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Developing multiple regression models from the manufacturer's ground-source heat pump catalogue data

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ABSTRACT

The performance of ground-source heat pumps (GSHP), often expressed as Power drawn and/or the *COP*, depends on several operating parameters. Manufacturers usually publish such data in tables for certain discrete values of the operating fluid temperatures and flow rates conditions. In actual applications, such as in dynamic simulations of heat pump system integrated to buildings, there is a need to determine equipment performance under operating conditions other than those listed. This paper describes a simplified methodology for predicting the performance of GSHPs using multiple regression (MR) models as applicable to manufacturer data. We find that fitting second-order MR models with eight statistically significant *x*-variables from 36 observations appropriately selected in the manufacturer catalogue can predict the system global behavior with good accuracy. For the three studied GSHPs, the external prediction error of the MR models identified following the methodology are 0.2%, 0.9% and 1% for heating capacity (*HC*) predictions and 2.6%, 4.9% and 3.2% for *COP* predictions. No correlation is found between residuals and the response, thus validating the models. The operational approach appears to be a reliable tool to be integrated in dynamic simulation codes, as the method is applicable to any GSHP catalogue data.

1. Introduction

In order to reduce the fossil fuel consumption, ground-source heat pumps (GSHP) are becoming a widely employed technology for heating and cooling buildings and for domestic hot water production [1–5]. GSHP attract worldwide interest due to their environmental protection, energy efficiency and from being a renewable energy form [6–9].

In dynamic simulation applications, such as in the modeling of heat pump systems integrated to buildings, it is required to evaluate the heat pump performance under particular operating conditions. However, it becomes difficult to estimate the correct performance value at operating conditions which do not exactly correspond to those listed in the manufacturer's data tables [10,11].

In the present study we introduce a methodology based on multiple regression (MR) modeling which can be used to predict GSHP performance with good accuracy at particular design conditions. The parameters in the models are the operating secondary fluids (source and load) inlet temperatures and flow rates, the heat pump heating capacity (*HC*) and the coefficient of performance (*COP*). The analysis presented is based on three manufacturer performance tables of three commercially available GSHPs in heating mode.

The operational method for the identification of MR models can be integrated in dynamic simulation tools such as EnergyPlus and TRNSYS in order to predict the performance of GSHP at particular operating conditions. The same approach can be employed for the development of MR models for the performance simulation of any GSHP system in heating or cooling mode using the corresponding capacity table from the manufacturer catalogue. Our hypothesis is that the proposed method can help in the selection of the most appropriate GSHP evaluating with precision its performance, and thus increase the potential of GSHP implementation in buildings.

The paper is organized as follows. Next section introduces the methodology employed in the study based on step forward multiple regression modeling. The regression analysis, including a

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Nomenclature

Acronyms

COP	coefficient of performance
CV	coefficient of variation
GSHP	ground-source heat pump
HC	heating capacity
HE	heat extracted
MR	multiple regression
P	compressor power input
RMSE	root mean square of error

Symbols

β	regression coefficient
ε	residual
μ	mean
t	temperature (°C)
v	flow rate (L/s)
x	independent variable
y	dependent variable

Subscripts

i	inlet condition
j	number of response
l	load
n	number of predictor variables
o	outlet condition
s	source

description of the manufacturer specification tables, a general overview of regression models, the statistical evaluation of the identified MR models, and the proposed approach validation is presented in Section 3. Section 4 presents a discussion about the findings and Section 5 is some concluding remarks.

2. Methodology

The purpose of the study is to introduce a general methodology based on MR modeling able to determine the heat capacity and the coefficient of performance of GSHPs in heating mode from different working fluid temperatures and flow rates. Essentially, an optimal set of operating parameters from the manufacturer data tables would be to find relationships between the response variables (*HC* and *COP*) versus four operating parameters: the source flow rate (v_s), the load flow rate (v_l), inlet load temperature at the heat pump condenser (t_{il}) and inlet source temperature at the heat pump evaporator (t_{is}). The compressor power input (*P*) and heat extracted (*HE*) can then be deduced from *HC* and *COP* values. In the study, t is temperature, v is flow rate, subscripts i, l and s are short for the heat pump inlet conditions, load and source, respectively. Fig. 1 shows the schematic diagram of the GSHP system for space heating.

The method consists in selecting a sample of observations from the specification table, which can be used for the development of MR models. The performance data of the remaining observations in the manufacturer table are then compared to the predictions calculated from the identified models. The statistical analysis further evaluates the models' robustness and prediction accuracy, determining the models' goodness-of-fit and the coefficients of variation (CV) of the prediction residual errors.

An important aspect of the selection of the observation sample is that it needs to provide a fair representation of the entire input space. In this concern, the observation sample is selected in a way that there are an equal number of low-range, mid-range and high-range values for each of the variables, and the combination selection is appropriately spread out so that the whole input space is represented. Each combination of particular operating conditions corresponds to an observed value of *HC* and *COP* from the manufacturer catalogue. Since there are four independent variables (v_s, v_l, t_{il} and t_{is}), a complete factorial design as used in statistical experiments would require 81 observations. For the purpose of the study, we propose three incomplete factorial designs using Latin squares, i.e. three samples containing 12, 24 and 36 observations respectively, in order to evaluate the influence of the sample size on model accuracy.

The approach involves using multiple linear regression of the first and second order to estimate the heat pump *HC* and *COP* values in heating mode under specified conditions of the four operating parameters (t_{is}, t_{il}, v_s and v_l). As seen in Figs. 2–5 below, although some of the relationships are close to linear, others are distinctly non-linear, and thus the higher order terms are introduced to allow linear regression on non-linear relationships.

3. Regressions analysis of manufacturer's performance data

3.1. Description of manufacturer's data tables

The principle of GSHP technology is to make use of the low-grade geothermal energy of the earth at a relatively lower depth through ground heat exchangers. A GSHP system will extract/discharge thermal energy for all of its applications [12–15]. In order to make it easier for engineers when it comes to GSHP selection and sizing for a particular building, GSHP manufacturers offer performance data tables from their catalogue. In heating mode, such specification tables give data of compressor power input (*P*), heat extracted (*HE*), heat capacity (*HC*) and *COP* as a function of the inlet and outlet load temperatures (t_{il} and t_{ol}) of the distribution circuit fluid entering and leaving the heat pump condenser, the inlet and outlet source temperatures (t_{is} and t_{ls}) of the earth connection fluid entering and leaving the heat pump evaporator, and the load and source flow rates (v_l and v_s), in the distribution and ground loops respectively. The specification tables of the cooling mode are arranged identically, giving observations of cooling capacity (*CC*), heat rejected (*HR*) and cooling energy efficiency (*EER*) as a function of temperature and flow rate parameters. Unlike the capacity tables in heating mode, the distribution and the ground circuits are respectively the source and the load side in cooling mode. Table 1 provides the technical features of the three commercially available GSHPs considered in the study (called HP1, HP2 and HP3).

The working operations in heating mode of the studied GSHPs range between the interval limits shown in Table 2. However there are some conditions for which operation is not recommended by the manufacturer. These extreme conditions for the three studied equipments are as following:

- HP1: When t_{is} varies between −1.1 and 10 °C, v_s cannot vary between 0.95 and 1.45 L/s;
  When t_{is} varies between 21.1 and 32.2 °C, t_{il} cannot vary between 26.7 and 48.9 °C.