Thermal design tools in Australia a comparative study of TEMPER, CHEETAH, ARCHIPAK and QUICK

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Abstract

After a brief review of the development of thermal design tools world-wide, those available in Australia are considered and four are selected for validation. A review of validation methodologies is followed by simulation results compared with measured data obtained from simple test cells. Some preliminary results are presented The current continuation of the work is outlined.

Introduction

The development of computer programs for building energy analysis had started in the 1960s (Hall & Patterson, 1980; Judkoff, 1988). The early programs were computerised versions of empirical handbook procedures, mostly based on steady-state heat flow calculations. Soon after the 1973 energy crisis attention was focussed on energy efficient building design, thus it became necessary to evaluate the dynamic thermal behaviour of buildings.

Over three hundred programs have been reported (Burgess, 1979; Littler, 1982; Rittlemann & Ahmad, 1985), ranging from simple rule-of-thumb applications to complex dynamic models. The dynamic models may be based on harmonic, response factor or finite difference calculation methods, but there are some essentially steady-state methods with some correction terms included for thermal storage effects. Often the models developed are claimed by the authors to have been validated, but wide acceptance usually depends on validation by third parties.

Validation methodology

Validation can be defined as establishing the degree of accuracy of a model, by testing the theoretical correctness of the calculation methods and by comparing the results with performance data measured in a real building. Validation is necessary to establish the credibility of a model but also to ensure the continuous improvement of the model (Clarke, 1982). Once a program is validated, it may be used as a reference for the validation of others.

Systematic validation work started under the auspices of the International Energy Agency (IEA), at the Solar Energy Research Institute (SERI) in the USA and later at the Building Research Establishment (BRE) funded by the Science and Engineering Research Council (SERC) in the UK. The Commission of European Communities (CEC) also funded a major validation project. Judkoff (1983) distinguished three distinct techniques for validation, each being capable to reveal errors in the modelling process:

1. analytical verification: model predictions compared with known exact solutions of carefully designed problems (Bowman & Lomas, 1985), limited scope but useful to investigate errors in the algorithms
2. inter-model comparison (software-to-software comparison): comparing the simulation results for the same hypothetical building by different programs; useful and may be convenient, especially if one of the models compared has been previously validated, but does not replace the third kind
3. empirical validation (software-to-real measurement comparison): the ultimate measure of assessing the validity of a program.

In any of these techniques, but especially with inter-model comparisons, consideration of predicted performance should be supplemented by sensitivity

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analyses and parametric studies. Irving (1988) and Lomas (1991) suggested a range of techniques for sensitivity analysis.

The SERC/BRE group extended the SERI validation methodology to include an examination of algorithms for the individual thermophysical processes operating in the building and by developing standard building specifications and improved statistical techniques for the evaluation of simulation models (Irving, 1988). The techniques were used in the validation of ESP, SERI-RES, BLAST, DEROB and HTB2 (Bloomfield, 1985).

The American Consulting Engineers Council (ACEC) and the Building Energy Design Tool Development Council (BEDTDC) make a distinction between validation (to establish accuracy and reliability) and evaluation (to assess usefulness and usability). They also distinguished programs primarily used as research tools and those suitable for practising designers, for use as design tools.

Design tools used in Australia

Various thermal simulation programs have also been developed in Australia. The best known ones are: TEMPER and BUNYIP, based on a finite difference method, CHEETAH, a more user-friendly version of ZSTEP, based on a response factor method, TEMPAL, using the method of 'advancing means', HARMON, now included in ARCHIPAK, based on the BRE admittance procedure and CAMEL, based on the Carrier air conditioning load calculation method. Several overseas programs are also in use, notably TRNSYS, QUICK and ESP II.

All these programs were validated by their authors, but not all were included in independent validation studies. Fitzgerald (1971) carried out a comparative study of several programs, which included TEMPER. Results of this program were well within the range of results by the others.

Williamson et.al (1984) undertook an evaluation study of four programs: ZSTEP, TEMPER, TEMPAL and TRNSYS, for the Australian Housing Research Council (AHRC). None of the programs produced results matching the measured performance, but ZSTEP and TEMPAL produced results of acceptable accuracy.

Leifer et al (1988) did a comparative evaluation of three programs: CHEETAH, HARMON and TEMPER, using a single-zone hypothetical building. Temperatures predicted by TEMPER were found to be higher than those by the other two programs. The project was rather limited and some of the results are inconclusive.

Deeble et al. (1988) also proposed a validation methodology for Australian thermal performance design tools, along lines similar to the SERI and SERC/BRE methodology. His proposed project does not seem to have materialised.
There appears to be a lack of thorough validation studies and the need to carry out such a study has been established. The first question was, which programs should be included. Selection criteria were established as

- easy availability in Australia,
- documentation sufficient for thorough understanding of the model,
- availability of feedback and technical advice from the authors/developers of the program, should an ambiguous situation or other problems arise.

Starting with the above list of programs, some were eliminated. BUNYIP is an extended version of TEMPER, to model various installations; as far as the building's performance is concerned, it does not offer anything beyond TEMPER. CHEETAH is the microcomputer version of ZSTEP, so the latter need not be considered separately. With TEMPAL it was not possible to obtain a copy or documentation: indeed it seems to be a research tool rather than a design tool, used only by its authors. CAMEL was disqualified for another reason: it is primarily an air conditioning design program, its load calculation does not use a true dynamic model, essentially it is a steady state calculation, with some fudge-factors added. Thus the final selection was CHEETAH, TEMPER, ARCHIPAK & QUICK.

Experimental setup and data

The test data were obtained from the 'COOL-WALL / THERM-WALL project carried out at The Queensland University of Technology (QUT, then QIT) in 1982, for the evaluation of various passive systems. Eleven test huts were built on the roof of the architecture building and monitored from February to September, 1982. Two of these were found to be suitable for simulation by the selected programs: the all-foam building and the concrete block walled building. These are shown in Figs. 1 and 2 and their description is summarised in Table 1.

The climatic data measured in situ included hourly values of dry and wet bulb temperatures, wind speed and direction and global horizontal solar radiation, which satisfies the criteria for data to be used with empirical validation, as stipulated by Lomas & Bowman (1986).

Possible 'disturbing' influences were eliminated: the test cells were well sealed to prevent any infiltration. The cells had no windows, thus there was no direct solar gain. Ground heat transfer was avoided by constructing the test cells on an insulated roof deck and add a layer of insulation to render it practically adiabatic. What was tested is only the ability of the four models to predict the heat transmission through walls and roof and its temperature consequences.

TABLE 1

Roof	200 mm polystyrene (both bldgs.) covered with black polyethylene sheet absorptance = 0.94 overhang = 0.4 m on all sides
Walls	a) 200 mm polystyrene foam slab b) 200 mm solid concrete block absorptance = 0.2 (both)
Volume	1 m^3
Ventilation+infiltration	nil (sealed building)
Internal heat gain	nil
Ground reflectance	0.2 (assumed)

Thermal properties of the materials used in the four programs are given in the following Table 2.

TABLE 2

property	TEMPER	CHEETAH	ARCHIPAK	QUICK
CONCRETE				
resistivity (m.K/W)	0.69	0.69	0.61	0.69
capacitance (kJ/m^{2}K)	2112	2112	-	-
density (kg/m^3)	-	-	2300	2300
specific heat (J/kg.K)	-	-	1000	1000
POLYSTYRENE (EPS)				
resistivity (m.K/W)	28	28	27.7	27.7
capacitance (kJ/m^{2}K)	5	5	-	-
density (kg/m^3)	-	-	16	16
specific heat (J/kg.K)	-	-	1590	1590

The U-values calculated by the three programs for walls, roof and floor are shown in the following Table 3. In QUICK there is no possibility to output the U-value.

TABLE 3

U-value (W/m^{2}K)	TEMPER	CHEETAH	ARCHIPAK
concrete block wall, 200 mm	3.70	3.60	3.10
EPS walls, 200 mm	0.17	0.20	0.17
EPS roof, 200 mm	0.17	0.20	0.17
floor (EPS+concrete)	0.32	0.30	0.30

The response of the test cells was measured in terms of both dry bulb and globe temperatures, but due to the small size of cells and the absence of ventilation, the two sets of temperatures were identical.

Analysis methodology

In order to ensure a uniform basis of comparison, both the building description and the climatic data input were carefully considered.

Some limitations were encountered with the thermophysical properties of materials in both TEMPER and CHEETAH. The built-in libraries of properties were not accessible, thus in some instances the closest values had to be chosen. In ARCHIPAK and QUICK it was possible to add or modify the values according to the advice of the material suppliers.

Some assumptions were necessary in each program: for TEMPER, CHEETAH and QUICK the floor was taken as being above an unconditioned space, whilst in ARCHIPAK a ventilated underfloor space was assumed. The projecting roof overhang was only modelled in CHEETAH, the other three programs have no facility to consider shading on opaque walls.

Problems occurred also with the climatic data input. In TEMPER the temperature maximum and swing are input, the program takes the minimum and maximum as occurring at 6:00 and 14:00 hours and fits a sine curve to the two points to obtain hourly values. There is no facility to input hourly data. For this reason days were selected for simulation where the hourly temperature distribution was near-sinusoidal. There is no possibility for inputting solar data, but the internally generated radiation values can be attenuated by specifying a cloudiness index (Wickham, 1987).

In CHEETAH a weather data file can be generated. Here the only problem was that the program requires hourly diffuse and direct normal radiation values, whilst the data measured was horizontal global irradiance. The measured hourly values were split into beam and diffuse components and using the calculated solar altitude and azimuth angles, the direct normal irradiance was calculated, by the SUNCALC module of the ARCHIPAK program. ARCHIPAK also uses minimum and maximum temperatures. The latter is taken as occurring at 14:00 h, but the minimum is taken as at the hour before sunrise (which is calculated). However a 'research' version was written, which allows the input of hourly values for both temperature and radiation. The QUICK weather file readily accepts hourly values of dry bulb temperature, humidity, global and diffuse solar radiation (Cento, 1991).

The behaviour of both test cells on a large number of days was simulated. As an illustration, here the response on a clear and sunny day is presented. Fig.3 shows the climatic data for that day. It should be noted that the temperature plots (Figs.4 and 6) use an expanded temperature scale: 20 to 45°C and 25 to 35°C, respectively, in order to give a better resolution. If a normal 0 – 45°C ordinate were used, all lines would overlap.

Lightweight test cell

Quick was unable to model this test cell, because of its very low thermal mass. Graphic comparison of measured and the three sets of simulated response is shown in Fig.4. The response curves of CHEETAH and TEMPER show a phase shift with respect to the measured data: with such very lightweight buildings both programs use a steady-state algorithm, which gives an instantaneous response. CHEETAH is also showing a peak temperature some 9.1°C higher than the measured value. The curve of ARCHIPAK's results is nearest to the measured curve.

A more explicit indication is given in Fig.5, which plots the differences between calculated and measured values for the three programs. Table 4 shows some comparison statistics using some figures of merit which have been employed also by Judkoff (1983), Lomas (1991) and Bauman et al.(1983). These figures of merit are:

temperature difference	$dT = Tp - Tm$
largest temp.difference	$D = \max dT$
smallest temp.difference	$d = \min dT$
mean temp.difference	$Dav = \mathrm{sum}(dT)/N$
abs.value mean temp diff.	$absD = \mathrm{sum}\lvert dT \rvert /N$
root mean square temp.diff.	$RMSdT = [\mathrm{sum}(dT^2)/N]^{1/2}$

where Tp = predicted temperature
Tm = measured temperature
N = number of hours (24)

The most significant of these measures is the RMS temperature difference. In terms of this ARCHIPAK shows the lowest value: 1.57 K, TEMPER 2.01, CHEETAH 4.13 K.

High mass test cell

The 1 m^3 high mass test cell was simulated by all four selected programs. The resulting temperature profiles are compared with measured internal temperatures in Fig.6.

TEMPER and CHEETAH predictions are higher than the measured values in the morning hours. The peak predicted by CHEETAH is lower than the measured value, but it is in phase. The peak of the TEMPER prediction is similar to the measured peak, but with a phase shift (delay) of about three hours. The ARCHIPAK-predicted temperature response starts reasonably close to the measured one in the early morning hours but it exceeds the measured values until midday, then it follows the measured profile fairly closely.

The performance curve predicted by QUICK is somewhat lower than the other curves, but it shows a phase shift (lead) of some three hours in both minimum and maximum. The minimum predicted is the same as the measured, but the maximum is about 2°C lower.

Fig. 7 plots the temperature differences between each of the four programs and the measured data. All measured and predicted temperatures lie within a band of +/- 2.5 K. Table 5 presents a summary of comparison statistics, using the various figures of merit defined above. In terms of RMS temperature difference ARCHIPAK and CHEETAH are quite close together, whilst TEMPER and particularly QUICK show a much greater deviation.

Conclusions

With the very lightweight test cell both TEMPER and CHEETAH show an immediate response to external temperature changes, causing a phase shift (lead) with respect to the measured curve. ARCHIPAK results are in phase, but higher than the measured values.

With the high mass test cell TEMPER results lag some three hours behind the measured values and whilst the peak temperatures are similar, TEMPER underestimates the night-time cooling. Both facts seems to indicate that TEMPER overestimates the effect of thermal mass. CHEETAH seems to overestimate the delay by about one hour, but over-predicts the temperatures up to about 11:00 h whilst under-predicting these in the afternoon. These facts again indicate an overestimation of the mass effect, although to a lesser degree than TEMPER. The behaviour of ARCHIPAK is similar to that with the lightweight cell. QUICK underestimates the daytime heating, but its main problem is that it does not seem to recognise the delaying effect of the building mass: it shows a phase shift (time-lead) of some three hours.

All four programs give a better approximation of the real thermal response of the heavyweight building than of the very lightweight one.

Continuation of the work is aimed at identifying the reasons for the above divergence of predictions and the extension of validation to include floor, window, ventilation and internal heat gain effects.

Acknowledgement

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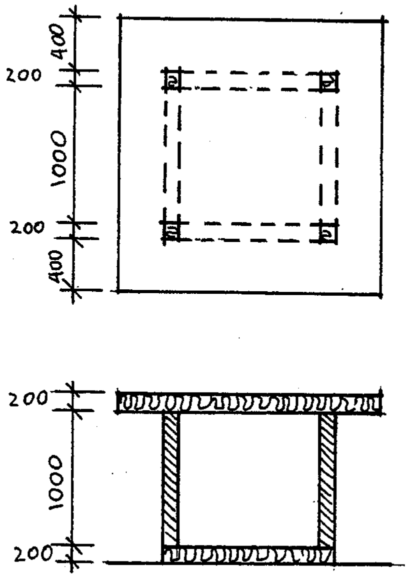


Fig.1

Solid concrete block design

All walls are solid concrete block, the roof is expanded polystyrene (EPS)

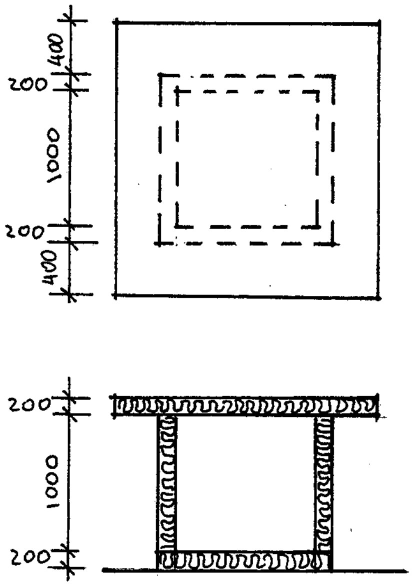
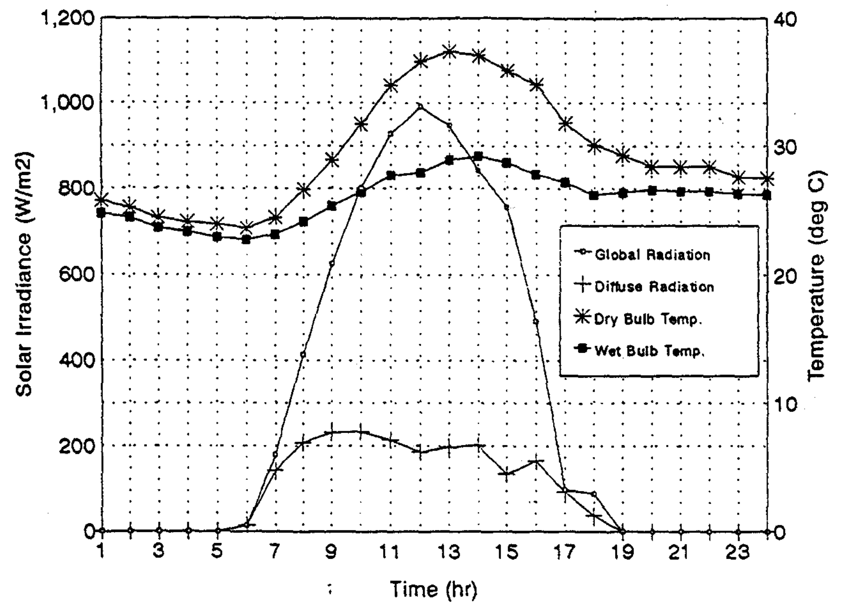


Fig.2

Lightweight, well insulated design

Wall sections are also made of expanded polystyrene (EPS)



Climatic data: February, 18, 1982.

Fig.3

Table.4 Statistical comparison of measured and predicted air temperature.

for Foam Test Building (FEB 18, 1982)

Model	Difference between measured and predicted temperature						
	Max. Temp (° C)	Time (hr)	Min. Temp (° C)	Time (hr)	Mean Temp (° C)	Absolute mean temp (° C)	Root mean square temp. (° C)
TEMPER	4.5	10	-2.4	18	0.23	1.58	2.01
CHEETAH	9.1	13	-3.5	19	1.45	3.01	4.13
ARCHIPAK	2.4	3	-0.8	20,22,23	0.92	1.40	1,57

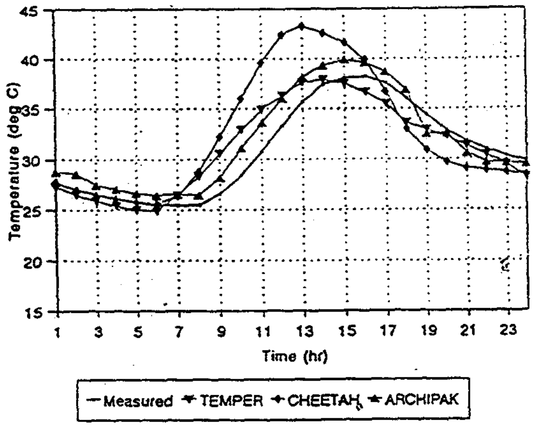
Table.5 Statistical comparison of measured and predicted air temperature.

Concrete Test Building (FEB 18, 1982)

Model	Difference between measured and predicted temperature						
	Max. Temp (° C)	Time (hr)	Min. Temp (° C)	Time (hr)	Mean Temp (° C)	Absolute mean temp (° C)	Root mean square temp. (° C)
TEMPER	1.5	2,3,4	-1.3	15,16	0.32	0.93	0.29
CHEETAH	0.7	4,5,7,8	-1.4	16,17,18	-0.30	0.77	0.08
ARCHIPAK	1.2	6	-1.0	23	0.23	0.60	0.06
QUICK	0.7	10,11	-2.5	19,20,21, 23	-1.05	1.28	0.24

Fig.4

Comparative performance of thermal design tools for foam test building
Feb. 18, 1982.



Comparison of temperature difference for faom test building
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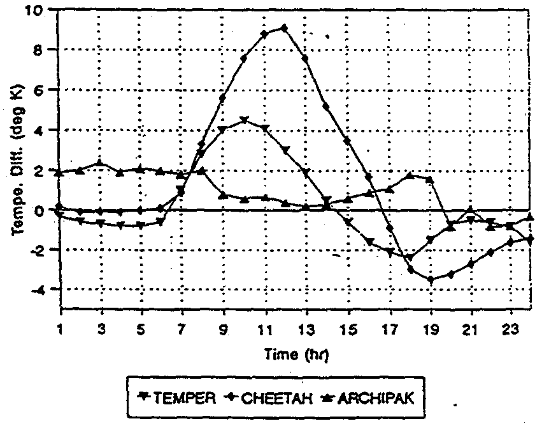
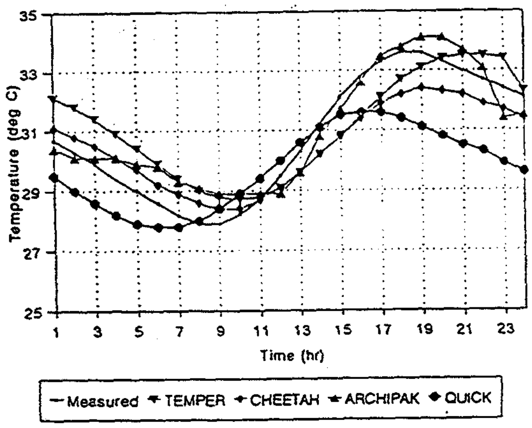


Fig.5

Fig.6

Comparative performance of thermal design tools for concrete test building
Feb. 18, 1982.



Comparative performance of thermal design tools for concrete test building
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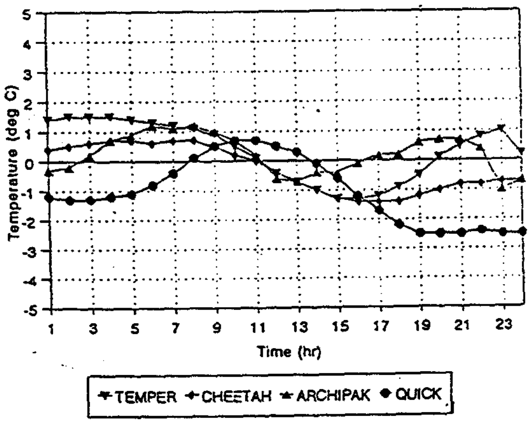

Fig.7