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Modeling of a direct expansion geothermal heat pump using artificial neural networks

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ABSTRACT

The real potential for energy savings exists in heating, ventilation, and air conditioning systems in general, and especially in geothermal heat pumps systems. Recent studies indicate that a mere 1% improvement in the efficiency of such systems generates millions of dollars in savings at the national level. This efficiency can be optimized when better control strategies are implemented. A first step in the control and optimization process is to establish a model that describes the system's behavior. In this study, artificial neural networks were selected for modeling a particular type of heat pump called direct expansion geothermal heat pump because the ground heat exchanger is a component of the heat pump, and thus directly plays the role of condenser or evaporator according to the operation mode. The data collection methodology and the algorithms used for training are presented. Of the four algorithms tested in this study with variable numbers of neurons in the hidden layers, the model obtained using the Levenberg–Marquardt (LM) algorithm with 28 neurons in the hidden layer appears to be the best, with an average coefficient of multiple determinations of about 0.9991, an average RMS of 0.16330, and an average COV of 2.9319.

1. Introduction

In recent years, artificial neural networks (ANN) have become an alternative to traditional methods of statistical data analysis in several disciplines of human activity, including in economics, ecology and environment [1], biology and medicine. They are used to solve the problems of classification, prediction, modeling, control, optimization, categorization, pattern recognition and associative memory [2]. In the specific context of data processing, the ANN is an approximation method of complex systems that are difficult to model using traditional methods [3]. The modeling process of dynamic systems using conventional approaches (analytical and experimental validation) begins by first establishing all the governing equations of all physical phenomena characterizing the system as a function of parameters and multiple variables; the numerical methods needed to solve these equations are then chosen based on assumptions, and sometimes, in the case of heat transfer, by adjusting correlations transfer coefficients available in the literature to obtain a better model in agreement with the experimental data. This exercise can sometimes be difficult and complex to realize [4]. ANN therefore offers alternatives to these conventional methods of overcoming their limitations using approaches based on experimental data, and allows the extraction of nonlinear implicit relationships between the desired input–output variables that cannot be obtained by conventional methods [5]. The principle is very simple, and consists of a learning phase during which the various components of the network are evolving until the network has completed the desired task followed by the use phase, where the model is tested with a new input value. However, for the ANN to provide a reliable prediction model, data to be processed must be representative of the system [6], hence the need to clearly define the problem and to elaborate the experimental process for collecting data.

ANN works by distributing the values of variables in automata called neurons by analogy with human neurons. These units are organized in architecture: input layer–hidden layer–output layer connected to each other by connections with associated weights. The network output is calculated using a transfer function whose choice depends on the type of input variables used. When the inputs are positive, the function of the log-sigmoid transfer is used, and when data has negative values, the sigmoid tangent function is operated [4,7].

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Nomenclature

COP	coefficient of performance for heating
T_{wi}	cooling water inlet temperature (°C)
T_{wo}	cooling water outlet temperature (°C)
P_{fi}	inlet pressure of the geothermal evaporator (kPa)
T_{fi}	inlet temperature of the geothermal evaporator (°C)
P_{fo}	outlet pressure of the geothermal evaporator (kPa)
T_{fo}	outlet temperature of the geothermal evaporator (°C)
P_{dis}	discharge pressure (kPa)
C_{pw}	heat capacity of water (J/kg K)
$\dot{m}$	cooling water flow rate (kg/s)
W_c	power consumed by the compressor (W)
Q_h	heating capacity (W)
N	number of neurons in the hidden layer
N_s	number of loop selected
T_i	start time (min)
T_f	stop time (min)
T_s	simulation time (s)
BNHL	best neurons number in hidden layer

The overall objective of the ANN is to find the best weight configuration of connections between neurons used to associate an appropriate output for each input configuration.

In the specific areas of refrigeration, air conditioning and heat pumps (RACHP), ANN is often used as follows:

- Modeling and prediction of vapor compression systems,
- Modeling of refrigeration system and heat pump components,
- Modeling and prediction of vapor absorption systems,
- Prediction of the properties of refrigerants,
- Control RACHP,
- Heating and air conditioning systems,
- Energy analysis of a building.

Most of the applications of ANN in RACHP and energy analysis are summarized by Mohanraj et al. [4] and Kumar et al. [6]. The different network architectures used are: multi-layer feed forward, radial biased function network, generalized regression neural network and adaptive neuro fuzzy systems. However, the most commonly used is the multi-layer feed forward network, with its popular learning back-propagation algorithm (BPA).

In this study, we use an ANN model to predict the performance (heating capacity and the coefficient of performance) of a particular type of geothermal heat pump (GHP) called a direct expansion (DX) heat pump (Fig. 1). The geothermal heat pump has attracted renewed interest over the last decade because of the advantages it offers as compared to its secondary loop (SL) counterpart [8] (Fig. 2). While geothermal secondary loop systems design methods and simulation tools are available in the literature [9–12], those of DX heat pumps are still only covered in experimental studies. The performance prediction of a thermal system is a prerequisite for its design, process optimization and control, which is why the ANN is recommended for estimating the performance of thermal systems in engineering applications [5]. In addition, there is a real energy savings potential in geothermal systems when a good control policy is provided for efficient use [13]. For example, a mere 1% improvement in the energy efficiency of these systems resulted in annual savings of millions of dollars nationwide [14], and our recent study shows that the direct expansion geothermal heat pump can provide 70% energy savings as compared to electricity [15]. However, the first step in a process control is the identification and modeling of the system to predict its behavior. The work presented here is

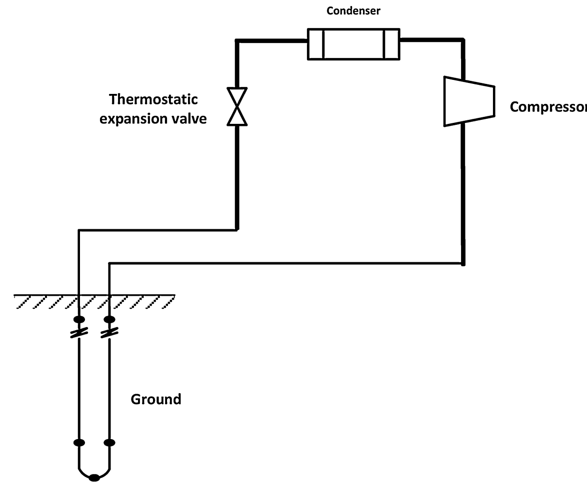

Fig. 1. Schematic of a direct expansion geothermal heat pump (DX).

part of this, and therefore proposes an ANN model that can be used even online to simulate and develop appropriate control strategies for DX heat pump. Although there are few publications on the DX heat pump in the literature as compared to its secondary loop counterpart (Fig. 1) over the past decade, some works on DX heat pumps systems have indeed been done. The list of research works summarized by [15], as well as those on secondary loop systems, are listed by Esen and Inalli [16].

2. Methodology

2.1. Using of the model

The aim of this work is to model a DX heat pump capable of adapting DX heat pump operation to real building loads. Indeed, there is a potential for energy savings in GSHP when a good control is assured. [13]. This ANN model will thus be integrated into the development of an Intelligent Building System (IBS) which uses a supervisor and a coordinator to set control strategies for local controllers [17]. More specifically, it can be integrated into simulation tools of DX heat pump systems as a model of behavior or to create a neural network loop to perform an adaptive control [18], and finally, as a reference model to adapt other DX heat pumps used in real time [14,17]. In the latter case, it will be necessary to implement a real-time training algorithm based on the recursive least

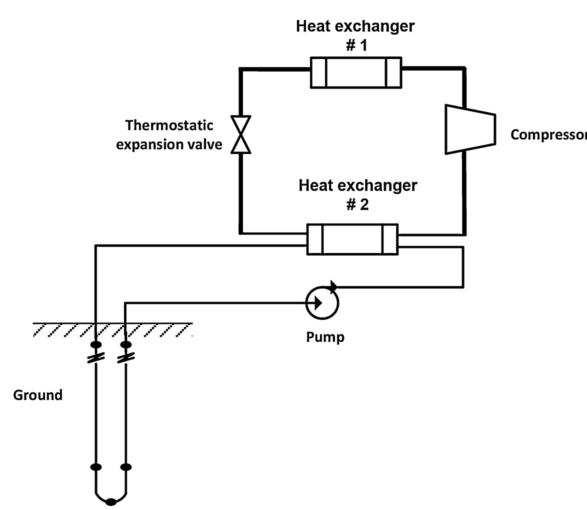

Fig. 2. Schematic of a traditional secondary loop geothermal heat pump.