A BUILDING AND PLANT REAL TIME SIMULATION SYSTEM

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INTRODUCTION

This paper introduces an emulation system for simulation of the thermal process of building and plant named ESAC (Emulation Set for Air-Conditioning systems) developed at Tsinghau University. This project was started in 1984, and a prototype system was presented in 1985 [1], since then a great progress has been made and several applications have been explored.

The main purposes of the system are:

* to study the dynamic properties of buildings and HVAC systems. A detailed second by second simulation can be performed of buildings with many zones and connected with HVAC systems. The thermal and the dynamic flow inertia of HVAC equipment and water/air networks has been treated in detail. The performance of sensors and controllers can also be simulated using detailed models.

* to understand the energy consumption of HVAC systems with different thermal inertia and operating under different control algorithms.

* to develop and validate HVAC system controllers. Through a display/control panel (DCP), most types of controllers for HVAC systems can be connected to ESAC and this can simulate the building and HVAC system in real time. The ESAC can represent the building, the HVAC system and the sensors. It supplies an environment to accurately the real system and hence allow the development of hardware and software for controllers.

* to train system managers. The DCP has manual operation facilities consisting of voltmeters to display system information and switches with which the manager can operate the system in the same way as he would operate a real system.

The structure of the software of ESAC is a kind of network-modules structure. A building and plant system can be described with three or four networks: the network of fabric and zones describing the whole or part of the building geometry; the air-flow network and the water-flow network connecting every air handler and heating/cooling source; and the controller and sensor network describing the relationship between the controllers, sensors and operators if the user is not going to connect a real controller to the ESAC. In this way, flexibile system is supplied so that most kinds of HVAC system with any type of equipment can be described and simulated by ESAC as long as the user can develop particular models for any unusual equipment.

An outline of the hardware and the main structure of the software is presented, the mathematical model and the relevant algorithms are then discussed. Finally, some examples of applications are illustrated.

MAIN CONSTRUCTION OF THE HARDWARE AND THE SOFTWARE

1. Hardware

The hardware of the ESAC consists of two IBM personal computers and the DCP. One of the computers function as a master computer and performs most of the calculation work; the other computer is used as an auxiliary computer which performs the following actions:

1. sending instructions to the master computer;
2. providing the master computer with values for the outdoor air parameters, heat and moisture sources in every zone, and external parameters such as the water temperature, and signals of equipment breaking down;
3. receiving and treating information fedback by the master computer;
4. recording information from the master computer, and plotting out the data if it is required;
5. transmitting data between the master computer and the DCP;
6. calculating the "natural room temperature" and sending values to the master computer ("natural room temperature" will be expained later).

Depending on the selection made by the user, the simulation process can be controlled in four ways:

1. the user can input commands at the keyboard of the auxiliary computer during the simulation;
2. the user can operate the switches at the DCP to control the simulation process;
3. controllers can be connected to the DCP in order to control the simulation process,
4. the master computer can itself simulate a user-defined control system

There are A/D and D/A translators in the DCP and several digital I/O ports are connected from the DCP to the auxiliary computer. The simulation results such as temperatures and humidities are translated into analogue signals (current or voltage), to supply to controllers as the output signals from sensors. The DCP can also receive analogue signals which are the output of controllers and translate them into digital data and send to the master computer to control the simulation process. The digital I/O ports receive the on/off control commands from controllers and supply the feedback signals as the system operation state to the controllers. All of the channels can be configured by the user at the beginning of a simulation.

It is also possible to operate manually via the DCP. It displays all the analogue and digital signals from the computer using voltmeters and lights. Switches and regulatable voltage producers can be used by the operator to control the HVAC system as if he were operating a real HVAC system.

If a user wishes to control the simulation process using only the auxiliary computer and to display the results on its screen, for example for a dynamic properties study, the DCP is unnecessary and can be disconnected.

2.Software

With the ESAC software package, it is expected that the user could describe any system he wants to analyse, and the ESAC can construct a simulation program automatically according to the input descriptive information, and produce the executable code so that the user can run it at any time.

The software in the master computer is composed of the following parts:

(1) System description part:

* Inputting in a tabulate fashion according to menus displayed on the screen. The user can define his system as four networks, and describe components as elements of the networks. ESAC has an information database including detailed information about most of the HVAC equipment and building materials in China and this is easy to access. The user can also input new equipment and new materials for his system, which will be added to the database for future use;

* Creating data files for user's system in accordance with the input information;

* Automatically constructing a simulation program in FORTRAN corresponding to the information input.

(2) Simulation package: This includes a group of modules representing various components, sensors and controllers for HVAC systems, and some general purpose modules for I/O and timeing. The modules in this simulation package could easily be improved. As the interfaces of the modules for every component are in the same format, it is very convenient to add in a new component module to the package.

(3) Operation and management system

The functions of the software in the auxiliary computer are:

* sending control commands to the master computer;

* receiving system status information from the master computer;

* allowing the user to change the external parameters and to make a simulation of an accident by keyboard;

* allowing the user to choose the real time/simulation time ratio to determine the simulation speed;

* calculating the natural room temperature to send to the master computer;

* displaying the simulation results and saving them on disk;

* controlling the I/O operation between the master computer and the DCP.

BUILDING AND HVAC SYSTEM DESCRIPTION

A system is described with four networks: the fabric network, the air-flow network, the water-flow network, and, if the user is not going to connect the DCP, a sensor and controller network.

1. Air-flow Network and Water-flow Network

The air-flow network includes all of the components connected with air such as the air handling equipment, fans, dampers and ducts, zones. In order to analyse infiltration and internal air flow between zones, gaps in windows, doors and other air flow pass are also included in the air-flow network. The network describes how these components connect together by means of a (0,1) matrix, and gives the information about each component in detail. In the same way as the air flow network, the water network gives the components and their connections for the heating and cooling water systems.

2. Fabric Network

Any building can be considered to be composed of walls. All of the walls can be described by a wall network. The spaces defined by the walls are zones and are connected by an air-flow network. The connections between the fabric surfaces and zones, and the connections between the surfaces in one zone which transfer heat to each other by long wave radiation are also defined by the fabric network. The construction and thermal properties of the walls are also included in the wall network.

3. Controller and sensor

If the user is not going to connect a real controller to ESAC, the behaviour of the controllers and sensors and how they are connected to each other also need to be described. The control and sensor network gives the connections between controllers and sensors and gives the detailed information about each controller and sensor. The sensors for measuring the state of air and water are connected to the air or water network. The controller will operate equipment in either the air or water network; so that the information about connections between controllers and relevant equipment is also included in the control network.

MATHEMATICAL MODEL AND THE HYDRODYNAMIC NETWORK ALGORITHM

1. Basic Equation

Assuming that fluids are incompressible and flows are one dimensional, the hydrodynamic equation of motion is:

$$\frac{dV}{d\tau} = -\frac{1}{\rho}\frac{\partial P}{\partial x} - \frac{g}{\rho}\frac{\partial H}{\partial x} \quad (1)$$

Combining every banch of the network, the flow in the network can be described as:

$$\frac{dG}{d\tau} = (B\ E\ B^T)^{-1}\ B\ (DH - S\ |G|\cdot G - \Delta Z)\ \frac{g}{\rho} \quad (2)$$

where G is a vector consisting of the flow rate in every banch; ΔZ, a vector consists of the potential head difference in every banch; DH, a vector gives the pressure increment of a fan or a pump in every branch; and S and E are diagonal matrices expressing the length/(cross-sectional area) and the resistance coefficient of each banch respectively. The matrix B describes the loops in the network, that is:

b_{ij} =1 , if ith branch is in the jth loop and is in the same direction as the loop;
b_{ij} =-1, if ith branch is in jth loop and in the direction opposite to the loop;
b_{ij} =0, if ith branch is not in jth loop.

During the simulation process, the matrix B and the vector ΔZ are fixed as the structure of the system cannot be changed, while the S, that is, the flow resistance coefficient, may be changed due to the regulation of dampers or valves and opening/closing doors or windows. The DH is the pressure head of fans or pumps, is a function of G.

2. Stability analysis

Equation (2) is a non-linear time dependent difference equation. If there is a large difference between the real parts of the eigenvalues of a system, the simultaneous equations describing the system are believed to be "stiff". The maximum time constant of the system is corresponding to the inverse of the minimum eigenvalue and the minimum time constant corresponds to the inverse of the maximum eigenvalue. If there is a very large eigenvalue in the system, a very small time step must be used in the simulation thus leading to very long computer run times and cannot "real time" simulate.

The selection of different branches to construct the basic loops for matrix B will result in different eigenvalues, so the selection of a suitable tree for the matrix B to minimize the maximum eigenvalue becomes very important. Detailed analysis [2] shows that the branches with large values of (length)/(cross-section area) or flow resistance cofficient should avoid being selected into the tree. Therefore, the ESAC is a general-purpose simulator in which the branch resistance may be changed greatly for example by opening and closing windows, even the (length/cross-section area) may be changed greatly. Therefore, ESAC reconstructs the tree, that is the matrix B, as soon as a branch resistance is changed greatly, so as to ensure a region of stability as great as possible to the system in the simulation process.

3. Stiff problems and MMKP method

If Eq. (2) is not stiff, an explicit method is applicable. In ESAC, Shampine's RKS3-4 pair of formulas [3] is used. However, the explicit method is invalid in solving stiff simultaneous differential equations. In this case, a Modified MKP method (MMKP) has been developed by the authors [2].

The MKP method [4] is suitable for solving the steady flow process in hydrodynamic networks. Modification is made to ensure it acceptable in solving the dynamic flow process. From Eq.(2):

$$F(G)=B\ ((DH - S\ |G|\cdot G - Z)\frac{g}{\rho} - E\ \frac{dG}{d\tau})=0 \quad (3)$$

Eq. (3) can be solved by Newton iteration and the result can be represented by:

$$\Delta G^{k+1}=M^{-1}\ F(G^k), \qquad M=-B\ D\ B^T \quad (4)$$

where G is the flow rate in the branches of the basic tree. As the matrix M is a positive definite matrix, it can be inverted by the Cholesky method (Square-root method). Analysis [2] shows that with MMKP method, for all situations, the iterations are convergeat for Eq. (2).

THE MATHEMATICAL MODEL FOR BUILDING

The ESAC software package includes a series of models for the simulation of HVAC equipment and buildings. The equipment models include heating/cooling coils, electricity heaters, electricity humidifiers, ducts, fans, flow mixing and separating, water banks, fan-coil units, controllers, sensors and so on. The thermal inertia of equipment such as heating/cooling coils, electricity heaters, electricity humidifiers, water banks sensors and fan-coil units are considered, and their thermal behaviour can be described by normal differential equations. The time lags of ducts are considered as well as thermal inertia, so this can be described in partial differential equations. [2] discusses all of the models in detail. In order to save space, only the building model is described below.

1. The Natural Room Temperature

To simulate the HVAC system in real time and to understand the dynamic behaviour of control, a second by second simulation is necessary. The influence of weather on a building is relatively low frequency and need not be calculated every second. To reduce the computing work it is essential to separate the influence of the HVAC system and control from the influence of the climate. Based on this idea, a new concept of NATURAL temperature of the building has been developed. The zone and wall temperatures are divided into two parts: natural temperature and artificial temperature. The natural temperature is defined to be the temperature that would result without a HVAC system or any artifical factors or infiltration. It is dependent on the solar radiation and the outside temperature only. Assuming the outside convection cofficient is constant, the system for natural temperature will be linear and all of the non-linear factors contribute to the artifical temperature. Also, because the solar radiation and outside temperature change slowly, the natural temperature can be simulated using hourly time steps. In ESAC, the natural temperature is calculated by the frequency response method [5] before the main simulation calculations start.

The real zone temperature T is found from:

$$T=t'+t$$

where t' is the natural temperature, and the t is the artifical temperature and given by:

$$Cr\frac{dt}{d\tau} = Q + p\, GsiCa\, (Tsi-t-t') - \sum_{k=1}^{m} hF_K(t-t_K) \quad (5)$$

where Cr is the thermal mass of the zone; Gsi is the air flow rate from the ith branch to the zone (this could be the air supplied by the HVAC system, the infiltration rate or the air flow from other zones). Tsi is the relevant temperature of the ith branch; t is the artifical temperature at the surface of the kth wall; F is the surface area; and h, the internal convection coefficient.

2. Heat Transfer Through Walls

The heat transfer in the kth wall of the wall network can be described by:

$$\frac{\partial t_k}{\partial \tau} = a_k \frac{\partial^2 t_k}{\partial x^2} \quad (6)$$

for x=0,

$$K_k(0)\frac{\partial t_K}{\partial x} = h_{k1}[t_k(0) - t_{a1}] - \sum_{i=1}^{p} h_{ik1}[t_i - t_K(0)] \quad (7)$$

for x=L,

$$k_k(L)\frac{\partial t_K}{\partial x} = h_{k2}[t_{a2} - t_K(L)] + \sum_{i=1}^{m} h_{ik2}[t_i - t_K(L)] \quad (8)$$

Where all of the temperatures are artificial temperatures. The t_{a1} and t_{a2} are the environmental temperatures at both sides of the wall; they should be the zone temperatures and the value at the last time step can be used for internal surfaces, they should be zero for external surfaces. The last term in Eq.(7) and (8) describes the long wave radiation between internal surfaces. For external surfaces, this term is also zero.

The wall network gives the connection between walls, zones, and the surfaces which can see each other, expressed as a (0,1) matrix. Combining with the equations for every wall, and approximating them by a finite different method, the heat transfer in the wall system can be described by a linear matrix equation and can easily be solved with second by second time steps.

APPLICATION EXAMPLES

1. Investigation of the Control Strategies for a Constant Temperature Room

The ESAC was used for finding of the suitable values of P, I, D for PID controllers in a constant temperature room system as shown in Fig.1. The room temperature needs to be kept within 20±0.1 C° and the humidity should be within 55±2%. Three PID controller were used for control of the water valve (d), electrical heater (8) and the vapour humidifier (1). Several groups of PID values were tested for each controller and the best values were found which kept the room temperature and humidity within a minimums range and save energy. Fig.2 shows part of the simulation results.

2.Simulation of a Hotel with a Fresh Air Supply System and Fan-coil Units in Each Room

Fig.3 shows the cross-section of 4 - 18 th floor of the Zhaolong Hotel in Beijing. A central air-conditioning system supplies fresh air to each room, in which a fan-coil unit is fixed. A cool water system supplies chilled water to each fan-coil. To simplify the system, the 270 guest rooms are divided into nine zones according to their orientation, heat gain, and construction as shown in Fig.3. The schematic diagrams of the simplified air network and water network are shown in Figs.4 and 5. Fig.6 shows some of the simulation results. During the simulation, all of the fan-coils were controlled by on-off controllers.

The influence of the thermal inertia of the fan-coil unit upon the indoor air temperature can be found from the results. The influence of the indoor heat output upon the water flow rate of the pumps and the on/off time ratio of the fan-coil unit also appear in the simulation results.

3. Effect of Piston Air Flow in an Underground Railway System

The piston air flows in the Shanghai underground railway system were also analysed by a modified form of the ESAC software to predict the thermal environment of the underground system. Part of the simplified schematic is shown in Fig.7. The air flow in the system depends upon:

(1) the cross-sectional area and length of the tunnels and friction factors of the tunnel walls;

(2) the cross-sectional area and length of the trains and their speed;

(3) the number of trains in the tunnel and their positions;

(4) the construction of the tunnels and the platforms;

(5) whether there is natural or forced ventilation in the system.

The system investigated has 10 stations with about 300 branches. Some of the simulation results are shown in Fig.8. More detailed simulation results and discussions has been presented in [6].

References

1 Yan. Q. S., Jiang Y. and Zhu Y. X., A digital real time emulator for HVAC systems, Proceedings of CLIMA 2000, vol. 6, pp707-711, Oct. 1985

2 A buiding and plant real time simulation system, Zhu Yingxin, Thesis for the degree of doctorate, Tsinghau University, Beijing China, April, 1989

3 Shampine L. F., Solving ordinary differential equations for simulation, Mathematics and Computers in Simulation, vol. 20, no. 3, Sept. 1978

4 В.Я. Хасилева и Т.П. Меренкова, Методы Алгоритмы Расчёта Тепловых Сетей, «Энергия», 1978

5 Zhao Q. Z. and Jiao F. X, Calculation air-conditioning load on the basis of frequency response of buildings, The national congress on HVRAC, Oct. 1986, Tangsha, China (in Chinese).

6 Jiang Y. and Zhu Y. X., Experiment and theoretical analysis of piston action in subway systems, The third international conference on underground space and earth shaltered building, Sept. 1988, Shanghai, China

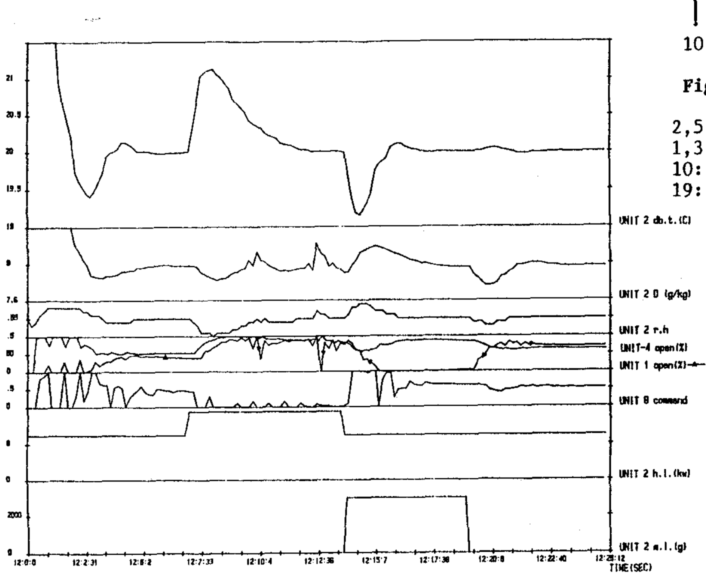

Fig.2 Simulation result of the constant temperature system

db.t: room temperature, °C; D: room humidity, g/kg; r.h : room relative humidity; -4 open: open ratio of valve d; 1 open: open ratio of humidifier 1; 2 h.1: heat gain in room; 8 command: the open ratio of the electric heater.

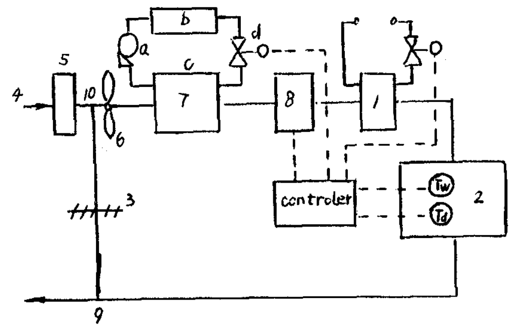

Fig.1 Schematic of a constant temperature room with a HVAC system and control

(a) pump; (b) cool source; (c) water coil; (d) valve; (1) vapour humidifier; (2) room; (3) damper; (4) atmosphere; (5) filter; (6) fan; (7) water coil; (8) electrical heat; (9) flow split; (10) flow merge

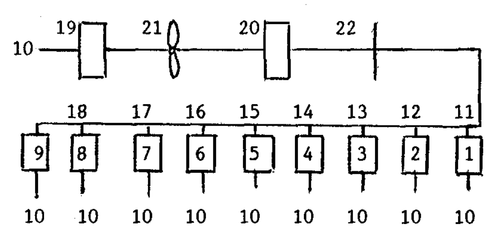

Fig.4 The schematic of the fresh air network

2,5,8: zones each includes 60 rooms;
1,3,4,6,7,9: zones each includes 15 rooms;
10: atmosphere; 11-18: flow splits; 21: fans;
19: water coils; 20: mufflers; 22: damper.

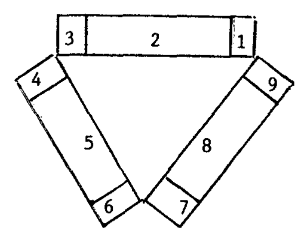

Fig.3 The vertical view of the Hotel

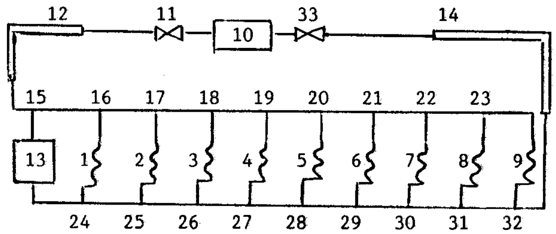

fig.5 The schematic of water network

1-9: fan-coils; 15-23: flow splits;
24-32: flow merges; 12,14: long pipe;
11: valve; 10: chill units;
13: water coils; 33: pumps

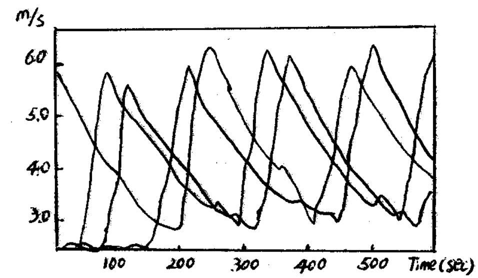

Fig.8 Simulation result of the air flows underground

The air velocities in different tunnels, m/sec

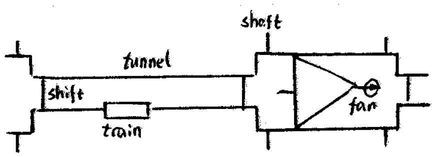

Fig.7 A part of the simplified schematic of the air system in the underground

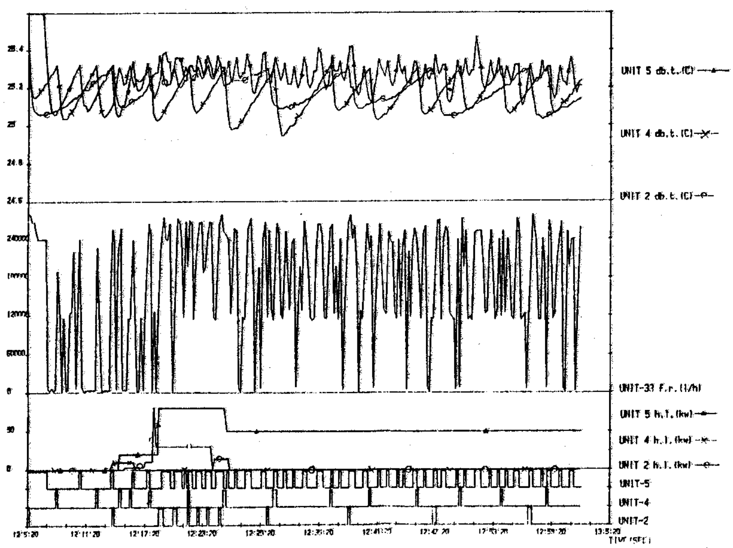

Fig.6 Simulation result of the AC system in the hotel

db.t: room temperature, °C; 33 f.r: the flow rate of pumps 33;
h.1 : heat gain of a room, kw; -5, -4, or -2: on/off of fan-coils