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PHYSICS OF PASSIVE SOLAR BUILDINGS*

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Summary

Primary emphasis in the paper is on methods of characterizing and analyzing passive solar buildings. Simplifying assumptions are described which make this analysis tractable without compromising significant accuracy or loss of insight into the basic physics of the situation. The overall nature of the mathematical simulation approach is described. Validation procedures based on data from test rooms and monitored buildings are outlined. Issues of thermal comfort are discussed. Simplified methods of analysis based on correlation procedures are reported and the nature of the economic conservation-solar optimization process is explored. Future trends are predicted.

Introduction

Passive solar buildings are ones which use environmental energies to offset some or all of the need for heating or cooling by artificial means. The environmental energy of major interest for heating is solar radiation which is incident on the building and for cooling it is heat flow to the air surrounding the building perhaps in combination with wind effects and also long wave radiation from the building to the environment.

Artificial heating of the building by means of a furnace or artificial cooling by means of an air conditioner is referred to as "auxiliary energy." Although both strategies normally have the effect of reducing the auxiliary energy requirements we distinguish between "conservation" strategies which tend to reduce auxiliary heating by reducing the total energy requirement, and "passive solar" or "natural cooling" strategies which reduce the auxiliary energy by promoting energy transfer through the external surfaces of the building. Although the distinction is not very precise, conservation consists of a "demand side" strategy while passive solar or natural cooling consists of a "supply side" strategy. As we shall see, these strategies work well together to achieve building designs which minimize auxiliary energy requirements for a fixed total added building cost.

In the 10 years since the terminology was coined, there has been considerable discussion over definition of terms and particularly the words "passive" and "natural" to describe the approaches being taken. Passive is generally meant to include approaches in which the energy flows are by natural means. By definition, this precludes the use of a fan or a pump to cause energy to flow. Energy flow is by radiation, convection, or conduction. "Passive solar" normally refers to the use of solar radiation either for its heating or natural daylighting value. "Natural cooling" generally refers to other, passive non-solar approaches.

The emphasis in this paper will be on the supply side strategies and particularly on passive solar heating. This is not to underestimate the importance of correctly analyzing heat flow through walls by conduction and convection, air leakage through cracks in the external fabric of the building (infiltration), or conduction through the ground surrounding the building, or any other conservation strategies.

This analysis is generally referred to as determining the building "load", energy which must be supplied either by auxiliary energy or by passive means. It is the analysis of the passive energy flows and in the temporary storage of heat within massive elements of the building that will comprise the primary emphasis of the discussion. The analysis of these loads is often simplified, perhaps oversimplified, in order not to be distracted from an accurate evaluation of the effectiveness of various passive solar and natural cooling strategies. It is assumed that a discussion of a more precise analysis of loads will be the subject of other papers in this session and that a thorough analysis of an actual building would include careful attention to these details. When used sensitively and sensibly, the simpler load models are often surprisingly accurate, especially for smaller buildings where the cost of a more complex analysis is not justifiable.

Analysis Approach

In a fundamental sense the analysis of energy flow by natural means is a very complex and formidable task. Fortunately the most complex of these problems can be bypassed without loss of significant accuracy by the use of simplifying

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assumptions. The three most important of these are the following:

- Radiation flow can generally be regarded as either short wave or long wave. The short-wave solar radiation spectrum from the sun, as altered by its transmittance through the atmosphere, is quite complex. But for building analysis it is not usually necessary to track through a detailed spectral analysis. The most important thing to know accurately is the glazing transmittance and this is usually calculated based on measured data as a function of the angle of incidence. For the simple case of glass, a classic calculation using the Fresnel equations and measured absorption characteristics is quite adequate. By far the knottiest problem has been the prediction of the solar radiation, as modified by the atmosphere. This is normally treated by separating direct or beam radiation and diffuse radiation scattered within the atmosphere. A variety of atmospheric models have been used with varying success.

- Once the short-wave solar radiation enters the building through the glazing, very little is scattered back out, normally less than 5%. The effect of energy transport within the building by long wave thermal radiation is so dominant that the energy moves to all of the enclosing surfaces of a direct gain space quickly. Although some analysts have developed detailed radiation flow models and view factors for thermal radiation flow between surfaces, it is seldom worth the effort. Surfaces directly in the sun may be temporarily warmer than others but within a few hours this energy will be found distributed around the space quite uniformly.[1] In special cases of extreme geometries or large aspect ratios some detailed analysis may be warranted. Even in this case simplified models based on wye-delta transformations are very useful.[2]

- When a building is separated into a series of different spaces connected by doorways, energy flow by convection through the doorway becomes a significant and important mechanism, tending to aid the distribution of energy throughout the building. The energy flow rates obtainable are quite significant with modest temperature differences between spaces and often adequate for heating north rooms with modest heat loads. Engineering correlations have proved to be a reasonably accurate method of predicting these important convective effects.[3]

By far the most successful analytical approach has been mathematical simulation of the energy flow in the building using finite difference techniques. The building can be regarded as a simple thermal network with significant heat-storing masses within the building connected by thermal conductances.[4] The situation is analagous to an electrical network with resistive and capacitive elements only. The result is a set of simple first-order differential equations which must be solved simultaneously. Some of the energy transport mechanisms result in non-linear terms although most of the radiation flow terms can be reasonably well characterized using linearized equations since the total temperature range, on an absolute temperature scale, is relatively small. This is not true, however, of the convective effects.

These equations are normally solved either using implicit or explicit finite-difference techniques. The computation marches through time, simulating the energy flows in the building and predicting temperatures. Auxiliary energy is supplied, as required, to maintain established comfort conditions.

The advantage of explicit solutions is the simplicity of the analysis although mathematical stability and accuracy requirements may force a time step of only 10 or 20 minutes. If simulation of an entire year performance is required, this can be very time consuming.

Implicit solutions are normally performed using central differencing in both time and space (Crank-Nickolson technique). The difficulty with this approach is the computing time required to solve the simultaneous differential equations which typically number at least 7 and sometimes upwards to 100. The problem is usually solved by linearization and either matrix inversion or other standard techniques.[4]

Experience has shown that the overall problem is usually quite linear or bi-linear. Thus, only one or two matrix inversions may be necessary. Also, wall sections behave quite linearly and thus Green's function type of solutions are appropriate. These take different forms variously called transfer functions (not to be confused with Fourier transforms), and weighting functions.

In larger buildings simulation of the performance of the auxiliary energy system can be very important and complex. In the more complex building simulation codes this is normally done using a library of routines representing different equipment packages.

The simulation is driven using hourly temperature and solar radiation data for the site of interest. Calculations are typically done for selected periods of both extreme and average weather conditions in different seasons and also for an entire year in order to predict overall auxiliary energy requirements.

Typically, a simulation for an entire year using a series of 11 different differential equations requires about 60 seconds of computing time on a large (CDC-7600) mainframe computer.[4] Such problems are sometimes run on minicomputers and even microcomputers, in which case the computing time may be several hours.

Validation of Mathematical Techniques

The mathematical simulation equations described above are validated by comparing results from actual monitored buildings with predictions made using the analysis techniques. For these calculations the input data to the analysis are usually the measured solar radiation and outside temperature. The calculated and measured data comparisons are done based on temperatures observed at various points within the building and the auxiliary energy requirement.

In an actual occupied building it is very difficult to accurately know all of the important parameters. "Occupant effects" can have a significant influence on the results and these are difficult to control in most instances. There are very few cases where an entire building has been constructed simply for the purpose of obtaining monitored building results.

In order to address these concerns, a dual approach has been taken. Data are taken in small "test rooms" which are inexpensive to build and can be operated under carefully controlled conditions. Several sets of test rooms have been built at different places within the US. A second advantage to this approach is that the building can be made sufficiently simple so that the analysis is not confused by extraneous geometric complexity which is not important to the physics of the energy flow. The most comprehensive set of test rooms have been built at the Los Alamos National Laboratory, starting with two test rooms in the winter of 1976-77 and building up to 14 test rooms during the last two winters.[5]

These test rooms are small cubicles measuring 5 feet east-west by 8 feet north-south by 10 feet high. They are moderately well insulated frame structures with fiberglass and foam insulation and are sealed to reduce infiltration. The south side of each test room is dedicated to a passive solar feature such as a window, a Trombe wall, or an attached sunspace. The test rooms are most often operated with the inside temperature controlled to a fixed level by means of resistance heating elements in the room. The effectiveness of different strategies can be compared directly in side-by-side tests by comparing auxiliary heating requirements. The test rooms also give data for the validation of the computer codes.

Another level of validation data are obtained from actual lived-in buildings. Here the intent is to obtain information which might not be available in test rooms such as the effect of door openings between a house and a sunspace and multistory and multiroom effects. Evaluation of the data is very time consuming and difficult because of the many variables involved. Because of the complexity and cost, very few of these buildings have actually been successfully monitored in a comprehensive way.

The general results of the model validation work have been very encouraging. Relatively simple models seem to give quite accurate predictions of performance. It is generally possible to predict temperatures inside the test rooms to within 1 or 2°C under conditions when inside-outside temperature differences are in the range of 20°C. Auxiliary energy requirements can be predicted to within about 4% of the total building heating load.[6] This correspondence has given confidence in the use of the mathematical techniques to develop other tools suitable for design analysis.

Data comparisons from lived-in monitored buildings have also given confidence. The level of auxiliary heat requirements is generally reasonably close to predictions based on the mathematical models. The error in the comparisons is generally within the range of uncertainty of the data.

Comfort

The physiological study of thermal comfort is an old and established field. Energy-balance models for humans based on the various mechanisms of heat loss have been well developed and calibrated using data from a variety of subjects taken in carefully controlled tests.[7]

Human response to thermal imbalance or physiological stress has been characterized in terms of "percent of people dissatisfied" and a scale has been developed to quantify this.

The various parameters which characterize comfort have been identified and the influence of each has been investigated. The primary variables are air temperature, mean radiant temperature, relative humidity, air motion, the metabolic rate of the person, and the amount of clothing worn. Based on these, thermal comfort can be quantified and standards established.

During the heating season, the most influential parameters are the air temperature in the building and the mean radiant temperature. Thus calculation of the temperature of the surrounding walls is particularly relevant. In passive solar buildings it is particularly important to evaluate and quantify thermal comfort effects and determine single parameters which can be compared with an overall measure of the cost of auxiliary heat. Methods for developing such parameters have been proposed.[2]

Simplified Methods of Analysis

Few building designers have the capability, the inclination, the equipment, or the time to use the computer simulation analysis. Most designers ask for simpler methods which are amenable to analysis using hand calculators in which estimates can be developed in a few minutes. Correlation techniques have emerged as a reasonable procedure which meet these requirements and give reasonable accuracy.[8]

In a correlation technique one seeks to relate a parameter of interest, such as solar savings fraction, to one or more correlating parameters (generally dimensionless). Success is much more likely if the correlating parameters chosen preserve some essence of the overall physics governing the energy balances.

For solar energy systems it has been appropriate to correlate on the basis of a one-month interval, that is, to use monthly weather data to predict monthly performance.

A month has been found to be a particularly convenient time interval, being long enough that statistical variations tend to average out and short enough so that the basic weather statistics are stationary. Furthermore, only eight to twelve calculations are then required in order to predict annual performance. The prediction of monthly performance leads to relatively high standard errors (±8%, typically) but annual performance is predicted with a standard error of only ±3%, typically. This is adequate for design purposes, being significantly less than the year-to-year variation which can be anticipated.

A second feature is that the correlations are done using "data" developed from hour-by-hour computer simulations. Thus the correlation techniques are a second-generation analytical procedure, and their results are intrinsically no better than those obtained from simulations. The correlation techniques, however, are at least two orders of magnitude easier to use in terms of the computing power and the computing time required.

The hour-by-hour simulations which are used as the basis for the correlations are done with a detailed model of the building in which all of the different design parameters are specified. The only design parameter which is changed is the ratio of the glazing area to the building load coefficient of the building. Typically about four different values are chosen so that the correlation should adequately reflect variations in this key parameter.[9]

Thus the correlations do not allow the designer to estimate performance variations due to changes in any of the many other design parameters and the correlations relate only to the reference design used in the simulations.

In order to overcome this difficulty, sensitivity calculations have been done using the hour-by-hour simulation codes. The procedure is to perform a series of year-long simulations for several different values of one of the design parameters, holding all other parameters at the reference level. These results are generally presented in graphical form and allow the designer to see the effect of changing one particular design parameter. This procedure is followed for each of the different design parameters.[9]

Correlation techniques are especially amenable to use in microcomputer routines which can be used in a design office. Very quick answers can be obtained during the schematic design and design development phases of a building to aid in deciding between different design options. This would include tradeoffs between various conservation options and passive solar options.

Conservation vs Solar

When one looks at conservation and passive solar as demand side and supply side strategies, respectively, two possible viewpoints emerge. One is that they are in competition and the other is that they augment one another. In a sense, both viewpoints are valid as discussed below.

Competition exists because if energy savings are made by a reduced demand using a conservation strategy, then less solar collection area will be needed to achieve a particular performance level. Thus the more insulation sold the less will be the demand for glass and concrete for Trombe walls.

The other point of view, and the one which leads to more rational building design, is that conservation and passive solar work well together as a pair of strategies which can produce a building which uses minimum energy for a fixed initial investment.

The problem is easily resolved in a mathematical sense by looking at the nature of the mathematical functions which result from the energy analysis. In order to see this most clearly it is useful to use the simplified methods of analysis because they lead to a better appreciation of the overall nature of the performance surface.

Suppose we start with a conventional tract house located in Dodge City, Kansas. This base or "reference" house has only nominal levels of insulation and no explicit passive solar features; that is, building orientation and window glazing are chosen with no reference to solar orientation.

The various conservation options which are available consist of discrete choices which can be made for insulation levels in the wall, ceiling, and perimeter, number of window glazings, and various strategies which might be taken to control infiltraton, including airtightness, sealing of the house and the possible use of inside-outside air exchangers with heat recovery. As shown in Ref. 10, the overall cost of conservation savings varies as an inverse function of the overall building heat loss coefficient. Convenient algorithms for selecting among the various conservation strategies can be developed by assuming that the cost-load functions are smooth inverse functions which pass through the discrete points available.

Figure 1 shows the results of the analysis for the Dodge City, Kansas example, using reasonably current estimates of the add-on costs for both conservation and solar strategies. The costs of conservation and solar are individually plotted on the Y-axis and X-axis, respectively. The solid curved lines show paths of constant energy savings for a heating season compared to the reference house.

Lines of constant initial investment are straight lines connecting equal cost points on each axis, such as the $4000 dotted line shown on Fig. 1. The minimum energy use for a fixed initial investment corresponds to the locus of points where the dashed lines are tangent to the curved lines. This locus of points is labeled the "optimum mix" line on Fig. 1. In economic parlance this is called an "expansion line". It represents a constrained optimum solution in which the initial investment is limited.

Of course the other dimension of interest in the economic optimization of either conservation or solar is the value of the future cost of fuel which will be saved. This leads to a fairly typical problem in life-cycle economics. The normal problems with performing analyses of this

kind are uncertainties in predicting the future cost of fuel and the problems of discounting that back to a present value. This entails consideration of interest rates and a number of other economic factors. The optimum mix line on Fig. 1 provides a methodology for allocating resources between conservation and solar but gives no guidance as to how far out that line it makes economic sense to proceed.

The value of future fuel savings can be added to the equations and a global optimum can be obtained. One way of presenting this information is to show contours of constant life-cycle savings on a plot having the same X-axis and Y-axis coordinates as Fig. 1. This is shown in Fig. 2 for some assumed values of fuel cost and financing scenario. The details are given in Ref. 10. The important thing to notice on Fig. 2 is the shape of the optimization surface. It is a relatively steep-sided surface with a moderately flat top. This is a very typical result. Note that the global optimum point on Fig. 2 lies along the optimum mix line on Fig. 1.

There are two policy implications of these observations. The first is that the optimum mix path is a good strategy which leads to a global optimum for some assumed future financial scenario and thus it always makes sense to design along this line. The second implication is that it's not so important to be precise about the optimization process but rather to use it as a general guide to get in the overall vicinity of the optimum.

Optimizing a building design is somewhat like climbing a mountain. Seen from a distance the mountain, covered with trees, seems fairly smooth and it's easy to make out the overall shape and locate the summit. A hiker on the mountain has an entirely different perspective. He can't tell much about the overall shape of the mountain but is absorbed in the detailed structure in his vicinity which was obscured and ignored by the faraway viewer. The hiker may attain the top of a local outcropping thinking that he has reached the summit when he is still far below it.

So it is with the designer trying to find the best design strategy. He may waste a lot of time looking for a local optimum when he's in the wrong place altogether. All he really wants to do is get near the top knowing that attaining an exact optimum is rather meaningless because the costs are not that well known anyway. The shape of the constant life-cycle cost contours define a surface which is a rather flat-top mountain with steep sides (see Fig. 2). Once the designer is in the right vicinity only small changes in life-cycle cost can be made by relatively large shifts in level of conservation or passive solar. This is the case because the performance changes are just about offset by the cost changes. At this point the designer will be far more concerned with other factors which drive the design, such as convenience of framing, availability of materials, and aesthetics.

In a practical sense tables can be constructed which provide the climate-dependent performance factors used in the optimization process for different passive design strategies and different locations. Simple functions result which allow the designer to quickly find optimum levels of insulation and other conservation strategies which represent an economic balance with the level of passive solar performance being achieved.

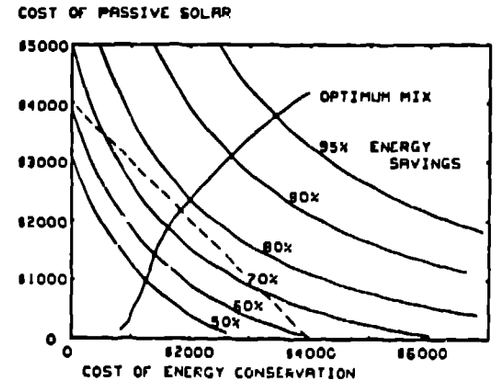

Fig. 1. Performance map showing the energy savings expected for different initial expenditures.

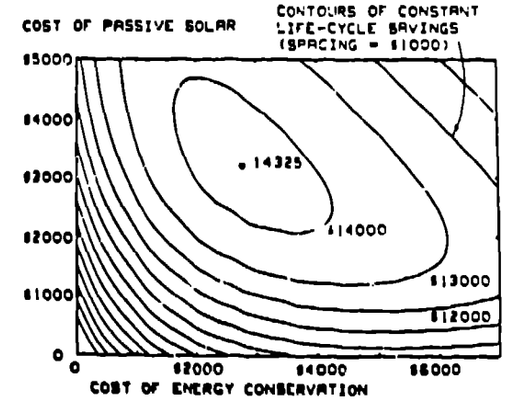

Fig. 2. Life cycle savings (in present dollars) compared to the conventional house. (The coordinates are the same so that Fig. 2 can be overlaid on Fig. 1. Back-up heating is electric.

Future Trends

The analysis of energy flow in buildings has been neglected and we are still in the infancy of our knowledge regarding this important field. Better understanding of energy flow mechanisms and the effects of these on human comfort are needed. Study of natural cooling mechanisms is just beginning. These are intrinsically more difficult because the system is open to the environment rather than being closed as in the case of a building in winter. The effects of air buoyancy and wind driven effects in the building are dominant, whereas they are minor in the case of a heating analysis.

Future trends can be anticipated in several complementary directions. One is a more detailed study of some of the important heat transfer mechanisms such as convection between adjacent spaces. Another will be in increasing the number of different system design options which have been analyzed in detail and their characteristics tabulated. A variety of analytical design tools will be developed and validated appropriate to different designer levels and building types. Feedback of data from monitored test rooms and buildings will play a continuing important role.

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