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Development and Testing of a Reformulated Regression-Based Electric Chiller Model

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ABSTRACT

This paper presents the development of a new electric chiller model and the testing of it and three public domain electric chiller models. These models enable analysis for the optimization of the design, optimization of the controls, commissioning, and diagnostics for chilled water plants. The four models were tested for their accuracy in predicting power over the range of operation and evaluated for their ease of calibration from readily available data sources for existing and new equipment. In testing and evaluation, each of the three existing public-domain models was found to have limitations. Of particular concern was the inaccuracy of these models in predicting the power usage of chillers with variable condenser water flow and centrifugal chillers operating with variable-speed drives at low loads. This paper describes a reformulation of one of these models to specifically address these issues. The validation testing included both manufacturer-supplied and field-monitored data. In all of the tests the newly reformulated model effectively produced lowest error values for power prediction across a range of chillers including centrifugal, reciprocating, screw, and scroll compressors. Relative to the other models, this new model predicts power more accurately for variable condenser water flow and low-load variable-speed applications.

OBJECTIVE

Accurate and cost-effective simulation of chilled water plants and equipment is essential to a range of design, control, and operational issues: it is employed in the comparison of design alternatives (Taylor et al. 1999), the optimization of control algorithms, the commissioning of chilled water plants (Hydeman et al. 1999), and in the development of diagnostic tools (Sreedharan 2001). In turn, the success of all of these efforts is a strong function of the accuracy of the component models within the simulation (Kammerud et al. 1999). Through experience, target accuracies of 3% to 5% coefficient of variation root mean squared errors (CVRMSE)[1] for prediction of power usage have been deemed acceptable for component models.

To achieve the target accuracy and to meet the practical needs of the engineer, an ideal model of an electric chiller would meet all of the following criteria:

- Be accurate in the prediction of power over a wide range of cooling load as well as evaporator and condenser temperatures.
- Be responsive to variations in flow through both the evaporator and condenser.
- Be easy to calibrate with readily accessible data.
- Be easy to incorporate into simulation tools (both current and in development).
- Represent a wide-range of equipment configurations including
    - air- and water-cooled condensers,
    - all of the commercially available compressors, and
    - all of the compressor unloading mechanisms.

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[1] CVRMSE and mean bias error (MBE) are estimates of error used in evaluation of simulation tools (Haberl and Bou-Saada 1998). See Equations 10 and 11.

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- Be responsive to variable speed driven centrifugal machines at low loads both with and without condenser relief.[2]

METHOD

To meet our objectives, we undertook the following steps:

1. We researched available public domain models and methods to calibrate them. It is important to note that we only evaluated a subset of the available models.
2. We selected the DOE-2 chiller model as a base since it was relatively accurate, it existed in simulation tools, and it was relatively easy to calibrate to either manufacturer's or field-measured data (Hydeman and Gillespie 2002).
3. We modified the DOE-2 model to respond to variations in condenser water flow.
4. We further modified the DOE-2 model to respond to variable speed driven chillers at low loads.
5. We developed a method for calibration of the modified DOE-2 model.

We tested the models against four sets of data: (1) a very rich set of manufacturer's data for a constant-speed chiller with variable condenser water flow, (2) a very rich set of manufacturer's data for a variable-speed chiller with varying load and condenser water temperatures, (3) a large but less rich set of manufacturer's data representing 132 chillers (Table 1), and (4) field-measured data with the chiller models calibrated to manufacturers' data.[3]

Preliminary Model Identification and Screening

The authors uncovered and tested three publicly available electric chiller models: the model used in the DOE-2 program (DOE 1980), the model presented in the ASHRAE primary systems toolkit (Le Brun et al. 1999), and the Gordon and Ng model used in ASHRAE Research Project 827 (Brandemuel et al. 1996; Gordon et al. 2000). In addition to testing these three models, the authors tested two means of calibrating the DOE-2 model. For the purpose of this paper we will refer to these models as follows:

Model reference	**Model description**
DOE-2 A (DOE2a) and DOE-2 B (DOE2b)	A black box regression model with three equations and 15 regression coefficients developed for the DOE-2 simulation program. The authors used two different techniques for calibration of the part-load performance equation.
Gordon-Ng (GNg)	A physical model of a fixed-speed centrifugal chiller used in ASHRAE RP-827. For this paper we used a more current version that was revised for variable flow.
Primary Toolkit (PT)	A physical model presented in the ASHRAE primary systems toolkit.
Modified DOE-2 (ModDOE2)	A modification of the DOE-2 model presented in this paper.

It should be noted that several available models were not included in our tests and evaluations. These include the models used in the simulation tools BLAST, Trace, HAP, and EnergyPlus. In each case we were unable to uncover the details of these models in time for our study. We plan to include each of these models in future testing.

To test the four models, the authors developed calibration techniques. The format of the DOE-2 model is presented in the program documentation (DOE 1980). The process to calibrate it is described in the paper by Hydeman and Gillespie (2002). This model requires separate full-load and part-load data for direct calculation of the regression coefficients. The sole difference between the two techniques employed in this research is that the DOE-2 A model uses only part-load data to develop the energy input ratio as a function of part-load ratio (EIRFPLR) coefficients and the DOE-2 B model uses combined full- and part-load data to develop these coefficients.

The Gordon-Ng model is fully described in their paper (Gordon et al. 2000). This model has three coefficients that can be directly determined through linear regression. Each of these coefficients represents a physical property of the chiller.

The primary toolkit model is a complex component-based physical model, with different full-load and part-load model equations. Distinct compressor models are employed to represent the different compressor types. The calibration of this model requires separate full- and part-load data. The suggested calibration method is a grid-type search method, which is computationally inefficient. Sreedharan (2001) describes a reformulation of that model that can be calibrated to readily accessible performance data using more efficient, although iterative, numerical solution techniques. Because of the complexity of the calibration techniques, this model was only tested on a subset of the test data.

In early testing (Hydeman et al. 1997; Hydeman and Gillespie 2002), the authors found that there were practical limitations to each of the existing public domain models. The DOE-2 model was unresponsive to variations in condenser water flow and had large errors in the prediction of power from variable speed driven centrifugal chillers at low loads.

The Gordon-Ng model was generally accurate for fixed-speed centrifugal chillers but inaccurate for other compressors. As a physical model, its parameters have diagnostic value, but its physical foundation limits its application: it is not appropriate for variable-speed drives, noncentrifugal compressors, or air-cooled condensers. Of all the models, the Gordon-Ng is the easiest to calibrate to field-measured data as it doesn't require separation of the full- and part-load data.

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[2] *Condenser relief* refers to a rating condition that reduces the temperature of either the outside air (air-cooled equipment) or entering condenser water (water-cooled equipment) as the load drops (ARI 1998).

[3] Due to complexities in calibrating the primary toolkit model, we only tested it against the first two datasets.

TABLE 1

Manufacturer	Model Line	Compressor	Unloading Mechanism	Number of Data Sets
Manufacturer A	19EX	Centrifugal	Inlet Vanes	4
Manufacturer A	19FA	Centrifugal	Inlet Vanes	1
Manufacturer A	19XL	Centrifugal	Inlet Vanes	5
Manufacturer A	19XR	Centrifugal	Inlet Vanes	8
Manufacturer A	19XR	Centrifugal	VSD	11
Manufacturer A	30HR	Reciprocating	None	1
Manufacturer A	23XL	Screw	Slide Valve	9
Manufacturer B	CVHE	Centrifugal	Inlet Vanes	3
Manufacturer B	CVHF	Centrifugal	Inlet Vanes	6
Manufacturer B	CVHE	Centrifugal	VSD	3
Manufacturer B	CVHF	Centrifugal	VSD	2
Manufacturer B	RTH	Screw	Slide Valve	3
Manufacturer B	RTW	Screw	Slide Valve	1
Manufacturer B	CGWD	Scroll	None	1
Manufacturer C	YK	Centrifugal	Inlet Vanes	16
Manufacturer C	YT	Centrifugal	Inlet Vanes	14
Manufacturer C	YK	Centrifugal	VSD	2
Manufacturer C	YT	Centrifugal	VSD	18
Manufacturer C	YS	Screw	Slide Valve	7
Manufacturer D	PEH	Centrifugal	Inlet Vanes	8
Manufacturer D	PFH	Centrifugal	Inlet Vanes	7
Manufacturer D	PFS	Screw	Slide Valve	1
Manufacturer E	MS	Reciprocating	None	1
Subtotals (Number of Data Sets by Type)				
Centrifugal Chillers (fixed speed)				72
Centrifugal Chillers (variable speed)				36
Reciprocating Chillers				2
Scroll Chillers				1
Screw Chillers				21
Total				**132**

The primary toolkit model is very hard to calibrate to readily available data (Sreedharan 2001). It requires numerical search methods that are beyond the experience of most practicing engineers. It is also not appropriate for variable-speed drives. The primary toolkit model can be used for different compressors and air-cooled condensers, but distinct model formats are required for different compressors and/or condensers.

After early testing of these models (Hydeman and Gillespie 2002), the authors sought to improve upon the DOE-2 model. This model was reformulated to utilize the leaving condenser temperature and terms were added to the part-load equation to account for temperature dependencies. The specific modifications are detailed below.

Development of the Modified DOE-2 Chiller Model

Like the DOE-2 model (DOE 1980; Hydeman and Gillespie 2002), the Modified DOE-2 model has three basic functions:

- The capacity as a function of temperature (CAPFT) equation (Equation 4) represents the available full-load capacity as a function of evaporator and condenser temperatures.
- The energy input ratio as a function of temperature (EIRFT) equation (Equation 5) represents the full-load efficiency (1/COP) as a function of evaporator and condenser temperatures.
- The energy input ratio as a function of part-load ratio (EIRFPLR) equation (Equation 7) represents the part-load efficiency as a function of part load. In the case of the Modified DOE-2 model, it also has terms for the condenser temperature.

Taken together these three equations can be used to predict power over a range of operating conditions (Equation 9).

The CAPFT and EIRFT equations use the chilled water supply and condenser water supply temperatures in the DOE-2 model and the chilled water supply and condenser water return temperatures in the Modified DOE-2 model. In both cases, these water temperatures are used as proxies for the refrigerant temperatures.[4]

The Modified DOE-2 model was developed in two steps. The first step was to reformulate the existing curve coefficients for the CAPFT and EIRFT function to utilize the leaving condenser water (or air) temperature in place of the entering condition. The authors discovered this improvement by examining the existing model's performance with variable flow conditions on both the evaporator and condenser. The existing model appeared to respond well to changes in the evaporator flow but not to changes in condenser flow (Figure 2, Table 3). With flooded heat exchangers, like chiller evaporators and condensers, the leaving fluid temperature is a better proxy for the saturated refrigerant temperature. Equations 4 and 5 below show the reformulated CAPFT and EIRFT equations.

The second step was to add coefficients to the EIRFPLR to account for variations in part-load efficiency as a function of compressor lift.[5] The existing DOE-2 model did not respond well to variable speed driven centrifugal chillers at low loads with a coincident range of entering condenser water temperatures. As described below, the relationship of part-load efficiency to compressor lift comes from the chiller controls utilizing both inlet vanes and variable-speed drives to modulate capacity. Through trial and error, four terms were added: two for condenser water return temperature, a cubic term for part-load ratio, and a cross term with condenser water return temperature and part-load ratio (refer to Equation 8).

Calibration of the Modified DOE-2 Model

Like the DOE-2 model, the Modified DOE-2 model can be calibrated using data from a manufacturer's selection program. A typical calibration dataset includes chiller capacity (*Cap*, tons), power (*Pwr*, kW), chilled water supply temperature (*CHWS*, °F), and condenser water return temperature (*CWR*, °F). The data must be separated into full- and part-load conditions.

If the condenser water return temperature is not directly available, it can be calculated from a simplified first law analysis as shown in Equation 1. This equation neglects the heat gain and loss from the chiller components to the room and should only be used if the condenser water return temperature is not directly available.

$$CWR_i = \frac{(Cap_i \times 12000) + (Pwr_i \times 3413)}{CondFlow_i \times 500} + CWS_i \tag{1}$$

It is good practice to normalize a DOE-2 based model to a reference full-load point (Cap_{ref} and Pwr_{ref}). The resulting normalized curve can be used in a library of curves for representation of chillers with small or mixed datasets.[6] This reference data point can be selected at random from any full-load operating condition but is typically selected at the design conditions (Hydeman and Gillespie 2002).

The process of developing the model coefficients begins with the calculation of the CAPFT and EIRFT functions from the full-load records in the calibration dataset. Calculate interim values for both CAPFT and EIRFT using the reference values for power and capacity in Equations 2 and 3.

$$CAPFT_i = \frac{Cap_i}{Cap_{ref}} \tag{2}$$

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[4] The DOE-2 models use outdoor air dry-bulb temperature as a proxy for condenser refrigerant temperature in air-cooled chiller applications.

[5] Compressor lift is a measure of the difference in the saturated evaporator and condenser pressures.

[6] This process, described as the "reference curve method," is described in detail in the paper by Hydeman and Gillespie (2002).

$$EIRFT_i = \frac{Pwr_i}{Pwr_{ref} \times CAPFT_i} \qquad (3)$$

Calculate the CAPFT and EIRFT regression coefficients using standard least squares linear regression techniques from the full-load data, the interim values (Equations 2 and 3), and the regression equation formats for CAPFT and EIRFT (Equations 4 and 5).

$$CAPFT_i = A_{CAPFT} + B_{CAPFT} \times CHWS_i + C_{CAPFT} \times CHWS_i^2 + D_{CAPFT} \times CWR_i + E_{CAPFT} \times CWR_i^2 + F_{CAPFT} \times CHWS_i \times CWR_i \qquad (4)$$

$$EIRFT_i = A_{EIRFT} + B_{EIRFT} \times CHWS_i + C_{EIRFT} \times CHWS_i^2 + D_{EIRFT} \times CWR_i + E_{EIRFT} \times CWR_i^2 + F_{EIRFT} \times CHWS_i \times CWR_i \qquad (5)$$

Calculate the EIRFPLR equation coefficients on the combined full- and part-load dataset. First calculate the values for EIRFT and CAPFT over the combined dataset using Equations 4 and 5 and the coefficients A_{CAPFT} through F_{CAPFT} and A_{EIRFT} through F_{EIRFT} calculated in the last step. Next, for each record in the combined dataset, calculate the part-load ratio (PLR) and an interim value for EIRFPLR using Equations 6 and 7.

$$PLR_k = \frac{Cap_k}{Cap_{ref} \times CAPFT_k} \qquad (6)$$

$$EIRFPLR_k = \frac{PWR_k}{P_{ref} \times CAPFT_k \times EIRFT_k} \qquad (7)$$

Calculate the EIRFPLR regression coefficients using standard least squares linear regression techniques from the combined full- and part-load data, the calculation of PLR (Equation 6), the interim value for EIRFPLR (Equation 7), and the regression equation format for EIRFPLR (Equation 8).

$$EIRFPLR_k = \begin{array}{c} A_{EIRFPLR} + B_{EIRFPLR} \times CWR_k + C_{EIRFPLR} \\ \times CWR_k^2 + D_{EIRFPLR} \times PLR_k \\ + E_{EIRFPLR} \times PLR_k^2 + F_{EIRFPLR} \\ \times PLR_k^3 + G_{EIRFPLR} \times CWR_k \times PLR_k \end{array} \qquad (8)$$

Using the coefficients $A_{EIRFPLR}$ through $G_{EIRFPLR}$ from the last step, calculate the value for EIRFPLR for all full- and part-load data records from Equation 8. From the combined data and the calculated values of the CAPFT, EIRFT, and EIRFPLR functions (equations 4, 5, and 8), calculate the predicted power for all full- and part-load data records with the following equation:

$$Pwr_k = P_{ref} \times CAPFT_k \times EIRFT_k \times EIRFPLR_k \qquad (9)$$

Testing of the Models

As previously noted, the authors tested the models against four sets of data:

1. A very rich set of manufacturer's data for a fixed-speed centrifugal chiller with variable condenser water flow,
2. A very rich set of manufacturer's data for a variable-speed centrifugal chiller with varying load and condenser water temperatures,
3. A large but less rich set of manufacturer's data representing 132 chillers (Table 1), and
4. Field-measured performance of a new fixed-speed centrifugal chiller. The chiller models were calibrated to "zero-tolerance" manufacturer's data that had been verified in a factory witness test.[7]

Due to difficulties in calibrating the primary toolkit model, it was only tested against the first two datasets.

Errors for each test were assessed using the coefficient of variation of the root mean squared error (CVRMSE, Equation 10) and the mean bias error (MBE, Equation 11). The CVRMSE is similar to an R^2 error. It measures the degree of data scatter. The MBE indicates the degree of bias in the model. A positive MBE indicates a model that tends to overpredict power, a negative MBE indicates underprediction. Least squares regression techniques will generally produce models with an MBE of 0 against the calibration dataset. CVRMSEs run from between 1% to more than 10%. As previously stated, the target is to get ≤5% CVRMSE (Kammerud et al. 1999).

$$CVRMSE = \frac{\sqrt{\dfrac{\sum_k (PwrPred_k - Pwr_k)^2}{\sum_k 1}}}{\dfrac{\sum_k Pwr_k}{\sum_k 1}} \qquad (10)$$

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[7] "Zero tolerance" data are data that are certified by the manufacturer to meet the following criteria: 1) the capacity of the chiller will be equal to or greater than the specified data, and 2) the effiency (kW/ton) of the chiller will be equal to or less than the specified data. A factory witness test is an acceptance test of a chiller witnessed by an owner or their representative at a factory test facility. If the chiller fails to meet the specified zero tolerance performance at the witness test, liquidated damages may be applied. The process of applying zero-tolerance data and factory witness tests in chiller procurement is described in the *CoolTools™ Chilled Water Plant Design Guide* (Taylor et al. 1999).

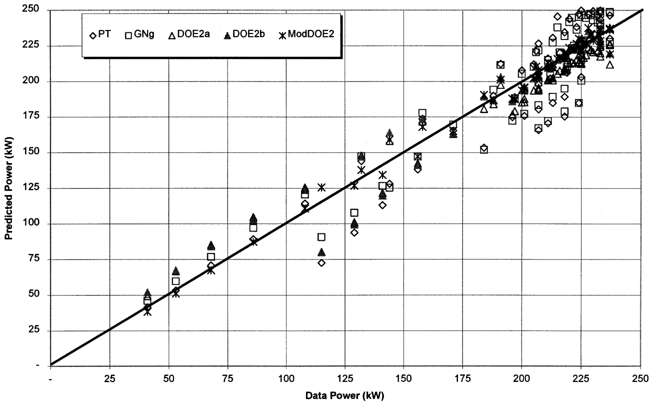

Figure 1 *Predicted power of all models for centrifugal chiller with VSD.*

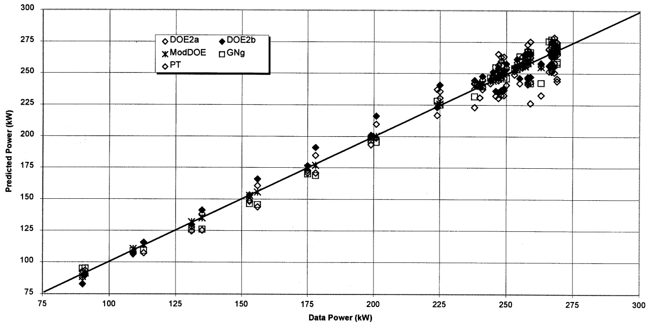

Figure 2 *Predicted power of fixed-speed centrifugal chiller with varied condenser water flow.*

$$MBE = \frac{\dfrac{\sum_k (PwrPred_k - Pwr_k)}{\sum_k 1}}{\dfrac{\sum_k Pwr_k}{\sum_k 1}} \qquad (11)$$

Manufacturers provided the first two datasets to assist in the model development and testing. The data were produced from ARI certified selection software and included the ARI Standard 550/590-1998 tolerances for both capacity and efficiency (ARI 1998).

The dataset for the variable-speed centrifugal chiller with fixed condenser water flow represents a 400 ton chiller designed for 44°F chilled water supply at 960 gpm and 85°F condenser water supply at 1,200 gpm. The design power was 233 kW (0.58 kW/ton). The dataset included 63 records, 47 at full load and 16 at part load. The condenser and evaporator flows are constant in this dataset. The chilled water supply temperature varied from 40°F to 50°F and the leaving condenser water temperature varied from 65°F to 100°F. The results from testing with these data are presented in Figure 1 and Table 2.

The dataset for the fixed-speed centrifugal chiller with variable condenser water flow represents a 575 ton chiller designed for 45°F chilled water supply at 750 gpm and 85°F condenser water supply at 1,125 gpm. The design power was 244 kW (0.65 kW/ton). The dataset included 52 records, 36 at full load and 16 at part load. The condenser flow varied from 500 gpm to 1,125 gpm in both the full- and part-load data. The evaporator flow was constant. The chilled water supply temperature varied from 43°F to 50°F and the leaving condenser water temperature varied from 70°F to 108°F. The results from testing with these data are presented in Figure 2 and Table 3.

TABLE 2
Error Statistics for Centrifugal Chiller with VSD

	All Points		Part Load Only		Max%
	CVRMSE	**MBE**	**CVRMSE**	**MBE**	**Error**
DOE2a	6.5%	–3.8%	12.2%	–0.2%	30.2%
DOE2b	4.9%	0.0%	12.5%	0.8%	30.4%
ModDOE2	2.7%	0.0%	4.4%	0.8%	10.4%
GNg	9.2%	0.2%	10.6%	3.1%	21.1%
PT	10.5%	–0.1%	13.8%	–1.5%	36.8%

TABLE 3
Error Statistics for Fixed-Speed Centrifugal with Varied Condenser Water Flow

	All Points		Varied Flow Only		Max	Max Percent
	CVRMSE	**MBE**	**CVRMSE**	**MBE**	**Error (Abs)**	**Error**
DOE2a	3.8%	–1.4%	3.5%	–2.1%	17.3	6.7%
DOE2b	3.4%	0.0%	2.5%	–1.1%	15.7	8.2%
ModDOE2	0.7%	0.0%	0.3%	0.1%	7.9	3.0%
GNg	2.9%	0.0%	2.0%	0.8%	20.5	7.8%
Toolkit	5.1%	–0.2%	3.6%	0.9%	32.7	12.6%

The third dataset represented manufacturer-supplied data on 132 distinct chillers spanning more than 4,000 data records. All of these data were produced by ARI-certified selection software. These records represented a range of water-cooled chillers as documented in Table 1.

The authors collected these data on the 132 chillers through performance-based chiller bids (Taylor et al. 1999). The data include many sets of "zero-tolerance" data that were verified in some cases through factory witness tests. The results of these tests are in Table 4.

TABLE 4
Error Statistics for all Chillers

	DOE-2a	DOE-2b	ModDOE-2	GNg
Average CVRMSE	3.3%	1.9%	1.6%	3.1%
Max CVRMSE	20.3%	9.5%	6.2%	12.1%
Average MBE	–0.9%	0.0%	0.0%	0.0%

TABLE 5
Error Data for IBM Field Chillers

	DOE-2a	DOE-2b	ModDOE-2	GNg
CVRMSE	6.0%	5.6%	5.3%	9.3%
MBE	–3.7%	–3.2%	–3.0%	8.2%

For the final test, the authors calibrated all but the primary toolkit model with zero-tolerance manufacturer's data and subsequently checked the models' performance on data collected in the field. The field data had very high quality. The site had industrial-grade sensors (magnetic flow meters and three-wire platinum RTD temperature sensors) and programmable logic controllers. The sensors and transducers were calibrated prior to collecting the data (Hydeman et al. 1999). The results of the field test are in Table 5 and Figures 3 and 4.

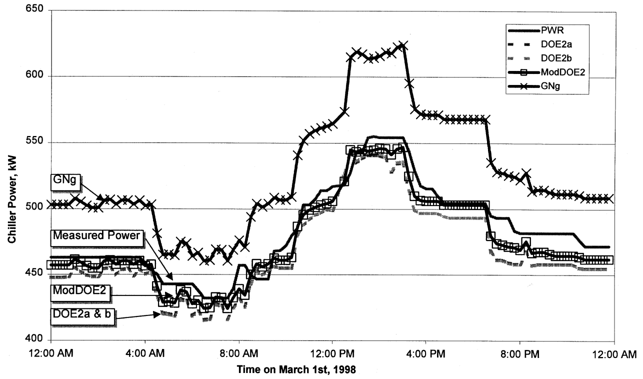

Figure 3 *Chiller power (measured and modeled) for March 1, 1998.*

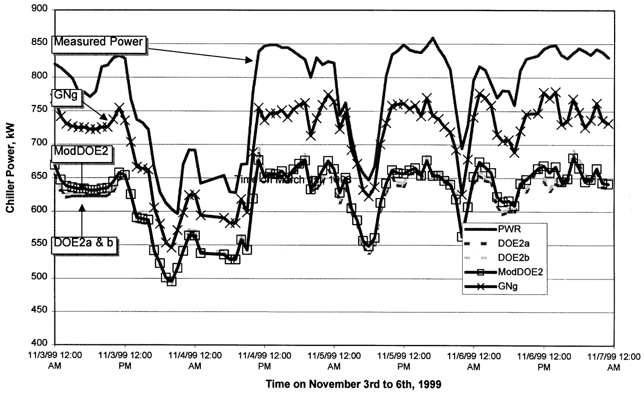

Figure 4 *Chiller power (measured and modeled) for November 3 to November 6, 1999.*

DISCUSSION

Variable-Speed Drive

The modified DOE-2 model was developed to improve the performance of the DOE-2 model with variable-speed drives. At low loads and varying condenser water temperatures, the existing DOE-2 model produced errors as high as 37% predicted power error. The primary toolkit, Gordon-Ng, DOE-2 A, DOE-2 B, and modified DOE-2 models were calibrated and tested against these data. Figure 1 displays the actual power vs. predicted power for each of the models for this dataset. As can be seen in the chart, the modified DOE-2 model predicts power use more accurately than the other models, particularly at part-load conditions. Table 2 summarizes the error for the four models from this test. As depicted in Table 2, the CVRMSE for the Modified DOE-2 model is 2.7% while the next closest is the DOE-2 B at 4.9%. Relatively speaking, the Modified DOE-2 model predicts even more accurately over the set of part-load data with a CVRMSE of 4.4%. At part load, the rest of the models have CVRMSEs >10%.

Physical models such as the Gordon-Ng and primary toolkit have a disadvantage in modeling the effects of variable-speed control on a centrifugal chiller because the chiller controls employ two modes of operation: variation of the speed of the compressor and variation of the inlet vanes. Further complicating the matter, chiller controls are very complex and rely on sensors internal to the chiller. These controls are set to preferentially operate the variable-speed drive for efficiency and utilize the compressor inlet vanes to keep the chiller out of "surge" conditions.

Black box models like the DOE-2 models can capture this mixed mode control to a greater extent because it is a repeatable function of both compressor lift and load. As previously noted, and as depicted in Figure 1, the DOE-2 A and B models were not responsive because they lacked temperature correction at part load. The modified DOE-2 model improved the prediction by adding condenser temperature and load terms to the EIRFPLR function.

The effects of the two modes of control can be seen in Figure 1. The cluster of part-load data points above the reference line depicts VSD operation. The VSD is employed when deep condenser relief occurs in tandem with the unloading of the chiller. The largest errors are found below the reference line during part-load operation with no condenser relief. These points indicate unloading largely by the inlet vanes of the compressor. The DOE-2 A, DOE-2 B, primary toolkit, and Gordon-Ng models substantially underestimated the power usage during operation of the inlet vanes.

Variable Condenser Water Flow

The modified DOE-2 model was also designed to more accurately predict power during variable condenser water flow applications. The existing DOE-2 model often produced errors over 5% and couldn't be used to evaluate design and control alternatives that varied the condenser flow.[8] The primary toolkit, Gordon-Ng, DOE-2 A, DOE-2 B, and modified DOE-2 models were calibrated and tested with these data. Figure 2 depicts actual power vs. predicted power for all of the models. Table 3 summarizes error data for all of the models over this dataset. As can be seen in Figure 2 and Table 3, the modified DOE-2 model predicts power much more accurately than the other models. Over the full- and part-load datasets, the modified DOE-2 CVRMSE is 0.7% while the next best is the Gordon-Ng at 2.9%. The maximum error for the modified DOE-2 model is between one-half and one-fourth that of the other models.

Full Data Set

The authors tested all of the computer models except the primary toolkit with 132 sets of manufacturers' data (see Table 1). The primary toolkit model was omitted from this test, as it was impractical to calibrate this model for 132 different machines.[9] As with the previous tests, we calibrated each model with manufacturer-supplied data and then tested for their power prediction for the same dataset. We then compared the predicted power vs. the actual power to assess how well each of the models fits the actual data. The results of this test are presented in Table 4. Over the entire set of data, the modified DOE-2 chiller model predicted the most accurately with the least average and maximum errors over all but 13 chillers.[10] The average CVRMSE for the modified DOE-2 model was 1.6% while the DOE-2 A and B models produced CVRMSEs of 3.3% and 1.9%, respectively. The maximum CVRMSE for the modified DOE-2 model was ~6%. The maximum CVRMSEs for the DOE-2 B and Gordon-Ng models were both ~10% while the DOE-2 A model had a maximum CVRMSE of over 20%.

In reviewing the results from Table 4, it appears that the DOE-2 B model is almost as good as the modified DOE-2 model for most chillers (based on the average CVRMSE data). The evidence suggests that this is the case with constant-speed chillers with fixed condenser flow. Although 36 of these chillers were variable-speed centrifugal machines (see Table 1), the majority of these data were collected with only part-load operation coincident with deep condenser relief. In addition, none of the 132 chillers had data for variable condenser water flow. As demonstrated in the previous tests, the modified DOE-2 model was three times as accurate as the DOE-2 B model on a variable speed driven chiller at part-load operation and variable amounts of condenser relief and almost five times as accurate on the constant-speed chiller with variable condenser water flow.

Field Test

The authors tested all of the computer models except the primary toolkit on a new chiller installed in the field. Each model was calibrated against zero tolerance manufacturer's data. Those data were subjected to a factory witness test. The chiller was a single-stage fixed-speed centrifugal chiller installed in a plant with a 2:1 variation in both the evaporator and condenser flows.

The models that had been calibrated to the manufacturer's data were tested against data measured in the field. The field data were collected with the use of industrial-grade sensors. These sensors were calibrated prior to the data collection in 1998. Four months of field-measured data were used in this test. Each of the calibrated models was used to predict power over the four-month period using measured values for cooling load, evaporator temperatures, and condenser temperatures. These predicted powers were compared to the actual power data collected at the site. The results of this test are presented in Table 5. As indicated in Table 5, all four models estimate the actual power relatively well, with the modified DOE-2 model having a slightly better performance than the DOE-2 A and B models.

Figure 3 presents the actual power and the four predicted powers for March 1, 1998. Although the modified DOE-2 model appears to follow the actual power more precisely on this day, the overall predictions of the modified DOE-2 model are not significantly more accurate than those of the others. It is interesting to note that all models have a significant bias as can be seen in the MBE (Table 5).

Figure 4 presents the actual power and the four predicted powers from November 3 through November 6, 1999. As can be seen in this figure, the error of all four models increased drastically over time. This is likely due to a loss in the operating efficiency of the chiller through fouling, although it could be due to some error introduced into the data collection system. Condenser fouling is the likely culprit. This is an industrial site that uses reclaimed water for the tower makeup and never shuts the tower down for cleaning. As can be seen from Figure 4, the actual power had grown drastically so that

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[8] The existing DOE-2 model looked only at entering condenser water temperature and had no terms for condenser water flow. Two separate condenser water flow conditions at the same entering temperature were treated as the same condition by the existing model.

[9] The calibration of the DOE-2, modified DOE-2, and Gordan-Ng models was fully automated. The primary toolkit model could not be automatically calibrated to the performance data for these 132 chillers.

[10] On 13 chillers the DOE-2 B model was slightly more accurate than the modified DOE-2 model. Eleven of these chillers were from the same manufacturer and were open-drive machines. The average difference of the CVRMSE for these 13 chillers was 0.2%. In essence, these chillers were predicted so accurately that the difference in computer models is negligible. We believe the modified DOE-2 model was penalized as the condenser water return temperature was calculated using Equation 1. This equation neglects heat loss from the open drives and overpredicts the temperature of the return condenser water temperature.

all of the models' predictions consistently fell short of the actual power. The change in the efficiency of the chiller between November 1999 and March 1998 is much greater than any difference in the efficiency prediction of the models.

CONCLUSIONS

As demonstrated in all tests, the modified DOE-2 model is the most accurate of the four tested across a wide range of electric water-cooled chillers when properly calibrated. The Modified DOE-2 model provides the most significant accuracy improvements for variable-speed drive and variable condenser water flow applications. For all fixed-speed chillers with no variations in condenser water flow, the existing DOE-2 model, properly calibrated, provides nearly the same results. The Gordon-Ng chiller is almost as accurate for fixed-speed centrifugal chillers regardless of condenser water flow. The modified DOE-2 model can be applied to any chiller type without limitations.

An advantage of the physical models is that once calibrated, their performance can be extrapolated beyond the range of the calibration data. Both the DOE-2 and modified DOE-2 models will produce unpredictable results if queried outside of their calibrated range. For small calibration datasets, reference curve methods of calibration are recommended (Hydeman and Gillespie 2002). Furthermore, as seen in the relative performance of the DOE-2 A and B models, it is important to use both the full- and part-load data combined for calibration of the EIRFPLR coefficients in the DOE-2 and modified DOE-2 models.

The improvements in the modified DOE-2 model were made with only small complexities added in the modeling process, and existing simulation programs using the DOE-2 model could easily be modified to use the modified DOE-2 model. However, they will have to iterate on the cooling tower and chiller algorithms to converge on the leaving condenser water temperature. In simulations that we have made using the new model, a bounded bisection search algorithm will converge in 5 to 20 iterations depending on the convergence criteria.

The results from the field data test highlight an important lesson: commissioning matters. Regardless of whether the chillers' performance degraded through time through fouling or was misread through errors introduced in the control system, the slight differences between the models were very small compared to the apparent increase in the chiller power. Although this industrial site is not representative of commercial building maintenance procedures, the results clearly indicate a challenge to the estimation of chilled water plant performance. Equipment performance drift could easily overshadow the uncertainty in the equipment component models. Through continuing performance verification, these problems can be identified and corrected in the field. Luckily this is beyond the scope of this paper and will be left to other research efforts to grapple with.

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