVAP} is not constant over the year (Fig. 8).

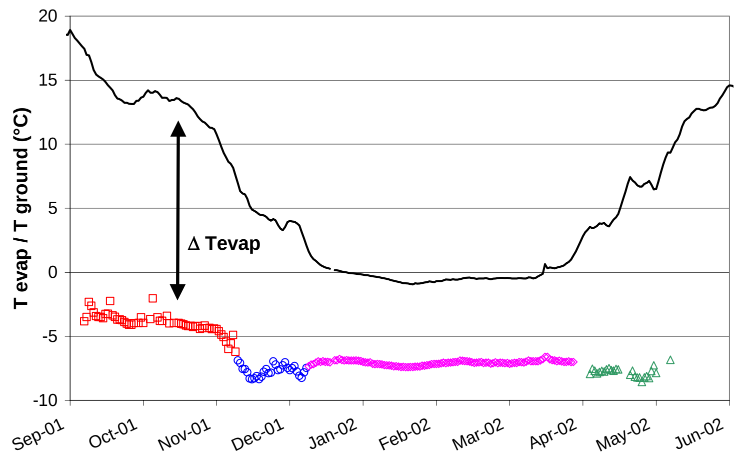

Fig. 8. T_{EVAP} (□: autumn; O: early winter; ◊: winter; Δ: spring) and T_{GROUND} (-) over one year.

This variation is due to complex heat exchange phenomena. The thermal transfer is better during winter when the ground is partially frozen (heat transfer by latent heat and soil more compact). During spring, the soil is less compact due to the melting of the ice and the voids left in the soil: its thermal conductivity decreases. In autumn, the soil becomes more compact due to the effect of rain in summer and autumn. Given ΔT_{EVAP} and T_{GROUND} varies in similar ways, the evaporation temperature variation over one year is low. This implies that the performance of a ground-to-floor heat pump is very stable.

As mentioned above, T_{COND} is not constant due to the heating up of the floor with the duration of the heating cycles over one day. T_{COND} is well-correlated with the running percentage of the heat pump over one day (Fig.9). This percentage is also correlated with the thermal losses of the house, proportional to the difference between $T_{OUTDOOR}$ and T_{INDOOR} (Fig.10).

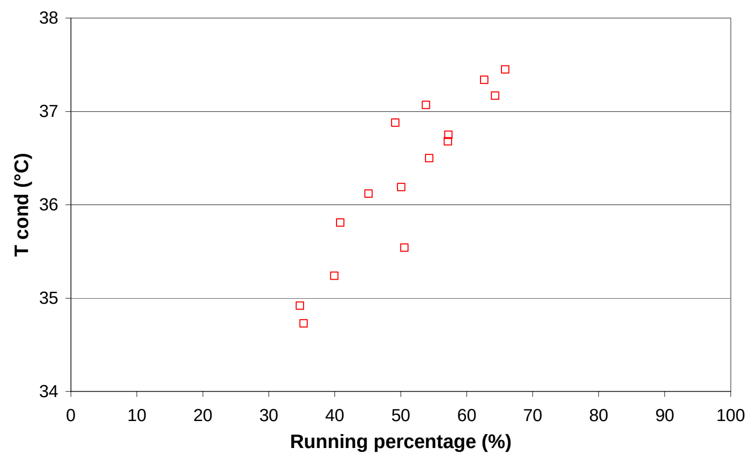

Fig. 9. T_{COND} versus running percentage of the heat pump for the same value of T_{EVAP}.

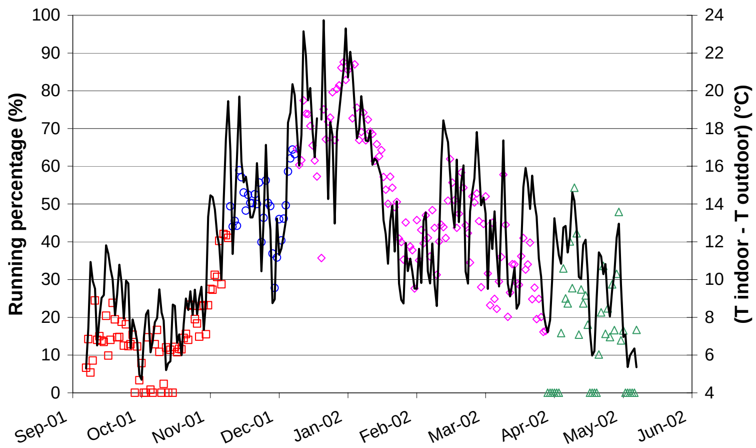

Fig. 10. Running percentage of the heat pump (□: autumn; O: early winter; ◊: winter; Δ: spring) and heat demand over one year (-).

The annual amount of heat Q_{YEAR} depends on the thermal losses of the house and can be evaluated efficiently with thermal building software like TRNSYS [Sautier et al. 2005]. The annual electrical consumption E_{YEAR} can then be computed if COP values are known. These values can be computed if T_{EVAP} and T_{COND} can be evaluated. These temperatures depend on the modeling of the heat exchangers, which is a complex task and is not straightforward to date. This modeling is the bottleneck to solve in order to predict SCOP values for a given heat pump.

5 CONCLUSIONS

The results of the monitoring of both heat pumps gave SCOP values ranging from 2.69 to 2.96. The analysis of these results gave a correlation between daily COP values and T_{EVAP} and T_{COND}. Condensation temperatures are well-explained with the daily running percentage of the heat pump, which is also correlated to the heat demand of the house. Evaporation temperatures are related to ground temperatures but in a complex way not easy to model to date.

6 NOMENCLATURE

COP	instantaneous coefficient of performance (-)
COP_{DAY}	daily coefficient of performance (-)
E_{DAY}	energy used by the heat pump over one day (kWh)
E_{YEAR}	energy used by the heat pump over one year (kWh)
h	specific enthalpy of the refrigerant (J kg^{-1})
P	pressure (bar)
P_{COND}	condensation pressure (bar)
P_{EVAP}	evaporation pressure (bar)
$Po_{EL\ BATHROOM}$	electrical power of the heater in the bathroom (W)
$Po_{EL\ BEDROOMS}$	electrical power of the heaters in the bedrooms (W)
$Po_{EL\ COMP}$	electrical power of the compressor (W)
Q_{DAY}	heat supplied by the heat pump over one day (kWh)
Q_{YEAR}	heat supplied by the heat pump over one year (kWh)
q_V	volumetric flow of refrigerant in the heat pump (m^3 s^{-1})
SCOP	seasonal coefficient of performance (-)
T	temperature (°C)

T_{FLOOR}	temperature of the heating floor in the house (°C)
T_{INDOOR}	indoor temperature of the house (°C)
T_{GROUND}	temperature of the ground at a depth of 0.6 m (°C)
$T_{OUTDOOR}$	outdoor temperature (°C)
ΔT_{EVAP}	difference between T_{GROUND} and T_{EVAP} at the evaporator (°C)
ρ	density of the refrigerant in the heat pump (kg m^{-3})
Φ_{COND}	heat flow released at the condenser (W)

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