Generalized Performance Maps For Single And Dual Speed Residential Heat Pumps

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ABSTRACT

This paper presents generic equipment models that capture the performance of families of similar heat pumps equipment and that can be used in building simulation programs. Mapping has been carried out for families of single and dual compressor speed ducted split systems and the correlations are being implemented as components for building simulation. The units mapped ranged in nominal capacity from 1 to 5 tons (3.5 - 17.6 kW) and 2 tons to 5 tons (7.0-17.6 kW) for the single and dual speed units, respectively. Equipment models for building simulation were generated based on the ASHRAE secondary toolkit direct expansion model. Single sets of correction factor equations were found for each family in heating mode and cooling mode by first aggregating normalized performance data of all the units in each family and then mapping the normalized performance characteristics using the ASHRAE toolkit model (Brandemuehl, 1993). The dual speed unit model was split into two parts; one set of coefficients for low speed and another for high compressor speed. These models are based on modern equipment currently on the market and provide a useful update to the currently available standard direct expansion air conditioner models in building simulation programs. The generalized models generated in this study were compared to established performance models based on the ASHRAE toolkit model for cooling and the DOE 2.1 RESYS routine for heating mode operation.

1. INTRODUCTION

Computationally efficient models for building simulations are usually provided as empirical models constructed from experimental data. The ASHRAE toolkit model uses polynomials and a bypass factor approach derived from experimental data for direct expansion coils (Brandemuehl et. al 1993). A similar model for heat recovery heat pumps was generated from experimental data by Mercer (2003). Further development on direct expansion coil models was conducted by a generic rating-data-based method (Yang and Li 2010). The toolkit model is the basis for the generalized performance maps developed in this study and the results are compared with the ASHRAE toolkit mode's default correction coefficients in cooling. The generalized heating operation maps are compared against the DOE 2.1 RESYS routine with default coefficients (Winkelmann et al 1993).

2. HEAT PUMP PERFORMANCE DATA

The data used to model the heat pumps in this study was generated using a detailed component based simulation program provided by the manufacturer of the heat pumps. The test suite includes seven single compressor speed units rated SEER 13 with capacities from 1.5 ton to 5 tons (3.5 - 17.6 kW) in increments of 0.5 tons (1.76 kW) and four dual compressor speed units rated SEER 16 with capacities from 2 tons to 5 tons (7.0-17.6 kW) in 1 ton (3.5 kW) increments. In generating the data, the heat pumps were assumed to be at steady-state operation under standard atmospheric pressure, with 10 °F (5.6 °C) superheat and 25 ft. (7.62 m) of refrigerant piping, half exposed to the outdoor and half exposed to the indoor conditions. The refrigerant charge level is determined at AHRI cooling rating conditions of 95°F (35°C) ambient dry bulb temperature and 67°F (19.4°C) indoor wet bulb with the cycle simulation subcooling set to 10°F. The same charge level determined in cooling mode was used for heating mode operation. .

The cooling simulations were performed on each unit with ambient temperatures from 55 to 115 °F (12.8-46.1°C) in 5 °F (2.8°C) increments and indoor wet bulb temperatures from temperatures from 49.4 to 77 °F (9.77-25°C) with a constant indoor dry bulb temperature of 80°F (26.7°C). The heating simulations had ambient temperatures from 0 to 55 °F (-17.8-12.8°C) in 10 °F (5.6°C) increments and indoor dry bulb temperatures from 55 to 75 °F (12.8°C). Each unit was simulated under 3 airflow speeds.

3. EMPIRICAL MODELING APPROACH AND RESULTS

3.1 Model Outline

The single and dual speed units were modeled using the ASHRAE toolkit model, which captures the effect of the airflow rate and the indoor and outdoor air temperatures and humidity through Equations (1)-(6).

$$\dot{Q} = \dot{Q}_{rat} \cdot f_{cap,t}(T_{in,wb}, T_{out}) \cdot f_{cap,m}(\dot{m}/\dot{m}_{rat}) \quad (1)$$

$$COP = COP_{rat} \cdot f_{cop,t}(T_{in,wb}, T_{out}) \cdot f_{cap,m}(\dot{m}/\dot{m}_{rat}) \quad (2)$$

$$f_{cap,t} = a_1 + b_1 \cdot T_{out} + c_1 \cdot T_{out}^2 + d_1 \cdot T_{in,wb} + e_1 \cdot T_{in,wb}^2 + f_1 \cdot T_{in,wb} \cdot T_{out} \quad (3)$$

$$f_{cap,m} = X_1 + Y_1 \cdot (\dot{m}/\dot{m}_{rat}) \quad (4)$$

$$f_{cop,t} = a_2 + b_2 \cdot T_{out} + c_2 \cdot T_{out}^2 + d_2 \cdot T_{in,wb} + e_2 \cdot T_{in,wb}^2 + f_2 \cdot T_{in,wb} \cdot T_{out} \quad (5)$$

$$f_{cop,m} = X_2 + Y_2 \cdot (\dot{m}/\dot{m}_{rat}) \quad (6)$$

where $\dot{Q}$ is the cooling or heating capacity in BTU/hr, $\dot{Q}_{rat}$ is the capacity at a rating condition, COP is the coefficient of performance, $\dot{m}$ is the airflow rate in SCFM. $T_{in,wb}$ and T_{out} are , respectively, the indoor air entering wet bulb and outdoor air entering dry bulb temperatures in °F. The rating condition for cooling mode is the AHRI standard 95°F (35°C) ambient dry bulb temperature and 67°F (19.4°C) indoor wet bulb. The heating mode rating condition is 47°F (8.3°C) ambient dry bulb temperature and 70°F (21.1°C) indoor dry bulb, 60 °F (15.6°C) wet bulb entering indoor air.

3.2 Sensible Heat Ratio and Dry Coil Operation

The relations in Equations (1)-(6) make use of indoor inlet wet bulb temperature and only provide total cooling capacity for wet coils. However, it is also necessary determine the sensible heat ratio for cooling mode and to determine the performance for dry coils (*SHR* = 1). The *SHR* model is based on the bypass factor approach (Brandemuehl et. al 1993), which involves solution of Equations (7)-(10) for apparatus dew point condition given inlet conditions and outlet enthalpy determined from total capacity mode along with NTU_{rat} and m_{rat}. For a dry coil, the toolkit model will predict a sensible cooling capacity greater than the total capacity and iteratively solves for an apparatus dew point humidity ratio that gives a unity SHR. In heating mode, the relations in Equations (1)-(6) are applied with $T_{in,db}$ replacing $T_{in,wb}$. The winter air temperature is assumed to be very dry and condensation on the outdoor unit is neglected.

$$SHR = \frac{h(T_{evap,in}, \omega_{adp}) - h_{adp}}{h_{evap,in} - h_{adp}} \quad (7)$$

$$h_{adp} = h_{evap,in} - \frac{h_{evap,in} - h_{evap,out}}{1 - BF} \quad (8)$$

$$BF = e^{-NTU} \quad (9)$$

$$NTU = \frac{NTU_{rat}}{\left(\frac{\dot{m}}{m_{rat}}\right)} \quad (10)$$

3.3 Heating mode operation

The DOE-2.1 RESYS routine that was used as a benchmark in heating operation arrives at the correction factors in Equations (1) and (2) using the cubic relations in Equations (11) and (12) instead of Equations (3) and (5). The form of the air mass flow rate corrections for capacity is the same as Equation (4) but the air mass flow correction for COP is also different from Equation (6) and is shown in Equation (13)

$$f_{cap,t} = a_3 + b_3 \cdot T_{out} + c_3 \cdot T_{out}^2 + d_3 \cdot T_{out}^3 \quad (11)$$

$$f_{cop,t} = (a_4 + b_4 \cdot T_{out} + c_4 \cdot T_{out}^2 + d_4 \cdot T_{out}^3)^{-1} \quad (12)$$

$$f_{cop,m} = \left[X_3 + Y_3 \cdot \left(\frac{\dot{m}}{\dot{m}_{rat}}\right) + Z_3 \cdot \left(\frac{\dot{m}}{\dot{m}_{rat}}\right)^2\right]^{-1} \quad (13)$$

3.3 Coefficients using Linear Regression

All the coefficients of $T_{in,wb}$, T_{out} and $\dot{m}/\dot{m}_{rat}$ in Equations (3)-(6) are found through linear regression on data to minimize the square of percentage deviation between predicted and actual values. In order for linear regression to be performed on Equation (1), which is non-linear in the coefficients, $f_{cap,m}$ was set equal to 1 and then the coefficients in Equation (3) were found through linear least squares regression using only data points where $\dot{m}$ is equal to $\dot{m}_{rat}$. This approach assumes that temperature and airflow rate are decoupled and it is possible to capture the effect of temperature changes completely with data containing fixed airflow rate. Regression was then performed on Equation (14) to find the coefficients X_1 and Y_1 from Equation (4). Equation (14) is a modification of Equation (1), effectively constraining the value of $f_{cap,m}$ to be equal to 1 when $\dot{m}$ is equal to $\dot{m}_{rat}$. This is in order to maintain consistency with the previous step of fixing $f_{cap,m}$ equal to 1 when $\dot{m}$ is equal to $\dot{m}_{rat}$which implies that Equation (15) must be true.

$$Y_1 + X_1 = 1 \quad (14)$$

$$\frac{\dot{Q}}{\dot{Q}_{rat} \cdot f_{cap,t}(T_{in,wb}, T_{out})} - 1 = f_{cap,m}\left(\frac{\dot{m}}{\dot{m}_{rat}} - 1\right) \quad (15)$$

The rated NTU that produced the best sensible heat ratio estimation was then found by minimizing the sum of the square of the residuals between the actual SHRs and those found from evaluating the expression in Equation (7).

3.4 Dual Speed Heat Pump Models

For dual speed units, the same approach outlined for single speed units was used. The high compressor speed was treated as a separate unit from the low compressor speed operation, resulting in two sets of cooling coefficients and two sets of heating coefficients for each unit. The correlation results of the linear regression on the single speed units are given in Tables 8-10.

3.5 Generalized Heat Pump Model Results

It was observed that the correction factors for single speed units were similar for given indoor and outdoor conditions. The same was true for the dual speed units. In order to simplify the models for use in building simulations, the data for each heat pump family (single and dual speed compressors) and operating mode (heating or cooling) was aggregated and aggregate models for each heat pump family were fit using Equations (1) –(10). The unit's rating data was also applied to the ASHRAE secondary toolkit's direct expansion cooling model and the DOE 2 model for heating with default coefficients. A comparison of the correction coefficients developed in the current study with the established models is helpful for deciding if heat pump efficiency changes necessitate an update to the established models.

Having a single heat pump model for a family of units enables appropriate equipment sizing when performing building simulations. Although some accuracy is lost for each unit, using a generalized map avoids the over and under-sizing problem of discrete equipment sizes.

Figure 1 through Figure 6 use parity plots to compare the prediction accuracy for capacity and power consumption of using generalized model for each family against using the default correction factor coefficients. Figure 1 through Figure 3 show the single speed heat pump results while Figure 4 through Figure 6 show the results for dual speed heat pumps. The sensible heat ratio predictions for cooling conditions are shown in Figure 7. For clarity, the parity plots show every other data point. Only the heating mode power prediction results are shown for the single and dual speed heat pumps as the cooling mode results are similar.

For the single speed heat pump family (Figures 1 – 3), the results for the generalized mapping show good agreement with the predicted power consumption having a maximum prediction error of 10% and maximum capacity prediction error of 10.7%. In contrast, use of the default parameters associated with the ASHRAE toolkit and DOE-2.1 RESYS models show poor performance for this family of units, particularly for power predictions. Although not shown, the results for power consumption in cooling mode are similar.

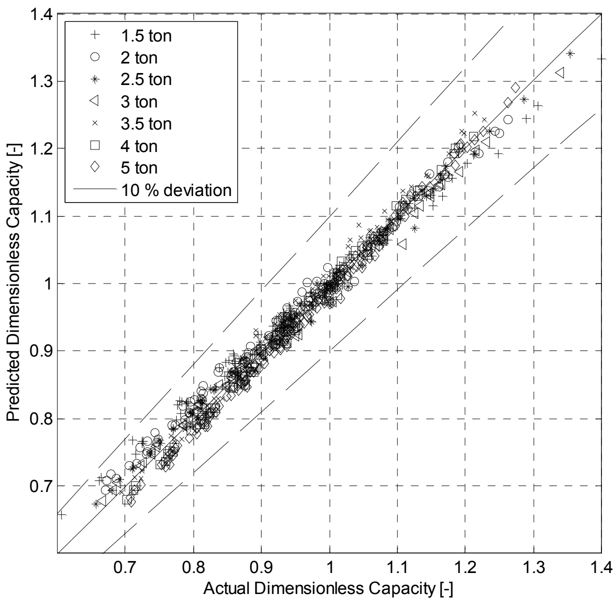

Figure 1: Parity plots for capacity in cooling mode using generalized map (left) and ASHRAE toolkit defaults (right) for single speed heat pumps.

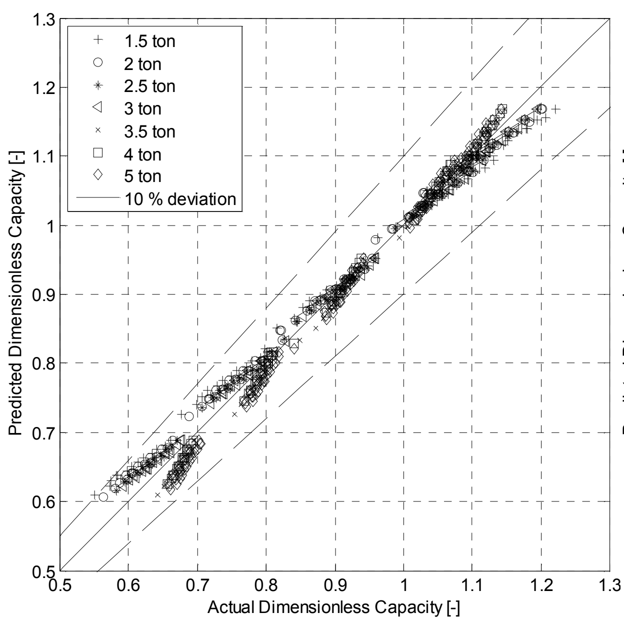

Figure 2: Parity plots for capacity in heating mode using generalized map (left) and DOE 2.1 RESYS defaults (right) for single speed heat pumps.

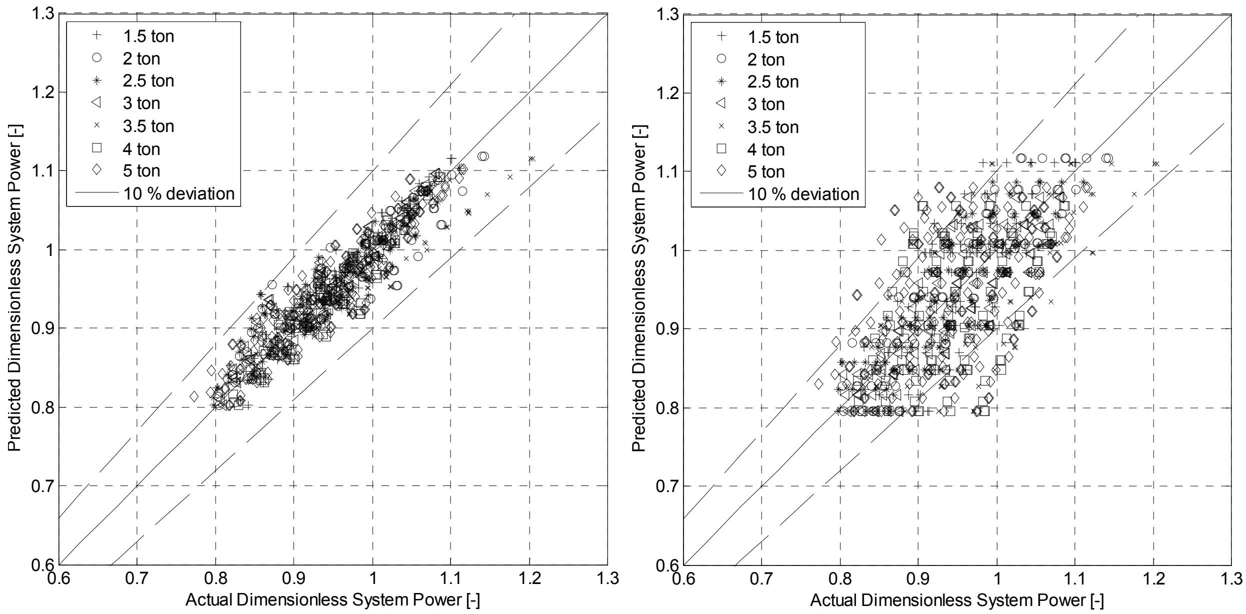

Figure 3: Parity plots for power consumption in heating mode using generalized map (left) and DOE 2.1 RESYS defaults (right) for single speed heat pumps.

The accuracy of the generalized model for the dual speed heat pumps (Figures 4 – 6) operating at low speed is comparable to that for the single speed units. However, the accuracy of using the default parameters for the power model is significantly worse than for the single speed case. Although not shown, high compressor speed results were similar to those for low speed.

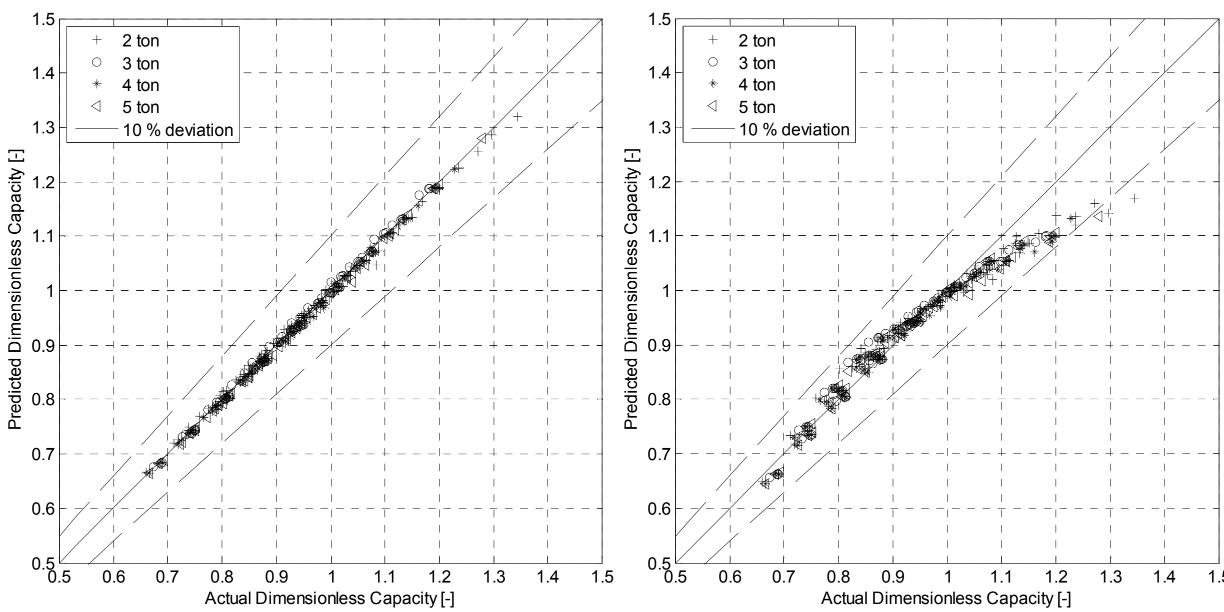

Figure 4: Parity plots for capacity in cooling mode using generalized map (left) and ASHRAE toolkit defaults (right) for dual speed heat pumps at low compressor speed.

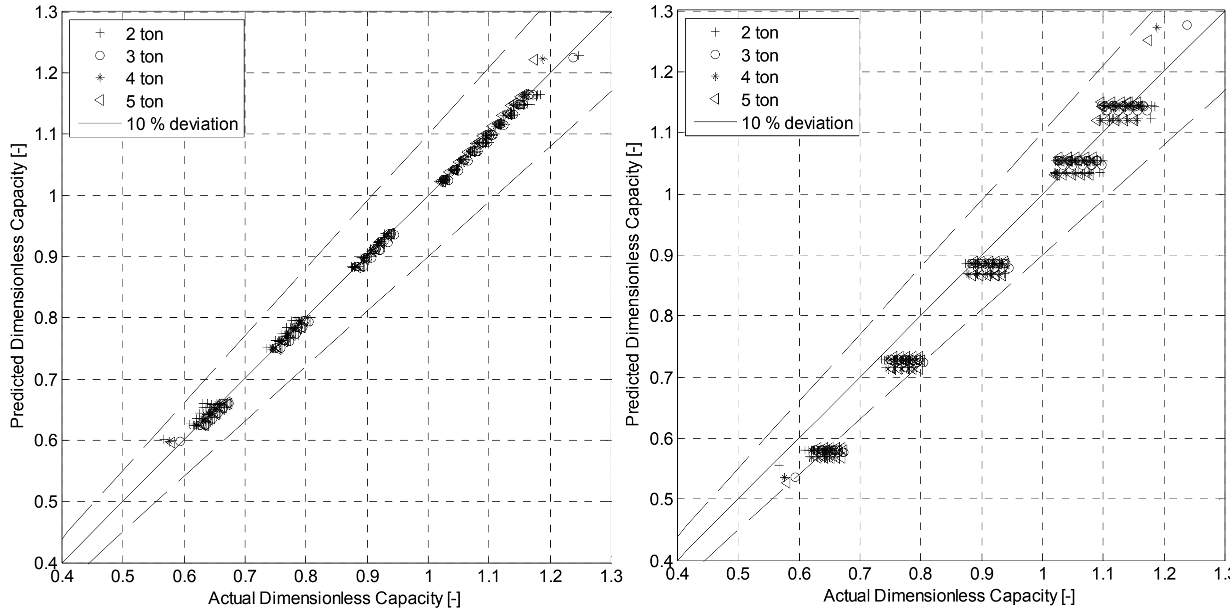

Figure 5: Parity plots for capacity in heating mode using generalized map (left) and DOE 2.1 RESYS defaults (right) for dual speed heat pumps at low compressor speed.

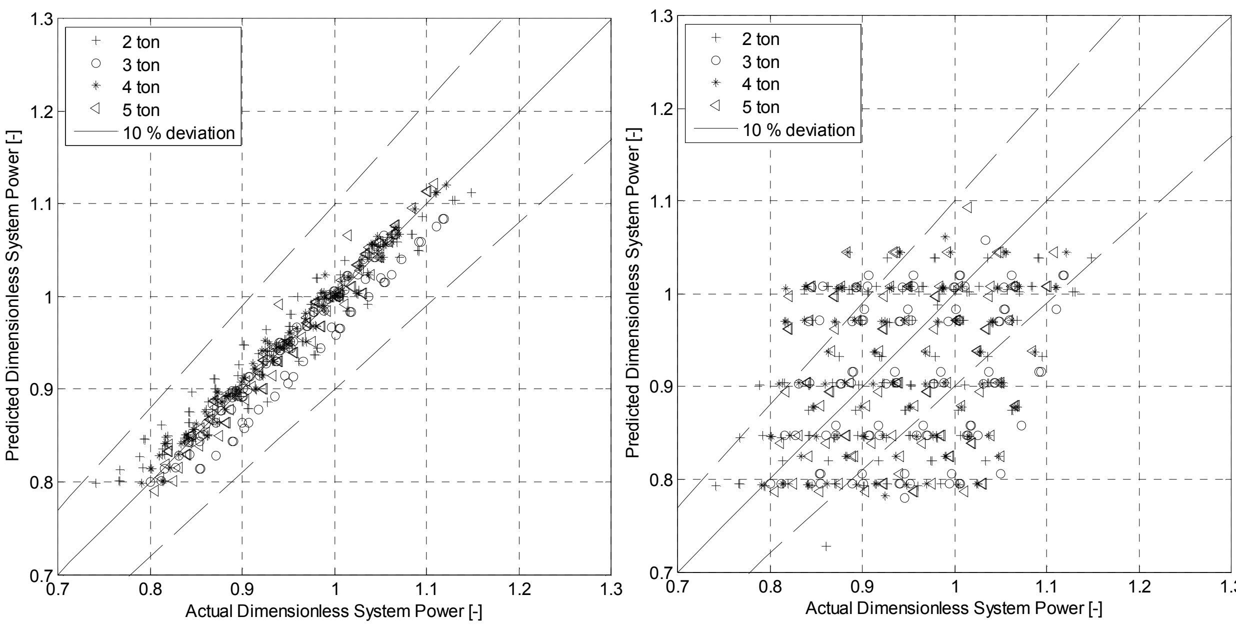

Figure 6: Parity plots for power consumption in heating mode using generalized map (left) and DOE 2.1 RESYS defaults (right) for dual speed heat pumps at low compressor speed.

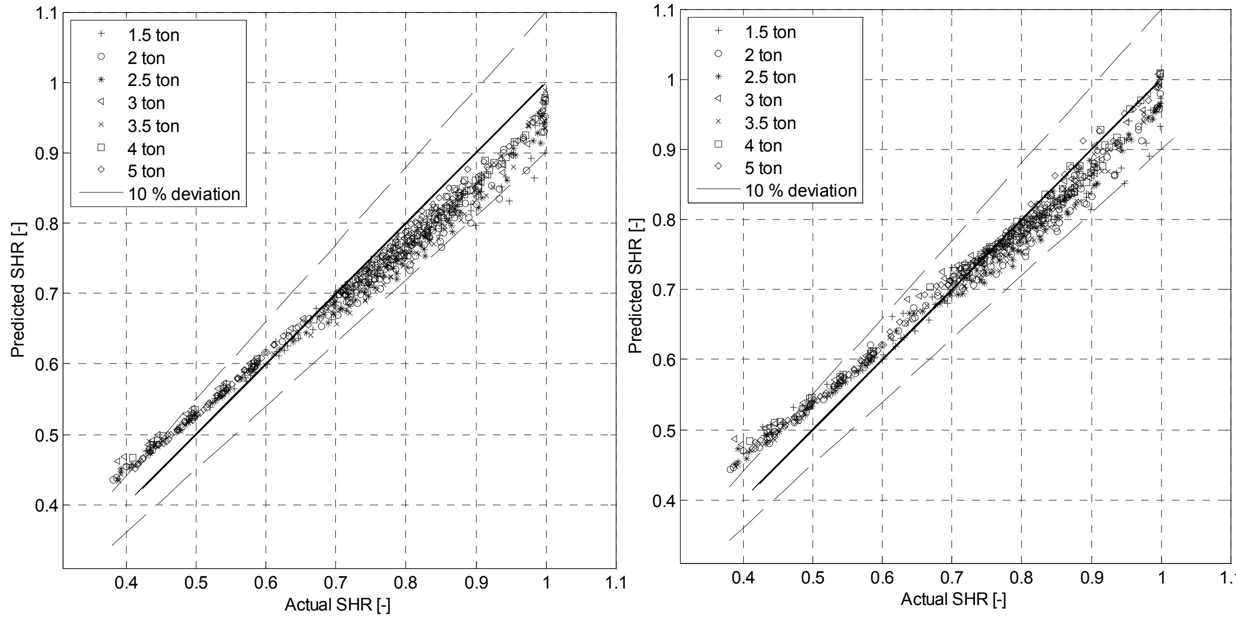

Figure 7: Parity plots for Sensible Heat Ratio using generalized map (left) and ASHRAE toolkit defaults (right) for single speed heat pump family.

As expected, the default coefficients' predictions were less accurate than the generalized map developed from fitting custom coefficients. The higher deviations of the cooling capacity prediction occur at lower outdoor ambient conditions of 75-80 °F (23.9-26.7°C). Capacity limitations are usually not encountered at these low ambient conditions and the model would perform well under normal cooling operations. Figure 8 shows the cooling mode operation of Figure 1 with the color bar representing outdoor temperature in degrees Fahrenheit. However, for power predictions there is a much greater range of errors when using the default correlations, especially for the dual speed heat pump. Predictions of SHR in cooling are similar for the updated and default parameter models.

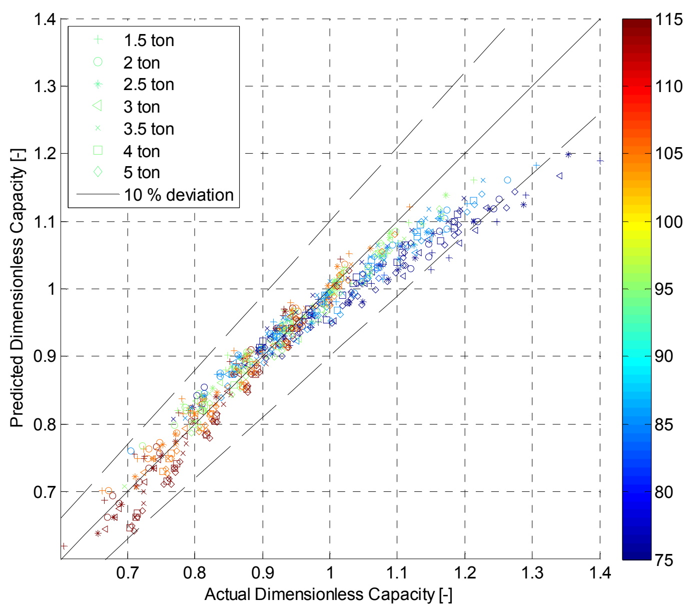

Figure 8: Parity plot for capacity in cooling mode using default ASHRAE toolkit coefficients for single speed heat pumps with color bar indicating ambient dry bulb temperature in °F.

Table 1-Table 2 compare the results obtained using individualized coefficients as well as the generalized map developed for this study and the default toolkit model. The last two rows of Table 1 and most of the high compressor

speed cases in Table 2 show a negative coefficient of determination for the toolkit model with default parameters, making the prediction for the 4 and 5 ton (14.1 and 17.58 kW) units in heating mode worse than just using the mean value for all predictions. Part of the reason for this is that the error from the capacity prediction combines with that from the efficiency prediction resulting in a large error in power prediction. The heating COP performance of the dual stage heat pump is significantly different from that predicted by the RESYS routine's default value as shown by Figure 9. The RESYS routine's poor COP prediction contributes to the power prediction error In addition, the default RESYS routine map was developed from single speed heat pumps and applying it to dual speed heat pumps would reduce the accuracy.

Table 1: Cooling and heating mode accuracy comparisons of the individual, generalized and default models for single speed heat pumps.

		Individual Coefficients					Generalized Family Coefficients					ASHRAE Toolkit Default				
Capacity [ton]	**Mode**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Capacity Max Error [%]**	**Power Max Error [%]**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Capacity Max Error [%]**	**Power Max Error [%]**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Capacity Max Error [%]**	**Power Max Error [%]**
1.5	C	0.9963	0.9653	0.9957	2.9	3.8	0.9699	0.9319	0.9807	8.6	3.6	0.8717	0.9425	0.7776	15.6	13.2
2	C	0.9869	0.9677	0.9831	4.5	3.7	0.9821	0.9507	0.9763	6.0	4.2	0.9174	0.9591	0.7614	13.1	16.1
2.5	C	0.9913	0.9717	0.9926	3.3	2.8	0.9890	0.9543	0.9688	4.3	5.2	0.9084	0.9638	0.7692	12.6	15.2
3	C	0.9955	0.9526	0.9969	3.2	2.6	0.9896	0.9483	0.9732	4.6	4.2	0.8955	0.9394	0.7590	13.7	15.7
3.5	C	0.9821	0.9704	0.9876	4.2	4.1	0.9835	0.9572	0.9672	4.3	7.2	0.9516	0.9653	0.6178	9.2	24.1
4	C	0.9961	0.9583	0.9991	2.2	1.1	0.9897	0.9553	0.9822	3.3	5.2	0.9288	0.9511	0.6279	10.5	22.9
5	C	0.9961	0.9736	0.9811	3.3	5.4	0.9812	0.9712	0.9758	4.9	6.9	0.8950	0.9675	0.7497	11.3	21.3
1.5	H	0.9997	-	0.9372	1.6	5.1	0.9767	-	0.9164	10.7	6.8	0.9465	-	0.1918	13.5	13.2
2	H	0.9994	-	0.9563	1.5	5.2	0.9867	-	0.8688	7.9	9.6	0.9405	-	0.7119	14.2	9.6
2.5	H	0.9997	-	0.9836	1.0	2.8	0.9913	-	0.8646	6.0	10.0	0.9306	-	0.7394	14.9	9.2
3	H	0.9999	-	0.9920	1.2	1.8	0.9928	-	0.9028	5.1	7.9	0.9266	-	0.6151	15.2	10.9
3.5	H	0.9997	-	0.9625	1.3	3.9	0.9928	-	0.8434	5.2	7.4	0.8357	-	0.2068	19.4	18.1
4	H	0.9999	-	0.9929	0.7	2.4	0.9932	-	0.8780	4.8	6.9	0.8564	-	-0.4986	17.6	19.2
5	H	0.9991	-	0.9122	1.3	5.9	0.9860	-	0.8720	6.7	7.2	0.8071	-	-0.1090	19.4	20.9

Table 2: Cooling and heating mode accuracy comparisons of individual, generalized and default models for dual speed heat pump family.

			Individual Coefficients					Generalized Family Coefficients					ASHRAE Toolkit Default				
Capacity [ton]	**Mode**	**Comp. Speed**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Max Capacity Error [%]**	**Max Power Error [%]**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Max Capacity Error [%]**	**Max Power Error [%]**	**Capacity R^2**	**SHR R^2**	**Total Power R^2**	**Max Capacity Error [%]**	**Max Power Error [%]**
2	C	low	0.9932	0.956	0.9914	4.2	4.3	0.9954	0.9530	0.9879	3.5	7.0	0.908	0.948	0.536	13.0	30.6
2	C	high	0.9943	0.945	0.9718	4.0	6.1	0.9925	0.9321	0.9514	3.9	7.3	0.924	0.940	0.591	11.6	25.8
3	C	low	0.9991	0.977	0.9974	1.3	3.3	0.9967	0.9506	0.9834	2.2	6.2	0.933	0.966	0.438	10.7	31.3
3	C	high	0.9961	0.964	0.9773	2.7	19.5	0.9916	0.9220	0.9259	2.5	8.3	0.941	0.953	0.515	9.7	25.3
4	C	low	0.9987	0.955	0.9940	1.9	4.5	0.9987	0.9477	0.9960	2.0	6.1	0.920	0.947	0.515	11.8	29.8
4	C	high	0.9967	0.938	0.9730	2.1	6.4	0.9966	0.9243	0.9726	2.3	8.9	0.920	0.932	0.698	11.6	21.9
5	C	low	0.9986	0.954	0.9953	1.3	4.9	0.9981	0.9451	0.9962	2.4	4.9	0.926	0.945	0.515	11.1	29.0
5	C	high	0.9973	0.931	0.9791	2.1	11.6	0.9971	0.9193	0.974	3.5	13.9	0.929	0.923	0.673	10.7	21.0
2	H	low	0.9979	-	0.9752	2.6	5.5	0.9965	-	0.9215	5.9	7.7	0.959	-	0.004	11.6	20.7
2	H	high	0.9979	-	0.9193	2.9	7.3	0.9957	-	0.7867	4.9	6.7	0.861	-	-0.466	19.4	25.2
3	H	low	0.9999	-	0.9959	1.5	1.2	0.9988	-	0.9158	2.0	5.3	0.936	-	-0.702	14.3	23.4
3	H	high	0.9962	-	0.8915	2.9	20.8	0.9959	-	0.7785	3.0	9.5	0.830	-	-0.228	19.9	23.1
4	H	low	0.9991	-	0.9722	3.8	5.0	0.9992	-	0.9796	3.9	3.9	0.946	-	-0.567	13.6	23.1
4	H	high	0.9968	-	0.8815	3.8	10.2	0.9981	-	0.923	5.5	11.0	0.863	-	-0.430	18.1	21.6
5	H	low	0.9993	-	0.9788	4.5	6.8	0.9985	-	0.9723	4.0	5.7	0.925	-	-0.768	15.2	22.9
5	H	high	0.9964	-	0.8903	3.9	13.7	0.9979	-	0.854	5.7	17.7	0.823	-	-0.664	19.3	20.5

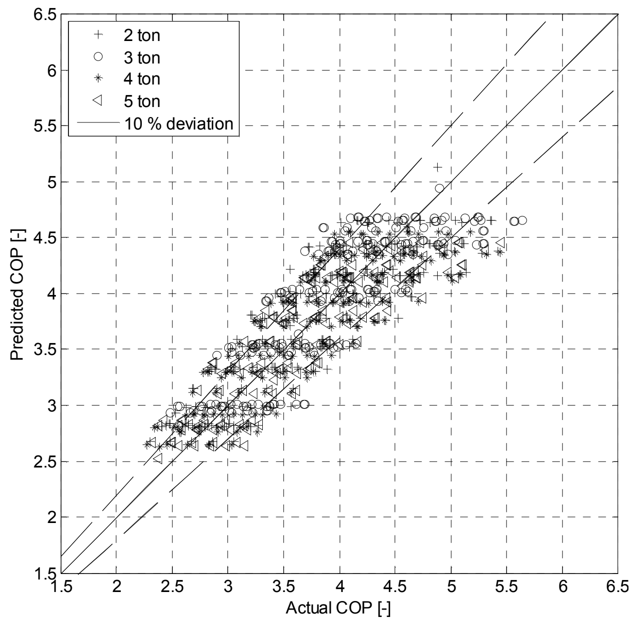

Figure 9: Parity plot for COP using ASHRAE toolkit default map for dual speed heat pumps at low compressor speed.

3.6 Equipment Mapping Coefficients

Table 3 and Table 4 contain the capacity and COP correction factor coefficients, respectively for the generalized mapping described in this study. The coefficients require the temperatures in Equations (1)-(5) to be given in °F.

Table 3: Generalized capacity mapping coefficients for single and dual speed heat pump families.

Family	Mode	Compressor Speed	a	b	c	d	e	f	X	Y	NTU rated
Single Speed	C	normal	3.008E-02	1.838E-03	-9.2000E-06	1.7785E-02	5.20000E-05	-9.10000E-05	0.86602	0.16776	1.63
	H	normal	4.969E-01	1.154E-02	3.4306E-05	-8.9949E-04	-7.64097E-06	-2.39056E-05	0.94420	0.12744	_
Dual Speed	C	low	3.109E-02	4.030E-03	-2.1000E-05	1.3616E-02	9.42000E-05	-8.80000E-05	0.78915	0.21339	1.47
		high	7.315E-02	3.226E-03	-1.7000E-05	1.4204E-02	8.11000E-05	-8.50000E-05	0.78141	0.21794	1.22
	H	low	4.140E-01	1.387E-02	3.9645E-05	7.7936E-04	-1.29073E-05	-4.34558E-05	0.97683	0.01924	_
		high	6.172E-01	1.321E-02	4.1876E-05	-2.1719E-03	7.31834E-06	-3.75364E-05	0.91446	0.00646	_

Table 4: Generalized COP mapping coefficients for single and dual speed heat pump families.

Family	Mode	Compressor Speed	a	b	c	d	e	f	X	Y
Single Speed	C	normal	8.222E-01	-1.670E-02	9.5200E-05	3.6969E-02	3.31000E-05	-2.60000E-04	0.92434	0.04732
	H	normal	1.268E+00	2.214E-02	-3.4135E-06	-1.2573E-02	4.63226E-05	-1.46332E-04	0.67919	0.18085
Dual Speed	C	low	8.723E-01	-1.923E-02	1.3300E-04	3.6595E-02	1.54000E-04	-3.80000E-04	0.69254	0.31794
		high	6.412E-01	-1.050E-02	5.4300E-05	2.8541E-02	4.47000E-05	-2.10000E-04	0.72611	0.37587
	H	low	1.279E+00	2.626E-02	2.4954E-05	-1.7364E-02	8.30521E-05	-2.09741E-04	0.56644	0.37009
		high	9.224E-01	1.529E-02	-3.3804E-06	-8.4144E-03	2.20280E-05	-9.32434E-05	0.75139	0.41024

5. CONCLUSION

Generalized maps were generated for families of single and variable speed compressor heat pumps for use in building energy simulation. These maps were found to be more accurate than the widely used ASHRAE toolkit model with default coefficients and DOE 2.1's default model at predicting the performance of the families of heat pumps under study. In particular, the default maps performed poorly at predicting the power consumption for dual speed heat pumps in heating operation. The accuracy of the default correlations decreases for operating conditions further away from the rating conditions and custom coefficients should be considered for these off-design conditions.

NOMENCLATURE

Variable	Definition (Units)
$\dot{Q}$	Capacity (BTU/hr)
COP	Coefficient of Performance (-)
a-f	Regression Coefficients
X,Y	Regression Coefficients
T	Temperature (°F)
h	moist air enthalpy (BTU/lbm)
$\dot{m}$	airflow rate (SCFM)
SHR	Sensible heat ratio (-)
BF	Bypass factor (-)
NTU	Number of transfer unit (-)
SEER	Seasonal Energy Efficiency Ratio (BTU/W-hr)

Subscript	Description
in	indoor return air
out	outdoor ambient air
wb	wet bulb
1-6	regression coefficient
rat	at rated conditions
adp	apparatus dew point
evap	evaporator

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