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SIMULATION OF BUILDING ENERGY SYSTEMS

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The theoretical basis and development status of the ESP building energy simulation system is reported. A brief description of ESP's user interface is then given, including a recent move to an expert interface.

INTRODUCTION

Traditionally, building and HVAC system designers have relied on a myriad of manual calculation methods as the basis of performance assessment at the design stage. These methods are based on numerous empirical simplifications and, in many cases, are confined to the steady state calculation domain.

With real energy systems, modelling complexities are present which act to expose the deficiencies of these traditional methods. Time varying boundary conditions cause complex transient effects; control actions are highly temporal and essentially non-linear; heat and mass transfers are inextricably linked together; and the interactions between regions of different time constants will pose numerical difficulties. In response to these problems, a number of computer-based modelling system have appeared in the marketplace. These systems attempt to model buildings and their environmental control systems in a more exacting manner, allowing the imposition of realistic boundary conditions and control constraints.

This paper describes the form and content of one such system; the ESP package developed at the ABACUS CAD Unit with support from the UK Science and Engineering Research Council. The paper is also concerned to demonstrate ESP's move toward an expert interface approach which should ensure that the model can be more effectively applied in practice.

Contemporary Modelling Methods

By analogy, a building can be likened to an electrical network. Fluid and capacity volumes are characterised by one or more variables of state such as temperature or pressure; the equivalent of voltage in an electrical network. Regions possess capacity and are linked by time-dependent resistances through which heat flux - equivalent to current - can flow. Mathematically, several equation types are required to represent such a network: parabolic and hyperbolic partial differential equations define transient conduction and air convection paths respectively; and shortwave and longwave exchanges, infiltration, and in some cases controls, require non-linear, perhaps complex, equation structures. And because these equations are inter-related, it is necessary to apply simultaneous solution techniques. In energy simulation, model accuracy and flexibility is determined by the way in which these equations are treated. Often some portion of the network is neglected completely, time invariant values may be assigned to one or more of the state variables or network resistances, simplifying boundary conditions may be assumed, or all derivatives may be eliminated to produce a steady state system. In broad terms the spectrum of existing techniques will fall into one of five categories: steady state, simple dynamic, response function, numerical and electrical analogue. Each technique is concerned, at its own level, to satisfy the laws of thermodynamics but, as modelling sophistication diminishes, so many of the active flowpaths are degraded or ignored and the method becomes indicative, not predictive, application limited, not general, and of low integrity vis-a-vis the real world.

The extant *dynamic* systems for building energy analysis are based either on response function methods or on numerical methods in finite difference or finite volume form (1). The former approach is appropriate to the solution of linear differential systems possessing time-invariant heat transfer resistances. In use it is usual to assume a high degree of equation decoupling. Numerical methods, on the other hand, can be used to solve time varying, non-linear systems of equations with no need to assume equation decoupling as a computational convenience. In the ESP system a numerical technique has been favoured for a number of reasons: to assure accuracy it is essential to preserve the spatial and temporal integrity of real energy systems by arranging that whole system (building + plant) differential equation-sets be solved simultaneously and repeatedly at each computational time-step; numerical methods, unlike the response function approach, have no need to assume superimposition and so can handle complex flowpaths and flowpath interactions; time-varying system properties can be accomodated; and processing frequencies can

be matched to region time constants to accomodate the so-called 'stiff' systems in which time constants can vary between regions of a building by more than an order of magnitude.

ESP'S Mathematical Model

The formulation of a model such as ESP involves several steps. Firstly, the continuous multi-zone building and multi-component plant is made discrete by subdivision into a number of interconnecting, finite volumes. These volumes then possess uniform properties which can vary in the time dimension. Volumes represent homogeneous and mixed material regions associated with air volumes, constructional elements and component heat transfer interfaces; it is not uncommon to have as many as 300 such volumes in a scheme to represent the energy balance within one building zone. Secondly, for each of these finite volumes in turn, and in terms of all surrounding volumes deemed to be in thermal or flow contact, a conservation equation is developed in relation to the transport properties of interest - heat energy or mass exchange for example. Thirdly, all differential equations are transformed to give the final state-space representation for subsequent numerical solution. It is normal to transform to *lumped parameter* or *time discrete* formulations, depending on the chosen solution method (as outlined later). Fifthly, control equations are added to prescribe, limit or impose conditions on system behaviour. And lastly, the entire equation-set is simultaneously solved for some small computational time-step to obtain the state variables for the current time-row and so allow equation-set re-formulation for the next time-step. Control discontinuities are avoided by time-step variation to ensure that an across-discontinuity integration is not attempted.

If the governing differential equations are known for any finite volume, then a finite difference representation can be directly applied. However this formal approach - differencing by Taylor series expansion - can prove cumbersome and difficult to apply in all but simple cases. Commonly encountered problems include the presence of interacting flowpaths, the temporal and positional dependency of system heat injections, the fact that volumes may not be homogeneous and can be of varying dimensions and shapes, the presence of heat flow in more than one dimension, and the interaction of heat and mass transfers. An alternative approach is to rely on formal balancing, which, in the limit, is the technique used to derive the differential equations in the first place. Consider a region I in thermal communication with surrounding regions 1, 2, 3 & 4 via conduction, convection, radiation and fluid coupling. Internal heat generation can also take place within the region. The heat transfer towards region I from the other regions at some time ξ is given by

$$q(j \rightarrow I, \xi) = \sum_{j=1}^{n} K(j \rightarrow I, \xi)[\theta(j, \xi) - \theta(I, \xi)] \quad n = 1 \rightarrow 4 \;\; (\textit{in this case})$$

where $K(j \rightarrow I, \xi)$ is a heat flow conductance which may be some non-linear function of the state variable; temperature in the case of sensible energy balance. Of course θ may represent some other state variable (such as pressure or enthalpy) with suitable adjustments made to K to represent the fundamental processes. Here K will represent conductivity, k, a convection coefficient, h_c, a long-wave radiation coefficient, h_r, and an air flow conductance, $\rho C\vec{v}$; ($\vec{v}$ *is a volume flowrate vector*), depending on the flowpath.

The heat stored within the region I over some finite time interval δt is given by

$$q_s = \frac{\rho(I, \xi)C(I, \xi)\delta V(I, \xi)}{\delta t}[\theta(I, t + \delta t) - \theta(I, t)]$$

where $\rho(I, \xi)$ is the density of region I at time ξ ($kg\ m^{-3}$), $C(I, \xi)$ is the specific heat ($J\ kg^{-1}\ C^{-1}$), and $\delta V(I, \xi)$ is the volume (m^3).

Now, in the limit, the rate at which heat is stored within region I is equal to the net rate of heat flow to the region and so, with $q(I, \xi)$ representing heat generation:

$$\frac{\rho(I, \xi)C(I, \xi)\delta V(I, \xi)}{\delta t}[\theta(I, t + \delta t) - \theta(I, t)]$$

$$= \sum_{j=1}^{n} K(j \rightarrow I, \xi)[\theta(j, \xi) - \theta(I, \xi)] + q(I, \xi) + \varepsilon.$$

where ε is the error resulting from equating the instantaneous flux balance to the change in storage over time. In conventional finite differencing this is equivalent to the truncation error resulting from the approximate representation of the derivatives.

In order to achieve unconditionally stable equations, while retaining maximum accuracy, it is usual to combine explicit, $\xi = t$, and implicit, $\xi = t + \delta t$, forms of the foregoing equation, giving after rearrangement

$$\left[\frac{2\rho(I,t+\delta t)C(I,t+\delta t)\delta V(I,t+\delta t)}{\delta t}+\right. \tag{1}$$

$$\left.\sum_{j=1}^{n} K(j\rightarrow I,t+\delta t)\right]\theta(I,t+\delta t)-\sum_{j=1}^{n} K(j\rightarrow I,t+\delta t)\,\theta(j,t+\delta t)-q(I,t+\delta t)$$

$$=\left[\frac{2\rho(I,t)C(I,t)\delta V(I,t)}{\delta t}-\sum_{j=1}^{n} K(j\rightarrow I,t)\right]\theta(I,t)$$

$$+\sum_{j=1}^{n} K(j\rightarrow I,t)\,\theta(j,t)+q(I,t).$$

In this form equation 1 is *time-discrete* in that both the time and space derivatives have been effectively differenced. It is, of course, possible to retain the time derivative; the scheme will then be *lumped parameter*. In building energy analysis there are three equation types required to describe the active flowpaths. First order ordinary differential equations are used to represent physical regions undergoing multiple heat transfers and possessing averaged thermophysical properties. Second order parabolic partial differential equations are used to describe capacity/insulation regions requiring detailed modelling. And hyperbolic partial differential equations are used to describe fluid flow and convective coupling. Obviously equation 1 is identically equal to the first type as the time increment approaches the limit. It has also been proved (2) that it will become identical to the second and third types if the so-called *semi-discretisation* is applied to the space variables with K assigned the appropriate meaning.

Time-discrete formulations offer many advantages since they give rise to linear algebraic equations which can be solved by matrix manipulation techniques endowed with knowledge of system behaviour. Indeed the method of equation 1 has been shown to be consistent, convergent and *A*-stable, providing the possibility of variable time stepping and well adapted for the solution of *stiff* systems (3). This is the method of ESP. For lumped parameter formulations, many standard solution packages exist. In any event modelling accuracy is entirely dependent on the time-dependent assessment of the coefficients of the active equations - representing heat transfer coefficients, heat injections and control conditions.

Equation 1 can now be applied to the finite volume types found in buildings. This will lead to three characteristic equation types: capacity regions undergoing transient conduction, with thermal storage and heat generation; surface layers experiencing conductive, radiative and convective heat transfer as well as heat generation; and fluid regions undergoing convective and advective exchanges and heat generation. Reference 1 gives the final form of these state-space equations and derives the formula for the coefficients of the finite volume state variables. Matrix equation topology is then demonstrated for single and multiple zone problems, for problems involving mass and energy balance, and for selected plant and control systems.

The same technique can now be applied to any plant network. Consider, as an example, the derivation of a simple state-space representation for a packaged air handling unit. The dynamic simulation of air conditioning systems is complicated by the fact that the working fluid (air) is not homogeneous, but comprised of a dry air and vapour mix. Also, a large number of components may be present with complex inter-component connections and control actions. Consider the simple air handling unit of figure 1. Outside air at temperature θ_o, humidity ratio g_o and enthalpy h_o is mixed with zone return air at temperature θ_r, humidity ratio g_r and enthalpy h_r and passed to a chilled water cooler, a humidifier and a re-heater to achieve the required zone supply conditions to offset the zone sensible and latent loads. In the usual way, it is possible to establish, for each component, an energy balance for any arbitrary time ξ. For the cooling coil this gives

$$m_1\ h_1 - m_2\ h_2 - m_c\ h_c + q_{e2} - q_{x2} = \frac{d(\bar{\rho}_2\ V_2\ h_2)}{dt}\ \Big|_{\ t=\xi} \tag{2}$$

with similar expressions emerging for the other components.

Here m is the mass flowrate of air/vapour mixture ($kg\ s^{-1}$), h is the mixture specific enthalpy ($J\ kg^{-1}$), q_{ei} the component i heat exchange with surroundings (W) and q_{x2} the cooling coil total heat transfer (W); $\bar{\rho}_i$ is the volume weighted mean density of component i ($kg\ m^{-3}$), V_i is the total volume of component i (m^3) and c relates to the cooler moisture extraction.

Note that since each component is represented by a single point, nodal capacity must be expressed as a function of the average component state. A more refined approach results from the introduction of a multi-node representation since then the capacity of each component element (air, metal casing, coil metal, water, etc.) can be treated separately. Such a refinement is demonstrated later for the cooling coil.

A mass balance, component-by-component, for the dry air and vapour phases separately, will yield for some time-row ξ, a corresponding state-space equation. For the cooling coil this gives

$$m_1^d - m_2^d = 0|_{t=\xi} \tag{3}$$

$$m_1^d\ g_1 - m_2^d\ g_2 - m_c = \frac{d(\rho_L\ V_c)}{dt}\ \Big|_{\ t=\xi} \tag{4}$$

where m^d is the mass flowrate of dry air ($kg\ s^{-1}$), g the humidity ratio ($kg\ kg^{-1}$) and ρ_L the density of liquid remaining in the cooler ($kg\ m^{-3}$), V_c is the cooler residual liquid volume (m^3) and m_c is the cooler vapour extraction rate ($kg\ s^{-1}$).

A time-discrete, energy balance representation can now be obtained for each component by concatenating the explicit and implicit forms of the type 2 equation. For component 2 this gives

$$\begin{aligned}[2\bar{\rho}_2\ (t+\delta t)\ V_2 + m_2(t+\delta t)\delta t]\ h_2\ (t+\delta t) - m_1\ (t+\delta t)\ \delta th_1\ (t+\delta t) \\ + m_c\ (t+\delta t)\ \delta th_c\ (t+\delta t) - \delta tq_{e2}\ (t+\delta t) + \delta tq_{x2}\ (t+\delta t) \\ = [2\bar{\rho}_2\ (t)V_2 - m_2\ (t)\delta t\ ]h_2\ (t) + m_1\ (t)\delta th_1\ (t) \\ - m_c\ (t)\delta th_c\ (t) + \delta tq_{e2}\ (t) - \delta tq_{x2}\ (t)\ .\end{aligned} \tag{5}$$

Now, since a building equation-set is not being considered here (it would of course exist in any ESP run), it is not possible to expand the q_{ei} terms by the introduction of a building exchange resistance based on fundamental heat transfer considerations. For the present purpose the assumption is made that the $q_{ei}(t+\delta t)$ can be determined independently and so this term is removed to the right-hand, or known, side of equation 5. Also, in the absence of a more detailed component model, the coil total heat transfer (between the cold fluid and the air stream) and condensate exit enthalpy must be assumed to be independently calculable from some free standing coil algorithm. This approach is attractive in that existing component models can be used in conjunction with the dynamic state-space representations. Alternatively, the internal component processes can be explicitly represented if the component model is made multi-node.

With reference to figure 2, which shows the overall system energy balance matrix equation, the state-space equation for component 2 becomes

$$a_{21}h_1\ (t+\delta t) + a_{22}h_2\ (t+\delta t) = b_{21}h_1\ (t) + b_{22}h_2\ (t) + c_2 \tag{6}$$

where:

$$a_{21} = -\ m_1\ (t+\delta t)\ \delta t$$

$$a_{22} = 2\bar{\rho}_2\ (t+\delta t)\ V_2 + m_2(t+\delta t)\ \delta t$$

$$b_{21} = m_1(t)\delta t$$

$$b_{22} = 2\bar{\rho}_2\ (t)\ V_2 - m_2(t)\ \delta t$$

$$\begin{aligned}c_2 = &-\ m_c(t+\delta t)\ \delta th_c\ (t+\delta t) - m_c(t)\ \delta th_c\ (t) \\ &+\delta t\ [q_{e2}\ (t+\delta t) + q_{e2}\ (t) - q_{x2}\ (t+\delta t) - q_{x2}\ (t)\ ]\ .\end{aligned}$$

The form of the figure 2 system of equations is simple for the simple problem considered here. For complex arrangements, involving recirculating loops, more complex matrix structures will result. But, for any system, two possibilities exist for matrix solution

- The cooling coil extraction flux and the heating coil addition flux (plus the internal heat transfer processes active in any other participating component) of the **C** matrix can be assessed by independent component algorithms, when given knowledge of current component state variables and future time-row control objectives.
- Alternatively, internal flux terms can be removed to the future time-row side of the matrix equation - $\mathbf{Ah}(t+\delta t)$ - and replaced by an expanded, multi-node equation-set which represents internal thermodynamic

processes directly.

These approaches are pursued later when an algorithm of the former type is developed and the formulation of a detailed component model is demonstrated. But firstly, a mathematical statement on system mass balance must be established.

By the same reasoning that was applied to the formulations for energy balance, a mass balance equation can be formulated by taking an equal weighting of the explicit and implicit forms of equations 3 through 4. Again focussing only on the cooling coil:

$$m_1^d(t+\delta t) - m_2^d(t+\delta t) = -m_1^d(t) + m_2^d(t) \tag{7}$$

and therefore with reference to figure 3:

$$d_{31}m_1^d(t+\delta t) + d_{33}^d(t+\delta t) = e_{31}m_1^d(t) + e_{33}m_2^d(t) \tag{8}$$

and

$$\begin{aligned}[m_1^d(t+\delta t)g_1(t+\delta t)] - [m_2^d(t+\delta t)g_2(t+\delta t)] - m_c(t+\delta t) \\ - 2\rho_L(t+\delta t)V_c/\delta t \\ = -[m_1^d(t)g_1(t)] + [m_2^d(t)g_2(t)] + m_c(t) - 2\rho_L(t)V_c/\delta t.\end{aligned} \tag{9}$$

Again, in the absence of detailed, multi-node component models, some independent algorithm must be formulated for the assessment of cooler vapour extraction rate based on current cooler conditions and control expectations. The component 2 vapour equation becomes

$$\begin{aligned}d_{42}[m_1^d(t+\delta t)g_1(t+\delta t)] + d_{44}[m_2^d(t+\delta t)g_2(t+\delta t)] \\ = e_{42}[m_1 d(t)g_1(t)] + e_{44}[m_2^d(t)g_2(t)] + f_4\end{aligned} \tag{10}$$

where

$$f_4 = m_c(t) + m_c(t+\delta t) + 2V_c[\rho_L(t+\delta t) - \rho_L(t)]/\delta t.$$

It is important to note that the mass balance matrix is merely a mathematical statement of inter-component linkages. In complex circuits, involving recirculating loops, nodes will be required to represent the branching points. Even then, matrix solution will not provide a unique result in the absence of information on the flow diversions occuring at each branching point. Either a flow simulation model must be established in which individual flowstreams and fittings are expressed in terms of characteristic flow equations, or assumptions must be made based on the desired diversion ratios at each branching point.

In any event, the system mass balance matrix equation will allow component mass flowrate determination against control action applied at any point in the plant network.

If nodes located downstream from a control valve do not experience a positive flowrate until some time after valve operation due to network inertia, this can be modelled by delaying the introduction of a non-zero mass flowrate to the matrix coefficient entry until some later matrix equation formulation, depending on the node location, fluid velocity and simulation time-step.

The two matrix equations - one for energy balance, the other for mass balance - in the form presented here will require component algorithms to establish the q and m terms as present within the **C** and **F** matrices.

We now continue with the formulation of a component algorithm; firstly in a form suitable for use as described above, and secondly in a form which allows the removal of the $q_{x2}(t+\delta t)$ terms to the matrix equation future (unknown) time-row. The component selected for this treatment is the cooler of the system of figure 1.

Free-standing component models. It is possible to derive an entirely free-standing component algorithm to represent the performance capabilities of any component. This algorithm then operates in tandem with the matrix equation reduction to limit component capabilities if system demands are too great. That is, the algorithms represent component operation whilst the matrix scheme represents component inertia and inter-component connections.

Consider a counterflow cooling coil. The following procedure - based on the sensible heat ratio method - is active in ESP to compute coil performance if a simple, one node state-space representation is chosen.

1. At any time-step, the following quantities are known: inlet water temperature and mass flowrate, θ_{wi} and m_w; inlet air dry bulb temperature, mass flowrate, humidity ratio and enthalpy, θ_{ai}, m_a, g_{ai} and h_{ai}; airside,

waterside and metal thermal resistances, R_a, R_w and R_m; coil surface area, A; atmospheric pressure, P_a; and air and water specific heats, C_{pa} and C_{pw}.

2. Calculate the coil bypass factor, β, from
$$\beta = \exp[-A/(C_{pa} m_a R_a)].$$

3. Guess coil effectiveness, E, perhaps the previous time-step value.

4. Guess sensible heat ratio, *SHR*.

5. Calculate the coil U-value, U, the number of heat transfer units, *NTU*, and the capacity-rate ratio, *CRR*, from
$$\phi_1 = (m_a C_{pa})/SHR$$
$$\phi_2 = m_w C_{pw}$$
$$C_{\min} = \min(\phi_1, \phi_2)$$
$$C_{\max} = \max(\phi_1, \phi_2)$$
$$U = 1/[(R_a SHR) + R_m + R_w]$$
$$NTU = AU/C_{\min}$$
$$CRR = C\min/C\max.$$

6. Establish if guessed E and *SHR* match by applying:
$$E = \{1 - \exp[-NTU(1 - CRR)]\}/\{1 - CRR \exp[-NTU(1 - CRR)]\}.$$

If $CRR \rightarrow 1$, $E = NTU/(1 + NTU)$

7. If not matched, return to step 4 and iterate until *SHR* is established corresponding to guessed E.

8. Evaluate coil heat transfer from
$$Q = C_{\min} E(\theta_{ai} - \theta_{wi}).$$

9. From Q calculate outlet air enthalpy, h_{ao}.

10. Calculate the saturation enthalpy, h_s, at coil surface temperature from
$$h_s = (h_{ao} - \beta h_{ai})/(1 - \beta).$$

11. Determine the coil surface temperature, θ_s, and saturation humidity ratio, g_s, from the saturation enthalpy and atmospheric pressure.

12. Calculate outlet air temperature, θ_{ao}, and humidity ratio, g_{ao}, from
$$\theta_{ao} = \beta(\theta_{ai} - \theta_s) + \theta_s$$
$$g_{ao} = \beta(g_{ai} - g_s) + g_s.$$

13. Calculate the corresponding sensible heat ratio, SHR', from
$$SHR' = (\theta_{ai} - \theta_{ao}) C_{pa}/(h_{ai} - h_{ao}).$$

14. Compare SHR' with *SHR* and, if different, return to step 3 and iterate until agreement is obtained.

15. Eventually - perhaps after changing coil parameters to achieve desired coil performance - terminate algorithm, and insert Q in system matrix equation to give final circuit enthalpies and humidity ratios.

Component matrix representation. Alternatively it is possible to introduce a number of equations to the system matrix equation to represent, directly, internal component processes. For example, Holmes (4) has suggested the following coil model, consisting of two first-order, ordinary differential equations:
$$C_w \frac{d\theta_1}{dt} = \frac{\theta_o - \theta_1}{R_1} - \frac{\theta_1 - \theta}{R_{mw}} \tag{11}$$
$$C_m \frac{d\theta}{dt} = \frac{\theta_1 - \theta}{R_{mw}} - \frac{\theta}{R_a + R_4} \tag{12}$$

$$\theta = \frac{\theta_2(R_a + R_4)}{R_4}$$

where $\theta_o = \theta_{wi} - \theta_{ai}$; $\theta_1 = \theta_{wo} - \theta_{ai}$; $\theta_2 = \theta_{ao} - \theta_{ai}$; $R_1 = 1/(m_w C_{pw})$; R_{mw} is the metal + water film resistance; $R_4 = 1/(m_a C_{pa})$; C_w is the water thermal capacity ($J\ K^{-1}$) and C_m is the metal thermal capacity.

Equations 11 and 12 define a 2-node component model. A finite difference approximation applied to these equations gives the final state-space representations:

Air equation

$$-\left[\frac{2C_m(R_a + R_4)}{\delta t R_4} + \frac{R_a + R_4)}{R_{mw} R_4}\right]\theta_{ai}(t + \delta t)$$

$$+\left[\frac{2C_m(R_a + R_4)}{\delta t R_4} + \frac{(R_a + R_4)}{R_{mw} R_4} + \frac{1}{R_{mw}}\right]\theta_{ao}(t + \delta t)$$

$$-\frac{1}{R_{mw}}\theta_{wo}(t + \delta t) = -\left[\frac{2C_m(R_a + R_4)}{\delta t R_4} - \frac{(R_a + R_4)}{R_{mw} R_4}\right]\theta_{ai}(t)$$

$$+\left[\frac{2C_m(R_a + R_4)}{\delta t R_4} - \frac{(R_a + R_4)}{R_{mw} R_4} - \frac{1}{R_{mw}}\right]\theta_{ao}(t) + \frac{1}{R_{mw}}\theta_{wo}(t)$$

Water equation

$$\left[\frac{2C_w}{\delta t} - \frac{(R_a + R_4)}{R_{mw}^2} + \frac{1}{R_{mw}}\right]\theta_{ai}(t + \delta t)$$

$$-\frac{(R_a + R_4)}{R_{mw}^2}\theta_{ao}(t + \delta t) + \left[\frac{2C_w}{\delta t} + \frac{1}{R_1} + \frac{1}{R_{mw}}\right]\theta_{wo}(t + \delta t)$$

$$= -\left[\frac{2C_w}{\delta t} - \frac{1}{R_{mw}} + \frac{(R_a + R_4)}{R_{mw}^2}\right]\theta_{ai}(t) - \frac{(R_a + R_4)}{R_{mw}^2}\theta_{ao}(t)$$

$$+\left[\frac{2C_w}{\delta t} - \frac{1}{R_1} - \frac{1}{R_{mw}}\right]\theta_{wo}(t) + \frac{1}{R_1}[\theta_{wi}(t) + \theta_{wi}(t + \delta t)]$$

Figure 4 shows the addition of these equations to the plant system energy balance matrix equation.

Some 25 component models now exist, in state-space form within ESP's plant components database, available for selection for interconnection to define a network. The matrix to emerge is then interlocked with the building matrix for simultaneous processing. Any number of control loops can then be defined to determine flux injections on the basis of sensed nodal conditions. And, the control action can vary from time-step to time-step as a simulation proceeds.

ESP's solution technique

Consider figure 5, which shows a multi-zone building served by a simple central heating system. The matrix equation to result is also shown; note the high level of sparseness and the location of equation clusters in a manner which reflects system connectivities.

Within ESP this matrix equation is never formally established. Instead, a series of partitioned matrices are defined, each one representing multi-layered construction heat flow and containing information which links them to the whole system equation-set at the construction boundaries. Zone energy balance matrices, one for each zone, are also extracted at this stage along with the matrix which represents the plant network. All coupling information is retained and held in these matrices. The solution of the entire system - held in partitioned form - now need only address the filled elements of the overall super-matrix. Also, as a solution is pursued, it is possible to accomodate any spatial position of control loop sensor and actuator and to incorporate temporal considerations within any control law. The underlying objective is to process each partitioned matrix as far as possible to allow the extraction of

one or more *characteristic equations* (or *CE*'s) which embody the dynamics of the related component. These *CE*'s are then gathered together for onward processing to produce a set of whole-system *CE*'s which relate sensor states to control action. The whole-system *CE* set is then solved in terms of user imposed control statements so that back substitution can commence to give the state variable solution vector for the future time-row of the current computational time-step.

Because of the partitioning, different components can be processed at different frequencies; partitioned matrices can even be bypassed if their contents have not changed substantially since the previous time-step. Of course, many complexities accompany the computation of equation coefficients: the time dependent estimation of long- and short-wave radiation processes, surface convection coefficients, inter-zone air flow and casual source injections will require many algorithmic formulations. These, and the overall solution technique, are elaborated elsewhere (1).

The generation of *CE*'s for plant networks deserves special mention. With the air conditioning system of figure 1 the matrix equation cannot be processed until component input/extract fluxes are known for the future time-row of any time-step. For this reason iteration will be required. One technique is to proceed as follows.

Step 1

At each time-step establish

$$\mathbf{Ah}(t + \delta t) = \mathbf{Bh}(t) + \mathbf{C} \tag{13}$$

$$\mathbf{D}\Phi(t + \delta t) = \mathbf{E}\Phi(t) + \mathbf{F} \tag{14}$$

and initialise $q_{ei}(t + \delta t)$, $q_{x2}(t + \delta t)$, $m_c(t + \delta t)$ and $m_h(t + \delta t)$ to zero.

Step 2

Assume no humidification or dehumidification and determine circuit humidity ratios, $g_i'(t + \delta t)$, from

$$\Phi(t + \delta t) = \mathbf{D}^{-1}[\mathbf{E}\Phi(t) + \mathbf{F}]. \tag{15}$$

Set $\delta g = (g_5' - g_5)$ where g_5 is the desired humidity ratio ($kg\ kg^{-1}$).

If $\delta g < 0$ go to step 3
> 0 go to step 4
$= 0$ go to step 5.

Step 3

Humidification required; determine $m_c(t + \delta t)$ to give required $g_5(t + \delta t)$ from the iterative application of equation 15. Then go to step 5.

Step 4

Dehumidification required; determine $m_c(t + \delta t)$ to give required $g_5(t + \delta t)$ from iterative application of equation 15. From cooler algorithm determine minimum $q_{x2}(t + \delta t)$ to give required $g_2(t + \delta t)$.

Step 5

Estimate $q_{ei}(t + \delta t)$ from known component conditions (unless a building matrix is present so that component casing nodes are coupled to containing zone nodes).

Step 6

With $q_{x4}(t + \delta t)$ remaining at zero and $q_{x2}(t + \delta t)$ set at the value determined from step 4 (or zero if step 4 was bypassed), determine circuit enthalpies, $h_r'(t + \delta t)$, from

$$\mathbf{h}(t + \delta t) = \mathbf{A}^{-1}[\mathbf{Bh}(t) + \mathbf{C}]. \tag{16}$$

Set $\delta h = (h_5' - h_5)$, where h_5 is the desired supply enthalpy ($J\ kg^{-1}$).

If $\delta h < 0$ go to step 7
> 0 go to step 8
$= 0$ go to step 9.

Step 7

Re-heat required; determine $q_{x4}(t + \delta t)$ from the iterative application of equation 16. Then go to step 9.

Step 8

Further cooling, then humidification required; determine $q_{x2}(t + \delta t)$ from the iterative application of equation 16. From cooler algorithm assess new $m_c(t + \delta t)$ and determine new $m_h(t + \delta t)$ to give required $g_5(t + \delta t)$ from iterative application of equation 15.

Step 9

The desired supply conditions are now achieved, corresponding to

$$\text{minimum } [abs\ q_{x2}(t + \delta t) + q_{x4}(t + \delta t)]$$

that is for minimum cooler and re-heater energy.

Since the duty and entering and leaving air states are now known, active component algorithms can be invoked to determine internal operating conditions - such as coil outlet water temperatures or required chilled water flowrates. Should the component be unable to perform as required then it can be reset to its limiting condition (that is, in the present example, one or more of $q_{x2}(t + \delta t)$, $q_{x4}(t + \delta t)$, $m_c(t + \delta t)$ or $m_h(t + \delta t)$ can be fixed). In the presence of a building matrix equation, any deviation from the required supply condition will be manifest in an environmental penalty for some time after. If control constraints are imposed prior to simulation, then some limit condition may be indicated during steps 4 or 8. In this case, supply conditions will not be met and conditions will deviate from the set point. Note that the procedure of steps 1 through 9 is entirely independent of component location since the matrices represent the linking protocol. In ESP it is also possible to bypass this procedure by establishing a number of control loops which act, throughout simulation, to fix coil and humidifier inputs, at each time-step, on the basis on conditions sensed elsewhere.

User interface developments

ESP is written in Fortran77 and comprises some 100,000 lines of source code addressing I/O, simulation processing and database management. Until recently a model of this type would have been confined to a mainframe environment and so would only be accessible by a small number of designers. Now ESP is operational on a number of *UNIX*[*] workstations such as the SUN, Apollo and Whitechapel. These systems are particularly interesting because of their low cost: a Whitechapel MG-1/452, for example, costs around 10,000 pounds sterling and comprises

multi-tasking computer unit with 2Mbytes RAM
45 Mbytes Winchester disk
0.8 Mbytes Floppy disk
floating point unit
high resolution, bit-mapped screen
window manager
detachable keyboard
mouse
Unix operating system
numerous software tools (for word processing etc.)

This juxtaposition of workstation technology and advanced engineering design software not only improves CAD availability, it also permits considerable improvements to the user interface. For example, multi-windowing, multi-tasking capabilities allow several tasks to be undertaken at the same time - perhaps several simulations are in progress while building perspectives are being prepared for incorporation in the project report being compiled in a separate window. Pop-up menu command selection, and process initiation by icon (picture) selection, makes program control much easier, and so helps to make the software less user hostile. Consider the operation of ESP. This is a three stage process as follows

1. A design hypothesis is specified by offering up information on building geometry, construction, plant and control. ESP can only operate with a full and complete data set. But since all data items are assigned defaults, a user need only enter the information to hand. The point here is that it is preferable to rely on a sophisticated mathematical model utilising a full data set, sensibly derived, than to simplify the model (by removing or restricting the active flowpaths) to allow operation with a reduced data set.

2. A rigorous, first principle simulation is now performed. This produces the time-series evolution of all variables of state which characterise the entire building.
3. System performance is assessed by interrogating the simulation output to obtain an insight into the underlying causal relationships and so identify cost effective changes to the design hypothesis.

ESP's native mode of operation is by graphical menu interaction in which commands are selected from a menu displayed on the graphics terminal. In this way a user can pick a path through the various program modules; but first a user must master the meaning of each menu command and the most productive paths through the multi-menu system. This operational mode is extremely powerful in the hands of a trained operator but is entirely inappropriate for the intensive but infrequent user usually found in design practice. It is here that the new technologies can help. Under UNIX a number of rules scripts have been established, corresponding to the performance assessment methodologies to be obeyed by ESP in seeking the answer to a given design question. Rules scripts can be endowed with intelligence so that the output resulting from a script will depend on the simulation results and on the expertise of the user who invoked the script. Thus, if an engineer were to select a script which asks the question, '*Will the building be comfortable in summer ?*', then the script would automatically initiate a number of processes to establish zone conditions, rank order the overheating regions (if any), determine the causal factors, and then display information on zone temperatures, energy balances, air movement, relative humidity and climatic conditions. If the same script is selected by an architect then the output may well be very different: a summary message on the prevailing comfort levels would be followed by relevant causal information displayed in graphical form and accompanied by pointers to potentially fruitful design intervention. The point is that entire ESP performance assessments are initiated by simply pointing to appropriate icons displayed on the terminal screen. This expert interface allows the designer to concentrate on design performance appraisal rather than having to struggle with some complex command protocol. Table 1 lists the performance assessment scripts currently existing for ESP and other ABACUS software.

It is important to note that developments of this kind, however attractive, are nevertheless largely cosmetic and cannot resolve fundamental problems at the technical level. In the longer term it is appropriate to pursue developments which would allow the more efficient construction of advanced models. A plan of action has recently been formulated (5) which involves the production of a *Kernel* system for next generation software developments. The intention is to provide the software primitives required by advanced energy simulation models and to develop a software *harness* which can be used to connect these primitives (in a run time environment) according to model templates developed by those groups (in the private or public sector) who have a desire to do so. The result will be a software development environment which encourages collaborative developments by permitting ease of integration of any new technique.

Conclusions

A number of advanced energy modelling systems are now available in the marketplace and the first attempts are being made to integrate these systems with drafting software. With advances in machine technology, the cost/performance ratio of these CAD systems is improving rapidly so that the technology is becoming more available.

To address some of the problems which still remain, a research project has recently commenced. Its aims are to develop software tools to assist in the construction of advanced energy simulation systems. The result will be a next generation architecture, possessing high integrity and easy to modify as new theories, interface techniques and performance assessment methodologies emerge. These are the developments which will finally allow the creation of a truely integrated CAD approach to building design.

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