Computers in the Design of Passive Solar Systems

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ABSTRACT

The current state of development of passive solar design tools is reviewed. The advantages and disadvantages of simulation and correlation methods are discussed. A bibliography is provided which lists most of the design tools developed or used by the solar community.

INTRODUCTION

Design tools for solar buildings usually can be classified either as simulations or correlations. Simulations provide information on system performance over short (hourly) intervals of time. They allow monthly or annual auxiliary energy use to be determined by summing the hourly contributions. Correlations provide estimates of long-term (monthly, annual) performance in terms of known design variables and average meteorological conditions. Correlations, either in graphical, analytical, or tabular form, are generally derived from simulation results.

SIMULATIONS

Simulations of passive solar buildings serve three distinct purposes. First, they provide a means of analyzing the dynamic performance of a specific building in response to selected meteorological data. Analyses of this type can be used for a variety of purposes, such as investigating temperature extremes and alternative control strategies and gaining an understanding of the dynamic relationships between energy supply, energy demand, and energy storage. Second, simulations can be used directly as a design tool for a specific building. The use of a simulation in this manner is often warranted for new types of systems or for large buildings where simulation costs are small in proportion to total design costs. The third and perhaps most useful purpose of simulations is to generate correlation design tools.

Simulations are developed by combining the conduction, convection, and radiation relationships which describe the heat-flow rates occurring in a building. With the exception of some natural convection processes, the heat-transfer mechanisms are well understood. Still, the formulation of a general simulation program for passive solar buildings is complex. Many heat-transfer surfaces are involved. Geometrical effects must be considered for calculation of both shortwave (solar) and longwave (thermal) radiation exchange. Energy storage in the building components must be taken into account. Beyond these complexities, major uncertainties remain in the form of unknown heat-transfer parameters, particularly infiltration rate and ground properties.

The irregular behavior of weather also complicates the analyses of solar energy systems. In a passive solar building, both the heating load and the useful solar contribution are functions of solar radiation, ambient temperature, and other meteorological variables. These variables are neither completely random nor totally predictable; they

are best described as irregular functions of time, both on a small (hourly) and large (seasonal) scale. In general, solar energy systems exhibit a non-linear dependence upon the weather which is further complicated by time lags introduced by thermal capacitance or storage effects. It is usually not possible to accurately analyze these systems by calculating their responses to average weather conditions. Because the forcing functions are time varying on both small and large time scales, the analyses of these systems often require an examination of their performance over a long period of time. As a result, experiments become expensive and time-consuming. Moreover, it is difficult to vary parameters to ascertain their effect on the system performance. For this reason, computer simulations are powerful tools in the analysis and design of passive solar buildings. Properly formulated, a computer simulation can provide the same information on thermal performance as a physical experiment, but with a considerable savings of time and expense.

The many general simulation programs devised for analyzing energy use in passive solar buildings differ greatly in their complexity.* At one extreme are such large programs as DOE-2,[1] BLAST,[2] and DEROB[3] which are intended for researchers having access to large computing facilities. At the other extreme are simple network models developed for programmable hand calculators, such as TEANET,[4] PEGFLX and PEGFLOAT,[5] and TI-59.[6]

Validation of existing simulation codes has proceeded in two ways. First, comparisons have been made between simulation results and experimental data such as that from the Los Alamos National Laboratory and National Center for Appropriate Technology test cells.[7-9] A few careful measurements of energy flows in actual residences have also been compared with simulation results.[10-15] In general, however, the available experimental data useful for validating simulations are limited, partially for reasons indicated above and partially because it is difficult to measure accurately the actual heat flows occurring in a building. The recently initiated Class A performance evaluation program[16] sponsored by the Department of Energy (DOE) should provide abundant data on the thermal performance of buildings.** Preliminatry data from two of the nine buildings in the Class A network have been compared with simulation programs.[17, 18] The comparisons made thus far show reasonably good agreement between the calculated and measured results, but they also demonstrate inconsistencies in the experimental data.

Simulations have been validated in a second way: by comparing the results of different pro-grams. One example of such code-to-code comparisons is the 1980 SSEA exercise,[19] in which short-and long-term results from FREHEAT,[20] SUNCAT,[21] PASOLE/SUNSPOT,[22] TRNSYS,[23] and DOE-2[1] were compared for collector-storage wall and direct-gain buildings. After initial discrepancies caused by unclear or insufficient problem specification were eliminated, these programs showed excellent agreement (differences of less than 4%) in their estimates of the annual auxiliary heating loads. However, much larger discrepancies (up to 40%) were observed in their cooling load estimates. DOE-2,[1] BLAST,[2] SUNCAT,[21] and DEROB[3] were compared in a similar study,[24] the results (reported in two phases) of which are inconclusive. Phase 1 reports good agreement in the long-term heating- and cooling-load estimates for low-mass buildings after a few problems in the simulation codes were identified and corrected. Phase 2 reports "significant disagreement in predicting annual heating and cooling loads" among the four simulation codes. However, the annual heating loads predicted by three of the codes in phase 2 agree reasonably well, while the cooling-load estimates posed a problem.

Cooling loads are more difficult to estimate accurately than heating loads for several reasons. First, the difference between indoor and outdoor air temperatures is usually smaller in cooling applications so that the effect of solar radiation absorption on building surfaces is significant. (Solar effects can be considered using sol-air temperatures and sol-air degree days[25] in building energy-gain calculations.) Second, the ambient temperature may oscillate around the desired indoor temperature causing building thermal-capacitance effects to be important. Finally, a significant portion of the cooling load may result from the removal of water vapor from the air. Latent load calculations require information on indoor and outdoor humidities, as well as cooling equipment operating specifications.

Simulations provide the means to solve nonintuitive problems. For example, consider the design stage of a collector-storage wall. Should thermocirculation vents be added to the wall? The vents will alter the time distribution of energy entering the heated space, but will the addition of vents result in a significant reduction in the auxiliary energy required by the building? Can the auxiliary use then be reduced further by the addition of a small fan to circulate indoor air through the wall-glazing gap during times in which useful solar energy can be collected?

Arguments can be formulated to support both an increase and a decrease in auxiliary energy use resulting from the addition of vents. Utzinger et

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*Many of the simulation codes developed or used by solar researchers are listed in section A of the Bibliography. A relatively complete listing of building energy calculation procedures can be found in the review prepared by Kusuda.

**A Class A building is instrumented with hundreds of sensors which record building conditions at hourly or shorter intervals for several weeks under controlled conditions, in part, to rigorously check analysis and design tools used for passive solar research and design.
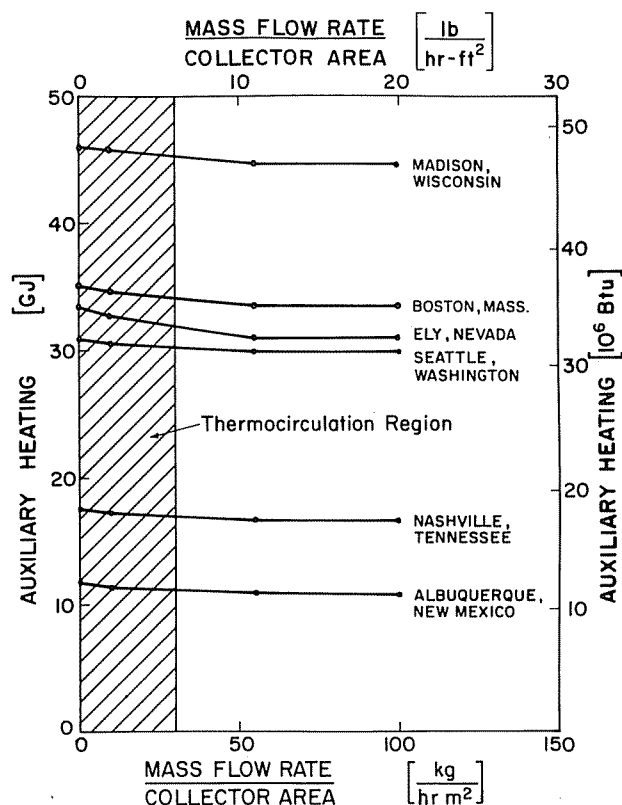
Figure 1: Auxiliary heating energy consumption is shown as a function of air flow rate for six U.S. locations.[26]

al.[26] used the TRNSYS program to answer these questions. The simulation results in Fig. 1 show the annual auxiliary energy use for heating plotted against the ratio of air-flow rate to glazing area of the collector-storage wall. These results indicate that the use of a fan to force circulation of air in the wall-glazing gap will not result in significant reduction in auxiliary use. In fact, eliminating the vents entirely will cause only a small increase in auxiliary use. An explanation which supports these conclusions can be developed by examining the heat-transfer processes occurring in the gap. While air circulation in the gap will result in increased energy convected from the wall surface to the air due to a higher heat-transfer coefficient in the gap, the energy convected from the air to the innermost glazing (and then out to the ambient air) will also increase for the same reasons. As a result, the energy loss from the collector-storage wall to the environment during the flow condition is only slightly lower than that during the no-flow condition.

One way to determine an optimum building design is to use simulations directly as a design tool. With a properly formulated simulation program and sufficient meteorological data, the annual auxiliary energy use of a proposed building design can be estimated. The design parameters (for example, window area, night insulation, R-values, wall construction) can then be varied to determine their effect on the auxiliary requirement. This process can be applied from the early to the late design phases. In the early or predesign stage, key design parameters can be varied sequentially over wide ranges to determine design sensitivities. In later design phases when the parameter ranges have been refined, many variables can be varied sequentially over their expected ranges to determine their optimal values.

Despite recent improvements in simulation methodology (see Refs. 27-31 and section B of Bibliography), simulations remain awkward design tools. Large simulation programs require detailed input and extensive computing facilities; the cost of a simulation study with such programs can be significant. At the other extreme, simple simulation programs, such as those which operate on inexpensive programmable calculators, execute too slowly to be practical for annual calculations. Simulation results obtained for an "average" day representative of a month or season are of questionable value because of the nonlinear dependence of building energy use on meteorological variables. However, one-day simulations using extreme weather conditions may be useful for determining maximum temperature excursions and for sizing thermal mass. Simulations which compromise some detail and generality for increased computing speed have been developed.[27-29] Simulations of this type may be the design tools of choice in the future. At this time, however, architects, engineers, and other individuals concerned with the design of residential buildings are more comfortable with the inexpensive, easy-to-use correlation methods than with simulations.

CORRELATIONS

The most popular correlation design tools for passive building analyses are the solar load ratio and solar savings fraction methods.[30-34] These methods identify important design-parameter/weather-data groups and use detailed simulations to empirically correlate these groups with the monthly fraction of the heating load supplied by solar energy. This approach is similar to that taken in the development of the F-chart method[35] for active solar systems and analogous to the method used in other engineering areas where numerous physical measurements are made and correlated.

The two outstanding features of the solar load ratio method, its simplicity and its accuracy for the design of popular system types, explain why the method has received widespread adoption. A difficulty with the original SLR method is its restrictiveness in the scope of system parameters which can be directly considered. For example, in the implementation described in *The Passive Solar Design Handbook*,[32] the effects of number of

glazings, night insulation, R-value, building thermal-storage capacity, collector-storage wall physical properties, and thermostat settings must be deduced from sensitivity plots for six locations. This difficulty has been reduced considerably by expanding the number of configurations for which correlations have been developed from six to ninety-four.[33, 34]

An alternative approach to estimating the auxiliary energy consumption is in the un-utilizability method for direct gain[36, 37] and collector-storage wall[38] systems. The un-utilizability method relies on solar radiation utilizability (a statistic of solar radiation data) to determine the fraction of the solar energy entering the building space which would cause the building space to become overheated. This fraction would not be useful in offsetting auxiliary energy. In the un-utilizability method, upper and lower theoretical limits on auxiliary energy consumption corresponding to hypothetical buildings having zero and very large energy storage capacity, respectively, are determined. The auxiliary energy use of an actual building must lie between these limits and is found from an empirical relation involving theoretical limits derived from computer simulations. The un-utilizability method allows more passive building design parameters to be considered than does the solar savings fraction method, but with more computation effort. Attempts to reduce the computational effort have been made by preparing tabular data to simplify the number of calculations[39] and providing location-specific design charts.[40] The additional computational effort is of little consequence, however, when these calculations are done on a small computer.

An obvious oversimplification of passive system correlation methods is that they attempt to describe the thermal performance of a passive building by considering only the passive component. These methods require, as input, information concerning the heat losses from the nonpassive building components. In most cases, the calculation of these heat losses requires far more computational effort than that needed to evaluate the performance of the passive system component and conservation measures used in the nonpassive components. In addition, calculations made in this manner neglect the effects of interactions between the performance of the passive system component and that of the conservation measures used in the nonpassive component. For example, it has been shown that the passive solar features will degrade the performance of an active solar heating system.[41] Similarily, the effect of thermostat night setback on overall energy use may be affected by the passive system. Effective building-analysis procedures, suitable for economic evaluation of energy conservation measures, must

consider the entire building, not just the passive solar features.

Many correlations are needed to estimate the heat losses from conventional building components. The *ASHRAE Handbook of Fundamentals*[42] provides correlations for infiltration rates as well as for heat transfer through doors, windows, walls, basements, and attics using the degree-day method. Degree days at a base temperature of 65°F (18.3°C) are available for hundreds of locations in the United States. However, due to increases in the levels of insulation, internal energy gains, passive solar features, and conservation measures, 65°F is ordinarily not the appropriate base temperature for evaluating degree days in a modern building. Correlations are available for calculating degree days at any base temperature and also for selected hours of the day.[34, 43, 44]

CONCLUSIONS

Considerable effort has been expended in developing design tools for passive solar buildings. As evidenced by section A of the Bibliography, many simulation programs are available. Most have the sophistication needed to determine the interactions between passive design features and other conservation measures. Yet, none of these simulation codes has become a popular design tool for residential applications, presumably because of the disadvantages cited above. Correlation methods, on the other hand, have become very popular, primarily because of their simplicity. However, these correlations are not as simple as they appear, because they require input information concerning heat losses from the nonpassive building components. Correlations are available for estimating the heat losses and gains for conventional building components. However, when all of these correlations are used, the estimation of the heating/ cooling energy use of a building becomes complex and is no longer amenable to hand calculations.

The disadvantages of both simulation and correlation methods are being alleviated by the availability of inexpensive microcomputers. These machines have the capability to incorporate the many correlations needed to estimate heating/ cooling energy use of buildings along with code to simplify information input/output. It is also possible to run carefully designed simulation programs on a microcomputer, eliminating many of the disadvantages of simulations.* The speed and storage per dollar of these machines are continually increasing. It is now necessary for designers to gain experience and confidence in operating these tools.

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*Section E of the Bibliography lists a number of technical papers on microcomputer programs useful for building energy design. Additional programs of this type can be found in the advertisements of technical and trade journals.

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