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Calculating energy utilization in residential housing

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Summary and Introduction

The primary objective of this research effort was to develop a mathematical model and digital computer program for accurately calculating the energy required by residential housing units.

This model was used to establish an accurate procedure for determining the monthly and seasonal energy requirements of all types of residential structures. It takes into account all the internal and external dynamic loads imposed on the structure, such as changing weather conditions and changes in appliance usage and occupancy inside the structure.

The mathematical model and digital computer program developed were verified by extensive calculations and field measurements applied to nine residential dwelling units. Four of these sites have identical two-storey frame construction, one of which was unoccupied throughout the project and was thus used as a control house or a minimum energy usage home.

The technical aspects of the project were developed by personnel at Edison Electric Institute.

Once the project was defined, the Electric Power Research Institute requested proposals and awarded a contract for project completion to the author at The Ohio State University.

Columbus area site selection

The Columbus site selection process involved choosing six recently constructed homes and three apartments which could be fully instrumented. To facilitate comparisons between energy consumption in each house, it was considered desirable to find homes that were occupied by families with the same number of people and about the same age and socio-economic status.

To distinguish between each site and to describe some of the characteristics of each site a four-letter code system was developed.

For example, the control home was designated CTSE, the first letter being the first letter of the owner's name or, in this case, control. The next two characters describe the type of house. The last letter tells the type of heating system.

Four of the sites selected: CTSW, ETSC, HTSG and KTSC, were similar in construction, being two-storey homes with aluminum siding and attached garage. House KTSC had the same orientation as the control house, CTSE, and was located next to site HTSG. House HTSG was the reverse floor plan of the control house and the house was rotated 24° from the control house orientation.

The fourth site, ETSC, was oriented in the same direction as the control house but was located in an area different from the control house and houses KTSC and HTSG.

The fifth house was located behind site HTSG and was designated HSLG. This house was a split level with stucco finish and attached garage.

The sixth house was a ranch style of brick and stucco construction with attached garage and was designated SRSG.

All of the above sites were in the northeast section of Columbus, Ohio.

The apartments selected were of the two-storey, townhouse type with a full basement. They were designated KAWG, OAMG and PAEG and were located in the northwest section of Columbus.

Complete US meteorological weather stations were located at sites KTSC and SRSG. The weather stations were installed by the OSU research team.

Instrumentation of Columbus sites

The purpose of the instrumentation was to measure the data points for validation of the simulated heating and cooling loads and energy consumptions.

Numerous types of instrumentation were required to measure

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Numbers in brackets on margins indicate numbered references at end of article.

meteorological variables, space temperatures, dew-point temperatures, and gas flow rates plus electrical consumptions.

All of the instrumentation selected was to be initially compatible with IBM System 7 computers or the instrumentation signals had to be adjusted to an acceptable level.

The major objectives in the selection of instrumentation and signal conditioning for 400 data points which are located at a variety of remote sites and must operate continuously for approximately 10,000 hours are: high reliability, interchangeability, commercial availability, accuracy, compatibility with an IBM System 7 computer, low cost, and a minimum of field adjustments, calibrations, modifications and maintenance.

In general, these requirements suggested the use of digital inputs where possible. However, each type of instrumentation was thoroughly reviewed and the appropriate selection made.

The IBM System 7 data acquisition system provided the channels for digital and analog inputs and integration. The System 7 establishes the following requirements for inputs:

1. Switch closure sensing, digital.
2. Applied voltage signal, digital.
3. Scan time base; a data scan rate of 200 per second.

A description of instrumentation used for each data point is included in the following paragraphs.

Electrical energy, fluid flows (natural gas, water and air) and on/off signals were measured with digital output.

Temperature measurements were made with linearized thermistors to take advantage of the relatively high sensitivity and linearity required for time averaging of the analog signals.

Kilowatt hour meters were altered to produce two voltage pulses for each revolution of the rotor by using a photon coupled interrupter module.

Natural gas positive displacement meters were altered to provide one voltage pulse for each revolution of the one-quarter cubic foot dial by use of a photon coupled interrupter module.

The cold water flow into the domestic hot water tanks was measured with positive displacement meters having magnetic drives for the dials. These units were altered to provide a switch closure signal for each revolution of the internal magnet.

Conditioned air flow velocities were measured with propeller anemometers mounted in the return air ducts. The output of one voltage pulse per revolution was obtained from a photon coupled interrupter module circuit mounted on the propeller shaft.

Temperatures were measured with thermistors having an essentially linear output.

Dew point was determined by a lithium chloride type moisture sensor with themistor temperature sensor.

Switch open/close devices identify manual and automatic functions of the following types:

1. Manual switching of power consuming devices, such as outside lights, exhaust fans, etc.
2. Automatic switching and power consuming devices, such as a furnace blower.
3. Manual opening or closing of doors and windows.

Total solar radiation and diffuse or sky radiation were both measured in the horizontal plane by temperature compensated pyranometers. The diffuse or sky radiation pyranometer was shielded from the direct solar radiation by a shadow band fixture.

Wind speed was measured with a rotating cup anemometer, mounted on a mast.

A vane type wind direction indicator with analog output indicated wind direction of use of a 360 degree, low friction potentiometer installed to provide an analog output.

At sites KTSC and ETSC the heating and cooling equipment was changed approximately every six weeks during the test year. The control house served as a comparison for the energy requirements for the other two houses. The different systems that were installed in each of the two houses were:

1. Gas furnance
2. Air-to-air heat pump
3. Electric furnace
4. Baseboard electric heaters

Air conditioning systems used were electric for all homes and were either of the conventional cooling only type or a heat pump.

The data recorded during the period of equipment changing was used to compare energy consumption of the system.

Thermal load analysis

The basic algorithms adopted for calculating thermal loads on structure under thermostat control are available in references (1,2,3). The general principle of the algorithms is the simultaneous solution of equations describing the heat flux at the interior surface of envelope elements. The load requirement on the heating and cooling systems is the algebraic sum of all envelope elements loads plus instantaneous heat gains and losses from people, lights, equipment, and air infiltration. Heat flux through envelope elements exhibiting thermal mass are calculated using the "response factors" technique.

The principles for calculating loads under controlled space temperature conditions are inadequate when the conditioned space is not under temperature control. Typically, space temperatures in residences are not controlled during mild weather conditions and during the summer cooling season when air conditioning equipment cycles off the thermostat at night.

An additional equation is required to account for the indoor temperature variable and must be solved simultaneously with the interior surface equations.

This equation relates the thermal capacitance of the space to the net space load. There are multiple energy storage elements in the conditioned space such as the air, interior partitions, floors, and furnishings. Each of these has specific capacities and response times.

All thermal storage elements were lumped into a single effective term to simplify the analysis. The equation used to relate thermal storage to net load is:

$$m \times c_p \times dT_a/dt = Q \ldots\ldots\ldots (1)$$

c_p = effective specific heat
m = effective internal mass
T_a = indoor air temperature
t = time
Q = space thermal load

The left hand side of Eq. 1 is transformed using Euler's approximation to:

$$m \times c_p \times dT_a/dt = m \times c_p \times (T_{a,t} - T_{a,t-1}) \ldots (2)$$

A solution to Eq. 1 for the present space air temperature is possible knowing the previous hours' space temperature. The concept used to simulate floating temperatures is a departure from ASHRAE where thermal masses are treated similarly to other envelope elements. It must be noted, however, that the ASHRAE algorithms may still be utilized in this program by simply setting the effective mass parameter to zero.

The thermal load algorithms are incorporated in a Fortran IV code deck. The program structure consists of a main stream and various subroutines. The function of the main stream is to accept input data describing the physical characteristics of a residence and to coordinate calling of the subroutines. All thermal, geometric and psychrometric calculations are performed in the subroutines as well as reporting of results. Fig. 1 illustrates the program logic flow.

```
┌───────── PROGRAM LOOP ( EXECUTED ONE TIME )
│      Read Physical Data
│ ┌─────── HOUR LOOP ( NUMBER OF HOURS STUDIED )
│ │ ┌───── DELAY ELEMENT LOOP
│ │ │
│ │ └─────
│ │ ┌───── INTERNAL ELEMENT LOOP
│ │ │
│ │ └─────
│ │ ┌───── WINDOW ELEMENT LOOP
│ │ │
│ │ └─────
│ │      Calculate Air Infiltration
│ │      Solve for Space Load or Space Air Temperature
│ │      Calculate Unconditioned Space Temperature
│ │      Output Hourly Results
│ └───────
│        Output Daily and Monthly Results
└───────── STOP
```

Fig 1. Logic flow diagram.

Several subroutines were developed to provide specific calculation functions.

A routine was added for predicting attic space air temperatures.

A routine for predicting air infiltration rates as a function of temperature and wind induced pressure differences across cracks in the thermal envelope was incorporated.

A routine for calculating temperature in adjoining unconditioned spaces such as basements, crawl spaces and garages was added.

A routine for predicting ground temperatures adjacent to foundation walls and floors based on a finite difference approach was developed and added.

Finally, a routine capable of simulating the thermal performance of single and double glazed window system as a function of thermal gradients across windows was incorporated.

The program was executed on the Ohio State University IBM 370/168 computing facilities. Memory core requirements are 260K bytes. Computing time requirements are 10 CPU seconds for each day of simulating loads. These core and time requirements are based on 60 envelope elements and would be substantially less for fewer elements. Recent optimization and modifications to the code suggest that the computing time requirements may be reduced by a factor of four.

Field validation

The relative accuracy of the ther mal load algorithms was checke against available field data collecte in the Columbus research resi dences. Hourly field data from tw weather stations consisted of ou door dry-bulb and dew point tem peratures, wind speed and dire tion, direct and indirect solar radia tion, and rainfall. Data availab from the residences included spac temperatures, humidity level power consumed by the heating an cooling systems and all majo electrical appliances, and air deliv ery rates.

Two questions had to b addressed concerning state accuracy levels of thermal load pro grams.

First, did sufficient field dat exist whereby the individual pro gram components could be inde pendently verified?

Secondly, could thermal loads be separated from heating and cooling system energy consumptions?

Concerning the initial question, the accuracy levels of a few individual components were established where field data permitted. These components were the attic temperature, ground temperature, air infiltration, and internal load routines.

It was not, however, possible to verify each and every program component singularly.

Field data to do this simply did not exist.

A critical question was whether thermal loads and energy consumption could be separated from the measured data.

Energy consumed by the heating and cooling equipment was available hourly from the field data and no direct load measurements were taken. Therefore, it would be necessary to back out system thermal efficiencies from the measured data. Load and energy are related by:

$$E = Q/\eta(Q) \qquad (3)$$

E = energy consumed
Q = thermal load
η = system efficiency

System efficiency has two components, conversion and distribution efficiencies, and is a function of the load.

Fig. 2 illustrates the hour by hour comparison of simulated and field measured baseboard energy consumption over a one week period. Shown at the top of the plot are actual outdoor air temperatures and horizontal solar radiation data. Simulated energy consumption was 1090 kWh compared to 1140 kWh measured for a difference of 4.4 per cent. Simulated hourly consumption ranged from 2.1 to 8.9 kWh compared to a measured range of 3.0 to 9.5 kWh. Outdoor temperature for the period ranged from -4.2°C to 17.6°C. Predicted space thermal loads ranged from 179 W to 7025 W during the validation period.

System models

A general modeling procedure was developed for central forced-air systems. The generality of the procedures provides continuity among the various system types studied and is also applicable to other systems.

Three system components are identified in the model:

- Heating and cooling equipment
- Thermostat controller
- Air distribution network

Each of the above components influences overall system performance.

A flow diagram for the system models is illustrated in Fig. 3.

The first step involves determining the rated capacity of the equipment, estimating the thermostat cycling rate, and initializing the equipment run time per cycle. A system loop is then entered where part-load equipment performance is determined. Supply air temperature leaving the furnace is calculated from the equipment models. Duct losses are then calculated in the air distribution model based on entering air temperature. Energy delivered to the conditioned space per cycle is calculated from temperatures and flow rate at the registers and is compared to the space load requirement. A fast converging technique is used to adjust equipment run times per cycle and the system loop is reiterated until energy delivered to the space is within prescribed limits of the load demands. Fuel requirements for the hour are finally calculated from equipment run time per cycle and number of cycles completed during the hour.

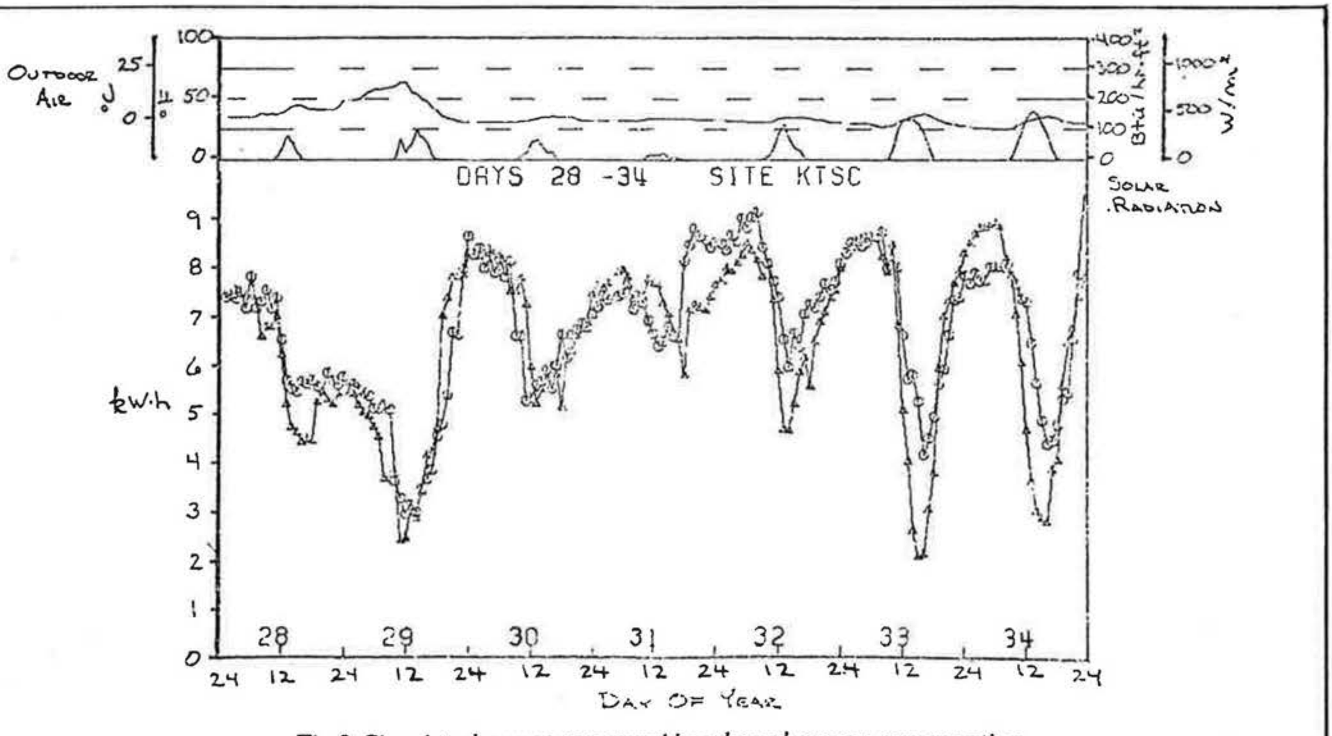

Fig 2. Simulated versus measured baseboard energy consumption.

HVAC SYSTEM MODEL LOOP (1 HOUR)

Determine Rated Output Capacity Equipment

Estimate Number Of System Cycles Per Hour

Estimate Equipment Run Time Per Cycle

HVAC SYSTEM PERFORMANCE ITERATION LOOP

Determine Energy Output Of HVAC Equipment Based On Run Time

DUCT LOSS ITERATION LOOP

Determine Duct Distribution Losses Based On Equipment Energy Output Per Cycle

Determine Total Energy Delivered To Satisfy The Load

Increment Run Time Per Cycle Until Conditioned Space Load Satisfied Or System Capacity Exceeded

Determine Fuel Requirements For Individual Energy Consuming System Components

Fig 3. System model logic flow.

Equipment

The equipment models provide two functions: first, to establish rated full-load capacities; and second, to provide actual capacities under cycling operation.

Rated full-load capacities are based on manufacturers' specifications.

Gas-fired furnaces are considered to deliver 75 per cent of rated input capacity.

Electric resistance furnace output is considered to be installed capacity.

Heat pumps and air-conditioners pose a more complex problem than the previously mentioned systems in that the manufacturers' rated capacities vary with time dependent variables.

The functional relationship for heat pump heating is expressed as:

$$q_o = f(T_{odb}, T_{edb}, T_{ewb}) \quad (4)$$

q_o = equipment output capacity
T_{odb} = outdoor dry-bulb temperature
T_{edb} = entering dry-bulb temperature
T_{ewb} = entering wet-bulb temperature

A computer routine was developed to convert rated performance data from tabular to equation format.

The routine determines
cients to a polynomial us
regressed fit.

Presently the routine is c
of accepting as input tabula
from several major heat
manufacturers.

The second function of
equipment models is to pr
part-load performance ch
teristics. Part-load perform
results in decreased efficiency
thermal cycling of the equipr
Energy is stored in equipment
ponents such as heat exchan
coils, and furnace shells while
equipment is running and dissi
during standby. When equipme
located in a non-conditioned s
such as a basement, much of
dissipated energy never reaches
conditioned space.

Air distribution network

The air distribution networ
the final component of the syst
models.

Thermal losses are always as
ciated with ductwork located in
unconditioned space such as a ba
ment or crawl space. Losses oc
between the central forced-air f
nace and the registers feeding t
conditioned space due to cond
tion, convection, and radiation.

A portion of these losses
recovered by the conditioned sp
since basements and crawl spa
are tempered by this loss. Howev
a definite penalty is incurred due
accelerated losses through foun
tion walls and floors.

A lumped parameter approach
again taken for modeling the air d
tribution network.

Air enters the duct system fro
the furnace en route to t
registers. Losses and therm
storage in the duct occur at so
mean supply air temperature. A
iterative solution is used due to t
convection and nonlinear radiati
loss terms.

Supply air temperature and flo
rate at the registers are calculat
knowing energy entering the
distribution network from t
equipment and losses to uncon
tioned spaces. Air distributi

(continued on page 44)