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Validation of Thermal Design Tools

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ABSTRACT

Validation is an integral part of any thermal model/design tool development. This study was aimed at the validation of the thermal design tools, TEMPER, CHEETAH, ARCHIPAK and QUICK. A high quality data set collected from PCL direct gain test cells at Peterborough has been used in this validation exercise. Thermal responses simulated by these design tools have been compared with the measured thermal response. A good agreement between thermal responses was observed for TEMPER and CHEETAH. The ARCHIPAK-predicted hourly temperatures were higher than the measurements for most of the day. QUICK underestimated temperatures by as much as 16.7°K at midday. The differential sensitivity analysis technique was used to explore the possible causes of these divergences from the measurements. It was concluded that in ARCHIPAK the handling of solar radiation had a flaw. The underestimation by QUICK was attributed to extensive lumping of parameters. The sensitivity analyses for TEMPER and CHEETAH were left incomplete due to their rigid structures of material data libraries.

INTRODUCTION

The development of computer programs for thermal and energy analysis of buildings started nearly three decades ago. Over three hundred programs of various degree of sophistication have been reported so far (Burgess, 1979; Littler, 1982; Rittlemann and Ahmad, 1985). The enormous development in computer technology has reduced the computation time, thus enabling a user, e.g. a building designer, to study in detail the thermal behaviour of a building, existing or on the drawing board.

Various international organisations have devoted significant funds and effort to the validation of thermal and energy models for building design. This has helped to identify any errors/flaws and to promote further development which in turn has increased the user confidence. Once a detailed model has been validated, it can serve as reference or bench mark for the validation of other tools.

To accomplish a thorough validation of a model, the use of a high quality measured data set is recommended for the comparison with the simulated results. The measurements can be carried out on existing buildings or scaled buildings (test cells). There are a few high quality data sets available in the form of handbooks and on floppy disks which can be used for the validation of thermal models.

This study is aimed at the validation of four thermal design tools available in Australia, i.e. TEMPER, CHEETAH, ARCHIPAK and QUICK which are based on finite difference, response factor, BRE 'admittance procedure' and semi-empirical methods, respectively, for the calculation of heat transfer through buildings' elements.

THE SELECTED VALIDATION METHODOLOGY

The selected validation methodology was developed by the Science and Engineering Research Council (SERC) and the Building Research Establishment (BRE) in the UK. As discussed by Lomas (1991), it consists of the following three distinct levels:

"Level 1. A base case prediction is obtained without regard to the measured thermal performance. These predictions, and the corresponding measurements, are then compared and if they differ by less than the errors in the measurements alone, the model is deemed to be satisfactory at Level 1 for the particular situation examined; if not, it is advisable to progress to Level 2.

Level 2. The total uncertainty in the prediction due to external errors in the model input data, is quantified. If the base case prediction for the parameters of interest differ from the measurements by less than the total uncertainty, the model is deemed to be satisfactory at Level 2 for the particular situation studied; if not, it is useful to progress to Level 3.

Level 3. The internal errors which cause the divergent predictions are detected, either by comparing the predictions of individual algorithms with detailed mechanism level data, or by using some other validation techniques."

The algorithms of three of the selected programs were not available, therefore, the validation was restricted to the first two levels of the above methodology.

DESCRIPTION OF TEST CELLS

Four cells were constructed on the PCL test site in Peterborough, UK (Lomas and Bowman, 1987a). These were monitored from late 1983 to July 1984. The data collected from the cells 1 and 2 were considered useful for validation purposes.

Cells 1 and 2 shown in Fig. 1 were direct gain cells with a thermal mass added. This consisted of a standard dense concrete storage wall for cell 1 and an air-permeable, no- fines concrete block wall (to allow free circulation of air through the open textured block) for cell 2. These were located just inside of the north wall of each cell.

The entire south wall of both cells was glazed with 4 mm clear glass, supported by mullion and a transom. The walls were of frame construction with stressed skin plywood facing. The roof was covered with waterproofing felt. The common attic for both cells was separated by a hardboard ceiling with insulation. Both cells had equal volume (10.4 m^3) separated by a well insulated party wall.

The floor and outside walls were insulated. The floors were supported on beams to have free circulation of air below them. Both cells had 43 different envelope elements. The supporting data on a floppy disk consisted of two 9-day periods: 25 Feb. to 4 March and 4 to 12 May 1984. The window of cell 1 had an insulating blind for the May period from 7 pm to 7 am. All the outside walls were painted off-white yielding an absorptance of 0.5.

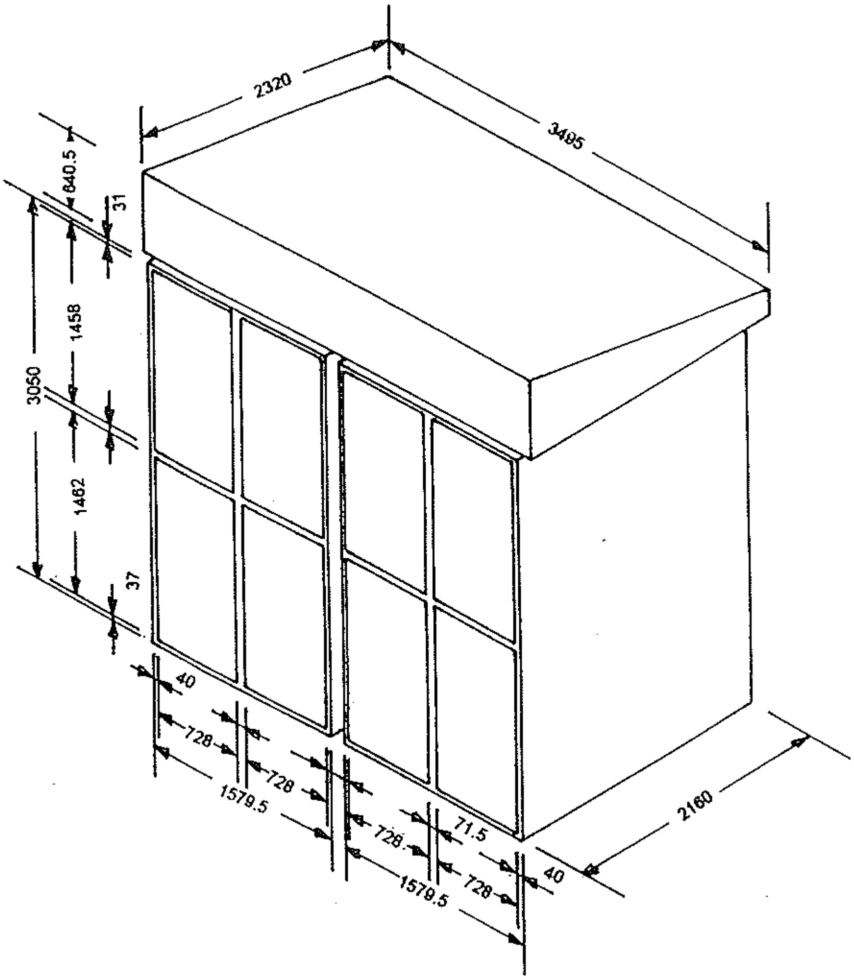

Fig. 1. PCL test cell 1 and 2 (Lomas and Bowman, 1987a).

MODELLING OF TEST CELLS

The test cells were modelled in detail by each program. All possible precautions were taken to eliminate any input data error. The selected thermal design tools simulate the thermal response on daily basis. The test cells were simulated for five different days. The results here presented are for May 12, 1984. The climatic conditions on this day were sunny and representative of other days in the May period.

The following modelling assumptions were made for the simulation:

1. in ARCHIPAK, the attic space was modelled as unventilated air space between ceiling and roof layers; however, the slope of the roof section was taken into account;
2. in QUICK, the attic space was defined similarly but the roof had to taken as a flat horizontal surface;

3. TEMPER allowed a maximum of ten heat transfer paths per zone, therefore the areas of small sections were merged into major sections;
4. the shading of west wall of cell 2 due to adjacent cell was not modelled as none of four design tools has facility to model the shading due to surrounding buildings or objects;
5. the placement of a blind at night time in cell 1 was not modelled in any of the four programs in May period;
6. in TEMPER and CHEETAH, thermal properties of materials were selected from their material libraries, and it was not possible to modify their values to match those given in the test cells handbook;
7. in TEMPER, the hourly ambient temperatures were generated on the basis of maximum measured dry bulb temperature (DBT) at 1400 hours and daily swing, as it does not accept hourly values of measured temperature.

SIMULATION OF THE BASE CASE

The base case simulated thermal responses of TEMPER, CHEETAH, ARCHIPAK and QUICK are compared with the hourly measured internal temperatures of cell 2 in Fig. 2. Figure 3 plots the differences from the measured values. The predicted response of TEMPER matches the measurement with an hour leading phase shift. CHEETAH- predicted thermal response is in good agreement with measured thermal response. The ARCHIPAK predictions are higher than the measured temperatures and show an hour delay. QUICK underestimates the thermal response during the day and a maximum temperature difference is 16.7°K. Due to this conspicuous behaviour of QUICK, the simulated results were sent to the developer of QUICK who confirmed them (Buys 1993).

The figures of merits defined in Table 1 were calculated for four design tools. On the basis of Root Mean Square (RMS) temperature difference, the performance of CHEETAH was best of all.

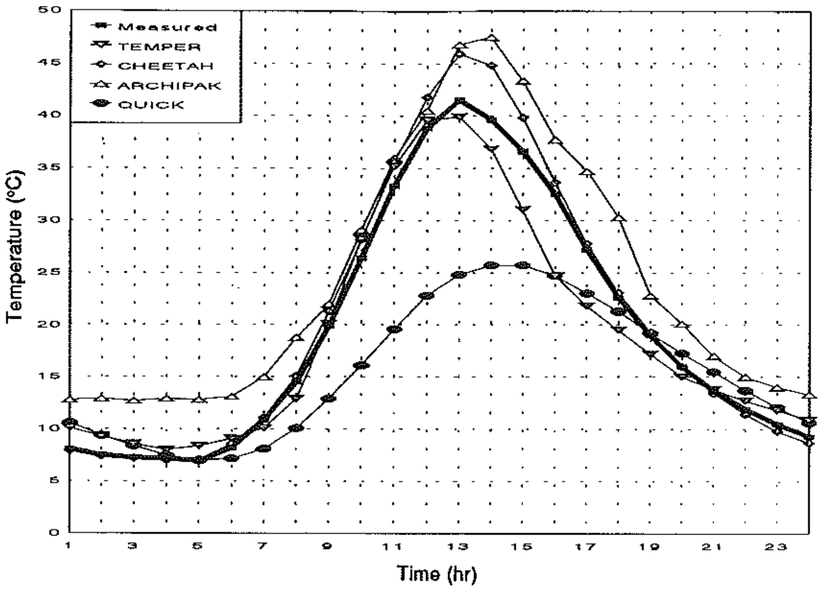

Fig. 2. Comparison of predicted and measured internal temperature for cell 2 on May 12, 1984.

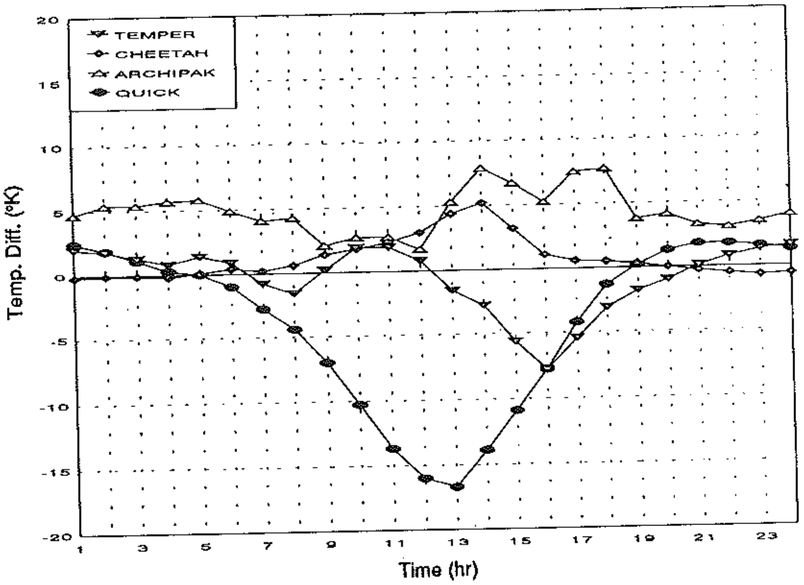

Fig. 3. Comparison of temperature differences for cell 2 on May 12, 1984.

Table 1. Definitions of figures of merit for the four design tools shown in Table 2.

Temperature Difference	dT	=	$T_p - T_m$
Maximum Temperature Difference	D	=	dT_{max}
Minimum Temperature Difference	d	=	dT_{min}
Mean Temperature Difference	D_{av}	=	sum(dT)/N
Absolute Mean Temperature Difference	$\|D\|$	=	sum$\|dT\|$/N
Root Mean Square (RMS) Temp. Difference	RMSdT	=	$(\text{sum}dT^2/N)^{1/2}$

Where T_p = predicted temperature
T_m = measured temperature
N = number of hours (24)

Table 2. Statistical comparison of measured and predicted air temperature Test Cell 2 (May 12, 1984).

Design Tool	Max.T (°C) D	Time (hr)	Min.T (°C) d	Time (hr)	MeanT (°C) D_{av}	Abs.mean dT (°C) $\|D\|$	RMS dT (°C)
TEMPER	1.9	10,11	–7.8	16	–0.6	2.0	2.7
CHEETAH	3.5	14	–1.4	7	0.9	1.2	1.8
ARCHIPAK	7.9	14	3.1	22	3.8	3.8	4.2
QUICK	2.5	1	–16.7	13	–5.0	5.1	7.6

RESULTS

TEMPER

The overall results are the second best of the four programs in the comparison of predicted internal temperatures of cells. Factors like deviation of thermal properties of materials from the actual materials as defined in the site handbook, deviation of external and internal film coefficients, approximation of external temperature profile, and calculation of solar position on the 22nd of a month, should be taken into account. These may have produced an internal cancelling effect, resulting in good agreement with the measurement.

CHEETAH

The predicted results of CHEETAH were almost coincident with the measurements and the best among the four programs. However, these should be interpreted with great care as internal and external film coefficients and thermophysical properties of materials were different from those specified in the site handbook. The possibility of a cancelling effect should not be ignored as the cause of good correspondence of predicted results with the measurement.

ARCHIPAK

Actual values of all variable were input, but the predicted temperatures are higher than those measured.

QUICK

Temperatures were consistently underestimated by this program during day time with a maximum temperature difference of 16.7°K. At night the hourly predicted temperatures were in reasonable good agreement with the measurement.

These conclusions make it necessary to explore all possible reasons, thus it is imperative to proceed to level 2 of the validation methodology to conduct sensitivity analysis.

Sensitivity Analysis

The deviations may be due to two types of errors i.e. internal and external. The external errors are introduced due to uncertainty in weather variables, thermophysical properties of materials and other design variables. Once the uncertainty in external errors is taken into account, then it is possible to determine the internal errors. There are three sensitivity analysis techniques available i.e., differential sensitivity analysis, Monte Carlo sensitivity analysis and Stochastic sensitivity analysis.

In the differential sensitivity analysis, one input parameter is varied before each simulation whereas the others are held constant. Thus this techniques determines the sensitivity of model for individual variable. The other two techniques determine the total sensitivity of a model only. In this particular validation exercise, differential sensitivity analysis technique was employed to reveal responses to individual variables.

Uncertainty in Prediction due to External Error

A range was specified of each input parameter, including the thermophysical properties of materials and weather variables. The specified range had 1% chance of being exceeded by value of each variable.

In the adopted procedure, two simulations were carried out: for maximum and minimum values of input variables. For TEMPER and CHEETAH, it was impossible to modify the thermophysical properties of materials due to their inaccessible material libraries. Therefore, sensitivity analyses were not carried out for them. It was possible to conduct the sensitivity analysis for ARCHIPAK and QUICK.

Uncertainty in Thermophysical Properties of Materials

ARCHIPAK showed a greater sensitivity in the thermophysical properties of materials than QUICK. A comparison of sensitivity for wood chipboard indicated an identical variation of ARCHIPAK with ESP and SERI-RES. The insensitivity of QUICK was thought to be due to extensive lumping of parameters (the basis of its mathematical model) and it has also been explained by Holm (1993) as:

> "one of simplifying procedures of QUICK is the fact that the building elements are lumped in the calculations. The concomitant disadvantage to the designer is that he cannot identify which building elements are the major players dominating the thermal performance of a building. The designer in a given situation does not know whether he should increase the interior mass, the insulation or the window size."

Sensitivity to Uncertainty in Other Parameters

The sensitivity of the four design tools was also determined for the uncertainty in weather and other variables such as absorptance of wall surfaces, ground reflectance, external and internal film coefficients, window U-value, etc. The major results from this sensitivity analysis were:

i) QUICK showed a strong influence of variation in the external film coefficients. For its minimum value, i.e. 5.0 W/m²K, the peak temperature was increased by 18.1°K from the base case value whereas ARCHIPAK simulated an increase of 8.2°K for the same variation.

ii) For the uncertainty in global solar radiation values, ARCHIPAK simulated response was not symmetrical, which indicated an imperfect coupling of the solar radiation subroutine with the dynamic thermal model.

Total Uncertainty in Prediction

The total uncertainty in the prediction was calculated by the Method of Quadrature Addition. In this method, the total uncertainty is determined by the following expression:

$$e_T = (e_1^2 + e_2^2 + e_i^2 + \ldots + e_n^2)^{1/2}$$

where: e_T = total uncertainty in prediction due to all input uncertainties,
e_i = uncertainty in prediction due to input i only,
i = number 1 to n,
n = total number of inputs.

The upper and lower one percentile bounds were determined by adding the total uncertainty in the base case hourly values. The measurement uncertainty was also added to uncertainties in the other inputs.

For the upper one percentile boundary, the difference for each input parameters was calculated and squared at each hour. Finally, the square of total squared difference was added to the base case value. The same steps were repeated for the calculation of the lower one percentile boundary.

Revealing Internal Errors

The calculated lower and upper one percentile bands for ARCHIPAK and QUICK are plotted (Figs. 4 and 5) with the base case and measured values of internal temperature.

The measured temperature for cell 2 was below 1% curve of ARCHIPAK from 0100 to 0800 hours and 1200 to 2400 hours. This results had only 1% probability of occurrence. Since all possible uncertainties in all input parameters were accounted for, this significant difference in results leads to conclusion that there are internal errors in the model.

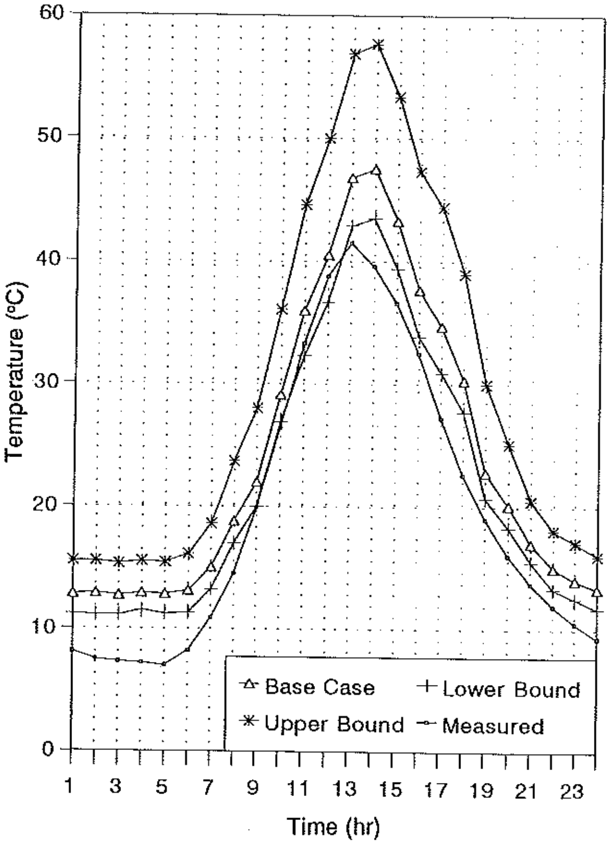

Fig. 4. Comparison of measured air temperature in cell 2 with the base case values predicted by ARCHIPAK, showing the upper and lower bound predictions to total uncertainty in all input parameters.

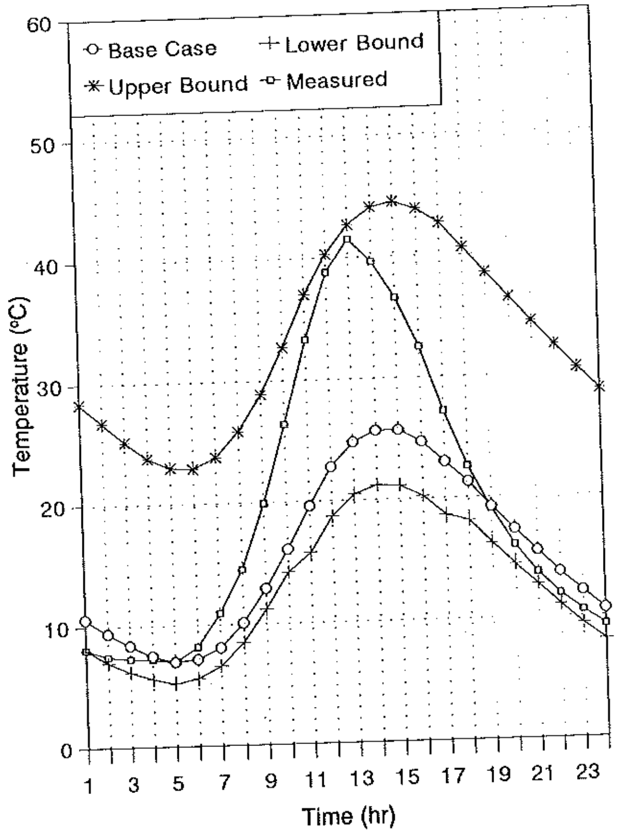

Fig. 5. Comparison of measured air temperature in cell 2 with the base case values ppredicted by QUICK, showing the upper and lower bound predictions to total uncertainty in all input parameters.

For QUICK, calculated lower and upper one percentile boundary surrounded the measurement profile. None of three curves (upper & lower 1% and base case) was anywhere near to the measurements. Therefore, it can be concluded that there are severe internal errors in the model.

Using the A-Class approach (in which the simulation is carried out in ignorance of real measurements and no manipulation of input is allowed) and quadrature addition, boundaries were also determined. It can be observed that the width of band in the B-Class approach (in which a good agreement between the measurement is obtained by massaging the inputs) is greater than with the A-Class approach.

If a conclusion is drawn on the basis of the B-Class approach then ARCHIPAK is capable of making an accurate prediction of air temperature, because the measurements are placed between the two extremes. The A-Class approach leads to the opposite conclusion. In subsequent work it has been found that this error of ARCHIPAK occurred only in the 'research' version (a modification to accept hourly measured radiation data). The original version (which accepts the input of daily total irradiation from which it estimates hourly values) gave much better results. Considering both approaches, the simulated results of design tool QUICK are invalid for these particular direct gain cells.

Applicability of the Results

The comparisons between measurements and predicted results are strictly limited and valid for PCL direct gain test cells. The results may be extrapolated to single zone, lightweight, direct gain and other similar structures.

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