Application of a Linear Fit Rating Method for Mixed Single-Speed Unitary Air Conditioners

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ABSTRACT

A method employing the simultaneous solution of two linear fits is used to determine the rated cooling capacity and seasonal energy efficiency ratio, SEER, of outdoor unit and indoor unit air-conditioner combinations not previously tested as a complete system. The information presented here outlines the formulation, verification, and application of the method to produce ratings. For the examples presented here, the calculated cooling capacity and SEER ratings were within ± 5 % for four of eight and ± 5 % for six of eight mixed systems, respectively, compared to test data. This method applies to split system residential air-source unitary air conditioners and heat pumps operating in the cooling mode, employing a single-speed, single-phase compressor. The rated cooling capacity of the highest sales volume combination used in obtaining the ratings of the mixed system must be less than 19 050 W (65 000 Btu h^{-1}).

INTRODUCTION

A given outdoor section is typically offered on the market in several air-conditioner models, which differ by the indoor sections they employ. For all models, the manufacturers must provide performance information, which consists of the Seasonal Energy Efficiency Ratio (SEER) and capacity at the 35 °C (95 °F) rating point, *Q*(95). Federal regulations require that only the highest sales volume indoor-section/outdoor-section combination, referred to as the matched system, be tested in a laboratory to obtain the ratings (CFR 2012a). For other combinations of indoor and outdoor sections, so called mixed systems, the federal regulations allow the use of simplified analytical methodologies upon approval by the U.S. Department of Energy (CFR 2012b).

The most commonly used simplified methodologies for rating mixed systems are those based upon publicly available *Q*(95) and SEER of the matched systems (e.g., Domanski 1989). The application of these methods requires as input the capacity of the matched evaporator, which is a major shortcoming because the rater is not often familiar with the matched system product line. Since an inaccurate prediction of the matched evaporator leads directly to inaccurate mixed system ratings, a different rating method that would exclude this is preferable. Instead of the matched evaporator capacity, the liner fit method outlined in this paper uses the outdoor section capacity and power, which are more readily available to the rater than the matched evaporator capacity. A more detailed description of this method is presented by Payne and Domanski (2006).

CONCEPT OF THE LINEAR FIT METHOD

Figure 1 shows a graphical representation of the application of the linear fit method to a split air conditioner. This method uses a linear fit of the mixed indoor coil (evaporator) cooling capacity as a function of the refrigerant saturation temperature at evaporator exit when the coil is subjected to standard indoor air condition (CFR 2012a). By imposing the mixed evaporator capacity line over that of the outdoor section (condensing unit) capacity line for the A-test, gross mixed system capacity and refrigerant saturation temperature at the evaporator outlet are determined. Then, by projecting the refrigerant saturation temperature onto the outdoor section power consumption plot, the power requirement for the outdoor unit is determined. To finalize the rating of the mixed system, the power of the indoor fan must be accounted for, as it contributes to the mixed system power, *P*(95), and reduces the cooling capacity, *q*(95). The result is the mixed system

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capacity, Q(95). The energy efficiency ratio at the A-test rating point, EER(95), can be then calculated by Eq. 1.

$$EER(95) = \frac{Q(95)}{P(95)} \tag{1}$$

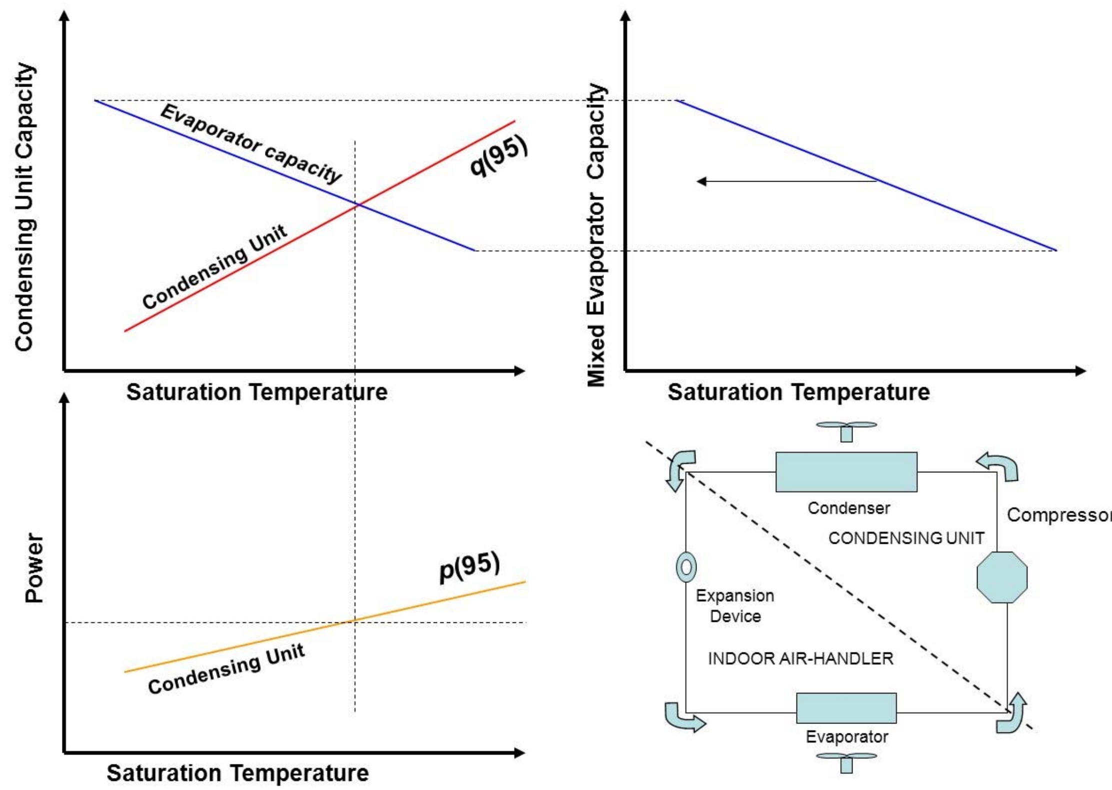

Figure 1: Graphical illustration of the linear fit rating procedure applied to an air conditioner

To conclude with the SEER calculation of the mixed system, a value of expansion device/fan delay correction factor, F_{exp}, for the mixed system is required.

$$SEER_{mixed} = SEER_{matched} \frac{EER(95)_{mixed}}{EER(95)_{matched}} F_{exp} \tag{2}$$

Where matched system $SEER = \left(1 - \frac{C_D}{2}\right) EER(82)$ for single-speed systems.

$EER(95)_{matched}$ and $EER(95)_{mixed}$ are used in Eq. 2 instead of $EER(82)_{matched}$ and $EER(82)_{mixed}$ because $EER(95)_{matched}$ can be calculated from the rated cooling capacity and power. If $EER(82)_{matched}$ is available, it can be substituted into Eq. 2 along with $EER(82)_{mixed}$. Using the ratio of $EER(82)_{mixed}$ and $EER(82)_{matched}$ is preferable.

MIXED EVAPORATOR AND OUTDOOR SECTION LINEAR FITS

Mixed Evaporators

Table 1 shows information on the tested mixed evaporators. Three evaporators were inclined single slabs, four were constructed in an A-shape configuration, and one in a semi-A-shape configuration. Three of the coils were equipped with a blower and required indoor fan power measurement; the remaining six coils were intended to have field-installed fans. Table 2 presents mixed evaporator linear fit coefficients based on laboratory tests performed in an environmental chamber (Payne and Domanski 2006).

Table 1: Tested Mixed Evaporators

Coil Number	Coil Configuration	Airflow Direction	Tube Outside Diameter	Expansion Device	Refrigerant
1	A	Horizontal	9.5 mm (0.375 in)	TXV	R22
2	Semi A	Horizontal	9.5 mm (0.375 in)	Piston	R22
3	A	Upflow	9.5 mm (0.375 in)	TXV	R22
4	Inclined Slab*	Upflow/Horizontal	9.5 mm (0.375 in)	Piston	R22
5	Inclined Slab*	Horizontal	9.5 mm (0.375 in)	TXV	R22
6	A	Horizontal	9.5 mm (0.375 in)	Piston	R22
7	A	Upflow	9.5 mm (0.375 in)	Piston	R22
8	Inclined Slab*	Horizontal	9.5 mm (0.375 in)	TXV	R410A

*indoor blower included

Table 2: Mixed Evaporator Capacity Linear Fit Coefficients and Fan Powers at A-Test Conditions

Coil	Evaporator Airflow $m^3 h^{-1}$ (scfm)	Fan Power W	Fit Standard Residual W (Btu h^{-1})	Slope W °C^{-1} (Btu h^{-1} °F^{-1})	Slope Standard Residual	Intercept W (Btu h^{-1})	Intercept Standard Residual
1	1721 (1013)	0	508.38 (1734.68)	-742.8 (-1408.17)	92.91 (176.12)	29223.85 (99713.83)	2327.57 (7942.01)
2	1368 (805)	0	258.89 (883.83)	-665.1 (-1260.93)	44.77 (84.87)	22348.89 (76257.54)	1118.97 (3818.80)
3	1621 (954)	0	219.00 (747.27)	-648.9 (-1230.09)	42.42 (80.41)	26613.89 (90810.3)	1059.61 (3615.54)
4	1279 (753)	271	117.29 (400.21)	-527.2 (-999.46)	22.29 (42.25)	21533.51 (73475.36)	558.73 (1906.46)
5	1954 (1150)	784	320.26 (1092.76)	-1047.4 (-1985.52)	79.84 (151.35)	41670.51 (142182.9)	2284.83 (7796.16)
6	2047 (1205)	0	85.13 (290.48)	-443.6 (-840.91)	14.84 (28.14)	18681.3 (63743.21)	367.73 (1254.73)
7	2360 (1389)	0	233.69 (797.39)	-766.6 (-1453.12)	41.26 (78.21)	29527.99 (100753.65)	1028.34 (3508.83)
8	849 (500)	364	31.68 (108.08)	-574.3 (-1088.66)	39.18 (74.27)	20909.65 (71346.67)	1058.35 (3611.24)

Mixed Evaporator and Outdoor Section Linear Fits

The linear fit for indoor coil capacity has the following form:

$$q_{coil} = C_{coil} + D_{coil} \cdot T_{evap} \quad (3)$$

If a fan is incorporated in the mixed indoor section, its electrical power, $P_{fan,mixed}$, must be measured with an uncertainty of ±1 % (95 % confidence level; for a single measurement). If no fan is supplied with the evaporator, it is necessary to calculate the default indoor fan power by Eq. 4.

$$P_{fan,mixed} = W_f \cdot V_{ind} \quad (4)$$

The heat added to the air stream by the supplied fan or by default becomes:

$$Q_{fan,mixed} = W_c \cdot P_{fan,mixed} \quad (5)$$

The linear fit correlations for the outdoor section cooling capacity and power at the A-test conditions have the following form:

$$q_{CD}(95) = C_{CD}(95) + D_{CD}(95) \cdot T_{evap} \quad (6)$$

$$p_{CD}(95) = E_{CD}(95) + F_{CD}(95) \cdot T_{evap} \quad (7)$$

The outdoor unit linear fits also use the evaporator exit saturation temperature; i.e., they include the effect of refrigerant pressure drop and heat transfer in the suction line. Table 3 presents the condensing unit linear fits and data provided by the manufacturers' association for validation of this rating procedure.

Table 3: Condensing Unit Linear Fit Coefficients for Power and Capacity at A-Test Condition

Condensing Unit Paired with Coil #	*q*(95) Slope W °C^{-1} (Btu h^{-1} °F^{-1})	*q*(95) Intercept W (Btu h^{-1})	*p*(95) Slope W °C^{-1} (W °F^{-1})	*p*(95) Intercept W	Refrigerant Liquid Temperature °C (°F)	Evaporator Exit Refrigerant Superheat °C (°F)
1	300.2 (569.1)	2217.7 (7567.0)	5.76 (3.2)	2717.1	37.2 (99.0)	6.2 (11.2)
2	163.2 (309.3)	2785.3 (9503.9)	35.64 (19.8)	1289.6	41.1 (106.0)	4.7 (8.5)
3	300.2 (569.1)	2217.7 (7567.0)	5.76 (3.2)	2717.1	35.2 (95.4)	11.6 (20.9)
4	263.3 (499.2)	22.7 (77.3)	38.7 (21.5)	1069.6	40.3 (104.6)	0.8 (1.5)
5	564.6 (1070.2)	2995.4 (10220.7)	32.94 (18.3)	4123.4	40.3 (104.6)	7.1 (12.7)
6	508.6 (964.1)	-2569.6 (-8767.8)	38.34 (21.3)	2278.8	49.4 (120.9)	2.4 (4.3)
7	336.6 (638)	3420.9 (11672.7)	172.8 (96)	-697.3	39.1 (102.4)	3.9 (7.1)
8	278.5 (528.0)	423.0 (1443.2)	11.52 (6.4)	1990.9	40.8 (105.4)	6.2 (11.2)

APPLICATION OF THE LINEAR FIT METHOD

Calculation of Q(95)

With the coil capacity coefficients from Table 2 and condensing unit capacity coefficients from Table 3, the linear fit method may be used to calculate cooling capacity at 35.0 °C (95.0 °F) for the mixed systems consisting of the mixed evaporators and their paired condensing units. The evaporator capacity must be corrected to account for liquid temperatures and superheats that may differ from the matched condensing unit (Payne and Domanski 2006). This correction was determined through simulations using EVAP-COND (Domanski 2006), a detailed simulation model for finned-tube evaporators and condensers. Table 4 presents the resulting mixed system capacities.

Table 4: Mixed System A-Test Capacity from the Linear Fit Method

Coil	T_{evap} °C (°F)	*q*(95) with condenser W (Btu h^{-1})	Indoor Airflow m^3 h^{-1} (scfm)	Q_{fan}(1) W (Btu h^{-1})	$Q_{\mathrm{mixed}}(95)$ W (Btu h^{-1})
1	8.29 (46.9)	10043 (34266)	1721 (1013)	370 (1262)	9673 (33005)
2	6.16 (43.1)	6691 (22829)	1368 (805)	294 (1003)	6397 (21826)
3	7.66 (45.8)	9856 (33628)	1621 (954)	348 (1188)	9507 (32440)
4	11.22 (52.2)	7661 (26138)	1279 (753)	271 (925)	7390 (25213)
5	6.27 (43.3)	16572 (56545)	1954 (1150)	784 (2675)	15788 (53870)
6	5.16 (41.3)	9099 (31046)	2047 (1205)	440 (1501)	8659 (29545)
7	6.42 (43.6)	11566 (39464)	2360 (1389)	507 (1730)	11059 (37734)
8	6.38 (43.5)	7153 (24405)	849 (500)	364 (1242)	6789 (23163)

(1) For units with no fan Q_{fan} was calculated to be 12.8906 W m^3 h^{-1} (0.365 W scfm^{-1}) of airflow.

Calculation of SEER

Calculation of the SEER, as defined in Eq. 2, requires the matched system rated SEER, the energy efficiency ratio at the A-test conditions for the mixed and matched systems, $EER(95)_{mixed}$ and $EER(95)_{matched}$, respectively, in addition to the value of the expansion device/fan delay correction factor, F_{exp}. See the detailed procedure for calculating $EER(95)_{mixed}$ that includes the fan power and fan heat corrections (Payne and Domanski 2006). F_{exp} is calculated based upon a survey performed by Dougherty (2004). The systems were broken down into four distinct categories, as listed in Table 5. Applying these findings to the value of the cyclic degradations coefficient produces values of F_{exp} for various combinations, as listed in Table 6.

Table 7 summarizes the SEER calculations for the mixed (tested) evaporators and their paired condensing units. $SEER_{matched}$ shown in the table and used in the calculations is the value certified by the matched system manufacturer.

Table 5: System Categories for Determining F_{exp}

System Category	System Pressure Equalization During Off Cycle	Indoor Fan Turn-Off Delay	System Components
A	Yes	No	Cap Tube, Orifice, Bleed TXV
B1	No	No	Non-Bleed TXV, Electronic Expansion Device, Liquid Line Solenoid
B2	Yes	Yes	Cap Tube, Orifice, Bleed TXV
C	No	Yes	Non-Bleed TXV, Electronic Expansion Device, Liquid Line Solenoid

Table 6: F_{exp} for Various Mixed and Matched System Combinations

		Matched System			
		A	B1	B2	C
Mixed System	A	1.000	0.990	0.990	0.974
	B1	1.010	1.000	1.000	0.985
	B2	1.010	1.000	1.000	0.985
	C	1.026	1.016	1.016	1.000

Table 7: Mixed System SEERs

Mixed System Designation Using Coil Number	$SEER_{matched}$	Calculated $EER(95)_{matched}$	AHRI Directory Verified $EER(95)_{matched}$	$EER(95)_{mixed}$	$SEER_{mixed}$ (1)
1	14.0	10.85	12.00	10.20	13.18
2	10.2	9.19	10.70	8.96	9.94
3	14.0	10.91	12.00	10.10	12.96
4	10.0	9.81	9.70	10.24	10.43
5	13.0	10.19	11.15	9.45	12.05
6	10.0	8.98	9.00	8.21	9.14
7	10.0	9.19	8.90	9.45	10.29
8	12.0	9.81	12.50	8.80	10.76

(1) Determined using the calculated $EER(95)_{matched}$

LINEAR FIT METHOD PREDICTIONS AND TESTING COMPARISON

A-Test Capacity Comparison

The first bar for each coil in Figure 2 presents the percent difference between the mixed system capacities, $Q_{mixed}(95)$, from the linear fit method and the AHRI testing at A-test conditions. Capacity predictions from the linear fit method were within ±5 % of the AHRI tests for four of eight coils. Among the four cases with poor predictions, the disagreement was as high as 14.5 %.

Figure 2 also shows evaporator saturation temperature percent differences between the linear fit method and mixed system certification tests. One can rationalize that a saturation temperature from the linear fit method that is lower than that from the certification tests (negative percent difference) should result in an overprediction of capacity while a higher linear fit method saturation temperature should drive toward the opposite effect. This physical rationale holds somewhat for Coils 1, 2, 3, 6, 8, and 9, while other coils do not conform. In particular, Coil 7, associated with the largest underprediction of $Q(95)$ of 14.5 %, has a 6.8 % underpredicted T_{evap} yet the predicted capacity is still 14.5 % low.

Looking back at the predicted $Q(95)$ presented in Figure 2, we can see that good predictions were obtained from four sources (Coils 1, 2, 3, and 9). Also good $Q(95)$ predictions were obtained for Coil 5; in this case the capacity calculated from evaporator and condensing unit linear fits underpredicted and overpredicted the mixed system capacity by a similar percentage. The result is a good prediction of $Q(95)$. In the cases with the largest $Q(95)$ prediction errors, Coils 6, 7 and 8, no offsetting of errors took place; even for Coil 8 where the linear fit method predicted the evaporator saturation temperature within 0.2 °C (0.4 °F). Since linear fit calculated capacity and mixed system test measured capacity for Coil 6 agree within 2.5 % while the condensing unit capacity overpredicts by 13.1 %, a suggestion can be made that the condensing unit correlation could be faulted for the $Q(95)$ overprediction. Using the same rationale, the evaporator capacity correlation for Coil 7 may be suspect. For Coil 8, the evaporator and condensing unit correlations yield similar capacities and disagree with the system test data by a similar capacity percentage, -12.2 % and -14.2 %, respectively, suggesting some certification testing irregularity.

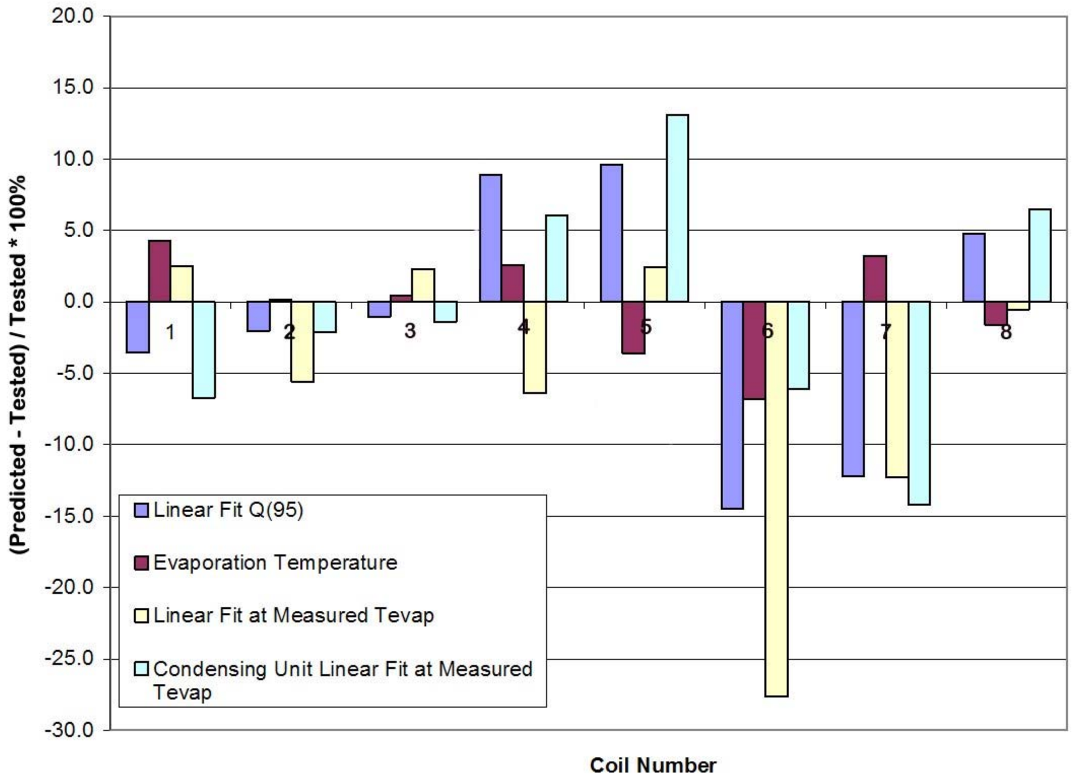

Figure 2: Comparison of mixed system A-Test capacities from certification (AHRI) tests and the linear fit method

SEER Comparison

Figure 3 shows the results of applying Eq. 2 to calculate the mixed system SEER. For each mixed system using the eight tested coils the measured SEER, calculated SEER, EER matched system, $EER(95)_{mixed}$, and percent difference in SEER with respect to the measured SEER are presented.

As seen in Figure 2, the $Q(95)$ disagreement was greater than ±5 % for Coils 5, 6, 7, and 8. Yet SEER disagreement is greater than ±5 % for only Coils 5 and 8. Clearly some offset of the capacity disagreement was compensated for in the EER ratio (condensing unit power ratio) and matched system SEER. The largest SEER disagreement occurs for Coil 5. The calculated values of mixed and matched EER(95) for Coil 5 produce a ratio of 0.927 as used in Eq.2; $EER(95)_{mixed}$ is 7.3 % lower than EER(95) of the matched system which translates into SEER of the mixed system being 7.3 % lower than the matched system. If the measured value of mixed system SEER were substituted in Eq. 2 along with the calculated value of the EER(95) matched system, EER(95) mixed system would have to be 7.70 instead of the calculated value of 9.45 to produce agreement between the measured and calculated values of mixed system SEER. Such a low value of EER(95) would not be allowed and thus tends to indicate that the condensing unit power linear fit must also be suspect. As seen in Figure 2 when the measured evaporating temperature was substituted into the condensing unit capacity linear fit, the $Q(95)$ capacity was overpredicted by more than 13 %. No power measurements are available for comparison, but the power linear fit in addition to the condensing unit capacity linear fit is a likely cause of the disagreement due to the excessive difference in mixed system EER required to produce a mixed system SEER that agrees with the measured value.

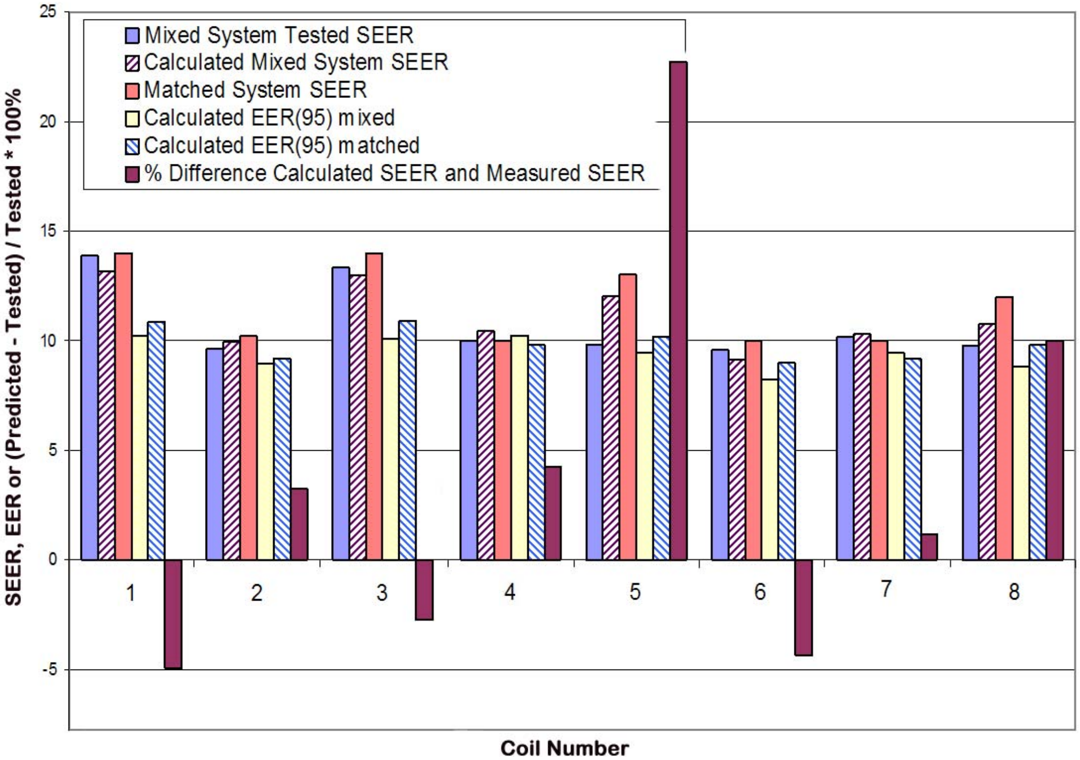

Figure 3: SEER and EER comparison for mixed and matched systems

CONCLUDING REMARKS

The paper outlines a linear fit method for rating mixed unitary air conditioners and presents its *Q*(95) and SEER predictions for a sample of eight mixed systems. The linear fit method produced $Q(95)_{mixed}$ results that were within ± 5 % of the tested values for four of eight mixed systems. Among the four cases with poor predictions, the disagreement was as high as 14.5 %.

Regarding $SEER_{mixed}$ values, six of eight predictions were within ± 5 % of the tested values, but offsetting of errors played a role in this agreement. Clearly some offset of the capacity disagreement was compensated for in the EER ratio and matched system SEER. For the same reason three of eight $SEER_{mixed}$ predictions were below the test-derived SEERs. A much more thorough discussion of coil testing may be found in Payne and Domanski 2005.

We have to recognize that that the uncertainties in the linear fit parameters are much larger than 5 %, depending on the number of data points used to generate the fits. Indoor coil and condensing unit manufacturers must take care in verifying their capacity and power linear fits; the linear fits, at the very least, should pass through their tested rating point data.

The presented linear fit method is applicable to systems employing single-speed compressors. This method can be extended to two-speed systems and to heat pumps operating in the heating mode for predicting the heating capacity and heating seasonal performance factor (HSPF).

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NOMENCLATURE

A-test = refers to AHRI Standard 210/240 standard test
C_{CD} = outdoor section capacity linear intercept, W (Btu h^{-1})
C_{coil} = indoor coil capacity linear intercept, W (Btu h^{-1})
C_D = cooling mode cyclic degradation coefficient
D_{CD} = outdoor section capacity linear slope , W °C^{-1} (Btu h^{-1} °F^{-1})
D_{coil} = indoor coil capacity linear slope, W °C^{-1} (Btu h^{-1} °F^{-1})
$E_{CD}(95)$ = outdoor section power linear intercept at the A Test conditions, W
EER = Energy Efficiency Ratio as calculated in AHRI Standard 210/240-2008, W/W (Btu W^{-1} h^{-1})
$F_{CD}(95)$ = outdoor section power linear slope at the A-test conditions, W °F^{-1} (W °C^{-1})
F_{EXP} = expansion valve mixed system SEER correction factor
matched = refers to a split air-conditioning system whose rated performance is determined by laboratory testing; also may refer to the evaporator which is used in the matched system.
mixed = refers to a split air-conditioning system whose rated performance is not determined by laboratory testing; also may refer to the evaporator which is used in the mixed system.
$p_{CD}(95)$ = outdoor section total power at A-test standard conditions without indoor fan power, W
P = electrical power, W
q = cooling capacity without indoor fan heat, W (Btu h^{-1})
$Q(95)$, $q(95)$ = cooling capacity at A-test conditions with/without accounting for indoor fan heat input, W (Btu h^{-1})
scfm = standard cubic feet per minute, equal to volume flow rate of air with a density of 1.201 kg m^{-3} (0.075 lb ft^{-3})
SEER = Seasonal Energy Efficiency Ratio as defined in AHRI Standard 210/240-2008, Btu W^{-1} h^{-1}
T = temperature, °C (°F)
TXV = thermostatic expansion valve
V_{ind} = indoor air volume rate of standard air, m^3 s^{-1} (scfm)
W_f = flow specific fan power multiplier of 775 W m^{-3} s^{-1} (0.365 W $scfm^{-1}$)

Subscripts

CD = condensing unit of the split system air conditioner
coil = refers to indoor coil or evaporator coil
evap = refers to the indoor coil or evaporator
f = fan
fan = refers to the indoor coil fan
ind = indoor
ref = refrigerant
suph = superheat

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