Proc. CIBSE A: Building Serv. Eng. Res. Technol. **19**(2) 61–66 (1998) Printed in Great Britain B461

Review paper

Summary A literature review is presented on the validation of thermal and energy models up to 1994. Over 65 different studies are reported here. The existing validation methodologies are reviewed. The validation process began in the early 1970s. However, there was little distinct validation methodology or procedure. Only a few high-quality, well documented data sets are available. It is concluded that much work is needed on detailed data collection, as in most of studies reported here, such data were not available. Many values had to be assumed, resulting in uncertainties in the reported comparisons.

Validation of building thermal and energy models

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Received 18 August 1997, in final form 11 November 1997

1 Introduction

The development of computer programs for building energy analysis began in the 1960s[1,2]. Early programs were merely computerised versions of the empirical manual procedures, which are based on either steady-state or steady periodic heat flows. Such methods are used for sizing heating, ventilating and air conditioning (HVAC) equipment. Systems designed by these methods are sometimes oversized and may never operate at full load and optimum efficiency[3].

Soon after the 1973 energy crisis, emphasis was placed on energy-efficient building design. It was therefore necessary to evaluate precisely the dynamic thermal performance of buildings. As a result, a new breed of models emerged as the next generation to replace the traditional methods[4]. This generation range from simple 'rules of thumb' to complex dynamic models. Over three hundred models have been reported so far[5–7]. Dynamic thermal models are based on steady-state, harmonic, response factor, finite-difference or analogue methods[8]. These elegant methods principally solve the heat diffusion equation. Complex methods are capable of predicting the time-varying thermal response of buildings to heat fluxes under changing climatic conditions and internal configurations[9].

The increased complexity of calculation employed in these methods and models has made the use of computers desirable if not essential[10]. With the reduction in the cost of computer hardware and the expansion of microcomputer memory, mainframe-mounted programs are being converted to microcomputer application.

2 Dynamic thermal models

Holmes[11] has defined the dynamic thermal model as 'a method to predict the magnitude, duration and time of occurrence of an event'. As described by Wiltshire and Wright[12] 'a thermal model can be viewed as formal description of the behaviour of a building and so require a description of all energy flow paths'. All the simulation models solve the mathematical equations which describe the conduction, convection and radiant heat exchanges occurring in a building[13].

However, these mathematical models are not exact replicas of reality but are based on various assumptions and approximations. They are regarded as valid over some range specified by their authors[14].

The increasing use of thermal models requires that their accuracy be assessed regularly. Validation is therefore an integral part of model development.

3 Validation and validation methodologies

Validation can be defined as the calibration of a model, in which its results are compared with one experimental data set representing a particular restricted case.

Validation is now widely recognised as essential to a gradual improvement in the quality of a model[8], since it increases confidence in the predicted result. Once a program is validated, it can serve as reference for checking other programs. Such an approach was adopted in California, USA, taking the program CAL/CON I as a benchmark[15], but the validity of results from this program was challenged as it was not itself validated. The rebuttal suggested comparing program predictions with experimental measurements[1].

Real validation work began at the Solar Energy Research Institute (SERI) in the USA, followed by the Science and Engineering Research Council (SERC), the International Energy Agency (IEA) and the Building Research Establishment (BRE) in the UK. The first comprehensive validation methodology was proposed by SERI as a result of two validation studies[16,17]. It comprised the following three distinct techniques[18], each claimed to be capable of revealing errors in the modelling process:

(*a*) analytical verification

(*b*) inter-model comparison (software/software comparison)

(*c*) empirical validation (software/experimental measurement comparison)

In analytical verification, the model predictions are compared with known exact solutions to carefully designed problems[19]. Within a limited scope of application, this technique is useful for investigatiing errors in the algorithms.

In inter-model comparison, the results predicted by different programs are compared by simulating a hypothetical building[19]. The disadvantage associated with this technique is that there is no absolute model against which the prediction can be compared. The previous work in this category has necessitated the use of measured data.

Empirical validation is the ultimate measure of assessing a program's predictions by comparing these with experiment. This technique has sufficient potential to assess the mathematical model in a simulation program[19].

Lomas[20] has further expanded the empirical validation process into three sub-stages and has claimed its capability of revealing internal errors in thermal models. The three models ESP, HTB2 and SERI-RES have been tested with this technique.

In addition to the above three techniques, sensitivity analysis and parametric studies are also considered as integral part of validation process. Different authors[14,20] have suggested various types of sensitivity technique.

The SERC/BRE group extended the SERI validation methodology by encompassing an examination of individual thermophysical processes operating in the building, the development of standard building specification and the development of improved statistical techniques for the evaluation of simulation models[21]. The computer codes selected for the evaluation and implementation of proposed techniques were ESP, SERI-RES, BLAST, DEROB and HTB2[22].

Deeble *et al.*[23] also proposed a validation methodology for the Australian thermal performance design tools based on lines similar to those of SERI, SERC and BRE validation methodology. Jensen[24] and Clarke[25] reported an empirical whole-model validation methodology proposed by the Model Validation and Development Subgroup in the PASSYS Reference Wall project. The components of this methodology are the same as those of the other methodologies mentioned above.

4 Review of comparative studies

Although comparative and validation studies were carried out in the absence of a distinct validation methodology, the previous work in this field by various researchers can be classified into three major validation categories as follows.

4.1 Analytical verification and inter-model comparison

Carroll[26] compared three programs NBSLD , BLAST 2 and DOE 2.1 for a single-family detached house simulated in six different United States climates using ASHRAE Test Reference Year weather data. The annual heating load predictions of NBSLD and BLAST showed a good agreement in all climates. DOE 2.1 underestimated heating load considerably for mild heating climates. Design day analysis for three typical days showed acceptable agreement under simulated loads for the three programs, but greater differences were observed in the DOE 2.1 results for a transitional design day when heating and cooling loads were smallest. These differences were due to the calculation of direct and diffuse solar radiation ratios and to the unsuitability of the standard weighting factor for modelling a very lightweight structure.

Judkoff *et al.*[16] compared the four building energy analysis codes DOE 2.1, BLAST, SUNCAT-2.4 and DEROB-III, using two simple direct gain building models with data from the Madison Typical Meteorological Year (TMY). Except for DEROB-III, annual heating and cooling loads of all other three codes were within a reasonable range. The predicted temperature response was different as between all four codes. Analytical techniques revealed an error in the DEROB-III temperature decay test, which was corrected in the later version. SUNCAT, DOE and the modified version of DEROB showed good agreement for the same test.

Wortman *et al.*[27] reported the development of an analytical verification technique comprising various tests which were subsequently applied to the three building energy analysis codes SUNCAT 2.4, DOE 2.1 and DEROB III. All three codes showed a good agreement for the steady-state and dynamic analytical solutions. This technique proved useful in detecting a programming error in the infiltration calculation, and greater heat loss from the building perimeter in DEROB III.

Judkoff *et al.*[17] again compared the same four codes (DOE 2.1, BLAST, SUNCAT-2.4 and DEROB-III) in two different climatic conditions. Annual heating and cooling loads disagreed significantly with respect to the previous study. Discrepancies in the predicted results were considered to result from dynamic interaction between mechanisms, rather than from mishandling any major mechanism in the four models.

Atkinson *et al.*[28] reported validation work by the Berkeley Solar Group for the computer model CALPAS3. The simulated results for temperature and energy requirement were compared with analytical solutions, with measured data for an occupied house and for a passive solar test cell. There was close agreement with the results of analytical tests, and excellent agreement with measured data.

Analytical validation of SERI-RES for various mechanisms indicated close agreement between SERI-RES and analyticlal test results. These results were similar to those produced with BLAST and DOE-2[29].

Littler[30] reported an inter-program comparison for ESP and SUNCODE using two different test cells, i.e. the LANL test cell and a 1 m cubic test cell. Significant differences were observed between the results predicted for the annual heating loads of the test cells. The hourly thermal responses of the programs agreed well for January and poorly for June. These discrepancies may be explained by different heat transfer coefficients in the two programs.

Leifer *et al.*[31] conducted a comparative evaluation of three thermal design tools, CHEETAH, HARMON and TEMPER using a single-zone building design model. Temperatures predicted by TEMPER were higher than those by CHEETAH and HARMON. The predicted responses of internal temperature to changes in design parameters were linear except for thermal mass.

Ahmad[32] simulated a hypothetical commercial building with BUNYIP, ASEAM and OASIS. The simulated OASIS cooling load was higher than those for BUNYIP and ASEAM. BUNYIP and ASEAM results for annual auxiliary energy consumption were in good agreement.

Uddin *et al.*[33] carried out an inter-model comparison between three PC programs (BESA, HAP and TRAKLOAD) with BLAST as reference using a four-zone building example from the BLAST manual. Predictions of energy budgets and sensitivities of results to change in load, systems and plants were compared. An acceptable range of variation was observed in the results. The monthly average predictions for plant energy were greater than the annual average.

Results from ESP, HTB2 and SERI-RES were compared by Lomas *et al.*[34] with the underlying objectives of identifying the problems for which they were suitable and vice versa by simulating a single zone inside a building. The predicted results of the computer programs showed good agreement for some design trends, although some situations showed significant differences. Possible reasons for divergence were thought to be the different algorithms and errors in the programs.

Bland[35] reported a set of analytical tests for the validation of conduction calculations in dynamic thermal models. These tests were developed in a project aimed at a model validation.

4.2 Empirical validation

Wooldridge[36–38] conducted a validation of TEMPER for an office building. The measured and predicted internal temperature showed good agreement over the whole comparison period.

Fitzgerald[39] carried out a comparative study of various dynamic thermal models including TEMPER for an office building. The cooling load predicted by TEMPER was well within the range of results produced by the other models.

Burch *et al.*[3] carried out an experimental validation of the NBS computer program using a data set obtained from a single room constructed in an environmental chamber. The predicted results for floating and thermostatted tests with various possible combinations of structural elements showed close agreement with measured values of hourly temperature and cooling loads.

Arumi[40] carried out the field validation of the DEROB/PASOLE system using data collected from different cells incorporating various passive solar design features. The cells were monitored by the Los Almas scientific laboratories. Agreement between measured and simulated values of thermal responses of test cells was consistently within a 5% margin of error.

Wheeling *et al.*[41] compared the predicted performance of SUNCAT with monitored data from direct-gain and Trombe wall test cells. Monitored data included hourly values of incident radiation, air temperature and thermal storage temperature. Inputting the tabulated values of thermal properties, a close agreement was obtained between measured and predicted air temperatures for the direct-gain test cell. Detailed instrumentation was suggested for monitoring test cells.

Arumi and Northup[42] carried out the field validation of the computer program DEROB using data collected from a monitored house. Beside microclimatic data, thermal responses at various location in the house were also recorded. Most of the predicted temperatures were within a 5% margin of error from measured values, with occasional departures in accuracy. Approximation in the geometry of a complex house, some flaws in the numerical model and uncertain behaviour of the occupant were considered likely causes of divergence between the two results.

Results from a finite-difference model were compared by Waters[43] with the measured data from a real building. The prediction of temperature response was found to be strongly dependent on the convection coefficients for various internal and external surfaces. Results from the model were also compared with those from the NBS calculation procedure using monitored data from the test cell built in an environmental chamber. For the floating test, the calculated internal temperature compared well with the measured thermal response. The comparison for thermostatted tests indicated that predictions depend prediction on the method used to describe the heat exchanges inside a room.

Kerrisk *et al.*[44] compared simulation results from a modified version of DOE-2 (an improvement to model passive solar building by the addition of a custom weighting-factor method) with measurements of heat extraction rates and air temperatures for four buildings. The comparison revealed that DOE-2 can model direct-gain passive buildings accurately and can simulate night ventilative cooling and 'water walls' approximately.

Kusuda and Bean[45] compared the calculated hourly cooling load and indoor temperature with measured data for a high-mass test building in an environmental chamber at NBS with the simulation results of the NBSLD computer program. Although simulated temperatures showed a close agreement with measured values, a considerable difference was observed between the predicted and measured cooling load profiles. A possible reason was thought to be the large amount of moisture released from the structure.

A comparative study of the NBSLD program was carried out with the measured data from one of the test houses in Houston, Texas, USA[46]. Hourly measured cooling loads and attic temperatures were compared with simulated results. Measured cooling loads were also compared with results from the other two simulation programs DOE-2 and BLAST-2. A good agreement was obtained between calculated and observed cooling loads.

Hunn *et al.*[47] used direct-gain test cell data from the NBS testing facility. The cell temperature was allowed to float during the period under observation. The measured air space temperature of the cell was compared with predictions by DOE-2. Agreement was good for clear days and poor for cloudy days. The investigation revealed that collected data were incomplete, and handbook values of material properties were used.

Szokolay and Ritson[48] and Ritson[49] carried out an empirical validation of HARMON using the measured thermal response of a test cell. There was good agreement between measured and simulated results. Later, an inter-program comparison of HARMON with TEMPER and TEMPAL for a typical house was undertaken. The temperature predicted by HARMON was identical to that of the other two programs.

Bauman *et al.*[50] reported two studies as part of the verification of the computer program BLAST. The first comparison was carried out for two different time periods (in September and December) between measured temperatures of highly solar-driven test cells and predicted results. The internal temperature was predicted correctly in September and incorrectly in December, this was due to over-estimating the thermal storage effect. The second study was carried out on a well insulated thermally massive structure built in a large environmental chamber. Predicted and measured cooling loads were comparable within the range of experimental error. Predicted and measured hourly heat fluxes for the ceiling, floor and walls showed similar trends. A possible cause of difference was considered to be comparison of instantaneous measured values with average hourly predicted values.

Judkoff *et al.*[18] simulated a residential test building at SERI with DOE 2.1A, BLAST 3.0 and SERI-RES using site-recorded weather and measured thermophysical property data. The measured energy performance data and those predicted by simulations were compared. The results indicated that input errors can contribute an over-estimation of 60% or more as compared with the measured energy requirement. Errors can be reduced by improving the input variables.

Colborne *et al.*[51] reported four different validation studies of DOE 2.1 using measured data from various single-family dwellings. In the first study, the simulated heating energy of DOE 2.1 was compared with the measured heating energy for two single-storey houses (one with a basement and the second with a ground slab) on a bimonthly basis. The simulated heating energy differed from measured values by up to 11%. In the third study, the simulated heating energy agreed to within 5% of the total measured heating energy for 75 single-family houses. In the final study, the measured space temperature and heating energy for an electrically heated unoccupied house showed good agreement with simulated results. The study also stressed the need for a validation methodology.

Arumi and Burch[52] carried out a simulation study with DEROB to provide a consistency check on data for six test buildings. Differences between total measured and predicted total loads for six buildings were within a range of 15% for three different seasons. The fractional differences were more obvious when they were compared for individual buildings. There was close agreement between hourly measured and predicted loads. Free-floating temperatures and three-dimensional wall heat fluxes were modelled adequately by DEROB.

An evaluation study of four computer programs (ZSTEP, TEMPER, TEMPAL and TRNSYS) was undertaken by Williamson *et al.*[53] for the Australian Housing Research Council (AHRC). None of programs accurately predicted the internal conditions of the test houses, but ZSTEP and TEMPAL produced reasonably accurate results.

Yuill(54) carried out a verification study of the BLAST computer program by comparing its predictions of temperature and energy consumption with monitored data from two houses. Despite using weather data for a remote site, good agreement was observed between measured and predicted energy consumption on annual and monthly bases. Measured and predicted hourly temperatures for basement, floor and attic also showed good agreement. These results indicated no systematic difference between the input data files.

Sorrell *et al.*[55] conducted a validation study to determine the accuracy of the three computer codes DOE 2.1B, EMPS 2.1 and TARP 84 using a validation data set consisting of measured energy use and internal space temperatures for the NBS test houses and the ORNL ACES control house. Comparison of computed and measured values of energy consumption, indoor and attic temperature for winter and summer periods showed satisfactory results, except that DOE-2.1B overpredicted cooling energy for high-mass NBS test houses and EMPS 2.1 underpredicted cooling energy for some cases. There was a good agreement for the low-mass structures for all the parameters compared.

Alereza and Hovander[56] compared the prediction of computer program ADM-2 (a derivative of DOE 2.1) with energy usage values obtained from the utility bills of 36 different buildings on annual and monthly bases. Computer-simulated results were within 10% of actual energy use.

Piedade *et al.*[57] compared the performance of the two simulation codes PASSIM and PRESOP with monitored data from three independent cells, for a variety of situations such as free running with and without solar direct gains, a massive building envelope and a short period of heat input. The predicted thermal responses of the two programs were identical for all simulated cells, but not with the measured results. The reason for the apparent discrepancy was attributed to difficulty in controlling air change rates, thermal conductances, temperature homogeneity of air and other elements, and reproducing these correctly in the simulation.

Stanzel and Hahne[58] simulated the PASSYS test cells with DEROB, ESP, HAUS and SUNCODE. These tests cells were investigated in a project of the CEC (Commission of the European Communities) and BmFT. Substantial differences were observed in the predicted thermal performance of passive solar components of the south wall. The programs predicted different results on the first day, and these differences widened when the south-facing window area increased.

Irving[14] summarised the review of 18 empirical validation studies reported by Bowman and Lomas[19] using four large dynamic thermal models (ESP, SERI-RES, DEROB and BLAST). The results failed to reveal the internal errors in the model, due to the masking effect of various external errors in input and measured data.

QUICK's simulated results were compared with the temperatures measured in various types of building with open and closed windows in 42 different validation studies[59–61]. The instrumented buildings included office blocks, shops, schools, residential buildings, town houses, medium- and high-mass experimental buildings, and low-mass well insulated buildings. It was claimed that QUICK's results compared well with measured performance parameters.

Robinson and Littler[62] compared results predicted by SERI-RES with measurements of thermal response and energy parameters for a 'super-glazed' and a double-glazed house. The energy parameters for the same buildings were compared with DESIGNER. The agreement between measured and predicted results for SERI-RES was good on both heating-season and monthly bases. However, the program underestimated the internal temperature and overestimated solar gain and building heat loss in the summer. The annual energy consumption compared well with the predicted results of DESIGNER.

Mohanty *et al.*[63] carried out an empirical validation of the design tool OASIS with the hourly measured cooling loads for an energy-efficient building. The predicted results were in good agreement with measurements.

The thermal responses for light- and heavyweight one cubic meter test cells were compared with the simulation results of TEMPER, CHEETAH, ARCHIPAK and QUICK. Measured and simulated thermal responses compated well for the first three thermal design tools. QUICK underestimated the thermal response for heavyweight test cells[64].

Jensen[24] discussed the whole-model validation of ESP-r using data sets from the PASSYS reference wall project. The predicted results were compared with the measured test room temperature. The dynamic response of the test cell was simulated accurately by the model.

Boulkroune *et al.*[65] validated ALLAN with measurements including radiator temperature, inside and outside wall temperatures and thermal responses for four rooms in an apartment. The discrepancies between measured and modelled results were lower than the stated accuracy of the sensor.

Ahmad[66] and Ahmad and Szokolay[67] carried out a validation study of the four thermal design tools TEMPER, CHEETAH, ARCHIPAK and QUICK using high-quality measured data sets for PCL direct-gain test cells at Peterborough, UK. Good agreement between measured and predicted internal thermal responses was observed for TEMPER and CHEETAH. The hourly temperatures predicted by ARCHIPAK were higher than the measured values for most of the day. QUICK underestimated temperatures by as much as 16.7 K at midday. Sensitivity analysis revealed a flaw in the ARCHIPAK solar radiation sub-routine. The underestimation of QUICK was attributed to extensive lumping of the parameters. CHEETAH and TEMPER's results could not be investigated further due to the inflexibility of databases of material properties.

5 Conclusions

The literature review has presented a summary of the development of thermal and energy simulation programs, validation techniques and analytical verification, inter-program comparisons and empirical validation of various thermal and energy simulation models. Inter-program comparisons and empirical validations have been conducted for various buildings ranging from simple test cells to large office buildings.

Most of the work in the empirical validation category has been conducted by experiments in the field and/or in laboratories using either scaled or full-size real buildings to monitor their thermal and/or energy performance. The monitored performance parameters were subsequently compared with the simulated results from the thermal programs under investigation.

Validation of different thermal models has identified various reasons for discrepancies between measured and predicted results. These discrepancies are thought due to incomplete data from test facilities and to instrumental errors. Predictions diverged further if there were any internal error in the model.

The literature survey has also highlighted the lack of availability of high-quality measured data sets. Only a few well documented measured data sets are available for validation purposes. More detailed experiments are therefore needed. These should be include measurement of all performance parameters, of on-site weather data and of actual thermophysical properties of materials, thus eliminating the uncertainties in all model inputs. Validation studies will then be more meaningful, and errors in the algorithms of thermal and energy models can be better investigated..

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