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# Simplified ground-source heat pump models for predicting heat extraction

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**Abstract**

Simplified heat pump models are needed for design of ground heat exchangers used with ground-source heat pump systems. Design engineers commonly have only manufacturer's data with which to construct a heat pump model that can predict heat extraction given building heating load. Earlier work has used simple polynomials to predict the ratio of heat extraction to heating. Unfortunately, manufacturers' catalog data do not always provide sufficient support to calculate the polynomial coefficients. Therefore, in the absence of experimental data, there is a need for simplified and acceptably accurate models exploiting a limited number of operating points. This paper presents a study of available manufacturers' data in North American and European markets. The available data vary from country-to-country, depending on the standards in use in each country. Then, a range of models are investigated, characterizing the results by the required inputs and the root mean square error. Results show acceptable accuracy of the models when compared to catalog data and allow providing recommendations on models to be used or avoided, depending on the available data.



*Keywords: Ground-source heat pump; simplified models;*

## 1. Introduction

Ground source heat pumps (GSHPs) represent a good solution to abate energy usage and reduce greenhouse gas emissions. However, the design of ground heat exchanger (GHE) fields is crucial to minimize installation costs and guarantee high efficiencies of the system for long-term operation.

The heat pump selection is important to the design of ground heat exchangers because it affects heat extraction from the ground during heating operation. Conversely, the ground heat exchanger performance (specifically, fluid temperatures provided to the heat pumps) affects the heat pump performance. In the common situation where systems are designed to meet building-specific hourly heating loads, simulations are used to predict the combined performance of the GSHPs and the ground heat exchanger field to achieve a solution that provides the needed heating capacity while minimizing energy consumption and installation cost.

Besides affecting the electrical consumption of the system and related operating costs, the choice of heat pumps directly affects the size of the ground heat exchanger field. Therefore, GSHP models are needed to design the ground heat exchanger field.

Detailed models of heat pumps, e.g. those that are based on vapor compression cycle simulations, are widely described in the literature. However, for most designers, only limited heat pump data from manufacturers' catalogs are available. The availability of data and temperature ranges for which data are provided vary from country-to-country, often depending on local standards. For example, North American manufacturers usually provide a wide range of operating points; fewer data points are presented in European catalogs and, in some cases, limited to a few specific rating conditions recommended by the standards.

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Therefore, simpler heat pump models are needed to calculate the ground heat extraction. In contrast to detailed models, these models should depend on easy-to-obtain catalog data rather than specific measurement campaigns.

International and national standards play a key role in defining the minimum energy efficiency requirements for new heat pumps and providing manufacturers with guidelines regarding the testing conditions and the documentation to be made available to users. Standards suggest performance calculation methods and define standard rating conditions for each country or area. In many cases, the standard rating conditions suggest a minimum data set to be presented in manufacturers' catalogs. Commonly, the performance of a heat pump is defined using the Coefficient of Performance (COP), which corresponds to the heating provided, divided by the heat pump's electrical consumption.

ISO 13612-2 Appendix A [1] describes a method to calculate a heat pump performance matrix with a single test result. The model is based on the Carnot method for calculating the COP of the heat pump, knowing the performance at the rating conditions. The Carnot COP corresponds to the COP for an ideal inverse thermodynamic cycle at specific operating temperatures. If the value of the actual COP is known for the real heat pump working at the same operating temperatures, it is possible to define how much worse the real inverse thermodynamic cycle is compared to the ideal one, using the Carnot effectiveness $\eta_{Carnot,0}$, (also known as 2nd law efficiency). As stated in [1], the accuracy of this model drops when the operating conditions are far from the rating point. A higher level of accuracy can be obtained using a larger number of operating points.

Some standard energy simulation programs incorporate simplified heat pump models with various levels of detail. In Energy Plus [2], two types of models for water-to-air and water-to-water heat pumps are used: equation fit models [3], [4], based on simple non-dimensional curves and parameter estimation models [5], incorporating a vapor compression cycle simulation, with parameters for internal components that require estimation.

In TRNSYS [6], the TESS [7] library contains a water-to-water heat pump model that linearly interpolates between the performance data provided in manufacturer's catalogs, given the values of the air flow rate, fluid flow rate, and entering fluid temperature. Users who want to provide their own performance data must adhere closely to the syntax of the sample file [8].

In a previous work [9], a novel TRNSYS type was developed modeling a heat pump with a vapor compression cycle simulation that incorporated the compressor's performance polynomials. The type is also available with a link to Refprop [10] for deriving the properties of the refrigerant. Although it is very flexible, the need for compressor polynomials might be a problem when they are unavailable from heat pump manufacturers or when the compressor brand and model are not specified in catalogs.

The Modelica Buildings Library [11] contains several heat pump models. The simplest model is based on the Carnot efficiency method. Moreover, models based on the equation fit model [4] and the parameter estimation model [5] from EnergyPlus are implemented.

For GLHEPRO [12], [13], manufacturer's data are used to fit 2nd order polynomials for the ratio of heat extraction to heat pump heating capacity and heat rejection to heat pump cooling capacity as functions of heat pump entering fluid temperature.

Similar equations used to quantify the performance of water-source heat pumps have been described in the literature. Proposed simplified models are generally based on industrial surveys and field test trials [14]-[16] used to derive the COP of ground source heat pumps.

This paper provides an overview of catalog data availability for the North American and European markets and reviews the literature on simplified and acceptably accurate models for predicting the ratios of heat extraction to heating. A range of models are tested for different data availability scenarios, and finally recommendations are made for models that can be used within ground heat exchanger design tools. The basis for most of the work is manufacturers' catalog data.

## 2. Methodology

Generally, water-source heat pump catalogs provide data on heat pump performance and heating capacity, depending on the source and load side temperature levels. Once the performance of a heat pump is known, it is possible to compute the heat extraction, given building heating load, using Eq. 1.

$$HE = HC \cdot \left(1 - \frac{1}{COP}\right) \tag{1}$$

Therefore, once the building heating load is determined using building simulation software and is assumed to be met by the heat pump, simplified models for calculating the COP make the calculation of extraction extremely straightforward. This formulation neglects compressor shell losses, which are usually small (less than 5% of the heating provided [17]).

After presenting the main characteristics of water-source heat pump datasheets, some selected catalogs are used in this paper to evaluate several models for extraction calculation for GSHP design purposes. This section presents the characteristics of the utilized data and the proposed models, along with conventions for labeling the data.

### *2.1. Availability of manufacturers' data*

The availability of manufacturers' data strongly affects the accuracy of models that do not rely on user-measured experimental data. As already mentioned, standards influence the documentation that manufacturers publish. However, many manufacturers provide data that goes beyond the minimal requirements, e.g., several values measured at different inlet temperatures when only a single point is required. The available data often differ from country to country, even for the same heat pump, depending on the selected market. In North America, data about the heat pump performance outside the rating conditions are often available and complete. The range of inlet water temperatures at the ground-coupled side of the heat pump is usually broad and covers temperatures that can go outside standard operating conditions. When available, manufacturers' data of operating points outside rating conditions are more limited in Europe than in North America. Characteristics and features of ground source heat pumps can also vary in different areas: for example, in North America, water-to-air heat pumps are the most widespread, while in Europe, ground-source heat pumps are generally water-to-water.

In order to characterize the data availability for the selected water-to-water heat pumps operating in heating mode, the data sets are labeled using the following code composed of five letters and one number:

W NA H 1 f
1 2 3 4 5

Where:

1. The first letter defines the type of heat carrier fluid at the heat pump load side, W-water;
2. The second and third letters represents the market's area, NA-North America, NE-Northern Europe, SE-Southern Europe;
3. The fourth letter defines the heat pump mode, H-Heating;
4. A sequential number is used to identify the different investigated units;
5. The last letter clarifies if the data refer to p-partial or f-full load operation.

The symbol reported under each variable in Table 1 indicates if it can be found in the catalog, varying for the different operating conditions ("Yes"), if it is omitted ("No"), or if it is derivable ("Der") using other information provided in the datasheet. The last row of Table 1 reports the rating heating capacity of the specific heat pump.

In Table 1, data sets of water-to-water heat pumps in heating mode can be subdivided into three main categories. The first group ("Group 1") includes data from North American manufacturers, characterized by the wide availability of operating points and variables, given for a range of entering temperatures and flow rates. In the second group ("Group 2"), catalogs do not provide data about the source and load fluid flow rates and leaving fluid temperature (typical of Central/Northern Europe). The third group ("Group 3") collects catalogs typical of Southern European manufacturers. In this case, generally, data are provided for a range of source and load side temperatures, considering a fixed temperature difference between the inlet and the outlet of the heat exchangers. Catalog WSEH4f, of a machine produced in South Europe, is part of Group 3. However, in this case the number of available operating points is limited to four rating points, provided for heating model only.

Table 1. Data availability for selected water-to-water heat pumps in heating mode.

| | Group 1 | | | | | | | Group 2 | | Group 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variable | WNAH1f | WNAH2f | WNAH3f | WNAH4f | WNAH5f | WNAH6p | WNAH6f | WNEH1f | WNEH2f | WSEH1f | WSEH2f | WSEH3f | WSEH4f |
| SEFT | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Der | Der | Der | Yes |
| SFfr | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes | Der | No | Der |
| LEFT | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Der | Der | Der | Yes |
| LExFT | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| LFfr | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes | Der | No | Der |
| HC | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Pel | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes | Yes | Yes | Yes |
| HE | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Der | Der | Yes | Yes | Yes | Der |
| COP | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Der | Der | Yes |
| HC rating [kW] | 50.6 | 14.7 | 14.2 | 16.4 | 24.5 | 10.8 | 13.3 | 7.57 | 3.51 | 8.3 | 13.1 | 8.2 | 18 |

### *2.2. Proposed Models*

Depending on the data availability discussed in the previous section, several models to calculate the performance of ground source heat pumps have been assessed based on the methods from the literature. First, these models have been applied to catalog data of the selected heat pump models. Afterward, based on the data availability, some models have been modified to reduce the RMSE in the COP calculation. Each model can or cannot be applied to a specific group of catalog data, depending on the data availability, as discussed in the previous section 2.1.

Once the COP is computed, the heat extraction can also be calculated using heating capacity reported in the datasheets using Eq. 1.

Table 2 summarizes the models applied to the catalogs of water-to-water heat pumps operating in heating mode. Some points can be made regarding the models:

- Models applicable to catalog data of the heat pumps produced in Northern Europe are different than the models suggested for North American and Southern Europe catalogs. The differences are because information about the source fluid flow rate and load fluid entering temperature are generally unavailable in the Northern European cases.
- Wh01 is the most complex model, as it is a function of the SFfr, the SEFT, and the temperature difference between the load-side outlet and the source-side inlet and its square. The equation's coefficients can be generated using the generalized least square (GLS) method from the catalog's data. The generalized least squares method is used to generate the equations' coefficients starting from the catalog data at determined reference conditions, giving the least differences between the model outputs and the catalog data. This model can be used when data for more than four operating conditions are available, due to the high number of required coefficients.
- Model wh03 uses generic coefficients given in [14]. Model wh02 uses the same equation form as wh03 but fits the coefficients using the GLS method.
- Model wh04 is the same proposed in [16], and coefficients can be computed using the GRG (Generalized Reduced Gradient) non-linear solver implemented in Microsoft Excel [18]. (The GLS method fits coefficients for linear combinations of functions, but cannot handle, for example, the multiple terms used to form an exponent in wh04).
- Equation wh05 is supposed to improve method wh04 using SEFT and LExFT as inputs, instead of SExFT and LEFT, as these data are generally available in all catalogs.
- Model wh06 is based on the work presented in [15], with a difference: the method consists in computing the COP starting from catalog data, while in [15], it was derived only after calculating the electrical power and heating capacity. This variation reduces the computational effort and allows the calculation in case data about the electrical consumption are unavailable.
- Model wh07 improves the wh06 by considering the whole temperature lift between the heat pump source and load sides, using the LExFT instead of the LEFT.

- Model wh08 is based on the Carnot method, but the COP is calculated differently from the standards. For the sake of simplicity and for minimizing the assumptions, it directly depends on the entering source and load side temperatures (the same is done for the Carnot COP at rating conditions), as in Eq. 2, instead of depending on the condensing and evaporating temperatures.
  The set temperature difference can be adjusted so that the COP does not reach remarkably high values (for example, higher than 8) for low temperature differences. In this work, the computation of the COP is calibrated using the available data sets. If only one rating condition is available, the $\Delta T_{set}$ can be set equal to 15°C and, the user can reduce or increase this value if the considered operating conditions lead to high values of COP.

$$COP_{Carnot} = \frac{LEFT+273}{\Delta T_{set}} \quad (2)$$

- For the Northern European catalogs, the LExFT replaces the LEFT in the equation, and the control on the Carnot COP is done on the SEFT: if the SEFT is higher than 13°C, it is considered equal to 13°C.
- Model wh09 is an alternative to model wh01 when data on the SEFT and the SFfr are unavailable, like in Northern European datasheets.
  When at least three operating points at rating conditions are available, they can be used to compute the coefficients for a model dependent on the temperature differences between the LEFT and the SEFT in North America (wh11) and the LExFT and the SEFT in Northern Europe (wh10).

Table 2. Data availability for selected water-to-water heat pumps in heating mode.

| | | Group 1 | | | | | | | Group 2 | | Group 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Model | WNAH1f | WNAH2f | WNAH3f | WNAH4f | WNAH5f | WNAH6p | WNAH6f | WNEH1f | WNEH2f | WSEH1f | WSEH2f | WSEH3f | WSEH4f |
| wh01 | $COP = c_0 + c_1 \cdot SEFT + c_2 \cdot SFfr + c_3 \cdot (LExFT - SEFT) + c_4 \cdot (LExFT - SEFT)^2$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh02 | $COP = c_0 + c_1 \cdot (LExFT - SEFT) + c_2 \cdot (LExFT - SEFT)^2$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh03 | $COP = 8.77 - 0.15 \cdot (LExFT - SEFT) + 0.000734 \cdot (LExFT - SEFT)^2$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh04 | $COP = c_0 \cdot \exp(c_1 \cdot SFExT + c_2 \cdot LEFT) + c_3 \cdot \frac{SFExT}{LFET} + c_4$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh05 | $COP = c_0 \cdot \exp(c_1 \cdot SEFT + c_2 \cdot LExFT) + c_3 \cdot \frac{SEFT}{LExFT} + c_4$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh06 | $COP = c_0 + c_1 \cdot SEFT + c_2 \cdot LEFT + c_3(SEFT \cdot LEFT)$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh07 | $COP = c_0 + c_1 \cdot SEFT + c_2 \cdot LExFT + c_3(SEFT \cdot LExFT)$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh08 | $COP = COP_{Carnot} \cdot \eta_{carnot,0}$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh09 | $COP = c_0 + c_1 \cdot LExFT + c_2 \cdot (LExFT - SEFT) + c_3 \cdot (LExFT - SEFT)^2$ | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh10 | $COP = c_0 + c_1 \cdot (LExFT - SEFT) + c_2 \cdot (LExFT - SEFT)^2$ Stand. | x | x | x | x | x | x | x | x | x | x | x | x | x |
| wh11 | $COP = c_0 + c_1 \cdot (LEFT - SEFT) + c_2 \cdot (LEFT - SEFT)^2$ Stand. | x | x | x | x | x | x | x | x | x | x | x | x | x |

The models presented in this section are evaluated using the RMSE (Eq. 3) calculated for the COP and heat extraction from the ground in heating operation. In Eq. 3, $y_c$ is the catalog value, $y_m$ is the modeled value, and $N$ is the number data.

$$RMSE = 100\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{y_{c,i}-y_{m,i}}{y_{c,i}}\right)^2} \quad (3)$$

## 3. Results

The present section analyzes the performance of the models characterized by RMSE. Figures 1 and 2 show the RMSE values calculated as in Eq. 3 for each set of catalog data of water-to-water heat pumps. The RMSE is relative to the COP (Figure 1), computed by applying the models discussed in section 2.2, and to the heat extracted from the ground (Figure 2). This last value is calculated using Eq. 1, starting from the thermal load demanded by the building, and met by the heat pump at different operating conditions, according to the catalog data. If the error is higher than 15%, in the graphs, a control bar is shown in the pink area (RMSE>15%) in place of the actual value for the specific model's RMSE. In the case of non-applicable models, the RMSE value is not shown.

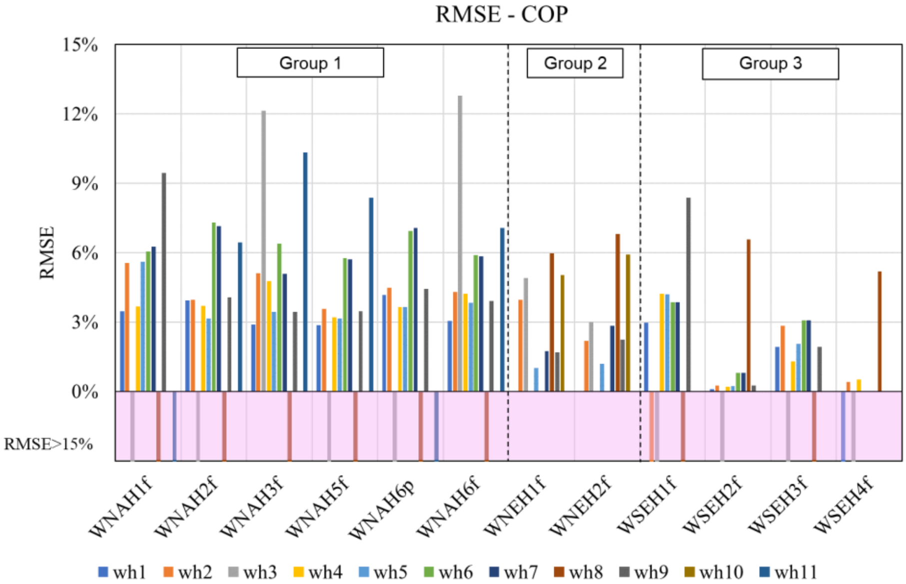


Fig. 1. RMSE for COP for the different catalogs and models.

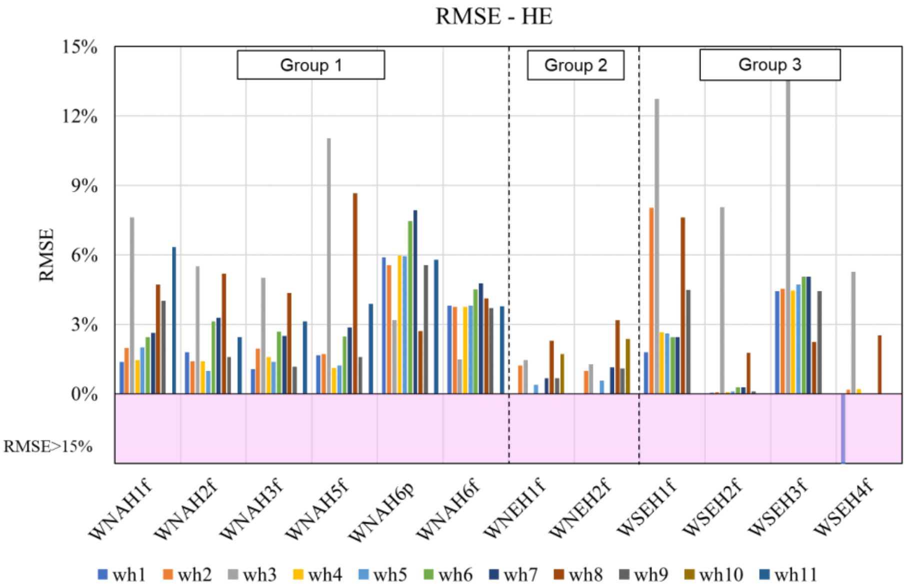


Fig. 2. RMSE for HE for the different catalogs and models.

In general, the deviation between catalog and simulated data is higher for COP values than for the heat extraction values. For example, the application of models wh03 and wh08 to all selected data sets leads to an average $RMSE_{COP}$ of 21% and 17%, respectively, but only to an $RMSE_{HE}$ of 6% and 4%. Moreover, models wh03 and wh08 are likely to overestimate the COP and the HE, compared to catalog data. The application of model wh01 leads to very good results when a wide range of data is available. However, model wh01 leads to high $RMSE_{COP}$ and $RMSE_{HE}$ when the number of operation conditions provided in the manufacturer's catalog is limited, like for the case of theWSEH4f data set.

The application of model wh11 leads to an $RMSE_{COP}$ up to 20% (WNAH1f) but results in an $RMSE_{HE}$ of only 6%. The application of the other models to the catalog data leads to an average maximum $RMSE_{COP}$ of 5% and an average maximum $RMSE_{HE}$ equal to 3%.

## 4. Recommendations

This section provides recommendations for applying the proposed models based on the available quantity of manufacturers' catalog data. In Section 2.1, the type of data available was used to divide the heat pumps into three groups. Table 3 show the average $RMSE_{COP}$ and $RMSE_{HE}$ for each group of water-to-water heat pumps operating in heating mode. In the table, when a model is applicable to the catalogs, the average RMSE is highlighted with a color: (a) green if the RMSE is lower than 5% (the results of the model are good), (b) light orange if its value is between 5% and 10% (the results of the model are acceptable), (c) orange when the RMSE is higher than 10% (the model is not recommended for that set of data). When the model is not applicable to a specific group of catalogs, it is indicated with "N/A".

Therefore, a decision-making process for choosing the most suitable model can be outlined as follows, depending on what types of catalog data are provided for the heat pump:

a. If only one data point is available, the only applicable models are the ones derived from the Carnot efficiency calculation (wh08) or from an experimentally derived curve (wh03). These models, in general, lead to higher $RMSE_{COP}$ but more than acceptable $RMSE_{HE}$.

b. If only rating conditions (three or four operating points) are available, models wh10, wh11 can be used. However, model wh08 can also be a good option.

c. If more than four operating points are available in the catalog data, the corresponding group from Table 1 can be identified by comparing the data available for the type of heat pump and operation mode to the data available for each group in Tables 1. With the group identified, Table 3 can be used to identify the best choices – that is the model or models with the lowest $RMSE_{HE}$. A secondary consideration may be the model performance in predicting COP, also summarized in Table 3. Taking first the model performance in predicting HE, and secondarily, the model performance in predicting COP, a final recommendation is made for each group in Tables 3. A "x" is used to identify the recommended model or models.

Table 3. Average RMSE by group of data and model and final recommendations.

| | Groups | wh01 | wh02 | wh03 | wh04 | wh05 | wh06 | wh07 | wh08 | wh09 | wh10 | wh11 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $RMSE_{COP}$ | Group 1 | **3%** | 4% | 19% | 4% | 4% | 6% | 6% | 24% | 5% | N/A | 12% |
| | Group 2 | N/A | 3% | 4% | N/A | **1%** | N/A | **2%** | 6% | **2%** | 5% | N/A |
| | Group 3 | **2%*** | 5% | 32% | **2%** | **2%** | **2%** | **2%** | 12% | 3% | N/A | N/A |
| $RMSE_{HE}$ | Group 1 | **3%** | **3%** | 6% | **3%** | **3%** | 4% | 4% | 5% | **3%** | N/A | 4% |
| | Group 2 | N/A | **1%** | **1%** | N/A | **0%** | N/A | **1%** | 3% | **1%** | 2% | N/A |
| | Group 3 | **2%** | **3%** | 10% | **2%** | **2%** | **2%** | **2%** | 4% | **2%** | N/A | N/A |
| Recommendations | Group 1 | x | | | | | | | | | | |
| | Group 2 | | | | | x | | x | | x | | |
| | Group 3 | x | | | x | x | x | x | | | | |

* *model wh01 is considered not-applicable to catalog WSEH4f, where only four operating points are provided.*

The results of the models are strongly affected by the accuracy and the level of detail of the manufacturer's catalog data: if the accuracy is high, the agreement between the models' results and field measurements will also be high. Moreover, the accuracy of the models improves if the catalog contains detailed information about the operation of the heat pump, for example, correction factors for different temperature differences at the load and source sides, or for the use of a mixture of water and glycol, or, in general, if it includes a relevant number of operating points.

Although the primary objective of these models is to derive the heat extraction from the ground, they might also be used to compute the COP of the heat pump. As already pointed out, the COP results are more accurate when the catalog data are numerous and precise.

## 5. Conclusions

This paper addresses a problem encountered when designing ground heat exchangers that are used with ground-source heat pump systems. Engineers designing the system typically only have catalog data for the heat pumps and the data provided vary with manufacturer and location. This paper focuses on simple models that can be used to determine the GSHP heat extraction required to meet building loads.

A review of available manufacturers' catalog data for water-to-water heat pumps in North American and European markets is presented, and catalog data are categorized by data availability. A range of models are investigated; their accuracy is evaluated by their ability to reproduce the catalog data and recommendations on which model to use are provided. The recommended models give acceptable accuracy in the calculation of the heat extraction, with no more than 3% RMSE when compared to catalog data. Nevertheless, the model accuracy depends on the range and quantity of catalog data.

The recommended models presented in this paper are suitable for single-speed water-to-water heat pumps in heating mode and quasi-steady operation. Further work is in progress to address water-to-air heat pumps and cooling mode. Additional research is needed to treat multi-stage and variable-speed heat pumps.

The investigation presented here is limited by its use of catalog data, which is based on steady-state operation and, in many cases, by proprietary models developed by the manufacturer. Comparisons against field measurements are in progress. However, additional comparisons to field measurements would be welcome.

### Nomenclature

| | | |
|---|---|---|
| $c_i$ | | Equation coefficients |
| COP | kW/kW | Coefficient of Performance |
| $COP_{Carnot}$ | °C/°C | Carnot COP |
| *Der* | | Derivable data |
| *GLS* | | Generalized least square |
| *GRG* | | Generalized reduced gradient |
| GSHP | | Ground source heat pump |
| HC | kW | Heating capacity |
| HE | kW | Heat extraction |
| LEFT | °C | Load entering fluid temperature |
| LExFT | °C | Load exiting fluid temperature |
| LFfr | l/s | Load fluid flow rate |
| N | | Number of data |
| Pel | kW | Electrical power |
| RMSE | | Root mean square relative error |
| SEFT | °C | Source entering fluid temperature |
| SFfr | l/s | Source fluid flow rate |
| Stand | | Data from rating conditions defined in the standards |
| $\Delta T_{set}$ | °C | Temperature lift between source and load side |
| $\eta_{Carnot,0}$ | [-] | Carnot effectiveness |
| $y_c$ | | Variable's value in the catalog |
| $Y_m$ | | Variable's value in the model |

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