Airside HVAC BESTEST: HVAC Air-Distribution System Model Test Cases for ASHRAE Standard 140

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Abstract

This paper summarizes recent work to develop new airside heating, ventilating, and air conditioning (HVAC) equipment model analytical verification test cases for ANSI/ASHRAE Standard 140, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs.* The analytical verification test method allows comparison of simulation results from a wide variety of building energy simulation programs with quasi-analytical solutions. Standard 140 is widely cited for evaluating software for use with performance-path energy efficiency analysis in conjunction with well-known energy-efficiency standards, including ASHRAE Standard 90.1, the International Energy Conservation Code, and other international standards. Airside HVAC equipment is a common area of modelling not previously explicitly tested by Standard 140. Integration of the completed test suite into Standard 140 is in progress.

Introduction

This paper documents a set of diagnostic analytical verification cases for testing the ability of whole-building energy simulation software to model the air distribution side of typical heating, ventilating, and air conditioning (HVAC) equipment. These cases complement the unitary equipment cases included in ANSI/ASHRAE Standard 140, *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs,* which test the ability to model the heat-transfer fluid and combustion side of common HVAC equipment. (ANSI/ASHRAE 2014; Neymark and Judkoff 2002, 2004; Purdy and Beausoleil-Morrison 2003) This new work was conducted by the National Renewable Energy Laboratory (NREL) in collaboration with a working group of international experts associated with the ASHRAE Standing Standard Project Committee (SSPC) 140. SSPC 140 is responsible for ANSI/ASHRAE Standard 140. The work builds off ASHRAE Research Project 865 (RP 865) (Yuill and Haberl 2002). RP 865 developed a test specification, and spreadsheet solutions intended as quasi-analytical solutions (QASs), for a number of typical HVAC configurations such as constant volume (CV) and variable air volume (VAV) reheat systems. At the time RP 865 was developed, the scope for input descriptions in its test specification was limited to two prominent whole-building energy simulation programs. The new work defines the test cases and specifications such that most building energy simulation programs with time steps of one hour or less can perform the tests and completes the process of verifying and reconciling the QASs.

Background: Building Energy Simulation Test and Diagnostic Method (BESTEST) and ANSI/ASHRAE Standard 140

The development of practical procedures and data for tool evaluation and improvement is part of an overall validation methodology that NREL, the International Energy Agency (IEA), and ASHRAE have been developing for many years. (Judkoff 1988, Bloomfield 1989, Lomas 1991, Judkoff and Neymark 2006, Judkoff et al. 2008/1983, ASHRAE 2013, ANSI/ASHRAE 2014). A more comprehensive listing of referenced work on building energy simulation software validation testing is included with the bibliography of Chapter 19 of ASHRAE (2013).

The methodology includes three ways to evaluate a whole-building energy simulation program's accuracy:

- *Empirical validation*, which compares calculated results from a program, subroutine, algorithm, module, or software object to monitored data from a real building, test cell, or laboratory experiment
- *Analytical verification*, which compares outputs from a program, subroutine, algorithm, module, or software object to results from a known analytical solution or to results from a set of closely agreeing QASs or verified numerical models
- *Comparative testing*, which compares a program to itself or to other programs.

https://doi.org/10.26868/25222708.2017.167

Further details are discussed in the Background section of *HVAC BESTEST* Volume 1 (Neymark and Judkoff 2002). The most recent updates, as of this writing, are published in the *2013 ASHRAE Handbook of Fundamentals* and elsewhere. (Judkoff and Neymark 2006, ASHRAE 2013, ANSI/ASHRAE 2014 [see Annex B23]).

NREL originally developed the BESTEST method in IEA Solar Heating and Cooling Programme Task 12 to test building thermal fabric (envelope) models and to diagnose sources of predictive disagreements. We identify the resulting test suite as "IEA BESTEST" (Judkoff and Neymark 1995a). This method of testing was adopted with some refinements by ASHRAE in accordance with procedures of ANSI, and now forms the basis for ANSI/ASHRAE Standard 140.

Since Standard 140 was first published, three HVAC BESTEST test suites developed within IEA Solar Heating and Cooling Programme, Task 22 have been added: two that address unitary space cooling equipment, and one that addresses fuel-fired furnaces. (Neymark and Judkoff 2002, 2004; Purdy and Beausoleil-Morrison 2003) Other test suites added to Standard 140 include building thermal fabric in-depth test cases for ground-coupled slab models (Neymark, Judkoff et al. 2008) and building thermal fabric test cases applicable to more simplified analysis programs commonly used for Home Energy Rating Systems (Judkoff and Neymark 1995b). The new in-depth airside HVAC equipment model test cases will be included in Standard 140 (ANSI/ASHRAE 2017).

Industry Use of Standard 140 and BESTEST

Many entities have adopted or cited Standard 140 and/or the component BESTEST suites. The impact of the work is apparent from the following:

- Standard 140 is referenced by:
  - ASHRAE building energy efficiency Standards 90.1 and 189.1 (ANSI/ASHRAE/IES 2016, ANSI/ASHRAE/IES/USGBC 2014)
  - International Energy Conservation and International Green Construction Codes (IECC 2015)
  - The U.S. tax code for certifying software used to evaluate building energy efficiency tax credits for commercial buildings (IRS 2008a); 13 building energy simulation programs are listed as qualified software for commercial buildings (U.S. DOE 2016)
  - Residential Energy Services Network (RESNET) low-rise residential building energy efficiency Standard 301 (ANSI/RESNET/ICC 2016); seven programs are listed as qualified for evaluating low-rise residential building energy efficiency, including for evaluating U.S. federal tax credits. (RESNET 2013, 2016; IRS 2008b)
  - State and federal agencies (e.g., California Energy Commission, Florida Building Commission, National Weatherization Program)
- Several European Union countries, as part of the European Community's Energy Performance Directive (European Union 2002), use software tools that have been checked with IEA BESTEST.
- Australia and New Zealand reference IEA BESTEST in their codes and standards.
- Researchers have translated BESTEST procedures into Dutch, German, and Japanese.
- A study comparing 20 whole-building energy simulation tools (Crawley et al. 2005) indicated that 19 of the 20 tools reviewed had been tested with at least one BESTEST procedure.
- Major international commercial equipment providers such as Carrier Corporation and Trane Company (respective authors of the HAP and TRACE whole-building energy simulation programs) are using BESTEST/Standard 140 for testing their software.
- BESTEST suites have been integrated within ESP-r (University of Strathclyde's advanced simulation tool, well known in Europe and Canada) for automated testing of revisions to the software.
- EnergyPlus, the U.S. Department of Energy's most advanced building energy simulation program, has automated the process of running Standard 140 tests and maintains its Standard 140 results on a website.

A more comprehensive listing, further discussion, and supporting references are included elsewhere (Judkoff and Neymark 2006, 2013).

Importance of the HVAC Air-Distribution System Modelling Problem

Most buildings in the United States, especially larger buildings with substantial space cooling loads, have ducted HVAC air distribution systems. Therefore, practical energy simulation models of larger buildings require the presence of ducted HVAC air distribution systems, either for modelling a typical planned building design or for developing comparative energy savings predictions for an advanced HVAC system (e.g., chilled beams) versus a typical ducted air distribution system.

As noted above, HVAC BESTEST cases originally published by NREL (Neymark and Judkoff 2002, 2004) and Natural Resources Canada (Purdy and Beausoleil-Morrison 2003) were previously added to ASHRAE Standard 140 (ANSI/ASHRAE 2014). These are analytical verification and comparative cases that test the ability to model unitary space cooling and space heating equipment. For the space cooling systems, these cases test the ability of programs to model the behavior of the working-fluid side of the system, using manufacturer design data presented as empirically derived performance maps. Many whole-building energy simulation programs are designed to work with this type of data because there are very little manufacturer's data that would support the alternative of first principles modelling. Similarly, the space heating cases test the operation of a furnace based on a summary of the manufacturer's performance data. These test suites only address air distribution systems superficially, and the original final reports for the HVAC BESTEST procedures indicate that complementary test cases for typical HVAC air distribution systems are needed. This means that if a model has good agreement for the current set of working-fluid-side mechanical equipment test cases, phenomena specific to airside HVAC distribution systems are not necessarily being correctly modelled.

Evolution of HVAC Air-Distribution System Model Test Cases

The work of ASHRAE RP 865 (Yuill and Haberl 2002) developed test cases that address airside HVAC distribution system modelling. RP 865 developed a set of test cases with two independently developed external spreadsheet solutions to evaluate HVAC air distribution system models utilized by building energy analysis computer programs. The test cases focus on system airflow and heat and mass balance. The cases are steady-state tests done at constant zone and ambient conditions. The test cases address seven different types of air handling systems, with testing conducted at six different sets of steady-state outdoor and zone conditions, and with various economizer outdoor air control strategies. The external spreadsheet solutions were initially produced independently by two different analysts during the original RP 865 project work for all the test case configurations. All spreadsheet calculations are based on fundamental physics principles, including the laws of conservation of mass and energy, and the properties of air and water presented in the *1993 ASHRAE Handbook of Fundamentals* (ASHRAE 1993).

The Current Airside HVAC Distribution System Diagnostic Test Cases

ASHRAE RP 865 (Yuill and Haberl 2002), described above, was adapted for Standard 140. The adaptation includes a set of 24 diagnostic test cases for airside HVAC distribution system models. These are steady-state analytical verification tests, where simulation results are compared to a QAS. Here a QAS is defined in Standard 140-2014 Addendum A (ANSI/ASHRAE 2017) as:

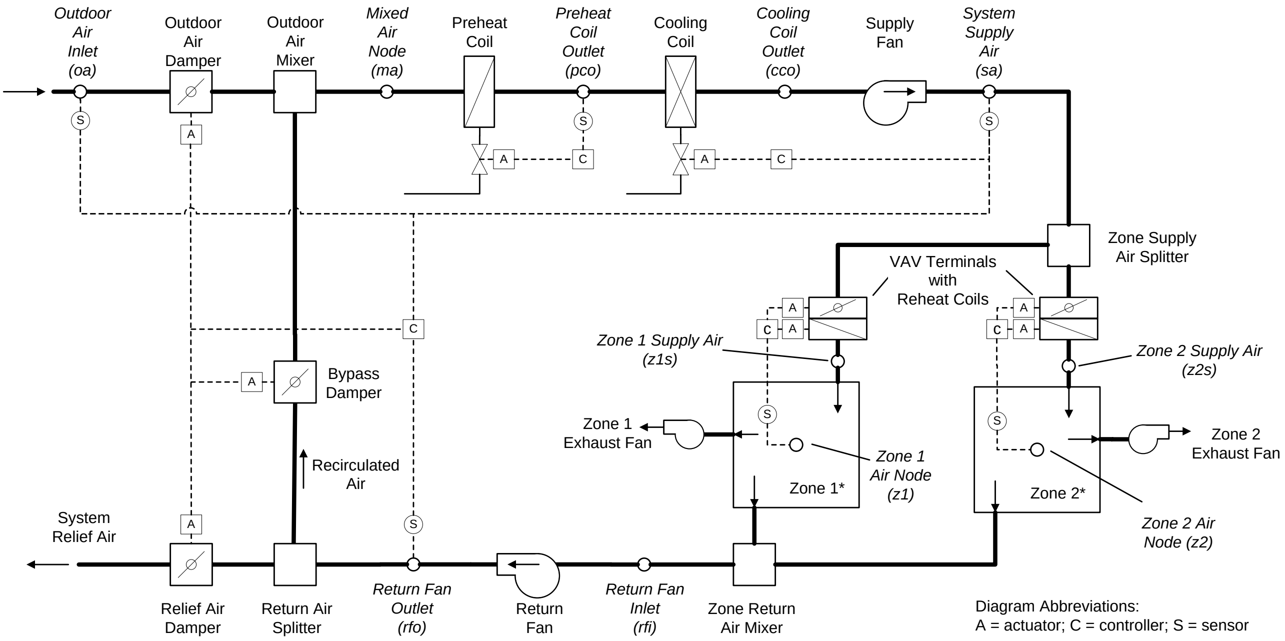
> "The mathematical solution of a model for a given set of parameters and simplifying assumptions; such a solution is allowed to include minor interpretation differences that cause minor results variations. ***Informative Note:*** Such a solution may be computed by generally accepted numerical methods or other means, provided that such calculations occur outside the environment of a whole-building energy simulation program and can be scrutinized."

The QAS constitutes a secondary mathematical truth standard as defined in ASHRAE Standard 140 (ANSI/ASHRAE 2014). The QAS may also be compared to other example simulation results provided in Part IV of Neymark et al. (2016). The primary importance of the QAS as a benchmark for comparing simulation tools is that it provides the basis for a narrower range of results disagreement than is generally available from software-to-software comparative tests without a mathematical truth standard (Judkoff and Neymark 2006; ASHRAE 2013). This is further discussed in Section 3.5 of Neymark et al. (2016).

The test cases are a subset of those developed as part of RP 865. The original research provided a technically sound conceptual starting point for the test specifications along with two separately developed solution spreadsheets intended as QASs. However, from this starting point NREL had three main technical challenges: a) to reconcile differences in the two analytical solutions into a single final QAS, b) to rework the test specifications such that they would be unambiguous for the input structures of most whole-building energy simulation programs with time steps of one hour or less, and c) to field test the usability of the test specifications with a variety of different simulation programs and associated software development groups from around the world. Details of the processes of improving the test specification and vetting the QAS are described in Parts III and II, respectively, of Neymark et al. (2016).

The tests include the following systems: Four-Pipe Fan Coil (FC), Single-Zone Air Conditioner (SZ), CV Terminal Reheat, and VAV Reheat. Figure 1 illustrates the schematic diagram for the VAV system, which has the most components of the four systems. The FC system is the simplest of the RP 865 systems: it is a single-zone system with heating and cooling coils, zone air exhaust, and limited outdoor air (no economizer control), and it does not include a return air fan. The FC system provides a good starting point for testing basic mass flow and heat balance modelling before addressing more complex air systems. In these test cases, the SZ system adds an economizer and a return air fan; the CV system further applies multiple (two) zones, system supply air temperature control, and terminal reheat coils; and the VAV system (see Figure 1) further applies a variable airflow supply fan and terminal zone supply air dampers. The final test cases are conducted at five different sets of steady-state outdoor and zone conditions in heating, dry-coil cooling, and wet-coil cooling modes, and with temperature and enthalpy economizer outdoor air control strategies applied to selected conditions. Table 1 summarizes the test case conditions for the VAV system test cases, which represent input parameter variation for all tested systems, except that the FC and SZ systems have only one zone, and the FC system does not have economizer cases. (See Nomenclature for abbreviations used in the table.) Primary output compared for these test cases includes coil sensible, latent, and total loads; zone sensible and latent loads; and cooling-coil leaving-air relative humidity. Additional diagnostic outputs at various points in the systems include dry-bulb temperature (and the ability to isolate fan heat effects), humidity ratio, specific volume, enthalpy, and mass flow rate. For these in-depth cases, plant energy use related to coil loads and fan electricity consumption is not considered.

NREL led the collaborative effort to vet and extensively revise the test case specifications for external use as a standard method of test that can be integrated with the tests of ASHRAE Standard 140. The collaboration included a number of software developer members of SSPC 140 along with other international software developers and participants. NREL also vetted the original RP 865 external spreadsheet solutions and merged them into a single QAS. The vetting process followed the procedure for developing analytical and quasi-analytical solutions defined by NREL in previous work (Neymark and Judkoff 2002) and involved checking all original equations by a third independent analyst. Spreadsheet result disagreements from the original work were reconciled by the third analyst; where needed, some details were reconciled in collaboration with the original solution developers. The vetting process also included comparison with previous solutions as QAS versions progressed. Details of QAS development are described in Part II of Neymark et al. (2016). The QAS also has good agreement with two of the simulation models that were able to most closely match the assumptions of the QAS, and observable differences between the QAS and the other simulation programs were explainable by modelling assumptions of those programs, consistent with the test case diagnostics. Perfect agreement among simulations and the QAS is not necessarily expected because many programs contain simplifying assumptions to ease the calculation burden (e.g., constant air density), and the QAS contains idealized simplifying assumptions (in order to be solved analytically) that cannot always be exactly reproduced by some simulation programs that are conceived and hardcoded with more realistic assumptions.



* Sensible and latent zone loads vary among the test cases.

Figure 1. Variable air volume terminal reheat (VAV) system schematic

Table 1. Airside HVAC equipment analytical verification test case descriptions—VAV system (SI units)

	Ambient		Zone	Zone	Zone Loads[a] (W)				
Case	**ODB**	**ODP**	**Num.**	**IDB**	**Sensible**		**Latent**	**Coil Load Type**	**Section Number**
	(°C)	**(°C)**		**(°C)**	**Heating**	**Cooling**			
No Economizer									
AE401	-29.0	-29.0	1	21.111	2931	0	586.1	High Heating	5.5.4.1
			2	22.222	2345	0	879.2		
AE403	15.5	-3.0	1	23.333	0	1465	586.1	Low Cooling, dry coil	5.5.4.2.1
			2	24.444	0	2345	879.2		
AE404	26.9	22.1	1	23.889	0	2931	586.1	High Cooling, wet coil	5.5.4.2.2
			2	25.000	0	3517	879.2		
AE405	24.9	2.4	1	23.333	0	1465	586.1	Low Cooling, dry coil	5.5.4.2.3
			2	24.444	0	2345	879.2		
AE406	23.0	20.9	1	23.333	0	1465	586.1	Low Cooling, wet coil	5.5.4.2.4
			2	24.444	0	2345	879.2		
Return Air Comparative Dry-Bulb Economizer Outdoor Air Control									
AE426	23.0	20.9	1	23.333	0	1465	586.1	Low Cooling, wet coil	5.5.4.3.1. AE406 with dry-bulb economizer
			2	24.444	0	2345	879.2		
Return Air Comparative Enthalpy Economizer Outdoor Air Control									
AE445	24.9	2.4	1	23.333	0	1465	586.1	Low Cooling, dry coil	5.5.4.3.2. AE405 with enthalpy economizer
			2	24.444	0	2345	879.2		

[a] Zone loads do not include outdoor air ventilation loads introduced by the mechanical equipment.

Results

The new test cases have been vetted by the industry. During six rounds of simulation trials, a total of seven industry participants comprised primarily of software developers from the United States, China, Japan, and the United Kingdom submitted results for seven separate whole-building energy simulation programs (see Table 2). Abbreviations indicated in Table 2 apply to Figures 2 through 5. The field-trial process was iterative in that executing the simulations led to refinement of the test cases, and the results of the tests led to improving and debugging the models. Improvements to simulation programs or simulation inputs made by participants must have a mathematical and a physical basis and must be applied consistently across tests. Arbitrary modification of a simulation program's input or internal code just for the purpose of more closely matching a given set of results is not allowed. All improvements were requested to be documented and justified in the modeller reports; see Part III of Neymark et al. (2016).

Improvements to the simulation models are evident by comparing the initial results set to the final results set. Initial simulation results for total coil loads obtained are shown for the FC and SZ systems in Figure 2 and for the CV and VAV systems in Figure 4 (abbreviations along these figures' x-axes are shorthand for the case descriptions, see Nomenclature). Figures 2 and 4 show each participant's results after the first "blind" round of simulations and before the QAS results were distributed to the working group for most of the programs.

The results shown in Figure 2 indicate that for the FC and SZ systems, there was initially 1% to 19% *average* disagreement for a given program versus the QAS results. The results shown in Figure 4 indicate that for the CV and VAV systems there was initially 2% to 37% average disagreement for a given program versus the QAS results. The additional complexity of specifying the CV and VAV systems (multi-zone with reheat) and inputting them in the models generated more initial disagreements than for the simpler FC and SZ systems. This emphasizes the importance of testing the different systems.

The final set of total coil load results for all the simulations and the QAS are shown in Figure 3 for the FC and SZ systems, and in Figure 5 for the CV and VAV systems (abbreviations along these figures' x-axes are the same as in Figure 2, except the temperature values are ODB/ODP [outdoor dry bulb/outdoor dew point] instead of ODB/OWB [outdoor wet bulb]). After correcting software errors and other model improvements using the diagnostic output, the mean of all simulated results of total cooling coil load for the tested programs are, on average, within 1.3% of the QAS results, with average variations among the test cases for a given program of up to 3%.

Table 2. Airside HVAC cases, participating organizations and models

Model	**Authoring Organization**	**Implemented by**	**Abbreviation**
Quasi-Analytical Solution (QAS)	PSU[a]/UNO[b]/TAMU[c]/NREL[d]/ JNA[e]/MDK[f], United States	NREL[d]/JNA[e]/MDK[f], United States	QAS/PSU-TAMU-NREL
DEEAP[g] 1.1.2	AAON, Inc., United States	AAON, Inc., United States	DEEAP/AAON
DeST[h] 2	Tsinghua University, China	Tsinghua University, China / LBNL[i], United States	DeST/TsinghuaU-LBNL
DOE-2.2 V48L	JJH[j]/LBNL[i]/UC[k], United States	NREL[d]/JNA[e]/MDKI[f], United States	DOE-2.2/NREL
EnergyPlus 8.2.0	DOE-BT[l], United States	GARD Analytics, Inc., United States	EnergyPlus/GARD
IES-VE[m] 2014.2	IES[n], United Kingdom	IES[n], United Kingdom	IES-VE/IES
LCEM[o] 3.10	MLIT[p], Japan	TTE[q], Japan	LCEM/MLIT-TTE
TRNSYS 17.01.0028	TESS[r]/UWM[s], United States	TESS[r], United States	TRNSYS/TESS

[a] PSU: The Pennsylvania State University, United States
[b] UNO: University of Nebraska - Omaha, United States
[c] TAMU: Texas A&M University, United States
[d] NREL: National Renewable Energy Laboratory, United States
[e] J. Neymark & Associates, United States
[f] Mike D. Kennedy, Inc., United States
[g] DEEAP: Detailed Energy and Economic Analysis Program
[h] DeST: Designer's Simulation Toolkit
[i] LBNL: Lawrence Berkeley National Laboratory, United States
[j] JJH: James J. Hirsch & Associates, United States
[k] UC: University of California, United States
[l] DOE-BT: U.S. Department of Energy, Office of Building Technologies, Energy Efficiency and Renewable Energy, United States
[m] IES-VE: Integrated Environmental Solutions - Virtual Environment
[n] IES: Integrated Environmental Solutions, United Kingdom
[o] LCEM: Life Cycle Energy Management tool
[p] MLIT: Ministry of Land, Infrastructure, Transportation and Tourism, Japan
[q] TTE: Takasago Thermal Engineering, Japan
[r] TESS: Thermal Energy System Specialists, United States
[s] UWM: University of Wisconsin – Madison, United States

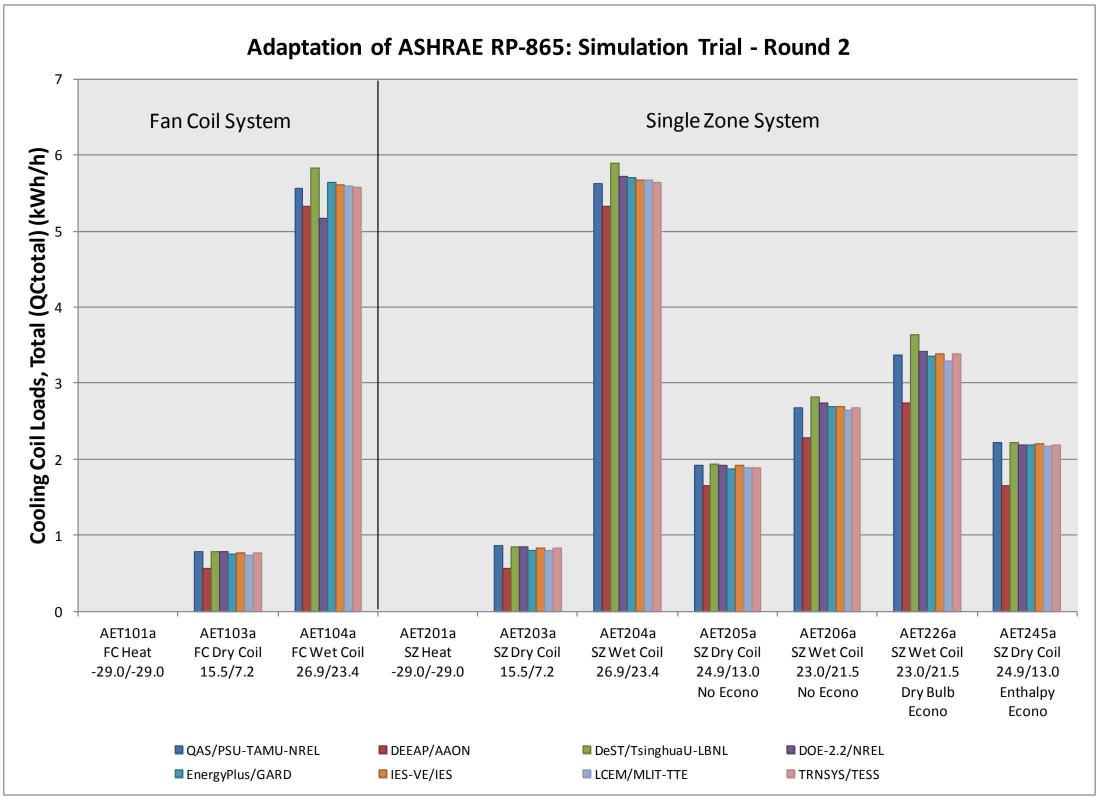


Figure 2. Airside HVAC BESTEST—total coil load, FC and SZ, before BESTESTing
(Abbreviations along x-axis describe test cases, numeric values are ODB/OWB; see Nomenclature)

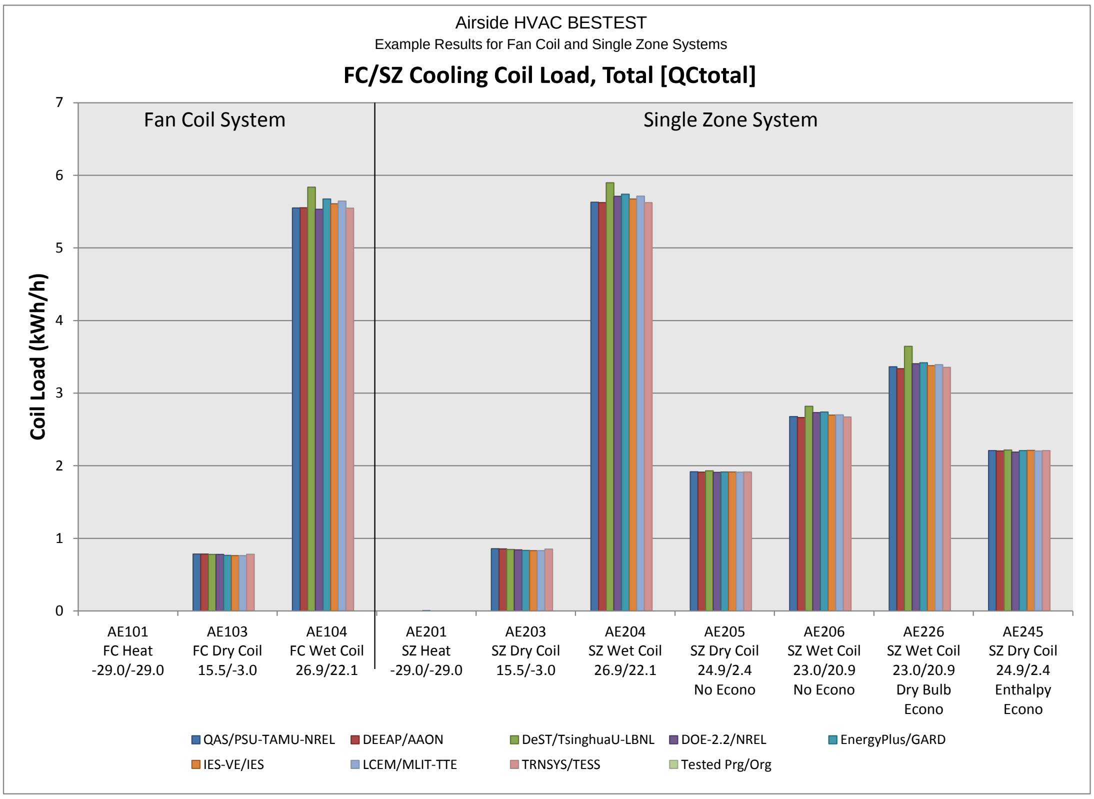


Figure 3. Airside HVAC BESTEST—total coil load, FC and SZ, after BESTESTing
(Abbreviations along x-axis describe test cases, numeric values are ODB/ODP; see Nomenclature)

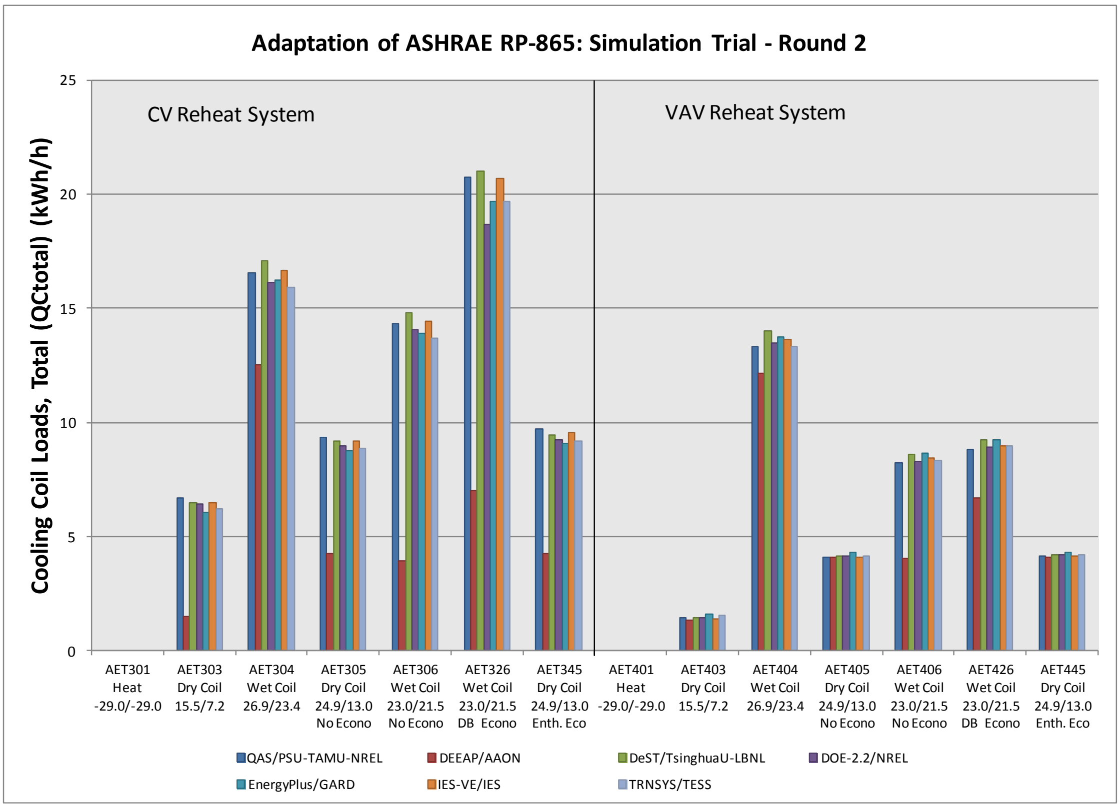


Figure 4. Airside HVAC BESTEST—total coil load, CV and VAV, before BESTESTing
(Abbreviations along x-axis describe test cases, numeric values are ODB/OWB; see Nomenclature)

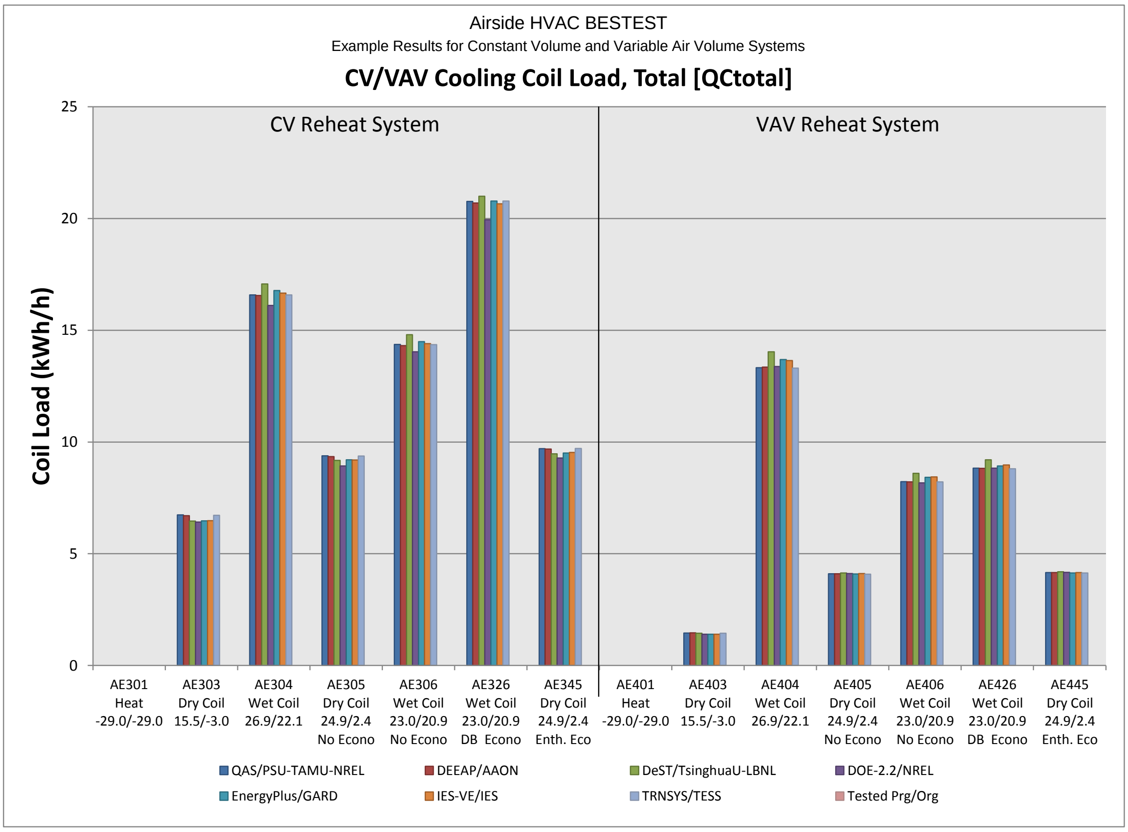


Figure 5. Airside HVAC BESTEST—total coil load, CV and VAV, after BESTESTing
(Abbreviations along x-axis describe test cases, numeric values are ODB/ODP; see Nomenclature.)

Conclusions

Major Accomplishments

The major accomplishments of the recent work were:

- Extension of the BESTEST procedures to include in-depth diagnostic analytical verification test cases for the air distribution side of typical HVAC equipment, based on ASHRAE RP 865 (Yuill and Haberl 2002).
- Development of unambiguous test specifications such that a variety of state-of-the-art building simulation programs with a variety of input structures and modelling approaches can perform the tests.
- Development of QAS results for all test cases by comparing, reconciling, and merging the two original external spreadsheet solutions from RP 865.
- Improved accuracy of or potential improvements identified for all but one of the models that participated in the simulation trials of the test cases.
- Development of a set of national and international simulation results representative of the range of legitimate modelling differences for the current state of the art in whole-building energy simulation computer programs.

The new test suite is in the midst of the ANSI/ASHRAE process for inclusion in Standard 140.

Technology Advancements and Findings

A number of important technology advances were made as a result of running the test cases:

- The QAS allowed diagnosis of errors and identification of potential areas for improvement that may have been missed in a comparative study of whole-building energy simulation programs versus each other, without a QAS benchmark.
- Of 26 program errors or potential improvements found, 17 were diagnosed and fixed, 2 are planned for investigation by the software authors, and 7 were unresolved. Several of the errors found affected some individual results by >20%.
- Seventeen input errors were found and corrected. These provided the basis for revealing a number of test specification ambiguities that were then clarified during the simulation trials, which underscores the importance of simulation trials in vetting test specifications before they are included in a standard method of test.
- Based on this work, there are a number of recommended areas for further investigation with respect to developing additional validation test cases for airside HVAC equipment modelling—see Recommendations below.

The QAS provides an effective reference or benchmark against which software can be tested, while the example simulation results indicate a reasonable range of disagreement for the current state-of-the-art simulation programs relative to the QAS. Based on results *after* several simulation trial iterations (“BESTESTing”) and resulting model improvements, all of the tested programs appear reliable for modelling these HVAC air distribution systems under the conditions tested, although use of constant system air density by some simulation programs causes modelling disagreements at extreme-low outdoor air temperatures for the specified CV system.

Advantages of the BESTEST Methodology

An advantage of the BESTEST methodology is that a program is examined over a broad range of parametric interactions based on a variety of output types, minimizing the possibility of concealing problems by compensating errors. Performance of the tests resulted in quality improvements, or identification of potential improvements, to all but one of the building energy simulation models used in the field trials. Some of the bugs that were found may well have been present for many years. The fact that they have just recently been uncovered shows the power of BESTEST and suggests the importance of continuing to develop formalized validation and diagnostic methods.

Recommendations / Test Cases for Future Work

For future work, we recommend developing an airside HVAC comparative test suite with annual hourly varying weather data, analogous to the HVAC BESTEST Volume 2 (Neymark and Judkoff 2004) working-fluid-side test suite. In addition to providing a robust range of realistic weather dynamics, applying one or more climates with hot humid summers and/or cold winters, this would allow scaling of disagreements among computer programs with respect to annual and peak energy use and cost. Further recommendations include replacing idealizations appropriate for the current QASs with more realistic specifications applicable to software-to-software comparative tests.

Acknowledgements

Gren Yuill and Jeff Haberl, authors of RP 865, graciously provided additional supporting material from the original research and valuable comments relating to quasi-analytical solution development and the original test specification.

The project participants who provided the majority of early simulation-trial work, preliminary sensitivity tests, feedback on the test specification, and modeller reports are listed as co-authors. We also gratefully acknowledge the contributions from modellers and authors of sections on additional computer programs that joined later on in this effort, including:

- Gordon Aird and Timothy Moore, Integrated Environmental Systems, United Kingdom: IES-VE
- Kentaro Kimura, Takasago Thermal Engineering Co., Ltd, Japan: LCEM
- Harunori Yoshida, Okayama University of Science, Japan: LCEM

The following simulation program author addressed program improvements during the simulation trials and provided other valuable commentary:

- Jeff Hirsch, James J. Hirsch & Associates, United States: DOE-2.2.

The following participants at the beginning of the project provided preliminary simulations and early valuable feedback on the test cases:

- Clemens Felsmann, Dresden University of Technology
- Kamel Haddad, Natural Resources Canada.

We appreciate the support and guidance of Amir Roth, U.S. Department of Energy (DOE) program manager.

We are also grateful for the ASHRAE organizational framework that facilitated this project.

This conference paper was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

Nomenclature

ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BESTEST	Building Energy Simulation Test and Diagnostic Method
CV	constant volume system
DB	dry-bulb temperature
Eco	economizer
Econo	economizer
Enth.	enthalpy
FC	fan coil system
HVAC	heating, ventilating, and air conditioning
IDB	indoor (zone) dry-bulb temperature
IEA	International Energy Agency
NREL	National Renewable Energy Laboratory
Num.	number
ODB	outdoor dry-bulb temperature
ODP	outdoor dew-point temperature
OWB	outdoor wet-bulb temperature
QAS	quasi-analytical solution
RESNET	Residential Energy Services Network
SZ	single zone system
VAV	variable air volume system

See Table 1 for abbreviations used in legends of Figures 2 through 5.

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