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The development and calibration of a generic dynamic absorption chiller model

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ABSTRACT

Although absorption cooling has been available for many years, the technology has typically been viewed as a poorly performing alternative to vapour compression refrigeration. However, rising energy prices and the requirement to improve energy-efficiency is driving renewed interest in the technology, particularly within the context of combined cooling, heat and power systems (CCHP) for buildings. In order to understand the performance of absorption cooling, numerous models are available in the literature. The complexities involved in the thermodynamics of absorption chillers have, however, so far restricted researchers to creating steady-state or dynamic models reliant on data measurements of the internal chiller state, which require difficult-to-obtain, intrusive measurements. The pragmatic, yet fully dynamic model described in this paper is designed to be easily calibrated using data obtained from the measurements of inflows and outflows to a chiller, without resorting to intrusive measurements. The model comprises a series of linked control volumes featuring both performance maps and lumped mass volumes, which reflect the underlying physical structure of the device. The paper describes the modelling approach, theory and limitations, along with an example of the implementation of the model in the ESP-r code complete with calibration and an application to a specific example.

1. Introduction

The increased use of air conditioning in buildings, including dwellings over the last 30 years has contributed to a significant increase in electrical energy consumption [1], particularly in southern European countries [2]. The conditioning systems installed are typically packaged, split vapour compression units [3]. Due to a general need to curb non-renewable primary energy and related CO_2 emissions (and possibly reduce escalating fuel costs), interest in less energy intensive forms of cooling are growing. Thermally activated absorption cooling powered either by heat absorbed through solar collectors [1,4] or from waste heat recovered from CCHP trigeneration systems [5,6], is possibly one of the most well known and researched alternatives.

1.1. The need for dynamic modelling

Historically, chiller systems have been designed against fixed operating conditions, and many steady-state models have been developed as design aids [7–10] or as tools to estimate energetic annual performance [11]. However, chiller systems will typically operate under dynamic conditions, due to (for example) 'On'/'Off' or modulating behaviour, start-up and shut down or other temporal fluctuations in operating conditions, as discussed by Jeong et al. [12] and Fujii [13]. Dynamic models [12,14–17], whilst intrinsically more complex, are therefore a more appropriate means to assess the actual performance of absorption chillers within a trigeneration system reliant on transient heat input such as that supplied by solar energy and subject to a fluctuating load. Further, in integrated building-plant models dynamic modelling is the only accurate way of producing a true representation of the behaviour of the chiller [18].

1.2. Existing dynamic models

Most of the existing attempts at dynamic absorption chiller modelling have resulted in the creation of detailed models of specific chillers [19] or detailed models of specific cycles and system configurations [20]. An alternative approach is to develop a model capable of being easily customised through calibration with data obtained for different units. Fu et al. [16] and Fujii [13] both present studies aimed at flexible and customisable models. Fu et al. [16] created an extension to the idea of the ABSIM modular program [10] to offer ABSLM, an object-oriented dynamic library, built using the language Modelica, which provides a component list (*e.g.* pumps, condenser, evaporator, *etc.*) enabling the creation of different types of absorption chiller configurations. Fujii [13] developed an object-oriented model capable of predicting the transient behaviour of absorption refrigerators with an arbitrary cycle configuration, using a triple-effect system as an example. Other examples of dynamic

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Nomenclature

Variables

A	area (m^2)
$\dot{c}$	mass weighted average specific heat capacity (kJ/kg K)
c	specific heat (kJ/kg K)
f	circulation ratio
h	specific enthalpy (kJ/kg)
M	total mass of node (kg)
$\dot{m}$	mass flow rate (kg/s)
m	mass of component inside the chiller (kg)
p	pressure (kPa)
t	time (s)
T	temperature (°C)
U	component total heat loss coefficient (W/m^2 K)
X	solution concentration of lithium bromide in water (%)

Greek letters

η	recovery heat exchanger effectiveness

Indices

chilled	chilled water flow circuit
cooling	cooling water flow circuit
el	electrical power
env	environment
g	internal node within the absorption chiller representing the thermal mass which is associated with the hot water circuit
high	high pressure of absorption refrigeration cycle found in generator–condenser
hot	hot water flow circuit
i	internal node within the absorption chiller representing the thermal mass which is associated with the chilled water circuit
j	internal node within the absorption chiller representing the thermal mass which is associated with the cooling water circuit
low	low pressure of absorption refrigeration cycle found in absorber–evaporator
ref	refrigerant
strong	chiller branch with the strong solution
th	thermal power
weak	chiller branch with the weak solution

models of absorption chillers include work carried out by Takagi et al. [15] which simulate the behaviour of a single effect absorption chiller using HVACSIM$^+$, and Nurzia [21] which uses the transient simulation code TRNSYS [22] to model a similar single-stage absorption chiller.

1.3. Requirement for a new model

The models described typically require the user to define the characteristics of the components comprising the desired absorption chiller such as the individual components' heat exchange surface area, individual internal component dimensions, solution composition and internal mass flow rates. This is a non-trivial task often requiring invasive experimental techniques which are difficult to perform and very time-consuming; potentially limiting the flexibility and adaptability of these models.

The scope of this research was therefore to create a functional dynamic model, which could be adapted to represent different chillers using easily obtainable data. The model concept is similar to that developed by the IEA ECBCS Annex 42 in [23] where the model of a generic engine-based CHP system was developed comprising performance maps linking key input and output parameters, coupled with lumped thermal masses that enabled transient thermal performance to be captured. The Annex 42 model was complemented by a calibration approach using non-invasive tests and measurements. The chiller model developed and described in this paper represents a single-effect hot water fed lithium bromide–water absorption chiller, the most apt for use in CCHP trigeneration systems [13].

2. Development of the proposed model

The chiller model was developed for the ESP-r building simulation tool [24] in which a complex system such as a building or a plant system can be reduced to series of discrete control volumes, represented by a node, to which the conservation of energy and mass can be applied [25]; this approach is extended to the modelling of the absorption chiller. Whilst this paper is focussed on the ESP-r tool, it should be noted that the model described in this paper can be integrated into other common, dynamic simulation tools such as TRNSYS [22] or EnergyPlus [26].

2.1. The control volume concept used to model the thermal transients inside the chiller

A single-effect absorption chiller can be described using a three node system with each individual node representing the thermal mass corresponding to one of the water circuits associated with the absorption chiller, specifically the chilled water, cooling water and hot water circuits. The concept is an evolution of the one outlined by Beausoleil-Morrison et al. in [27] who developed a steady-state chiller model for ESP-r.

Fig. 1 shows the chiller represented by a series of three control volumes and the respective energy flows within each node. Node i represents the chilled water circuit, incorporating the evaporator casing and the mass of refrigerant and chilled water. Q_i is the net energy process occurring internally within the control volume, which affects the incoming chilled water circuit. Node j represents the cooling water circuit, comprising the condenser, absorber and heat exchanger casing and the mass of refrigerant, cooling water and solution contained within them. Q_j, in this case is the net energy process occurring internally within the Node j, which affects the cooling water circuit. Finally, in the upper part of the diagram Node g represents the hot water circuit including the generator casing and the mass of solution and water contained within it. Similarly as for Q_i and Q_j, Q_g is the net energy process occurring in the respective control volume, which in this case affects the hot water circuit.

Applying basic energy and mass conservation individually on the three nodes, three partial differential equations, one for each node are obtained as follows:

For **Node *i***, for an incoming chilled water flow rate $\dot{m}_{chilled}$ having specific heat capacity $c_{chilled}$

$$\frac{M_i \dot{c}_i \delta T_i}{\delta t} = \dot{m}_{chilled} c_{chilled} (T_{17} - T_i) + Q_i, \tag{1}$$

where

$$Q_i = \dot{m}_{ref} (h_9 - h_{10}) \tag{2}$$

For **Node *j***, for an incoming cooling water flow rate $\dot{m}_{cooling}$ having specific heat capacity $c_{cooling}$

$$\frac{M_j \dot{c}_j \delta T_j}{\delta_t} = \dot{m}_{cooling} c_{cooling} (T_{13} - T_j) + Q_j, \tag{3}$$