A Simulation Model to Determine Energy Savings in an Air Conditioning Office Building

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Abstract

Energy saving and energy efficient equipment are attracting a lot of attention due to the escalating energy costs world wide. Selection of Heating, Ventilation and Air-Conditioning (HVAC) system for buildings is considered to play a vital role in energy consumption. However, proper selection of such a system depends primarily on an accurate cooling load calculation method. ASHRAE has developed different methods to estimate the accuracy of cooling load calculations. In this paper a method based on the finite difference technique is implemented to estimate the cooling load in an office building. The office building is cooled by a ceiling radiant cooling panel (CRCP) coupled with fan coil unit (FCU) using 100% fresh air. The simulation model of the office building showed that significant energy reduction could be obtained when using a ceiling radiant cooling panel.

Keywords: Air conditioning, Ceiling radiant cooling panel, Chilled water, Ventilation system, fan coil unit

1. Application of Explicit Method

To apply an explicit method in practice, consider the nodal subvolume of Figure 1. denotes to the rate of heat addition (external or internal) to the node. This element can be considered as an arbitrary subvolume of outer part of a building wall. Assume one dimensional flow and node i represents the subvolume having thermal capacity C, and connected by resistance Rij1 and Rij2 which stand for convective and conductive resistances respectively. If the node i is exposed to the solar heat input qi and has a temperature Ti at time t, then for a time interval Δt the quantity of heat Q entering the node i is expressed as [1]:

\[ Q = q_i \Delta t + \left( \frac{T_i^t - T_i^f}{R_{ij1}} + \frac{T_i^f - T_i^t}{R_{ij2}} \right) \Delta t \] (1)

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From first law of thermodynamics, this heat must give a rise in temperature of the node such as:

\[ Q = C_i \left( T_i^{t+\Delta} - T_i^t \right) \]

As Combining equations 1, 2 and designating \( t + \Delta t \) as \( t + 1 \)

\[ T_i^{t+1} = \frac{\Delta t}{C_i} \left( q_i + \frac{T_{j1}^{t}}{R_{ij1}} + \frac{T_{j2}^{t}}{R_{ij2}} \right) - T_i^t \left( \frac{1}{R_{ij1}} + \frac{1}{R_{ij2}} \right) + T_i^t \]

If node \( i \) is connected to \( n \) number of nods, then equation 3 becomes:

\[ T_i^{t+1} = \frac{\Delta t}{C_i} \left( q_i + \sum_{j=1}^{n} \frac{T_{j}^{t}}{R_{ij}} - T_i^{t} \sum_{j=1}^{n} \frac{1}{R_{ij}} \right) + T_i^t \]

Equation 4 is explicit in \( T_i^{t+1} \) and is equivalent to the first forward differencing scheme for the time derivative [1]. Explicit methods are unstable; therefore, equation 9 is used for stability condition [2].

2. Building Thermal Network

The space conditioned under the physical test is selected as small office which has dimensions of 4.22 m x 2 m with height of 3.056 m. All walls of the office consist of common brick (24 cm thick). The ceiling is made of 12 cm concrete, 2 cm air gap, 2 cm polyethylene insulation foam and 0.4 cm plywood. The floor is constructed of 39 cm concrete; 3 cm cement mortar and 3 cm tile. The 0.95 cm x 0.76 cm is made of a single clear glass with thickness of 3 mm where the door has dimensions of 1.95 m x 0.82 m soft wood (4 cm thick).

The building under investigation should be represented based on one or more of the above method. Figure 2 illustrates thermal network of a single wall (T lumping method) for the office building. Thermal network for the ceiling, floor, door and window can be determined in the same pattern. A complete view of the whole office building is shown in Figure 3. that composed of 8 parallel circuits, each of the will be ended at node (66) which represents the room air temperature node.

To evaluate the transient heat response of the office thermal network which is explained in Figure 3, the following assumptions are constructed:
- One dimensional conduction heat transfer through the office structure.
- Explicit method is used to solve transient heat conduction.
- Thermal properties of all materials are constant.
- All inside surfaces radiate and reflect thermal radiation.
- Inside temperature of the space is remained constant.
3. Solution of the Office Thermal Network

The following parameters were used to solve the office thermal network Figure 3:
- Ambient air temperature
- Solar air temperature
- Thermal resistance of the network
- Thermal capacitances

4. Solution of Network Equations for the Explicit Case

The explicit formulation avoids the need of iterative or matrix inversion techniques, since each future nodal temperature can be individually calculated for a time increment $\delta t$ from only the current nodal temperatures [2]. Thus from equation 5 new temperatures are successively calculated at each node, starting with given initial temperature distribution in a network for a given $\delta t$. Time is then incremented and the calculations are repeated. No iteration or matrix inversions are required. Only the stability requirement stated in equation 9 needs to be satisfied. In practice it is wise to use increment smaller than the maximum. The reason for this practice is a combination of the desire to improve accuracy by reducing truncation error in time and to avoid instabilities by staying safely below the upper limit of $\delta t$ [2].
The convective resistance, conductive resistance and thermal capacitance are computed from the following equations:

For convection

$$ R_{ij} = \frac{1}{h_{ij} A_{ij}} $$

(6)

For conduction

$$ R_{ij} = \frac{\delta_{ij}}{K A_{ij}} $$

(7)

For thermal capacitance

$$ C_i = V_i \rho c_p $$

(8)

For stability condition

$$ \sum_i \frac{\delta \tau}{R_{ij} C_i} \leq 1 $$

(9)

The capacitors of the interior nodes are all equal to C while the surface node has a capacitance C/2. Since the nodes with capacitance C have two resistors, R, connected to them, and that with capacitance C/2 has only one resistor connected to it, the stability criterion of equation 9 yields the same result for all nodes [Alan J. Champan, 1984]:

$$ \frac{2 \delta \tau}{RC} \leq 1 $$

(10)

5. Model of the office building with ceiling radiant cooling panel

The block diagram of the structured radiant ceiling panel with dedicated outdoor air system (DOAS) is shown in Figure 4. The chilled water passes to the fan coil unit to reduce the ambient temperature so as to supply an air temperature of 12°C and then, enters the panel with 14.2°C and exits with 16.8°C. The chilled water is then pumped to a chiller, recooled and returned to the ceiling. The function of fan coil unit is to remove the latent and partial sensible heat load of the space [E T. Mohamed, July 2009].

Figure 4. Schematic diagram of tested chilled ceiling panel with DOAS
6. Program objective

The finite difference method of a nonlinear system of equations and Matlab programming language (simulation) were used to solve equation 4, in order to calculate the transient heat flow through the office building and then, to evaluate cooling load of conditioned space. The program is run for a period of three days using the same data to minimize errors in finite difference solution. The flowchart describing the program is shown in Figure 5.

![Program flowchart](image-url)
7. Results of program

The simulation results of transient heat flow for different walls and ceiling which have been obtained from the run of program are shown in Figure 6 and Figure 7 below.

![Figure 6. Rate of transient heat flow for the walls and ceiling](image1)

![Figure 7. Rate of cumulative transient heat flow for the wall and ceiling](image2)

It is obvious from the above Figures the result of the second and third day are similar which demonstrate the correct solution.
8. Comparison between CRCP/DOAS and VAV system for peak power demand

Figure 8 shows a comparison between CRCP/DOAS and VAV system for peak power demand through this study. It is clear that from this Figure the CRCP/DOAS system with 100% fresh air can save more than 26.1% of input power over a VAV system with 100% fresh air. The reason for this is that the CRCP/DOAS uses minimum supply air (140 l/s) than VAV system (202.62 l/s) in case if 100% fresh air is used in each respectively. The other reason is attributed to the energy used by its pump (19.2W) which is less than by fan (40W) in VAV system.

![Figure 8. Comparison between CRCP/DOAS and VAV system for peak power demand](image)

8. Conclusions

From the previous study the following conclusion can be drawn as follows:

- Selection of Heating, Ventilation and Air-Conditioning (HVAC) system for buildings is considered to play a vital role in energy consumption.
- The simulation model of the office building showed that significant energy reduction could be obtained when using a ceiling radiant cooling panel.
- The above comparisons (figure 15) have shown that the CRCP/DOAS system saves 17.3% energy over the VAV system with recirculation air. On the other hand, the CRCP/DOAS system with 100% fresh air can save more than 26.1% of input power over a VAV system with 100% fresh air.
- Simulation model should be used to evaluate cooling load calculation of the buildings.

9. References