A Calculator Programming Technique for Estimating Thermally Optimum Wall Construction

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To forecast energy savings in a building energy study a method was needed to predict building energy usage both before and after the proposed option is implemented. The method originally chosen for prediction was the "bin method" as described in the 1976 ASRHAE Systems Handbook.[1] This method utilizes five degree outdoor dry-bulb temperature "bins". The amount of time corresponding to each temperature bin is recorded for a large number of cities in the United States.[2] Using this data it was possible to predict energy consumption of most buildings to within fifteen percent.

The ASHRAE Systems Handbook describes two other methods for predicting energy consumption, the degree-day mehtod and an hour-by-hour computational procedure. The degree-day procedure is a simplistic method designed to provide a quick estimate of building energy needs. The degree-day method considers only the bulding envelope, allowing no consideration of the type of system employed to heat and cool the building. The type of system used plays a significant part in the building energy consumption and many modifications for energy conservation must involve the system or its controls. For this reason the degree-day method was judged unsatisfactory. Hour-by-hour calculations offer accuracy unobtainable by the other methods; however, the calculations involved were too lengthy to be performed with a hand calculator. Also, data are available for only a limited number of cities throughout the United States.

The hour-by-hour method, although quite desirable, was judged to be unduly complicated for the original studies to be performed.

Models using the bin method were then developed to allow prediction of the building mechanical system and the building envelope interaction and their affect on energy consumption. Four basic types of systems were modelled and calculation sheets developed. The four are single zone air conditioning units, multizone and dual duct, variable air volume and heat pump systems.

Figure 1 in the appendix shows the schematic of the single zone system model. Figure 1 also shows the equations used to calculate the energy used by the system to condition the air within the space. The bin data lists the hours per year that the ambient air temperature falls within a five degree range or bin. The mean temperature in each bin was selected to represent the

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cold deck and hot deck temperatures, EQ.5. The heat required by the hot deck can then be determined knowing the amount of air passing through the hot deck; the hot deck leaving air temperature and the mixed air temperature determined as in the single zone model, EQ.6. This process is repeated for the cold deck, EQ.7. Again, as in the single zone model, these rates of heat gain and loss are multiplied by the hours listed for each bin, the totals of heating and cooling are obtained and then are adjusted for seasonal equipment efficiencies to obtain total energy required.

The variable air volume model, see Fig. 3, presents a case, as the name implies, where the supply air temperature is fixed and the combination of envelope and internal heat gains determine the supply air volume, EQ.8. The values for total heating and total cooling energy can be computed as before by knowing the volume of air to be supplied to the room, the supply air temperature and the mixed air temperature at each bin, EQ.10. The variable air volume model contains a preheat coil. The purpose of this heating coil is to maintain the mixed air temperature above a minimum value. Several cases were found where the required minimum outside air caused the mixed air temperature to fall below the set supply air temperature, see EQ.11. In a variable volume system the fan would simply have to supply less air and this would be an advantage insofar as energy consumption is concerned; however, the colder air temperature could cause uncomfortable drafts within the room so the preheat coil has been included.

The volume of manual calculations involved in examining just one alternative using the bin method suggested development of a calculation procedure using a hand-held, programmable calculator with permanent storage. Included with the calculator is a printer providing printed results for each temperature bin along with the cumulative total of heating and cooling required. The length of the programs requires all but a small percentage of the available program and memory space. This program requires both sides of a magnetic program storage card for program storage and one side of another card for headings and titles for the print-out. Bin data has been stored on magnetic cards for several cities in our area with occupied data on one side and unoccupied data on the other. These calculator programs have been used in many energy audits and have been found to greatly reduce the calculation time involved.

Concurrently with the development of these calculator programs, architects were asking our firm for a way to determine the insulation value to specify for new building construction. Initial attempts to develope a simple nomograph to relate the building yearly energy consumptions to building overall "U" value proved unsuccessful. While searching for information concerning these parameters an article entitled, "More Insulation Can Increase Energy Consumption"[3] by Lawrence G. Spielvogel, was discovered. In his article, Mr. Spielvogel uses the "bin" method to suggest that for a given building an optimum "U" value exists. Optimum in this case meaning a "U" value at which the building will use the least energy for heating and cooling.

Having developed calculator programs for predicting energy consumption, using the bin method, it was a simple matter to use these programs to obtain plots of heating energy and cooling energy required versus building overall "U" value. The information required to perform the plotting analysis includes building surface area, an estimation of building internal heat gains, including number of occupants and lighting levels, the amount of ventilation air required, the room setpoint temperature both summer and winter, night reset temperature if night reset is used, and whether or not an economizer cycle will be employed. The amount of air circulated to the room can be estimated if the floor area is known. This will be used in the case of the single zone or dual duct/multizone models or a supply air temperature can be selected in the case of the variable-air-volume model.

Having this information, the program using whichever system is chosen for the building, is run at least five times using each time a different "U" value. The five values for heating energy and the five values for cooling energy are then plotted versus the corresponding "U" values, see Fig. 4.

bin for calculation purposes. In the single zone model a room heat gain or loss is calculated for each bin. (In all cases throughout this discussion the term, "room", will be used to represent the space to be conditioned. The term, "room", could refer to a single room, a zone or several rooms, or the entire building.) Knowing the amount of air that will be supplied to the room, and the desired room temperature, it is possible to calculate the supply air temperature required to the room, EQ.1. Ignoring duct heat losses or gains this temperature is also the required coil discharge temperature. Knowing the amounts of return air and outside air to be drawn through the air handling unit, the coil entering temperature can be determined for each bin, EQ.2. Having determined the coil entering and leaving temperature, it is possible to calculate the rate at which heat must be added or removed by the coil, EQ.3. This rate of heat added or removed will be expressed in BTU/Hr. and when multiplied by the hours listed for the bin temperature for which it was calculated will provide us with the total heat, in BTU, required for a given year at that particular five degree range of outdoor temperature. After this procedure is repeated for each bin the total heat supplied to and removed from the conditioning unit will be known. To calculate the energy input to the conditioning unit seasonal efficiencies must be applied to both the heating and cooling totals.

The single zone system is the simplest of systems yet it can be seen that the calculation procedures are quite complex. This model will allow the examination of resetting the room air temperature setting or varying the amount of outside air used for ventilation and their affects on energy consumption. The model, of course, also allows examination of modifications to the building envelope.

The model also uses building internal heat gains as part of the room heat load, see EQ.1. The effects of varying internal gains can thus be taken into account.

The bin data is listed in three eight hour periods roughly corresponding to normal building occupied and unoccupied periods. The ASHRAE Handbook explains a method for correcting data for periods other than those listed in the bin tables. Calculating the total heat gains and losses for both occupied and unoccupied periods allows examination of the effects of unoccupied period temperature reset. Also to be accurate it must be recognized that during unoccupied periods the internal heat gains are substantially reduced. The effect of eliminating ventilation with outside air during unoccupied periods may also be determined.

Another modification to the ventilating system is to utilize outdoor air, when possible, for cooling. This is known as the "economizer cycle". The model chosen for the economizer cycle allows outside air to remain at a minimum from the lowest temperature bin to the bin when the room first requires mechanical cooling. From this point the amount of outside air is gradually increased to maintain a pre-selected mixed air temperature until the bin is reached which includes the mixed air temperature. At this point the supply air is one hundred percent outdoor air. This condition is maintained until we reach the bin containing the room setpoint. For all outdoor air temperatures higher than room setpoint the amount of outdoor air is reset to the minimum setting.

The dual duct/multizone model, see Fig. 2, shows a system employing simultaneous heating and cooling to maintain room air conditions. Here again, as with the single zone model, the temperature of air supplied to the room is determined from the combination of envelope heat gains or losses and the room internal heat gains, EQ.4. In this case, however, the room supply air temperature is not the coil leaving temperature. Instead we have a "hot deck", or heating coil, maintaining a constant leaving temperature and a "cold deck", or cooling coil, also maintaining a constant temperature. Mixing dampers in the unit, or nearer to the room in the case of a dual duct unit, mix varying percentages of the hot and cold air streams to obtain the necessary supply air temperature. The percentage of total room supply air moving through the hot deck can be determined knowing the required supply air temperature, and the

Curves are drawn and these curves are then graphically added to produce a total energy curve. The minimum point on this curve will correspond to the optimum "U" value.

For an example of this method, consider an office building located in Wichita, Kansas. The building contains 84,000 square feet on three floors. The envelope area is 50,440 square feet with internal gains of 1,200,000 BTU per hour. The single zone air handling systems chosen will move 60,000 CFM of air with a fixed 25 percent outside air during the occupied periods. Indoor temperatures are to be maintained at 78°F during the cooling season and 68°F during the heating season with night reset temperatures of 50°F heating and 85°F cooling. The envelope "U" values analyzed ranged from .1 to .4 and the results of the analysis are presented in Figure 4.

It can be seen that the minimum total energy consumption would be achieved with an overall "U" value of approximately .2. If the building internal gains were less the optimum "U" value would be lower. Conversely if the internal gains were greater the optimum "U" would be higher.

Lowest energy needs, however, are not always the entire analysis. In the case of a building using gas heat and electric air conditioning the cost of one million BTUs of cooling will be far greater than the cost of one million BTUs of heating. Another optimum point exists, then, the point of minimum energy costs. For the example presented the optimum "U" value, considering costs, would be higher than the optimum value for energy consumption, the object being to minimize the cooling energy required.

These programs provide a method to analyze a building's envelope, before construction, to determine the thermally optimum envelope heat transfer coefficients. The data obtained by this method must be reviewed realizing several inherent inaccuracies within the method itself. The bin method of estimating energy consumption, is itself not an exact method. Using the mid-point temperature of each temperature bin holds the calculations involved to a manageable level but produces a minor inaccuracy. The major drawbacks to the bin method as it is used in the programs are the inability to analyze the effects of solar heat gains and latent heat, the effect of thermal mass, or the effect of moisture content in the air.

Once the optimum overall "U" value has been determined the architect may decide on percentages of various wall and roof constructions to be employed within the building. The weighted average "U" values of these constructions must equal the overall "U" value found using the programs, however, the amount of glass and the orientation of the glass within the envelope will affect building energy consumption. For example, an architect may develope an envelope with very low "U" values for the roof and the walls on north, east, and south sides and decide the west wall should be all glass. The overall "U" value may match the predicted optimum but the energy consumption may be increased from that predicted by the west exposure solar gains.

The models, as they are now written, do not include any latent heat gains in reference to coil loads. The effect of the latent heat gain is to increase the cooling capacity required at any given set of temperature conditions. Tabulated with the ambient dry bulb temperatures in the bin data are the average coincident wet bulb temperatures. Humidity data could thereby be included in the model if greater programming space were available in the calculator.

The effects of solar insolation and humidity; however, have been assumed to be simply a constant addition to the cooling energy requirements as presented and therefore will not greatly affect the predicted overall optimum "U" value.

The models, as presented, have been written initially to predict building energy consumption and as such, provide information not required in the analysis of optimum envelope performance. The programs could be altered to print out only the cumulative totals of heating and cooling energy required thereby decreasing the time required for each iteration. Using these modifications a building could be analyzed in approximately two hours providing an excellent, inexpensive tool for building envelope analysis.

Further development of the building mathematical models will be carried out on a mini-computer allowing more program space than the hand held calculator. Initially the bin method will be used with further development occurring in the area of translating space loads into actual equipment energy requirements. Although more accurate building energy use determinations will be possible with further development of the programs the analysis of building envelope presented here will not be affected. The calculator programs present the simplest determination of the relationship between energy use and overall envelope heat transfer coefficient.

NOMENCLATURE

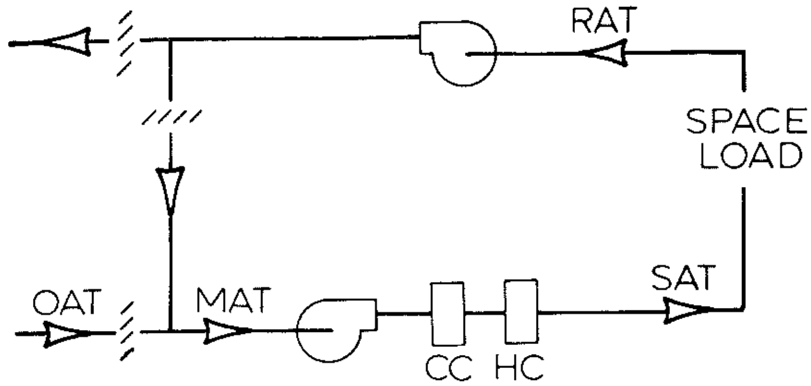
1.	"U" value	heat transfer coefficient (BTU $Ft^{-2} \circ F^{-1} Hr^{-1}$)
2.	SAT	supply air temperature to room
3.	RAT	room or return air temperature (assumed to be equal)
4.	OAT	outdoor air temperature
5.	MAT	mixed air temperature (mixture of outdoor and return air)
6.	CD	multizone unit cold deck
7.	HD	multizone unit hot deck
8.	CDT	cold deck leaving air temperature
9.	HDT	hot deck leaving air temperature
10.	I.G.	room internal heat gains
11.	A	building envelope area bordering on room
12.	CFM	air flow quantity (Ft^3 MIN^{-1})
13.	% OA	percent of coil entering air that is outdoor
14.	% RA	percent of coil entering air that is return air
15.	QCoil	heat removed from or added to the air stream by the coil
16.	CC	cooling coil
17.	HC	heating coil
18.	% CFM_{HD}	percent of total room supply air passing through the hot deck
19.	% CFM_{CD}	percent of total room supply air passing through the cold deck (equal to 1-%CFM_{HD})
20.	Q_{HD}	heat added to air stream by hot deck
21.	Q_{CD}	heat removed from air stream by cold deck
22.	$Q_{Preheat}$	heat added to air stream by preheat coil
23.	MAT_{Fixed}	mixed air temperature chosen to be maintained
24.	MAT_{Actual}	actual mixed air temperature
25.	PHC	pre-heat coil

REFERENCES

1. ASHRAE Handbook; Systems 1976 - Chapter 43, American Society of Heating, Refrigerating and Air Conditioning Engineers.

2. Air Force Manual 88-29; Facility Design and Planning Engineering Weather Data, Departments of the Air Force, the Army and the Navy, July 1, 1978.

3. Spielvogel, L.G., "More Insulation Can Increase Energy Consumption, ASHRAE Journal, 16, 1:61-63, January, 1974.



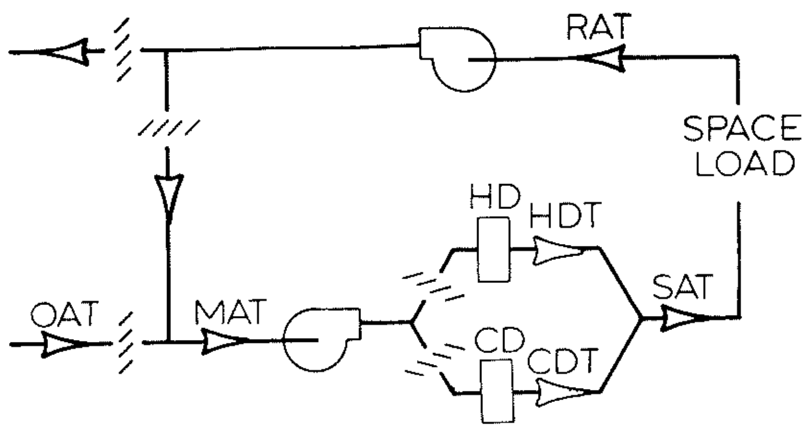
EQUATIONS:

$$1.\quad SAT = RAT - \left[\frac{[UA(OA \quad - RAT)] + IG}{1.085\ CFM}\right]$$

$$2.\quad MAT = \%OA(OAT) + \%RA(RAT)$$

$$3.\quad Q_{COIL} = 1.085\ CFM\ (MAT - SAT)$$

Fig. 1 Single Zone System Model



EQUATIONS:

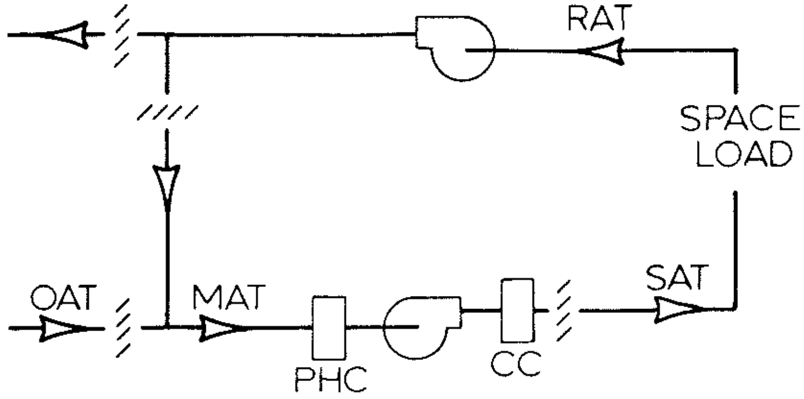
$$4.\quad SAT = RAT - \left[\frac{[UA(OAT - RAT)] + IG}{1.085\ CFM}\right]$$

$$5.\quad \%\ OF\ CFM\ THRU\ HD = \frac{SAT - CDT}{HDT - CDT}$$

$$6.\quad Q_{HD} = [(\%CFM_{HD})CFM]\ 1.085(HDT - MAT)$$

$$7.\quad Q_{CD} = [(\%CFM_{CD})CFM]\ 1.085(CDT - MAT)$$

Fig. 2 Dual Duct/Multizone System Model



EQUATIONS:

$$8.\ CFM = \frac{UA(OAT - RAT) + IG}{1.085\,(RAT - SAT)}$$

$$9.\ MAT = \%OA(OAT) + \%RA(RAT)$$

$$10.\ Q_{COIL} = 1.085\,(CFM)(SAT - MAT)$$

$$11.\ Q_{PREHEAT} = 1.085\ CFM\,(MAT_F - MAT_A)$$

$$\text{IF } MAT_{ACTUAL} < MAT_{FIXED}$$

Fig. 3 Variable Air Volume System Model

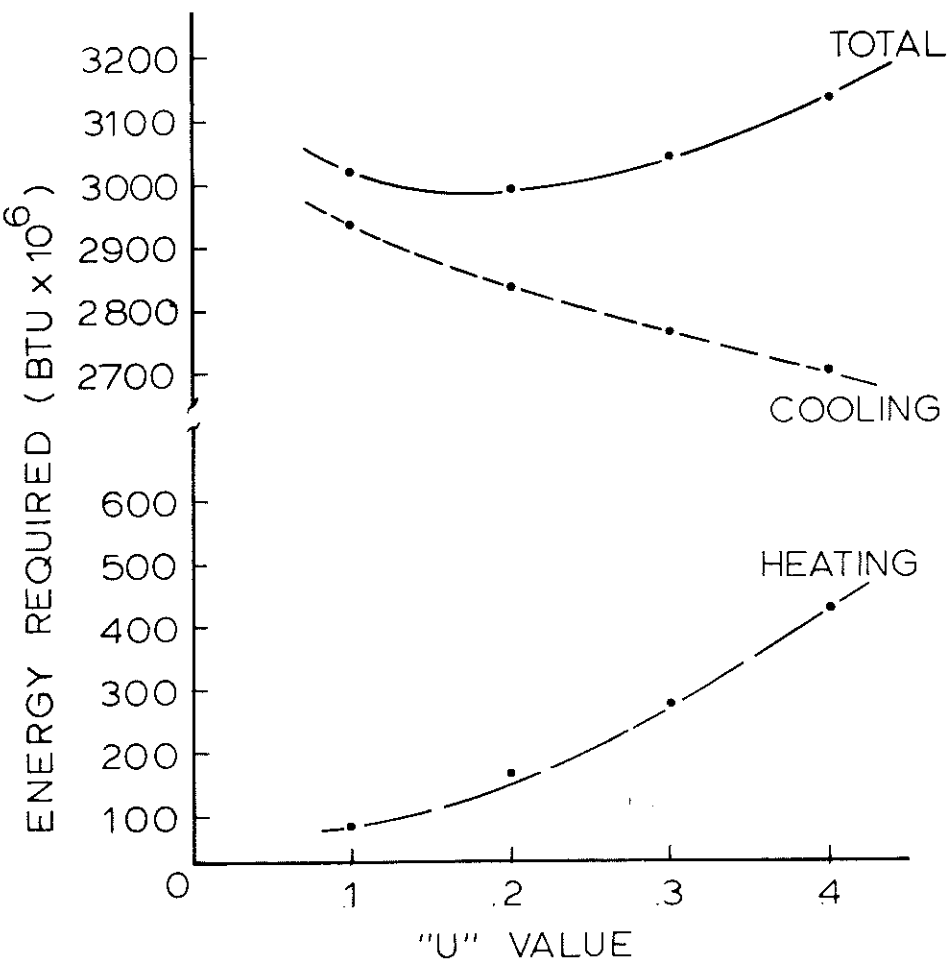


Fig. 4 Energy Use vs. "U" Value