Renewable Energy 86 (2016) 1009–1022

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Development of a dynamic artificial neural network model of an absorption chiller and its experimental validation

Amine Lazrak [a, b, c], François Boudehenn [b], Sylvain Bonnot [b], Gilles Fraisse [c], Antoine Leconte [b, *], Philippe Papillon [b], Bernard Souyri [c]

[a] ADEME, Angers, France
[b] CEA LITEN INES, Le Bourget du Lac, France
[c] CNRS, LOCIE, Université de Savoie, Le Bourget du Lac, France

ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form
25 August 2015
Accepted 8 September 2015
Available online 24 September 2015

Keywords:
Thermal systems
Absorption chiller
Performance estimation
Dynamic modelling
Artificial neural networks
System testing

ABSTRACT

The aim of this paper is to present a methodology to model and evaluate the energy performance and outlet temperatures of absorption chillers so that users can have reliable information on the long-term performance of their systems in the desired boundary conditions before the product is installed. Absorption chillers' behaviour could be very complex and unpredictable, especially when the boundary conditions are variable. The system dynamic must therefore be included in the model. Artificial neural networks (ANNs) have proved to be suitable for handling such complex problems, particularly when the physical phenomena inside the system are difficult to model. Reliable "black box" ANN modelling is able to identify the system's global model without any advanced knowledge of its internal operating principles. Knowledge of the system's global inputs and outputs is sufficient. The methodology proposed was applied to evaluate a commercial absorption chiller. Predictions of the ANN model developed were compared, with a satisfactory degree of precision, to 2 days of experimental measures. These days were chosen to be representative of the real dynamic operating conditions of an absorption chiller. The neural model predictions are very satisfactory: absolute relative errors of the transferred energy are within 0.1–6.6%.

1. Introduction

For more than 10 years now, the development of air-conditioning has provided increasing comfort and safety. Most commercial air conditioners (approximately 99%) use electricity-powered compression cycles. This system generates a paradox: the more air conditioners are installed in a city, the more heat is released into the urban atmosphere, and the more the ambient air temperature increases, decreasing the performance efficiency of air conditioners and increasing the cooling load of buildings [1]. Peak electricity demand for cooling must be tripled [2]. According to Pons et al. [1], part of the solution could be the use of thermally driven chillers powered by waste heat or solar energy.

Most thermally driven chillers available on the market are absorption chillers. The basic physical process consists of at least two chemical components, one of them serving as the refrigerant and the other as the sorbent. The operation of such systems is well documented and is not described here [3]. The main advantages of this technology are the continuous thermodynamic cycle and the high thermal coefficient of performance (COP_{th}), compared to the adsorption chiller.

Absorption chillers are available on the market in a wide range of capacities and are designed for different applications. However, only very few systems are available in a range below 100 kW of cooling capacity. Approximately 75% of these systems are single-effect absorption chillers [4]. Absorption chiller behaviour is highly dependent on the climate and building quality (these are the boundary conditions) [5]. For this reason, users need reliable information on the long-term performance of the system in the desired boundary conditions. This requires reliable and faithful models of absorption chillers under real conditions.

Two types of model can be used to predict the behaviour and performance of absorption chillers: physical (or "white-box") and empirical ("black-box") models. Physical models describe the entire absorption chiller thermodynamic cycle and heat exchanger

* Corresponding author.
E-mail address: antoine.leconte@cea.fr (A. Leconte).

http://dx.doi.org/10.1016/j.renene.2015.09.023
0960-1481/

Nomenclature

Variables

w	synaptic weight of the neural network [−]
y	vector of output data (target data) [−]
$\hat{y}$	vector of ANN output data [−]
z	output of a neuron [−]
f	activation function [−]
t	time [min]
N	size of the learning data [−]
nor	normalization bounds [−]
x	vector of data (usually input data) [−]
T	temperature [°C]
M	mass flow rates [kg h^{-1}]
q	number of model weights [−]
Cp	heat capacity [J kg^{-1} K^{-1}]
P	thermal power [kW]

Indices

E	evaporator
A	absorber
G	generator
C	condenser
AC	absorber–condenser
in	input
out	output
X	indicates E, AC or C
^	indicates the variable calculated by the ANN
th	thermal

Abbreviations

TD	time delay
BIC	Bayesian information criterion
ANN	artificial neural network
AF	activation function
Err	absolute relative instantaneous error
SFH	single family house
COP	coefficient of performance
SCS	solar combi-system
SSE	sum of square errors
MSE	mean squared errors
MLP	multi-layer perceptron
R^2	coefficient of determination [−]
Obj	objective function

Other

net	the selected model

performance and compute temperatures of external fluids. The heating and cooling capacities are then deduced from the latter. In contrast, black-box models only focus on external fluids, computing temperatures and power by a set of non-physical equations fitted with experimental data. Examples of these types of model have been thoroughly studied and compared in steady-state conditions in Refs. [6] and [7].

Among empirical models, artificial neural networks (ANNs) seem to be the most powerful mathematical tool to solve this modelling problem. In fact, it was shown that ANNs are universal function approximators [8], so they can be used to approximate the system function. ANNs were applied successfully to solve complex, non-linear, dynamic and multivariable problems. They tolerate errors, imprecisions and missing data as well [9]. ANNs were extensively used during the last decade and have been especially used to solve prediction modelling problems in renewable energy thermal systems [10–15]. The following presents selected studies that focus on modelling absorption chiller systems:

- In Ref. [16] the authors developed an ANN-based model of an adsorption chiller. The ANN has six inputs (three inlet temperatures and three flow rates) and three outputs (three outlet temperatures). The model developed is able to predict, with an error less than 2 °C, the output temperatures. However, because it was trained using a quasi-steady-state database, the ANN cannot predict the system's long-term behaviour.
- In Ref. [17] (a similar study is presented in Ref. [18] as well) the authors developed an ANN-based model of a solar-driven absorption chiller. The model developed was able to predict both the COP_{th} and the system cooling capacity with a low error. For this study, only five inputs were relevant to model the whole system, e.g. the inlet and outlet temperatures of the evaporator and generator, and the average temperature of the hot storage tank. The inputs of the modelling configuration used are not suitable to evaluate the performance of an absorption chiller when only inlet temperatures and flow rates are available.
- In Ref. [19] the authors modelled a double-effect absorption chiller in steady state using neural networks. The model was validated using experimental data of approximately 250 samples. The ANN used predicted the performance of the absorption chiller quite accurately (coefficient of determination R^2 greater than 0.99).
- In Ref. [20] the authors developed a control system based on an inverse ANN model. The static ANN model, which is an analytical function, requires a short computing time and consequently makes this methodology suitable for the on-line control of absorption cooling systems.

Further studies where static ANNs were used to model or optimize absorption chillers can be consulted in Refs. [21–24].

The studies from the literature presented above focus only on steady- or quasi-steady-state behaviour of the system, and the modelling configuration used in some of them does not help predict the long-term absorption chiller outlet temperatures and energy performance. Dynamic simulation plays a very important role in the description of the real performance of an energy conversion system, especially during the activation stage or part-load operation where time plays an important role. This problem is extremely relevant for absorption chillers, where the high mass of the internal components and the accumulation of the fluids inside the vessels usually make the transient period longer than for mechanical compression chillers [25]. The literature study shows that a complete method is needed to model absorption chillers in order to predict their operating temperatures and energy performance. Also, detailed physical models are complex, difficult to develop and to be integrated into simulation software because they are very time consuming. The current work presents a methodology to model absorption chillers in a dynamic way but using a faster model. Indeed, the method proposed does not assume any prior knowledge of the system to be modelled or its components. This makes the method generic and more relevant as a future tool to evaluate absorption chillers' energy performance in a certification