Carrier
Hourly Analysis Program 6.0

ASHRAE Standard 140-2017
Test Results

Carrier Software Systems
Carrier Corporation
Syracuse, New York

October 27, 2023
Rev June 21, 2024

Introduction

ASHRAE Standard 140-2017 *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs* sets forth procedures for testing building energy modeling software. This report documents results of Standard 140-2017 tests applied to Carrier's Hourly Analysis Program (HAP) v6.0.0.888.

About Standard 140-2017

ASHRAE Standard 140 specifies test procedures for evaluating the technical capabilities and ranges of applicability of computer programs that calculate the thermal performance of buildings and their HVAC systems. Because of the complexity of building energy simulation software, determining the accuracy and applicability of these programs is a challenging task. As the standard notes:

> *The tests are a subset of all the possible tests that could occur. A large amount of effort has gone into establishing a sequence of tests that examines many of the physical and mathematical models relevant to simulating the energy performance of a building and its mechanical equipment. However, because building energy simulation software operates in an immense parameter space, it is not practical to test every combination of parameters over every possible range of function. (1)*

The 2017 edition of Standard 140 contains tests for building envelope load calculations (Section 5.2), unitary space cooling equipment (Section 5.3), space heating equipment (Section 5.4), and air-side HVAC equipment (Section 5.5). Tests for further types of simulation calculations are under development and may be added in future editions of the Standard.

The Standard defines a series of specific test cases. For each test case an energy simulation is run using the subject software program being evaluated. The Standard provides sample test results generated by several "reference" software programs considered by the authors of the standard to represent state-of-the-art for building simulation. Reference programs vary for each test suite within the Standard and include such programs as DOE2.1E, DOE2.2, DEST, ESP-r, EnergyPlus, TRNSYS, TAS, and others.

It is important to note that Standard 140-2017 is a "method of test" standard and is therefore fundamentally different from other standards the reader may be familiar with such as Standard 90.1 or Standard 62.1. A "method of test" standard does not set forth formal pass/fail criteria for tests. Instead it simply defines standard procedures by which building simulation software may be tested. It is left to the tester of the software or the reader reviewing test results to determine the meaning of the test results. Some users of the Standard compare test results with those of the reference programs noted above. If the test results fall within or close to the range of results produced by the reference programs, the subject software is considered to yield acceptable accuracy. For example, if the subject program produces a value of 3.0 and the reference programs produced results ranging from 2.3 to 3.6, the subject program is judged to have acceptable accuracy.

Finally, the standard is careful to stress the extent to which these tests can be used to judge whether results are "accurate", "correct" or "incorrect":

> *"…[T]he building energy simulation computer programs used to generate these results have been subjected to a number of analytical verification, empirical validation, and comparative testing studies. However, there is no such thing as a completely validated building energy simulation computer program. All building models are simplifications of reality. The philosophy here is to generate a range of results from several programs that are generally accepted as representing the state-of-the-art in whole building energy simulation programs. … For any given case, a tested program may fall outside this range [of reference results] without necessarily being incorrect. However, it is worthwhile to investigate the source of substantial differences..." (2)*

Discussion of Test Results

The tables on the following pages summarize the results of Standard 140-2017 tests performed with HAP. A brief summary of the test suites follows.

Section 5.2 -Thermal Building Envelope and Fabric Tests. Tests in section 5.2.1 and 5.2.2 evaluate the calculation of space cooling and heating loads, considering the combined effects of thermal mass, solar heat gain, external shading devices, internally generated heat gains, infiltration, sunspaces, and thermostat setback and deadband control. Tests in section 5.2.3 are optional diagnostic tests used when problems appear in the prior tests. These tests were not performed. Tests in section 5.2.4 involve ground coupled heat transfer. The testing conditions are rather intricate and many software tools are not able to model these conditions. That was the case here.

Section 5.3 – Space Cooling Equipment Tests. Tests in sections 5.3.1 and 5.3.2 evaluate the calculation of energy performance for unitary space cooling equipment. The tests from the two sections are labelled 5.3A and 5.3B respectively in the results tables.

Section 5.4 – Space Heating Equipment Tests. Tests in 5.4.1 and 5.4.2 evaluate the energy performance of residential fuel-fired furnaces.

Section 5.5 - – Airside HVAC Equipment Analytical Verification Tests. Tests in this section evaluate the ability to model system mass flow and heat balance of common air distribution systems including fan coils, single zone constant air volume, constant air volume with terminal reheat, and variable air volume with terminal reheat.

Please note the following about data contained in the results tables on the following pages.

1. Test case numbering in Standard 140 is not always sequential. Therefore, non-consecutive test case numbers in the tables do not indicate cases were omitted.

2. Each table contains a concise listing of the higher level results from a test. Test result documentation required by Standard 140 is far more extensive than just the quantities listed on the following pages.

3. Complete testing results including results spreadsheets, modeler notes, and project input files are provided in a companion ZIP file posted on the carrier.com/commercial web site, as required by ASHRAE Standard 90.1, Appendix G simulation software requirements.

References

(1) ASHRAE Standard 140-2017, Foreword, page 4.
(2) ASHRAE Standard 140-2017, Foreword, page 6.

Table 1. Selected Test Results for Section 5.2 – Building Thermal Envelope and Fabric Test Cases

Case	Description	Annual Heating Load (MWh)		Peak Heating Load (kW)		Annual Cooling Load (MWH)		Peak Cooling Load (kW)	
		HAP	Std 140	HAP	Std 140	HAP	Std 140	HAP	Std 140
600	Low mass base case, S windows	4.467	4.296 to 5.709	3.945	3.437 to 4.354	7.930	6.137 to 7.964	7.346	5.965 to 6.827
610	Add overhang shading	4.470	4.355 to 5.786	3.911	3.437 to 4.354	5.719	3.915 to 5.778	6.959	5.669 to 6.371
620	E, W windows instead of S	4.454	4.613 to 5.944	3.789	3.591 to 4.379	5.109	3.417 to 5.004	4.615	3.634 to 5.096
630	E, W windows with fins	4.712	5.050 to 6.469	3.764	3.592 to 4.280	3.522	2.129 to 3.701	3.934	3.072 to 4.116
640	With thermostat setback	3.312	2.751 to 3.803	7.298	5.232 to 6.954	7.648	5.952 to 7.811	7.338	5.892 to 6.776
650	With nighttime ventilation	0.000	0.000 to 0.000	0.000	0.000 to 0.000	5.197	4.816 to 6.545	7.169	5.831 to 6.679
900	High mass base case, S windows	1.743	1.170 to 2.041	3.815	2.850 to 3.797	3.966	2.132 to 3.415	4.926	2.888 to 3.871
910	Add overhang shading	1.964	1.575 to 2.282	3.793	2.858 to 3.801	2.277	0.821 to 1.872	4.125	1.896 to 3.277
920	E, W windows instead of S	3.427	3.313 to 4.300	3.858	3.308 to 4.061	3.422	1.840 to 3.092	3.727	2.385 to 3.505
930	E, W windows with fins	4.116	4.143 to 5.335	3.843	3.355 to 4.064	2.331	1.039 to 2.238	3.304	1.873 to 3.080
940	With thermostat setback	1.302	0.793 to 1.411	5.362	3.980 to 6.428	3.565	2.079 to 3.241	4.985	2.888 to 3.871
950	With nighttime ventilation	0.000	0.000 to 0.000	0.000	0.000 to 0.000	0.390	0.387 to 0.921	3.495	2.033 to 3.170
960	Sun space	2.432	2.311 to 3.373	2.747	2.410 to 2.863	0.992	0.411 to 0.803	1.428	0.953 to 1.403

Note: In Table 1 the HAP results for Annual Cooling Load and Peak Cooling Load are outside the range of reference program results for a number of the test cases. This is because of the indoor convection algorithm used by HAP. The Section 5.2 test cases implicitly require modeling of natural convection within the space. That represents an application where there is no forced airflow such as supply airflow or ventilation – essentially radiant cooling and radiant heating with no ventilation. The only air movement in such a space is due to natural convection bouyancy effects of warm or cool surfaces. HAP is designed to model HVAC systems commonly used in commercial buildings, so HAP models forced air cooling and heating systems that include ventilation. The presence of air circulation due to forced air HVAC results in higher surface convection coefficients and a higher rate of convective heat transfer between surfaces and room air than in a room having no forced airflow at all. As a result, conversion of envelope and internal heat gains to load is faster than in a room with no airflow. That causes higher peak cooling loads and in some cases higher annual cooling load to occur than in the reference results which modeled natural convection. When we manually manipulated the HAP data passed to EnergyPlus for calculation to replace the forced air convection model with the natural convection model, the calculation results aligned well with the reference program results. That result is shown below in Table 2. However, due to the way Standard 140 is written, we did not think it proper to publish the natural convection results in Table 2 as official HAP testing results.

Table 2. Selected Test Results from Section 5.3A – Space Cooling Equipment Performance Test Cases

Case	Description	February Monthly Total					
		Total DX Unit Cooling Energy Consumption (kWh)		Supply Fan (kWh)		Evaporator Coil Load (kWh)	
		HAP	Std 140	HAP	Std 140	HAP	Std 140
CE100	Base case	1507	1512 to 1531	142	141 to 145	3770	3794 to 3841
CE110	Dry coil w/ reduced OADB	1050	1061 to 1089	123	122 to 133	3752	3756 to 3804
CE120	Dry coil w/ increased tstat setpoint	1004	1002 to 1012	116	110 to 117	3744	3739 to 3763
CE130	Dry coil w/ low PLR	95	105 to 110	9	8 to 10	190	215 to 220
CE140	Dry coil w/ reduced OADB and low PLR	64	65 to 69	8	6 to 8	189	195 to 199
CE150	Humid zone, latent at high SHR	1194	1183 to 1208	139	133 to 141	4501	4509 to 4543
CE160	Humid zone, inc. setpoint at high SHR	1129	1107 to 1140	127	119 to 129	4489	4491 to 4516
CE165	Humid zone, variable setpoint and OADB at high SHR	1482	1470 to 1502	147	142 to 150	4510	4529 to 4567
CE170	Humid zone, reduced sensible load	631	620 to 638	72	61 to 73	2217	2225 to 2237
CE180	Humid zone, increased latent load	1080	1077 to 1083	118	111 to 119	4475	4481 to 4535
CE185	Humic zone, inc. OADB at low SHR	1532	1538 to 1547	138	135 to 139	4497	4507 to 4583
CE190	Humid zone, low PLR at low SHR	162	160 to 165	18	14 to 18	567	573 to 579
CE195	Humid zone, increased OADB at low SHR and low PLR	237	245 to 252	21	18 to 23	571	595 to 602
CE200	Full load test at AHRI conditions	1461	1440 to 1480	152	149 to 155	5477	5436 to 5534

Table 3. Selected Test Results from Section 5.3B – Space Cooling Equipment Performance Comparative Tests

Case	Description	Total Space Cooling Energy Consumption (kWh)		Annual Cooling Indoor Supply Fan Energy Consumption (kWh)		Annual Total Space Cooling Coil Loads (kWh)	
		HAP	Std 140	HAP	Std 140	HAP	Std 140
CE300	Comparative test base case	35056	34746 to 35634	10862	10862 to 10880	78445	77823 to 80427
CE310	High latent gains	39468	39390 to 39973	10862	10862 to 10880	97454	96448 to 99342
CE320	High infiltration	39449	38745 to 40060	10862	10862 to 10880	97777	96084 to 99792
CE330	High outdoor air	40618	39438 to 40963	10862	10862 to 10880	104325	100730 to 105013
CE340	Infiltration and outdoor air	40180	39265 to 40619	10862	10862 to 10880	101553	99028 to 102728
CE350	Thermostat setup	31408	30547 to 32237	10862	10862 to 10880	67256	63635 to 69388
CE360	Undersized system	54658	54016 to 55299	10862	10862 to 10880	161093	159807 to 162974
CE400	Integrated DB economizer	30984	30846 to 32045	10862	10862 to 10880	64572	64918 to 68793
CE420	Economizer with DB limit control	33030	32530 to 33387	10862	10862 to 10880	71433	69611 to 72609
CE430	Integrated enthalpy economizer	32131	31772 to 32538	10862	10862 to 10880	68456	67141 to 69756
CE440	Economizer with enthalpy limit control	33328	32973 to 33691	10862	10862 to 10880	72523	71181 to 73711
CE500	Base case with no outdoor air	22899	22323 to 23138	2591	2369 to 2639	65561	63105 to 65996
CE500a	Base case May-Sept	17900	17391 to 18051	2000	1837 to 2035	50321	48440 to 50693
CE510	High part load ratio, May-Sept	35608	34609 to 35971	4014	3923 to 4099	112730	108974 to 114018
CE520	Reduced tstat setpoint (EDB = 15 C)	25734	24987 to 25781	3159	2871 to 3200	66160	63212 to 66571
CE522	Reduced tstat setpoint (EDB = 20 C)	24146	23544 to 24360	2841	2704 to 2904	65828	63157 to 66373
CE525	Increased tstat setpoint (EDB sensitivity)	20719	20242 to 21323	2164	1885 to 2221	65095	63002 to 65399
CE530	Dry coil	18409	17281 to 17875	2206	1833 to 2117	47091	44875 to 47002
CE540	Reduced tstat setpoint (EDB sensitivity)	20048	19061 to 20164	2535	2258 to 2573	47421	44980 to 47462
CE545	Increased tstat setpoint (EDB sensitivity)	16958	15687 to 16636	1925	1501 to 1871	46805	44775 to 46668

Table 4. Selected Test Results from Section 5.4 – Space Heating Equipment Performance Tests

Case	Description	Annual Furnace Load (GJ)		Annual Furnace Input (GJ)		Fuel Consumption Rate (1000 m3/s)		Annual Fan Energy (kWh)	
		HAP	Std 140	HAP	Std 140	HAP	Std 140	HAP	Std 140
HE100	100% efficiency	77.76	77.75 to 77.94	77.76	77.71 to 78.42	0.263	0.263 to 0.265	-	-
HE110	80% efficiency	77.76	77.75 to 77.94	97.20	96.92 to 98.02	0.329	0.328 to 0.332	-	-
HE120	80% efficiency with PLR = 0.4	31.13	31.10 to 31.25	38.30	38.27 to 38.56	0.130	0.130 to 0.131	-	-
HE130	No load	0.01	0.00 to 0.16	0.01	0.00 to 0.14	0.000	0.000 to 0.000	-	-
HE140	Periodic part load ratio	31.13	31.10 to 31.26	38.91	38.76 to 39.00	0.132	0.131 to 0.132	-	-
HE150	Continuous circulation fan	29.62	29.57 to 29.88	36.99	36.82 to 37.23	0.125	0.125 to 0.126	432	432.0 to 433.3
HE160	Cycling circulation fan	30.51	30.46 to 31.26	38.14	37.96 to 38.12	0.129	0.129 to 0.129	171	170.2 to 172.4
HE170	Draft fan	29.62	29.57 to 29.88	36.99	36.82 to 37.23	0.125	0.125 to 0.126	473	473.1 to 473.4
HE210	Realistic weather data	42.06	41.36 to 42.06	52.42	50.53 to 52.37	0.177	0.171 to 0.177	291	281.6 to 298.9
HE220	Setback thermostat	39.95	39.41 to 39.87	49.72	47.87 to 49.47	0.168	0.162 to 0.167	277	268.3 to 281.2
HE230	Undersized furnace	34.52	34.32 to 34.59	43.15	41.37 to 43.22	0.146	0.140 to 0.146	480	431.4 to 478.4

Table 5. Selected Test Results from Section 5.5 – Airside HVAC Equipment Analytical Verification Tests

Case	Description	Cooling Coil Total Load (kW)		Cooling Coil Sensible Load (kW)		Heating Coil or Preheat Coil Load (kW)	
		HAP	Std 140	HAP	Std 140	HAP	Std 140
	Fan Coil System Tests						
AE101	Base case, high heating 1	0.000	0.000 to 0.000	0.000	0.000 to 0.000	8.452	8.372 to 8.768
AE103	Low cooling, dry coil 1	0.765	0.762 to 0.780	0.765	0.762 to 0.780	0.000	0.000 to 0.000
AE104	High cooling, wet coil 1	5.718	5.533 to 5.836	3.480	3.480 to 3.543	0.000	0.000 to 0.000
	Single Zone CAV System Tests						
AE201	Base case, high heating 1	0.000	0.000 to 0.000	0.000	0.000 to 0.000	8.382	8.302 to 8.709
AE203	Low cooling, dry coil 1	0.828	0.830 to 0.856	0.828	0.819 to 0.852	0.000	0.000 to 0.000
AE204	High cooling, wet coil 1	5.821	5.623 to 5.897	3.548	3.547 to 3.608	0.000	0.000 to 0.000
AE205	Low cooling, dry coil 1	1.912	1.908 to 1.929	1.912	1.880 to 1.929	0.000	0.000 to 0.000
AE206	Low cooling, wet coil 1	3.247	2.664 to 2.818	1.693	1.646 to 1.731	0.000	0.000 to 0.000
AE226	Low cooling, wet coil 1 w/ integrated DB economizer	3.885	3.335 to 3.643	1.541	1.503 to 1.597	0.000	0.000 to 0.000
AE245	Low cooling, dry coil 1 w/ integrated enthalpy economizer	2.205	2.202 to 2.216	2.205	2.171 to 2.216	0.000	0.000 to 0.000
	Constant Volume Terminal Reheat System Tests						
AE301	Base case, high heating 1	0.000	0.00 to 0.00	0.000	0.00 to 0.00	3.582	2.95 to 3.79
AE303	Low cooling, dry coil 1	6.455	6.42 to 6.74	6.455	6.42 to 6.74	0.000	0.00 to 0.00
AE304	High cooling, wet coil 1	17.054	16.10 to 17.07	10.083	9.89 to 10.32	0.000	0.00 to 0.00
AE305	Low cooling, dry coil 1	9.198	8.93 to 9.38	9.198	8.93 to 9.38	0.000	0.00 to 0.00
AE306	Low cooling, wet coil 1	14.739	14.03 to 14.80	8.691	8.60 to 8.92	0.000	0.00 to 0.00
AE326	Low cooling, wet coil 1 w/ integrated DB economizer	20.787	19.94 to 20.99	8.148	8.23 to 8.47	0.000	0.00 to 0.00
AE345	Low cooling, dry coil 1 w/ integrated enthalpy economizer	9.510	9.29 to 9.71	9.510	9.29 to 9.71	0.000	0.00 to 0.00
	Variable Air Volume Terminal RH System Tests						
AE401	Base case, high heating 1	0.000	0.00 to 0.00	0.000	0.00 to 0.00	10.348	10.25 to 10.82
AE403	Low cooling, dry coil 1	1.410	1.40 to 1.47	1.410	1.40 to 1.47	0.000	0.00 to 0.00
AE404	High cooling, wet coil 1	13.774	13.31 to 14.03	7.294	7.33 to 7.46	0.000	0.00 to 0.00
AE405	Low cooling, dry coil 1	4.099	4.10 to 4.14	4.099	4.10 to 4.14	0.000	0.00 to 0.00
AE406	Low cooling, wet coil 1	8.439	8.17 to 8.60	3.546	3.57 to 3.68	0.000	0.00 to 0.00
AE426	Low cooling, wet coil 1 w/ integrated DB economizer	8.917	8.80 to 9.21	3.493	3.52 to 3.64	0.000	0.00 to 0.00
AE445	Low cooling, dry coil 1 w/ integrated enthalpy economizer	4.139	4.14 to 4.19	4.139	4.14 to 4.19	0.000	0.00 to 0.00