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Research Paper

Empirical modeling of the impacts of faults on water-cooled chiller power consumption for use in building simulation programs

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HIGHLIGHTS

- Developed empirical models to simulate chiller fault impacts in building models.
- Modeling of overcharging, excess oil, non-condensable, and condenser fouling.
- Predicted the amount of electricity and water consumption increase due to faults.
- Hotter and more humid climates worsen fault impacts.

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ABSTRACT

Empirical models of four chiller faults that can be applied within existing building models to study overall impacts are developed in this paper. The faults include overcharging, excess oil, non-condensables in refrigerant and water-side condenser fouling. A single generalized model structured was developed for these faults that forces predicted fault impacts to be zero with no fault and increase with increasing fault level. The models were trained and tested using available laboratory data for a water-cooled centrifugal chiller where all four faults were artificially introduced. The fault model behavior was studied and then they were integrated in hospital models from DOE commercial reference building models (Deru et al., 2011) and simulations were performed in different climates. The simulation results showed maximum increases of building electricity consumption, electricity peak demand and water consumption of the hospitals due to faults of 4.7%, 7.8% and 1.8% respectively. The fault impacts were found to be more severe in hotter and more humid climates.

1. Introduction

The evolution of low-cost sensors and control systems for buildings has led to the recent development and evaluation of methods for automated fault detection and diagnostics (FDD) applied to chillers. The FDD algorithms are designed to automatically identify faults that deteriorate equipment performance. For instance, Castro [1] demonstrated the use of clustering techniques to implement FDD algorithms for chiller faults on measurement data. Reddy [2] compared the performance of four different FDD algorithms for chillers using data from a water-cooled centrifugal chiller that was tested under various faulty conditions [3,4]. Zhou et al. [5] developed a model-based FDD algorithm for chillers based on a semi-empirical chiller model from Ma et al. [6]. Han et al. [7] developed a machine-learning-based FDD algorithm using data from Comstock and Braun [4]. Zhao et al. [8] developed a virtual condenser fouling sensor for chillers.

Chiller models are very useful in the development and evaluation of FDD algorithms. Reddy et al. [9] summarized four different methods to model chillers: thermodynamic and heat transfer based models, linear empirical models such as the chiller model in the DOE-2.1 building model [10], physical models and artificial neural network models. As an example, a thermodynamic and heat transfer based model was developed by Ma et al. [6] to be used in a building simulation program for the development of FDD algorithms for chillers. Another example is a physical model of a chiller and chiller faults developed by McIntosh et al. [11] to study chiller performance degradation due to faults. Although not included in the four methods described by Reddy et al. [9], a Kalman-filter based chiller model was used in Navarro-Esbrí et al. [12] to create a chiller fault detection algorithm. Furthermore, machine-learning based FDD algorithms such as those from Han et al. [7] typically use machine-learning algorithms to create a model of faulted chillers to be used in the chiller FDD.

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DOE-2 [13] and EnergyPlus [14] are commonly used building simulation programs that employ the linear empirical chiller model originally developed for DOE-2.1 [10]. This model uses a user-defined evaporator water outlet set point temperature, chiller cooling load requirement and condenser water inlet temperature to calculate chiller part-load ratio and power consumption using multiple empirical equations. TRNSYS [15] is another building simulation program that employs a water-cooled chiller model that relates the same inputs and outputs with an alternative approach based on a thermodynamic model. For any of these simulation programs, it is relatively easy to implement fault models that act on the outputs of the chiller models. For example, EnergyPlus allows the use of scripts programmed using a language called Erl to modify chiller model outputs.

Although Zhou et al. [5] demonstrated that a thermodynamic and heat transfer based model could be modified to simulate fault impacts in building models, it is much more convenient to modify the inputs and outputs from existing chiller models within a simulation program than to replace the underlying model. One simple example of this approach is from Magoulès et al. [16] who reduced the reference COP of an empirical chiller model by a constant value before running the building simulation. Although this is meant to model fault impacts, it is unrealistic because the impacts of faults on chiller COP change with different environmental conditions as shown in Comstock and Braun [3]. Another example is Cho et al. [17] where simulated fault impacts on cooling capacity and power consumption for split air conditioners were treated with multipliers applied to the non-faulted cooling capacity and power consumption. These multipliers could be applied to the outputs of a standard model within the building simulation library and thus do not require recoding or replacement of the air conditioner model. The use of this fault impact modeling approach in building simulation was demonstrated by Domanski et al. [18] for a residential building.

In the current paper, a fault modeling approach similar to the work of Cho et al. [17] for split air conditions is developed for chillers in order to enable fault impact studies for medium to large commercial buildings using an existing widely used building simulation package. The fault models were developed based on the chiller fault data collected by Comstock and Braun [4] and predict impacts on chiller power consumption of four different types of faults: overcharging, excessive oil, non-condensable in refrigerant flow and water-side condenser fouling. The models are based on a similar mathematical structure as Cho et al. [17] and can be applied directly to the outputs from existing chiller models. The training and validation procedures along with the application of the models using an existing building simulation tool are also discussed in this paper.

2. Review of faults

Overcharging of refrigerant beyond that specified by the manufacturer can occur during service and leads to increased compressor discharge pressure of the chiller compared to normal charge. This leads to an increase in the compressor power consumption.

An excess oil condition can also occur as a result of improper service and can cause an increase in viscous losses within the compressor. More refrigerant may also dissolve in the oil, and the effective mass of refrigerant circulating in the chiller may be reduced, leading a loss in efficiency.

The non-condensable in refrigerant fault occurs as a result of service when the chiller was not well evacuated prior to charging of refrigerant. As a result, the chiller operates with an air-refrigerant mixture instead of a pure refrigerant. Since air cannot be condensed in the refrigerant liquid during chiller operation, the air is typically trapped in the superheated vapor region downstream of the compressor. The accumulation of air increases the compressor discharge pressure and hence the compressor power consumption.

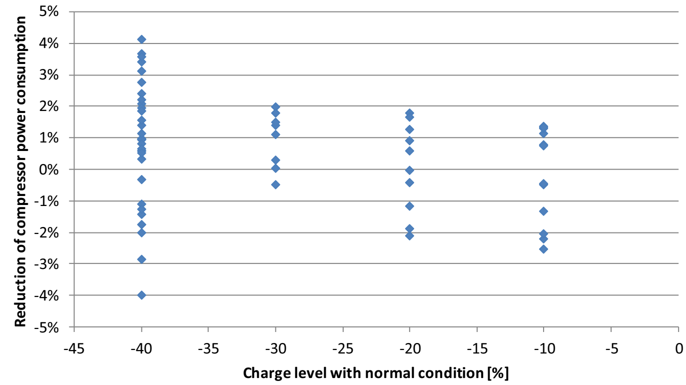

Fig. 1. Change of chiller power consumption with decreasing amount of refrigerant under a wide range of conditions (evaporator water outlet temperature from 277.35 K to 283.9 K, condenser water inlet temperature from 289.25 K to 303.36 K, evaporator water inlet temperature from 279.4 K to 289.5 K, evaporator water flow rate at 49 $m^3 h^{-1}$ and condenser water flow rate at 61 $m^3 h^{-1}$).

Water-side condenser fouling occurs due to build up of scale on tube services but was simulated by Comstock and Braun [3,4] through blocking of individual heat exchanger tubes. Water-side condenser fouling increases the water flow resistance and reduces the water flow rate. The fouling may also reduce the heat transfer area of the condenser. The reduction of water flow and heat transfer area reduce the heat transfer rate of the condenser and hence the efficiency of the chiller.

Comstock and Braun [3,4] also recorded data for a water flow reduction fault, refrigerant leakage and detective expansion valve. Water flow reduction faults can be modeled using existing chiller models by simply reducing water flow rate and therefore was not considered in this paper. The defective expansion valve data do not contain fault levels and cannot be modeled in the same way as other faults. Its low refrigerant data did not show a definite increase of chiller power consumption with the charge reduction as shown in Fig. 1 for a range of other conditions, and therefore were not modeled in this paper. Although performance was not sensitive to charge over the range considered for this water-cooled chiller, this does not suggest that charge effects are not important at lower charge levels for this chiller type or for other chillers within the charge range considered.

3. Experimental setup

Since the details of the experiments were given in Comstock and Braun [3], only a review of the experimental procedure is provided in this paper. According to Comstock and Braun [3], the experiments were conducted with a 316.5-kW water-cooled centrifugal chiller. The chiller compressor capacity was controlled to maintain a specified evaporator water outlet temperature, but a range of different set points was considered in the experiments. The chiller was tested under a variety of faults at different environmental conditions and fault levels as shown in Table 1 and Table 2 with a data acquisition frequency at 0.1 Hz.

Table 1
Environmental conditions in the chiller tests.

Evaporator water inlet temperature [°C]	6.3–16.2
Evaporator water outlet temperature [°C]	4.0–11.6
Condenser water inlet temperature [°C]	17.8–30.0
Evaporator water flow rate [$m^3 h^{-1}$]	48.6–50.0
Condenser water flow rate [$m^3 h^{-1}$]	60.1–61.9