# Integrated Comparative Validation Tests as an Aid for Building Simulation Tool Users and Developers

## ABSTRACT

*Published validation tests developed within major research projects have been an invaluable aid to program developers to check on their programs. This paper sets out how selected ASHRAE Standard 140-2004 and European CEN Standards validation tests have been incorporated into the ESP-r simulation program so that they can be easily run by users, and discusses some of the issues associated with compliance checking. Embedding the tests within a simulation program allows program developers to check routinely whether updates to the simulation program have led to significant changes in predictions and to run sensitivity tests to check on the impact of alternative algorithms. Importantly, it also allows other users to undertake the tests to check that their installation is correct and to give them, and their clients, confidence in results. This paper also argues that validation tests should characterize some of the significant heat transfer processes (particularly internal surface convection) in a greater level of detail in order to reduce the acceptance bands for program predictions. This approach is preferred to one in which validation tests are overly prescriptive (e.g. specifying fixed internal convection coefficients) as these do not reflect how programs are used in practice.*

## INTRODUCTION

Validation has been a part of program development from the beginning of the development of thermal simulation programs and thus there is a long history of its application. Through experience, a consensus has been reached on the various elements of the validation process (for example, Judkoff et al 1983, Jensen 1993, and Bloomfield 1999). These comprise the following:

- Review of theory
- Code checking
- Analytical verification
- Inter-program comparison
- Empirical validation

The first two of these are necessary for any technical software development. To permit future developments and re-use, high quality comprehensive documentation of the theory and its implementation is an essential element for state-of-the-art programs which are too complex for individuals to develop. The advantages and disadvantages of the other three techniques are well understood, as is the fact that all techniques need to be applied on a regular basis during program development.

The ESP-r program (ESRU 2005) has been the subject of numerous validation studies over a period of almost three decades. A summary of all the main validation studies is given by Strachan et al (2005). They comprise studies included as part of European projects, within several IEA Annexes/Tasks, within national studies and as part of PhD theses. It was observed that the early exercises were mostly focussed on empirical validation as this is the most obvious method to test program validity. However, these early studies indicated the difficulties with experimental studies – the need for high levels of instrumentation, consideration of all heat and mass flow paths/processes, accurate control and minimisation of uncertainty. Following this, a more balanced view was taken which emphasised the complementary nature of the various validation techniques.

Of particular note are the following three projects:

**IEA Annex 21/Task 12 Co-operative Project.** This comprehensive study (Judkoff and Neymark 1995, Lomas et al 1994) was concerned with analytical verification (testing for steady state and dynamic conduction, the incidence of direct solar radiation on external surfaces of arbitrary orientation, and the transmission of direct radiation through simple glazing systems), inter-program comparisons (development of BESTEST, focussed on passive solar spaces involving a diagnostic method – this was based on incremental changes to a base case model with comparisons between predictions from a number of detailed public domain programs) and empirical validation based on data from test rooms (using detailed monitored data from two small outdoor test cells). The work extended from 1988 to 1993 and involved many person-years of effort: for example, predictions from 17 programs were included in the empirical validation exercise.

**PASSYS.** This European project was concerned with the establishment of outdoor test cells. Part of the work was conducted by a model validation group (Jensen 1993), who undertook detailed analysis of the ESP-r program including a review of algorithms, inter-program comparison, analytical verification and sensitivity studies. A number of detailed empirical validation studies were also conducted. Again, this was a large project, extending from 1986 to 1993 and involving a number of research groups throughout Europe.

**IEA Annex 43/Task 34 Co-operative Project.** This project, started in 2004, intends to extend the work of IEA Annex 21/Task 12. It will focus on more complex tests involving, amongst others, multi-zone heat and mass transfer, double facades and the interactions between shading, lighting and loads. Teams from countries in Europe, North America and Japan are involved.

Although only a few of the larger studies are highlighted above, it is clear that significant resources are required to undertake thorough validation. And in spite of such multi-year, multi-team projects, there are numerous areas of program functionality that have not yet been fully tested.

A key observation from this large range of studies is that the validation tests are not persistent. By this it is meant that, although the program may have achieved reasonable agreement with measured data in empirical studies, or other programs in comparative studies, there is no certainty that this level of agreement is achieved several years later. For example, the original ranges obtained in the IEA Annex 21/Task 12 BESTEST qualification tests which have been adopted in ASHRAE Standard 140 (ANSI/ASHRAE 2004) were all obtained from simulations run with a number of programs about 12 years ago. There have been innumerable program developments and bug fixes in the intervening period, and as shown in a later section in this paper, program predictions have changed. This is the underlying reason why it is considered necessary to embed the tests and regularly monitor them to check if there have been significant changes in predictions. There is also a clear need for regular review of published ranges.

Embedding the tests to enable their easy application, particularly those tests in approved Standards, is also of benefit to program users concerned with validation and accreditation. Program developers are often asked by those who directly use the simulation program or those who commission simulation-based design appraisals regarding the confidence that can be placed in results and whether the program has been validated. Including the tests with the program allows users to check compliance with Standards for themselves, as well as confirming that the program has been properly installed. It is becoming increasingly important that programs are shown to comply with national and international Standards, and embedding the tests in the simulation program allows the check to be made easily by users, and possibly, in the future, by those in charge of program accreditation.

This paper sets out the facility developed within ESP-r and discusses the ASHRAE and CEN validation tests that have been incorporated into the structure. Results from the ASHRAE fabric and envelope tests and the CEN summer overheating tests are presented, highlighting some modelling issues. Two sensitivity studies are then described, involving changing the solar algorithm and the internal convection algorithm, to demonstrate how the embedded tests can be used to investigate the impact of code changes and to show how significant these choices are. Finally, conclusions are drawn and recommendations made for future work.

## FRAMEWORK FOR EMBEDDED VALIDATION

Ben-Nakhi and Aasem (2002) developed a set of solutions for dynamic heat transfer through opaque multi-layer constructions involving a step change in internal or external temperatures. Constructional thermophysical properties can be defined by the user, together with the inside and outside boundary conditions (given as either surface temperatures or air temperatures, or as adiabatic). Initial conditions, simulation period and simulation timesteps can be specified. Predictions from a thermal simulation program can be compared to the analytical solution.

What was novel about the work was that it was implemented within a simulation program (ESP-r). After the user specifies the input data listed above, a thermal zone is automatically created, a simulation performed and results extracted for comparison with the analytical solution. It is therefore straightforward to undertake the tests at regular intervals during program development, or to check on numerical accuracy and stability for any particular construction. Ben-Nakhi and Aasem set out the structure for embedding other validation checks and it is this structure which has been extended in the work reported here.

A significant recent development in energy simulation has been the inclusion of validation tests within standards, reflecting the increasing move towards performance-based standards instead of prescriptive standards. Of note are the adoption of the BESTEST comparative tests within ASHRAE Standard 140, mentioned in the previous section, and the inclusion of validation tests in proposed CEN European Standards (at present, those concerned with summer overheating and cooling load calculations). There are some differences in approach between the ASHRAE and CEN Standards. The ASHRAE Standard 140 is less prescriptive in specifying simulation parameters. The specified ranges of predictions for particular tests are sometimes large, reflecting the different assumptions and algorithms used by the various programs involved in the range setting. On the other hand, the CEN Standards are more prescriptive, for example by specifying the surface coefficients that should be used, and for this reason narrower tolerance bands are specified.

To demonstrate the usefulness of embedding validation tests, comparative tests from the ASHRAE Standard 140 that focus on the building thermal envelope and fabric loads, and from the CEN Standard 13791 (CEN 2004) that focus on summer overheating risk, have been included in the ESP-r program. It was intended that they were implemented so that they can be easily run by program developers and users.

## ASHRAE Standard 140 Building Thermal Envelope and Fabric Load Tests

The ASHRAE tests are grouped into high mass and low mass cases, and classed as either basic sensitivity tests or in-depth sensitivity tests. The tests are designed so that it is primarily the differences between pairs of tests that are of interest: for example, the difference in prediction between two models which are identical apart from a change in the external surface absorptivity. There is also a group with four free float tests and one test which has a second free float zone. Results are also presented in the Standard from all the individual models.

The basic sensitivity tests analyse the ability of software to model building envelope loads by varying the window orientation, shading devices, set-back thermostat and night ventilation. The in-depth sensitivity tests 195 through 320 analyse the ability of software to model building envelope loads for a non-deadband on/off thermostat control configuration with the following variations among the cases: no windows, opaque windows, exterior infra-red emittance, infiltration, internal gains, exterior shortwave absorptance, south solar gains, interior shortwave absorptance, window orientation, shading devices, and thermostat setpoints. In-depth cases 395 through 440, 800 and 810 analyse the ability of software to model building envelope loads in a deadband thermostat control configuration with the following variations: no windows, opaque windows, infiltration, internal gains, exterior shortwave absorptance, south solar gains, interior shortwave absorptance, and thermal mass.

Using ESP-r, the user can access the tests where they have the choice to run a specific group of tests, run individual tests or run all the tests. After selecting the models to be run, simulation is automatically invoked with pre-defined parameters without the need for user intervention. For every simulation, results analysis is also automatically invoked and the specific results for every test are recovered and saved in a file. In order to know what kind of results need to be recovered for each case, a recovery data file which is provided with each of the models is read in.

Apart from the free float tests, for every case selected in the groups, the files with the recovered results are scanned and the differences in the peak and annual heating and cooling loads are extracted. The results can be displayed or sent to an external file.

In addition to the simulation results, the minimum and maximum limits listed in the ASHRAE Standard 140 informative annexes are displayed to the user. A check is made whether or not the recovered results are within the specified range and an "outside" or "inside" message is given to notify the user. (It is worth noting that ASHRAE Standard 140 is a standard method of test and not a pass/fail standard.) Another set of predictions is also displayed. This could be from the previous released version of the program, so that program developers can determine the impact of coding changes on these standard tests.

As the tests are designed to separately stress most of the fundamental heat transfer processes, this is a useful diagnostic tool. Alternatively, it is possible to display the ESP-r predictions originally obtained in the IEA Annex 21 project which are published in the ASHRAE Standard 140, so that the magnitude of changes over the last 12 years can be quantified. These are the values presented in this paper.

The same approach applies to the free float and the individual tests. For the free float tests, the files with the recovered results are scanned for the minimum and maximum temperatures together with the time of occurrence and the annual average temperature. For all the other individual tests, the results are scanned for the peak heating and cooling loads, their time of occurrence and also for the annual heating and cooling loads. Some tests require more specific data to be extracted (either annual or hourly for a specific date). This additional data requirement is also specified in the results recovery data files, so that it can be extracted and presented to the user.

Figure 1 sets out the overall structure of the implemented approach.

## CEN Standard 13791: Calculation of room temperatures in summer without mechanical cooling

The CEN (European Standards Organisation) is currently producing a series of standards on calculation methods for the design and the evaluation of the thermal performance of buildings and building components. In this area, proposed Standard 13791:2004 (CEN 2004) is at the formal vote stage, whereby its implementation is imminent. The process of certification in Europe is based on defining a standard method to solve the problem and a performance based approach to certification. This process allows developers to either adopt the standard equations and solution process for compliance, or using their own equations prove that they are within the acceptable range of the published data. In the case of CEN Standard 13791:2004 the recommended approach is that of solving the governing equations using an implicit finite difference approach.

The CEN standard tests are implemented in a similar manner to the ASHRAE tests described above. Within proposed Standard 13791, four areas of the simulation tool’s performance are examined in separate tests. These tests are:

1. Transient response in a solid opaque construction to a 10˚C change in external temperature. This test examines the transient conduction algorithm in isolation as all other aspects of the model are fixed (radiation and convection coefficients).
2. Internal long-wave radiation under steady state conditions, given boundary temperatures and a solar gain to a surface.
3. Solar shading to examine the ability of a program to calculate the degree of shading of direct solar radiation for six shading device configurations, over a period of several hours.
4. An overall whole model test to examine the combined modelling of solar, conduction and internal radiation modelling for two single zone geometries. There are no shading devices in these tests, but there are heat gains from casual sources and ventilation air flows.

The proposed CEN Standard 13791 is specific in its application – a single zone model without mechanical heating or cooling for a warm period. It does not apply to spaces where solar can pass through, or which are adjacent to a sunspace or atrium, for which a more robust model would be required. The tests examine the software's ability to model the main thermal flow paths in buildings where there is no mechanical system.

The proposed Standard is prescriptive in specifying many aspects of the heat transfer processes. In some cases, these differ from how the processes are modelled in existing simulation programs. In the case of ESP-r, differences in modelling approaches were found in the handling of solar distribution, convective heat transfer coefficients, boundary condition specification and room air thermal capacity. Thus changes needed to be made at source code level to conform with the requirements of the proposed Standard (for example, allowing a new adiabatic boundary condition with exactly the same specification as that in the Standard). This type of intervention can be done only by program developers or other experienced users. Also, some of the required outputs were not available directly from the results module (which is needed for automatic recovery of results without user intervention for embedded tests): it was necessary to undertake multiple simulations to get the required data.

The specific validation tests, described below in more detail with results obtained, have been placed in the same structure as described above for the ASHRAE Standard 140 fabric and envelope tests. Again there are tolerance bands given in the Standard against which predictions can be compared, and it is possible to detect whether there have been changes in prediction from a previous application of the tests.

## RESULTS FROM IMPLEMENTATION OF ASHRAE STANDARD 140

It is not intended to give a complete set of results in this paper due to space constraints, so just one typical example from each category is given in Table 1. The table shows the results obtained from using the new embedded models. Figure 2 is a screenshot to show how results are presented to the user, which can also be redirected to a file. The table shows the test number, the output parameter, the predicted result, the inside/outside range check against the range given in the informative annexes of the ASHRAE Standard, the range limits, and finally the results from the runs carried out in IEA Annex 21 by De Montfort University using ESP-r in 1993. The internal convection algorithm is known to cause significant uncertainty in predictions (see later section in this paper). Therefore, these runs were done with the same internal convection algorithm as used in the IEA Annex 21 BESTEST simulations. This enables an evaluation to be made of the impact of other program changes over the last 12 years.

In Table 1:

- 910-900 is a "High mass basic sensitivity test" which tests south overhang/mass interaction (the difference between models 910 and 900).
- 610-600 is a "Low mass basic sensitivity test" which tests the effect of a south overhang (the difference between models 610 and 600).
- 900-810 is a "High mass basic and in-depth sensitivity test" which tests interior solar absorptance and mass interaction (the difference between models 900 and 810).
- 270-220 is a "Low mass in-depth sensitivity test" which tests south solar transmittance/incidence solar radiation (the difference between models 270 and 200).
- 650FF is a "Free float test" which tests venting of a free floating room.
- 410 is an "Individual test" which tests infiltration.

**TABLE 1**
**Results from selected ASHRAE 140 fabric and envelope tests**

| Test | Category | ESP-r (2005) | CHECK | Min Range | Max Range | ESP-r (1993) |
|---|---|---|---|---|---|---|
| 910-900 | Peak Heating Load (kW) | 0.010 | inside | 0.003 | 0.019 | 0.008 |
| 910-900 | Peak Cooling Load (kW) | -0.590 | inside | -1.122 | -0.310 | -0.992 |
| 910-900 | Annual Heating Load (kWh) | 207 | inside | 179 | 442 | 405 |
| 910-900 | Annual Cooling Load (kWh) | -1142 | inside | -1561 | -832 | -1311 |
| 610-600 | Peak Heating Load (kW) | 0.000 | inside | -0.011 | 0.001 | 0.000 |
| 610-600 | Peak Cooling Load (kW) | -0.590 | inside | -0.811 | -0.116 | -0.525 |
| 610-600 | Annual Heating Load (kWh) | 33 | inside | 21 | 98 | 59 |
| 610-600 | Annual Cooling Load (kWh) | -1702 | inside | -2227 | -1272 | -2222 |
| 900-810 | Peak Heating Load (kW) | -0.130 | inside | -0.166 | -0.089 | -0.129 |
| 900-810 | Peak Cooling Load (kW) | 1.060 | inside | 0.595 | 1.223 | 1.036 |
| 900-810 | Annual Heating Load (kWh) | -658 | outside | -1107 | -669 | -669 |
| 900-810 | Annual Cooling Load (kWh) | 1209 | inside | 975 | 1707 | 1080 |
| 270-220 | Peak Heating Load (kW) | -0.010 | inside | -0.034 | 0.218 | -0.004 |
| 270-220 | Peak Cooling Load (kW) | 5.870 | inside | 5.475 | 5.894 | 5.796 |
| 270-220 | Annual Heating Load (kWh) | -2418 | inside | -2761 | -1948 | -2434 |
| 270-220 | Annual Cooling Load (kWh) | 7951 | inside | 7342 | 9515 | 7342 |
| 650FF | Annual Hourly Max Temp (˚C) | 66.4 | inside | 63.2 | 68.2 | 63.2 |
| 650FF | Annual Hourly Min Temp (˚C) | -23.0 | inside | -23.0 | -21.6 | -22.6 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 650FF | Annual Hourly Aver Temp (˚C) | 18.9 | inside | 18.0 | 19.6 | 18.2 |
| 410 | Peak Heating Load (kW) | 3.880 | inside | 3.625 | 4.487 | 3.625 |
| 410 | Peak Cooling Load (kW) | 0.310 | inside | 0.035 | 0.814 | 0.035 |
| 410 | Annual Heating Load (kWh) | 8620 | inside | 8596 | 10506 | 8596 |
| 410 | Annual Cooling Load (kWh) | 11 | inside | 0 | 84 | 0 |

The following points were noticed in the results obtained.

a) There are, in some cases, significant differences in the current results from predictions obtained in the IEA Annex 21 work and those from the current version of ESP-r. There have been many code developments and bug fixes in the intervening years. Of particular note are updates in the solar algorithms (e.g. updates to some of the solar equations, including a change of algorithm for the anisotropic diffuse sky to use of the Perez (1990) model). This is investigated in a later Section of this paper.

b) There is now an occasional “outside” recorded, with one example given in Table 1. In some cases in the range setting in the IEA Annex 21 work, ESP-r predictions formed either the lower or higher limits of the identified range. Due to changes in the code, sometimes the predictions have changed to be outside the specified range. It is usually by a small amount, but nevertheless, may be of interest because it indicates that there may be a greater degree of variability between programs for this test than currently indicated in the informative annex to the ASHRAE Standard 140. It also underlines the need for the regular updating of the informative annex.

## RESULTS FROM IMPLEMENTATION OF CEN STANDARD 13791

Tables 2 to 6 show how simulation results for prediction of air temperatures, sunlit factors and operative temperatures compare against the test limits in the forthcoming Standard.

**TABLE 2**
**Results of CEN13791 conduction tests (air temperatures, ˚C)**

| Time (hrs) | Test 1 | | | Test 2 | | | Test 3 | | | Test 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r |
| 2 | 19.56 | 20.56 | 20.04 | 24.59 | 25.59 | 24.67 | 19.50 | 20.50 | 20.00 | 19.50 | 20.50 | 19.98 |
| 6 | 20.76 | 21.76 | 21.29 | 29.13 | 30.13 | 29.50 | 19.76 | 20.76 | 20.25 | 19.56 | 20.56 | 20.04 |
| 12 | 22.98 | 23.98 | 23.46 | 29.50 | 30.50 | 29.98 | 21.17 | 22.17 | 21.64 | 19.75 | 20.75 | 20.23 |
| 24 | 25.87 | 26.87 | 26.36 | 29.50 | 30.50 | 30.00 | 24.40 | 25.40 | 24.85 | 20.13 | 21.13 | 20.61 |
| 120 | 29.50 | 30.50 | 29.96 | 29.50 | 30.50 | 30.00 | 29.45 | 30.45 | 29.94 | 22.67 | 23.67 | 23.15 |

Table 2 shows a comparison between predictions and Standard 13791 results for the opaque conduction test. The test comprises four separate constructions subjected to a 10˚C change in external temperature. For each test the lower and upper acceptable air temperatures are given for the required times after the step change in external temperature. To implement the test no source code changes were necessary and the convective heat transfer coefficients had to be specified (overriding the system default). As can be seen, predictions lie within the limits prescribed for this test.

**TABLE 3**
**Results of CEN13791 internal long-wave radiation tests (air temperatures, ˚C)**

| | Test 1 | | | Test 2 | | | Test 3 | | | Test 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r |
| Result | 33.9 | 34.9 | 34.4 | 29.9 | 30.9 | 30.4 | 38.0 | 39.0 | 38.6 | 25.0 | 26.0 | 25.7 |

Table 3 shows the internal air temperature in each of the four zone configurations for the long-wave radiation test. Again, no source code modifications were necessary and for these tests only the convection coefficients were changed from the default approach adopted by ESP-r, with the solar gain to the single surface modelled as a controlled flux to that surface (it is not possible to have a solar gain in a zone comprising only opaque surfaces). As can be seen, predictions are within the required limits for this long-wave radiation test.

### TABLE 4
### Results of CEN13791 direct solar shading tests (sunlit factor, -)

| Time (hrs) | Test 1 | | | Test 2 | | | Test 3 | | | Test 4 | | | Test 5 | | | Test 6 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r |
| 7 | 0.00 | 0.05 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.05 | 0.00 | 0.00 | 0.05 | 0.00 | 0.95 | 1.00 | 1.00 | 0.00 | 0.05 | 0.00 |
| 8 | 0.48 | 0.58 | 0.50 | 0.42 | 0.52 | 0.49 | 0.00 | 0.05 | 0.00 | 0.95 | 1.00 | 1.00 | 0.84 | 0.94 | 0.87 | 0.00 | 0.05 | 0.00 |
| 9 | 0.19 | 0.29 | 0.23 | 0.71 | 0.81 | 0.77 | 0.00 | 0.50 | 0.00 | 0.95 | 1.00 | 1.00 | 0.66 | 0.76 | 0.73 | 0.02 | 0.12 | 0.07 |
| 10 | 0.16 | 0.26 | 0.21 | 0.92 | 1.00 | 0.98 | 0.13 | 0.23 | 0.19 | 0.95 | 1.00 | 1.00 | 0.34 | 0.44 | 0.40 | 0.67 | 0.77 | 0.73 |
| 11 | 0.25 | 0.35 | 0.30 | 0.95 | 1.00 | 1.00 | 0.25 | 0.35 | 0.33 | 0.85 | 0.95 | 0.87 | 0.00 | 0.05 | 0.03 | 0.95 | 1.00 | 1.00 |
| 12 | 0.28 | 0.38 | 0.35 | 0.95 | 1.00 | 1.00 | 0.28 | 0.38 | 0.33 | 0.79 | 0.89 | 0.80 | 0.00 | 0.05 | 0.00 | 0.95 | 1.00 | 1.00 |

Table 4 shows the sunlit factor for the test surface for each of the six configurations of shading device. The test specifies the solar location for each of the calculation times. It is not possible to explicitly set the solar position in ESP-r (it is a function of the site location and time). It was discovered by an iterative approach that the site location was 52˚N and 0.5˚W of the local time meridian for the 15th of June (the latitude and date were set in an earlier draft of the standard). The result for test 6 at 12 noon requires the solar shading to be calculated for a solar azimuth of 180˚ (due south) – this is parallel to the east-facing test surface, so it could be argued that the surface is neither in shade nor direct sunlight (although the test assumes that this is fully sunlit). As can be seen, the results are within the published ranges and thus comply with the solar shading test.

### TABLE 5
### Results of CEN13791 whole model tests for geometry A (operative temperature, ˚C)

| Test | Maximum operative temperature | | | Average operative temperature | | | Minimum operative temperature | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r |
| A1.a | 38.2 | 39.2 | 38.6 | 35.4 | 36.4 | 35.6 | 33.1 | 34.1 | 33.3 |
| A1.b | 33.6 | 34.6 | 34.2 | 28.9 | 29.9 | 29.5 | 25.0 | 26.0 | 25.7 |
| A1.c | 33.0 | 34.0 | 33.6 | 28.5 | 29.5 | 29.2 | 24.9 | 25.9 | 25.6 |
| A2.a | 37.1 | 38.1 | 37.6 | 35.4 | 36.4 | 35.9 | 33.9 | 34.9 | 34.4 |
| A2.b | 31.7 | 32.7 | 32.0 | 29.0 | 30.0 | 29.4 | 26.0 | 27.0 | 26.6 |
| A2.c | 31.9 | 32.9 | 32.4 | 28.6 | 29.6 | 29.3 | 25.9 | 26.9 | 26.6 |
| A3.a | 40.3 | 41.3 | 41.0 | 38.2 | 39.2 | 39.0 | 36.6 | 37.6 | 37.4 |
| A3.b | 34.9 | 35.9 | 35.6 | 31.1 | 32.1 | 31.9 | 27.5 | 28.5 | 28.4 |
| A3.c | 33.3 | 34.3 | 34.0 | 29.8 | 30.8 | 30.6 | 26.9 | 27.9 | 27.8 |

## TABLE 6

## Results of CEN13791 whole model tests for geometry B (operative temperature, ˚C)

| Test | Maximum operative temperature | | | Average operative temperature | | | Minimum operative temperature | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | High | ESP-r | Low | High | ESP-r | Low | High | ESP-r |
| B1.a | 35.4 | 36.4 | 35.9 | 30.0 | 31.0 | 30.8 | 26.7 | 27.7 | 27.3 |
| B1.b | 29.4 | 30.4 | 30.2 | *20.8* | *21.8* | *22.4* | 15.9 | 16.9 | 16.7 |
| B1.c | 27.6 | 28.6 | 28.4 | 21.0 | 22.0 | 21.8 | 15.7 | 16.7 | 16.5 |
| B2.a | 33.2 | 34.2 | 33.6 | 30.3 | 31.3 | 30.8 | 28.0 | 29.0 | 28.7 |
| B2.b | 26.2 | 27.2 | 26.5 | 21.7 | 22.7 | 22.2 | 17.4 | 18.4 | 18.2 |
| B2.c | 25.9 | 26.9 | 26.4 | 21.2 | 22.2 | 21.8 | 17.2 | 18.2 | 18.1 |
| B3.a | 35.5 | 36.5 | 36.3 | 32.2 | 33.2 | 33.2 | *29.8* | *30.8* | *30.9* |
| B3.b | 29.1 | 30.1 | 30.0 | 23.7 | 24.7 | 24.7 | *18.7* | *19.7* | *19.9* |
| B3.c | 27.2 | 28.2 | 28.0 | 22.2 | 23.2 | 23.2 | *18.1* | *19.1* | *19.2* |

The final set of tests requires a single zone model to be created and simulated for two geometries, three configurations of construction/boundary conditions and three ventilation schedules. In the "Test" column of Tables 5 and 6, the upper case character refers to the geometry (where A has a small window and B a large window), the number to the construction/boundary conditions and the lower case character to the ventilation schedule. Some modifications were needed to ESP-r source code and the input data, including:

1. A new boundary type was included to match the CEN definition of an adiabatic boundary – one which has equal solar gains on both sides.
2. External heat transfer coefficients were updated to account for radiation to the external air temperature (discussed below).

As can be seen all possible combinations are tested and predictions lie within the prescribed limits in all but four cases (shown in italics). This is probably due to several ambiguous definitions in the test specification:

1. External long-wave radiation should be considered in respect of exchanges with the sky and ambient air. The proposed Standard does not impose an algorithm for calculating sky temperature and the test does not specify the view factor of the sky.
2. Hourly-averaged solar radiation is provided for both horizontal and vertical surfaces, but the test does not state whether the averages are centred on the hour or half-hour.
3. There are numerous assumptions that are not physically realistic (e.g. time invariant solar distribution factors, a solar-to-air factor, no solar radiation lost from the zone although the internal surface absorptivity is only 0.6). It is therefore necessary to create models that are as close to possible to the intended situation, but in principle it is possible for a detailed simulation program to fail the tests because it is modelling the reality more accurately than required by the Standard.

Overall, the ambiguities will affect the predictions made for geometry B more than for geometry A as the window is twice the area in B compared to A; also the definition for the ceiling in construction type 3 is a roof connected to an unspecified boundary (ambient conditions were assumed).

There are two approaches to resolving some of the issues highlighted in the above discussion: either increase the acceptable temperature ranges, or improve the specification of the test. Both approaches have difficulties. In the former case, models with genuine mistakes could pass the tests and in the latter case it may make it more difficult to coerce simulation codes to conform with the requirements.

## RESULTS FROM IMPLEMENTATION OF OTHER BENCHMARKS

It is not possible for all aspects of simulation tool functionality to be covered by internationally agreed standards due to the time taken to reach agreement compared to the time taken to develop new functionality within simulation software. For this reason, a set of models aimed at testing ESP-r's full functionality is being developed. The tests are implemented in the same structure as described above, but can be used to check performance between versions of the system. The onus is on individual researchers to add models which test their developments, thus ensuring that a benchmark is created for their development.

Initially the available exemplar models were selected as the minimum set of models for comparison purposes. Furthermore a full set of performance indicators was used for each simulation. This enables the checking of parameters not included in current tests within Standards (e.g. prediction of relative humidity, advection loads between zones and flow patterns from CFD simulations). The possibilities in these tests are only limited by tool functionality. However, it must be remembered that the tests are for use as an inter-version check and no guarantee is made as to the validity of specific outputs, only their consistency.

It is intended to put these tests in the same structure as described for the ASHRAE and CEN tests described above, to allow developers to routinely check the effect of program changes. It is anticipated that the model types within this section will evolve over time. Some will be removed due to the creation of accepted Standards in that area – e.g. expanded ASHRAE 140 tests and new CEN standards. Table 7 shows a subset of these benchmark models currently run after each program update.

**TABLE 7**
**Example inter-version models and outputs**

| Model description | Solvers tested | Simulation period and time step | Example outputs |
|---|---|---|---|
| 3 zones, no control | Thermal | Summer, 60 minute | Zone dry bulb and radiant temperature statistics (max, min, mean, standard deviation), infiltration and ventilation loads. |
| | | Winter, 60 minute | |
| 3 zones, convective heater/ chiller | Thermal | Summer, 60 minute | Heating and cooling loads, relative humidity, zone energy balances. |
| | | Summer, 30 minute | |
| | | Winter, 60 minute | |
| | | Winter, 30 minute | |
| | | Summer, 60 minute | Repeat runs with extra results recovery e.g. surface energy balances. |
| | | Winter, 60 minute | |
| 3 zones, natural ventilation | Thermal and bulk air flow | Summer, 60 minute | Zone dry bulb and radiant temperature statistics (max, min, mean, standard deviation), infiltration and ventilation loads, solar and casual gains |
| | | Summer, 10 minute | |
| | | Winter, 60 minute | |
| | | Winter, 10 minute | |
| 3 zones, solar shading | Thermal and shading. | Winter, 60 minute | Zone dry bulb and radiant temperature statistics (max, min, mean, standard deviation), infiltration and ventilation loads, solar and casual gains |
| | | Summer, 60 minute | |

## SENSITIVITY STUDY – ANISOTROPIC DIFFUSE SKY MODELS

One benefit from including the tests so that they are easily available in the program is that it enables program developers to rapidly check alternative algorithms and to check whether a change to the program has resulted in significant changes to predictions. In both cases, it is possible to use diagnostic tests to check the impact on specific program areas for which the diagnostic tests are designed or on the impact with respect to Standards compliance. The fact that a large number of tests are involved increases the chances of detecting the impact of a change.

To demonstrate the use of the new facility, a study was undertaken of alternative anisotropic diffuse sky models. There have been numerous studies of such models but there is no definitive answer at present as to which is the most appropriate model to use. A good review of the current state of the art is given by Muneer (1997).

It was decided to run alternative algorithms for two cases:

1. Using low-level diagnostic cases focussing on accentuating the differences in solar algorithms. The low mass in-depth sensitivity test case 250-220 was chosen as it involved altering the external surface absorptance in the test building from 0.1 to 0.9, with no other changes.
2. Using Case 960 - a more realistic case with a sunspace – two zones (back zone and sun zone) separated by a common wall. The back zone is of lightweight construction and the sun room of heavyweight construction.

Running the tests was straightforward. ESP-r was sequentially configured with the alternative algorithms enabled. The identified test cases were selected and the automated simulation and results recovery initiated. The algorithms invoked in this test were Perez (1990), Perez (1987), Klucher (1979) and an isotropic model.

Tables 8 and 9 set out the results directly obtained from the program for the two cases selected. The ranges quoted are given in informative annex to the ASHRAE 140 Standard based on the results from programs in the original BESTEST simulations published in 1995. The column headed “CHECK” shows whether the current results (for the Perez 1990 model) are inside or outside the corresponding range. The values given as “reference values” are those obtained by ESP-r in the original IEA Annex 21 BESTEST study and also published in the ASHRAE Standard 140 annex. All the ranges and reference values are stored in a file, together with the model, so they can be easily updated should new ranges be obtained. Of more practical use, the reference values can be updated with the results obtained in the previous program release, so that it is easy to detect whether predictions have changed.

**TABLE 8**
**Case 250-220 low mass in-depth sensitivity test**

| Output parameter | Simulation result | | | | CHECK (against Perez 1990) | Min (Range) | Max (Range) | Reference value |
|---|---|---|---|---|---|---|---|---|
| | Perez 1990 | Perez 1987 | Klucher 1979 | Isotropic | | | | |
| Peak Heating Load (kW) | 0.000 | 0.000 | 0.000 | 0.000 | inside | -0.007 | 0.005 | -0.001 |
| Peak Cooling Load (kW) | 2.720 | 2.780 | 2.560 | 2.570 | inside | 1.043 | 3.699 | 2.800 |
| Annual Heating Load (kWh) | -2113 | -2120 | -2085 | -2081 | inside | -2193 | -1448 | -2193 |
| Annual Cooling Load (kWh) | 3195 | 3287 | 3024 | 3026 | outside | 1752 | 3027 | 3027 |

**TABLE 9**
**Case 960 high mass basic test**

| Output parameter | Simulation result | | | | CHECK (against Perez 1990) | Min (Range) | Max (Range) | Reference value |
|---|---|---|---|---|---|---|---|---|
| | Perez 1990 | Perez 1987 | Klucher 1979 | Isotropic | | | | |
| Peak Heating Load (kW) | 2.540 | 2.530 | 2.560 | 2.570 | inside | 2.410 | 2.863 | 2.410 |
| Peak Cooling Load | 1.140 | 1.170 | 1.120 | 1.130 | inside | 0.950 | 1.403 | 0.953 |

| Output parameter | Simulation result | | | | CHECK (against Perez 1990) | Min (Range) | Max (Range) | Reference value |
|---|---|---|---|---|---|---|---|---|
| (kW) | | | | | | | | |
| Annual Heating Load (kWh) | 2304 | 2265 | 2459 | 2483 | outside | 2311 | 3373 | 2311 |
| Annual Cooling Load (kWh) | 700 | 741 | 654 | 667 | inside | 411 | 803 | 488 |
| Annual Hourly Max Temperature (˚C) | 50.8 | 51.0 | 49.4 | 49.0 | inside | 48.9 | 55.3 | 48.9 |
| Annual Hourly Min Temperature (˚C) | 2.0 | 2.0 | 1.6 | 1.5 | inside | -2.8 | 3.9 | 2.7 |
| Annual Hourly Average Temperature (˚C) | 28.7 | 29.0 | 27.9 | 27.9 | inside | 26.4 | 29.0 | 27.5 |

There are two cases where the predictions fall just outside the indicative ranges when the Perez 1990 model is used. These are cases where ESP-r was used to set the suggested limits based on simulations undertaken in the Annex 21 work, and where subsequent changes to the code have pushed predictions outside the limits. Although there are differences in predictions caused by the choice of solar model, they are generally small compared to the range given in ASHRAE Standard 140. In these simulations, the internal convection coefficients were chosen to be the same as in the original Annex 21 study. As will be shown in the following section, this may not be appropriate.

## SENSITIVITY STUDY - INTERNAL CONVECTION

This section examines the sensitivity of the heating loads predicted for BESTEST case 600 upon the modelling of internal surface convection.

### Modelling Internal Surface Convection

The convective heat exchange between internal building surfaces (walls, windows, etc.) and indoor air significantly affects a room's energy balance. For example, this mechanism determines the timing and degree to which solar gains absorbed by internal surfaces warm the room air. The common approach for modelling this heat flow path within dynamic whole-building simulation programs is to employ the so-called *well-stirred* assumption (refer to Figure 3). This treats the room air as uniform and characterizes surface convection heat transfer ($q''_{conv}$) by a convection coefficient ($h_c$) and by the temperature difference between the room air and the internal surface.

Numerous researchers have examined the sensitivity of simulation predictions to the modelling of internal convection (Waters 1990, Irving 1982, Bauman et al 1983, Alamdari et al 1984, Spitler et al 1991, Clarke 1991, Lomas 1996, Fisher and Pedersen 1997, Beausoleil-Morrison and Strachan 1999 and Beausoleil-Morrison 2001). They have demonstrated that predictions of energy demand and consumption can be strongly influenced by the choice (made by program developer or user) of $h_c$ algorithm. Energy prediction sensitivities in the order of 20-40% have been observed. More significantly, in some cases the predicted benefits from design measures were found to be sensitive to the approach used to model internal surface convection. Despite this, most simulation programs still employ simplified approaches.

Clearly more detailed calculation approaches are required for this significant heat transfer path. A flow responsive method to improve the modelling of internal surface convection was put forward by Beausoleil-Morrison (2002) and implemented into ESP-r. Known as the *adaptive convection algorithm* (ACA), it employs a series of automated appraisals and user prompts during the problem definition stage to appraise conditions in each room. Each internal surface is attributed with a set of $h_c$ equations appropriate for the flow conditions anticipated over the duration of the simulation. As the simulation progresses, a controller monitors critical simulation variables to assess the flow regime. Based upon this assessment, the controller dynamically assigns (for each surface) an appropriate $h_c$ algorithm from amongst the set attributed at the problem definition stage. At the basis of this flow responsive method is a scheme for broadly classifying the principle convective regimes encountered within buildings and a suite of 28 $h_c$ correlation equations.

## Sensitivity Analysis

Eight simulations were performed with the case 600 model to investigate the impact of internal surface convection modelling. ESP-r's default internal convection treatment was employed in the first simulation. With this, the Alamdari and Hammond (1983) $h_c$ correlations for buoyancy-driven flow are used for all surfaces and at all time-steps of the simulation (a common approach with simulation programs and the approach usually employed by ESP-r users). This resulted in an annual heating load of 4,387 kWh.

The BESTEST procedure allows the use of fixed convection coefficients (internal and external) for programs which do not calculate $h_c$. The results reported for the majority of the reference programs in BESTEST (and thus in the informative annexes of ASHRAE Standard 140) employed this technique. A second simulation was performed with these fixed values. This resulted in an annual heating load of 5,266 kWh, 20% greater than the first simulation. These two results are contrasted in Figure 4, which also plots the range of the results produced by the BESTEST reference programs. The sensitivity in the heating load predictions to this one change in the modelling of convection is seen to span fully 62% of the range of differences of all programs considered in BESTEST.

The Alamdari and Hammond $h_c$ correlations employed in the first simulation are applicable for purely buoyant flow, and only where buoyancy is caused by a temperature difference between a surface and the surrounding room air. They are not appropriate for cases where buoyancy is generated by a heating device, such as a radiator, or when the convective regime is generated by a forced-air device. The BESTEST specification indicates that heating and cooling is supplied by a convective system. Consequently, it is believed that the use of the Alamdari and Hammond correlations is not appropriate in this case and therefore alternate $h_c$ modelling methods are investigated here.

Khalifa (1989) conducted experiments in a room-sized test cell to produce correlations specific to internal convection within buildings. The test cell's configuration was varied and experiments repeated to assess a number of common convection regimes. Convective heat transfer at internal surfaces was not measured directly, but rather $h_c$ was derived from temperature and heat input measurements. It is important to note that radiant exchange was neglected in this derivation. As such, it is believed that Khalifa's results tend to overestimate $h_c$. Although there are insufficient data available to determine the degree of overestimation, the errors would be greatest in the cases with large temperature differences between surfaces (such as a hot radiator facing a cold window). Notwithstanding, Khalifa's work represents a significant contribution, as he provides $h_c$ data for room configurations not analyzed by others.

Khalifa's correlations for rooms heated with circulating fan heaters were employed in the third and fourth simulations. In the fourth simulation Khalifa's $h_c$ correlation for vertical surfaces which experience impinging flow from the convective heater were employed for all walls and the windows, whereas in the third simulation Khalifa's $h_c$ correlation for walls that do not experience impinging flow were employed. These two simulations resulted in annual heating loads that lie in between those of the first two simulations, being 4.4% and 11.3% greater than the first simulation.

These first four simulations employ non-adaptive convection calculations, in that the methods used to calculate $h_c$ do not vary on a time-step basis. The adaptive convection algorithm, described earlier, was invoked for the next three simulations reported in Figure 4. All internal surfaces were attributed with convection calculation control data for the case of rooms heated with convective heaters that circulate air within the room. With this approach the simulator toggles between $h_c$ calculation methods as the simulation progresses. When the simulator senses that the heater is operating it employs the appropriate Khalifa correlations. And when it senses that the heater is inoperative it switches to the Alamdari and Hammond correlations, assuming that the flow is then governed by buoyant forces generated by surface-air temperature differences. Three variants were assessed. In the fifth simulation, all vertical surfaces were attributed with the Khalifa correlation for impinging flow. In the sixth simulation it was assumed that only the south facing wall and the windows experienced impinging flow. And in the seventh simulation the east, north, and west walls received the impinging flow. As illustrated in Figure 4 there is a 3.5% range in the annual heating loads predictions between these three ACA simulations and a significant difference between these three and the first simulation.

Finally, the eighth simulation was performed with the ACA but in this case the surfaces were attributed with convection correlations appropriate for mixed buoyant and forced flow in which the HVAC system circulates heated or cooled air to the room. This resulted in an annual heating load prediction that was 17% greater than the first simulation.

Based upon the information provided in the BESTEST procedure it is impossible to conclude which of the ACA simulations most realistically models the convective regimes within the room. The procedure simply does not provide sufficient information to specify the convective regimes. As these results show, details such as which surfaces receive impinging flow from a convective heater or how cooling is achieved can have an influence that is significant in the context of a validation exercise. Given this, future validation efforts should either specify convective regimes in a level of detail that is commensurate with the modelling of other significant heat transfer processes, such as envelope transmission and solar gains, or convection coefficients should be fixed to prevent erroneous noise between reference program results.

## CONCLUSIONS

Validation models and tests can be time consuming to set up and as a consequence, programs are only irregularly checked. There is a clear need for regular checking of program outputs against a whole range of standard tests, and also for regular assessment of what are deemed to be acceptable ranges for predictions. This requirement will become more pressing as simulation-based standards are introduced. The work discussed in this paper shows how it is possible to embed these tests to make it easy for developers and user to apply them. The benefits are:

- Program developers can check the impact of code modifications, algorithmic substitution etc.
- Developers can check compliance with regulations.
- User confidence is improved.
- Users can confirm that their installation is correct and check Standards compliance themselves.
- It avoids the repetition of constructing the models set out in the validation tests and therefore it reduces the associated possibility of error. It is sometimes difficult to construct the models when unusual modelling assumptions are required.
- Frequent checking will confirm the fact that a program continues to be within the specified tolerance bands. This is important as most state-of-the-art programs are under constant development.

The question of what are acceptable ranges for predictions in comparative validation tests is difficult to answer. If the programs are allowed to model the various heat transfer processes with their own methods, then the indicative tolerance bands will be wide (as in the case of the ASHRAE Standard 140 fabric and envelope tests) and programs with errors could still fall within the specified bands. On the other hand, if the way in which the processes are modelled is prescribed in detail, then tolerance bands will be narrow. However, in this case, more detailed and accurate ways of modelling may give out-of-range predictions. A related question is, if a program is used with a simplified way of modelling the particular heat transfer process in order to fall within the tolerance bands, whether this means the program always has to be used in this mode in order to claim compliance with Standards.

It is believed the way forward is to develop guidance on the most appropriate way to model the important heat transfer processes. As shown in this paper, it is particularly important for the internal convective transfer process - validation tests should indicate the flow regime so appropriate algorithms can be selected, and research undertaken to identify appropriate correlations for situations where they are not currently available. In this way, it should be possible to reduce the acceptable bands for program predictions without being unnecessarily prescriptive. This will also reduce the likelihood of a simulation program being selected for design work based on the fact it typically predicts, say, lower cooling loads.

It is intended that other tests, in addition to those described in this paper, will be put within the same structure described in this paper. This will include further tests within ASHRAE and CEN Standards, together with other tests being developed within IEA projects.

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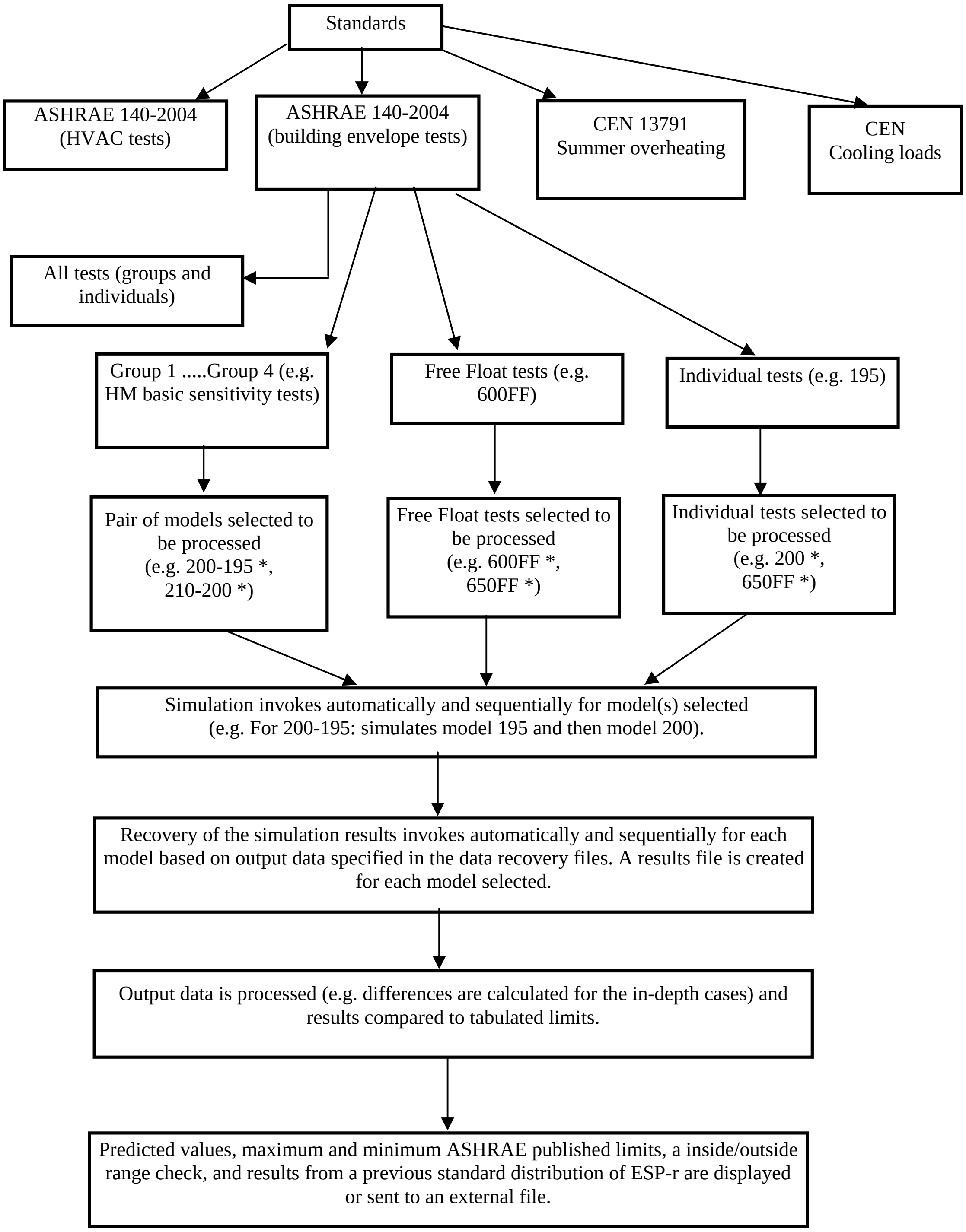
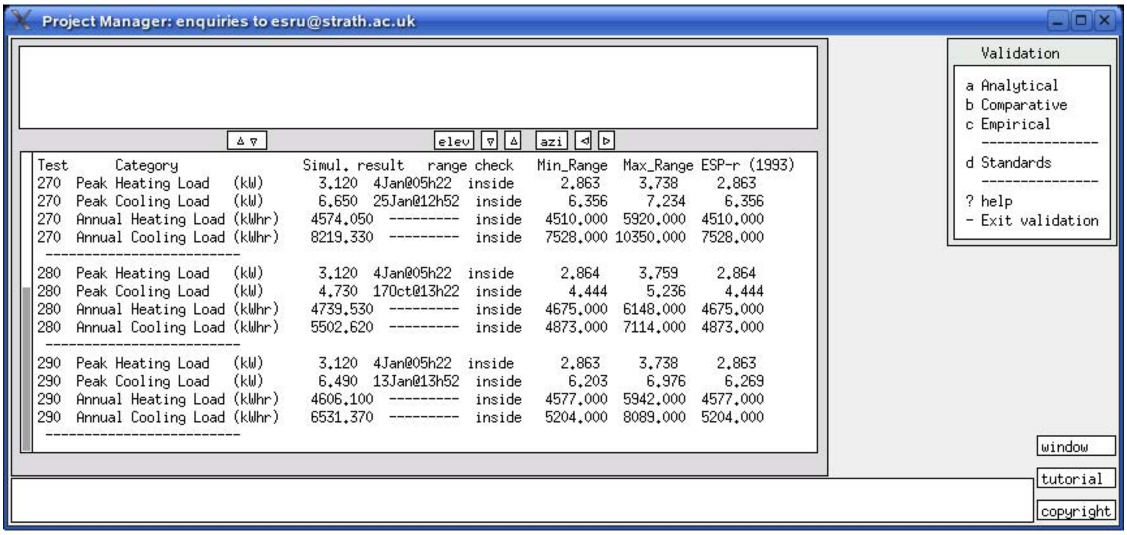


Figure 1: Implementation details



```
Test      Category               Simul. result   range check   Min_Range  Max_Range ESP-r (1993)
270  Peak Heating Load   (kW)       3.120  4Jan@05h22  inside      2.863      3.738     2.863
270  Peak Cooling Load   (kW)       6.650  25Jan@12h52  inside      6.356      7.234     6.356
270  Annual Heating Load (kWhr)   4574.050  ---------  inside   4510.000  5920.000  4510.000
270  Annual Cooling Load (kWhr)   8219.330  ---------  inside   7528.000 10350.000  7528.000
 -------------------------
280  Peak Heating Load   (kW)       3.120  4Jan@05h22  inside      2.864      3.759     2.864
280  Peak Cooling Load   (kW)       4.730  17Oct@13h22  inside      4.444      5.236     4.444
280  Annual Heating Load (kWhr)   4739.530  ---------  inside   4675.000  6148.000  4675.000
280  Annual Cooling Load (kWhr)   5502.620  ---------  inside   4873.000  7114.000  4873.000
 -------------------------
290  Peak Heating Load   (kW)       3.120  4Jan@05h22  inside      2.863      3.738     2.863
290  Peak Cooling Load   (kW)       6.490  13Jan@13h52  inside      6.203      6.976     6.269
290  Annual Heating Load (kWhr)   4606.100  ---------  inside   4577.000  5942.000  4577.000
290  Annual Cooling Load (kWhr)   6531.370  ---------  inside   5204.000  8089.000  5204.000
 -------------------------
```

Figure 2: Screenshot of validation test selection and results

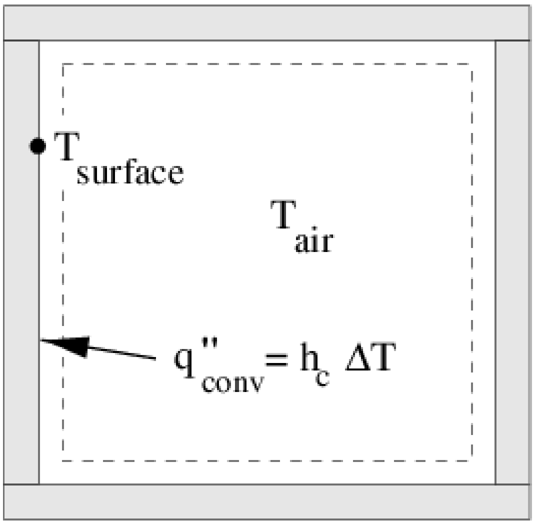


Figure 3: Well-stirred convection model

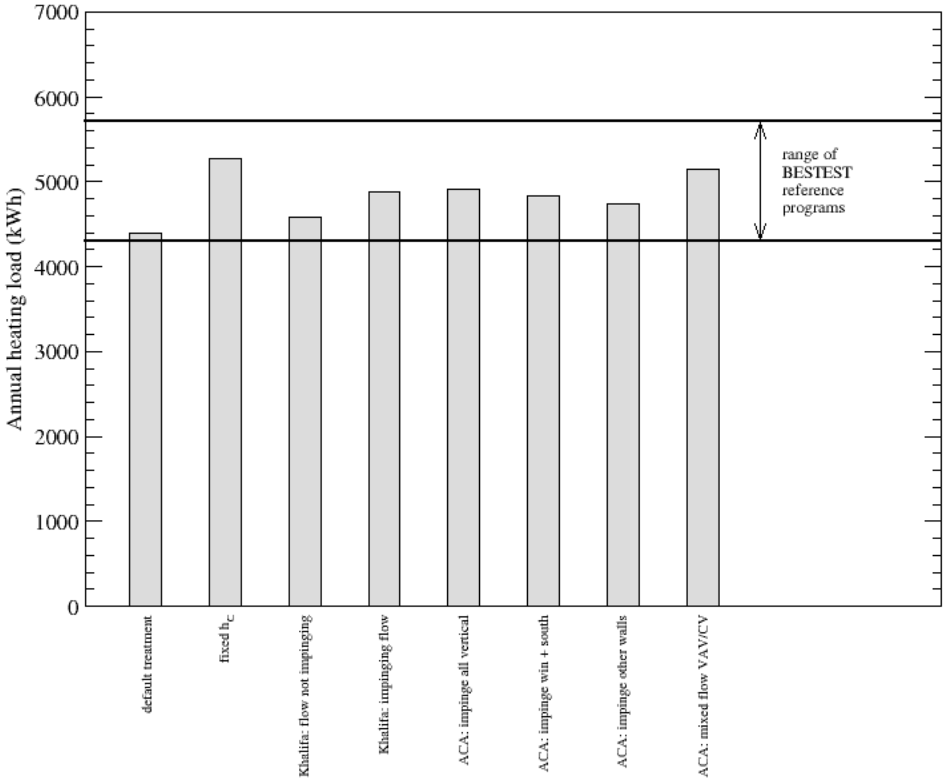


Figure 4: Sensitivity of case 600's annual heating load to internal convection modelling