#5344

DYNAMIC MODELLING OF INDOOR AIR HUMIDITY

F. W. H. Yik
Senior Lecturer
Department of Building Services Engineering
Hong Kong Polytechnic, Hunghom, Hong Kong.

ABSTRACT

This paper describes a computer simulation program being developed at the Hong Kong Polytechnic for dynamic modelling of heat and moisture transport in buildings. At present, the program can simulate simultaneous heat and moisture transfer in the walls and slabs of a room and its effect on the room temperature and humidity. Effects of outdoor weather and air-conditioning are simultaneously simulated. Presented in this paper include: discussions on why indoor humidity modelling is needed; a review of relevant works reported in various literatures; descriptions of the models incorporated into the program; and simulation results obtained by using the room and system models that have been developed.

INTRODUCTION

It is well known that humidity level affects occupants' comfort and performance of air-conditioning systems. When indoor humidity in an air-conditioned room is high, occupants would feel uncomfortable (Fanger 1970) and would try to lower the thermostat set-point so as to retain comfort. This would increase the space heat gain and hence more energy would be consumed for air-conditioning. Besides, prolonged high indoor humidity (>70%) would promote growth of molds and mildews at wall and furniture surfaces which might affect health of occupants and cause deterioration of materials in buildings. When the cooling load or the room sensible heat ratio in an air-conditioned room is low, indoor relative humidity rising above 70% is not uncommon in buildings situated in a place with humid weather like Hong Kong. High indoor humidity will also arise when the air-conditioning system is intermittently operated while there exist moisture sources (e.g. infiltration) during the shut-down period. Moisture adsorption and desorption effects of building materials also play an important role in indoor moisture content changes.

As most building materials like concrete, wood, wall finishes, etc. are porous materials (Whiteley et al. 1977), moisture can migrate into or out of the interstices of the material. This provides a storage capacity for indoor moisture, similar to the thermal storage effect for sensible heat. Part of the moisture brought into or generated within the air-conditioned space will be adsorbed by walls and furnitures which will be released back to the room air when the air-conditioning system is restarted after a night shut-down period. Wong & Wang's measurement (1990) showed that the latent load of an air-conditioned office building and a library in Hong Kong were both over ten times higher than what could be possible due to infiltration and internal sources during the morning start-up period. Since this extra latent load on the air-conditioning systems is seldom accounted for in system design, this may explain why complaints often arise from occupants about insufficient cooling during the morning hours in buildings in Hong Kong.

To address to the increasing user requirements in respect of higher standard of comfort, more stringent specifications of environmental conditions for process work and the demand for more efficient use of energy, building and air-conditioning system designers must be able to accurately predict the performance of the designed building and systems to ensure that the requirements will be met. The design processes often involve comparison of several alternative designs and selection of the optimal one from them. This is particularly important when innovative design ideas are employed to provide a solution whereas its economic viability needs to be justified. Detail analysis and evaluation of building and systems involve large amount of calculations which need to be carried-out with the aid of a computer and a good simulation program. At present, many building energy calculation and air-conditioning system simulation packages are available, both for commercial use and for research purposes. Unfortunately, except a few that are for research use (see next section), none of them can properly simulate indoor humidity variation due to the simultaneous effects of moisture adsorption and desorption of the building fabric and moisture extraction by the air-conditioning system.

Besides lacking in moisture modelling capability, these packages also have short comings in one way or the other. First, in these packages, values of thermal properties of building materials are often assumed to be constant values. Thermal conductivity of building materials however vary significantly with moisture content whereas the moisture content within the material also varies. For example, the thermal conductivity of a light weight concrete deviates by more than 10% over the normally assumed moisture content range of 3 to 5% (by volume) for a concrete external wall (Stuckes & Simpson 1986). This deviation in thermal property, if not taken into account, could give rise to over or under estimation of the heat flow through the building envelop and thus could lead to wrong sizing of equipment or even wrong choice of system selection. Second, building thermal load is normally calculated first, based on a constant indoor condition, and system performance are then determined based on the load calculated in the first stage. In reality, system performance affects the thermal load in buildings. Accurate estimation of them therefore needs a simultaneous solution (Clarke 1986). Third, radiation energy exchange among internal surfaces of a building zone are often estimated by over-simplified approaches (such as environmental temperatures based on a cubical enclosure with black surfaces (CIBSE 1986)). How a reference temperature should be established for calculation however is still subject to argument (Uyttenbroeck 1990, Davies 1990) and the accuracy of this kind of method is not always good in cases where room configuration is non-typical or when the actual temperature differences among internal surfaces are large.

To address to the local need for an appropriate simulation tool for thermal load and indoor humidity analysis, attempt is being made at the Hong Kong Polytechnic to develop a computer program that can properly model the heat and moisture exchange between the indoor air and the building envelop, and the heat and moisture extration rate of the air-conditioning system when it is in operation. At present, a simulation program has been developed which is an intermediate result of the work. The theories and approach adopted in development of models in the program are introduced and results of studies obtained by using this program are discussed in the following sections.

SIMULTANEOUS HEAT AND MOISTURE TRANSFER IN BUILDING MATERIALS

As moisture adsorption and desorption at porous building materials has a significant effect on indoor humidity variations, it must be properly modelled in the development of a simulation program for predicting indoor heat load and humidity variations. To do this, the theory of simultaneous heat and moisture transfer in a porous medium has to be employed in the program formulation.

Studies on simultaneous heat and moisture transfer in porous media have been actively pursued by engineers and scientists for more than 50 years and a number of theorectial models had been proposed for its description. Among the earlier works in this subject, those of Philip & DeVries (1957), Luikov (1964, 1966, 1975), Harmathy (1969), Berger & Pei (1973) and Whitaker (1977) provided much insight into the problem. However, to mathematically describe simultaneous heat and moisture transfer in a porous medium and to solve the resultant equations are much more difficult than to model sensible heat transfer alone. First, there are several possible mechanisms (and theories) of moisture transport in porous media, such as liquid diffusion, vapour diffusion, capillary flow, convective transport and evaporation and condensation, and it is well known that temperature gradient across the medium has a signicicant effect on the moisture flux (Luikov 1966, Harmathy 1969, Whitaker 1977). However, which mechanism is the dominant one in a particular material under a specified set of conditions is often unknown and it is possible that the moisture transport is a combined effect of more than one of the mechanisms. In fact, there is yet no single theory or formulation that is known to be universally adaptable for modelling moisture transfer in porous solids. Second, the moisture transport phenomenon depends also on the pattern of pore size and shape distributions that exist in the porous system and on how the voids are inter-connected but it is extremely difficult to accurately describe these for a real porous solid (Scheidegger 1974). Due to these complications, models invariably are full of hypothesis and assumptions which limit their generality of application.

The other difficulty that is often faced by modellers is the lack of material properties data for use with the moisture transfer models. Value of some transport properties vary drastically with moisture content in the medium, e.g. the moisture diffusivity of simple Fick's Law like models (Bomberg 1974) and the permeability of materials in simple vapour diffusion models (McLean and Galbraith 1988), but precise data are generally lacking or insufficient in the literatures. Also, the kind of required data differs between models developed based on one theory to another and in general they are not inter-convertable.

A comprehensive summary of different theories proposed by various researchers can be found in the report by Kerestecioglu et al (1988). In appendix A of that report, the model equations of the liquid diffusion, capillary flow, and evaporation and condensation theories and those of Luikov's, Philip and DeVries's and Berger and Pei's theories are described. It must also be mentioned that material properties data and sorption isotherm data for a collection of building materials for use with these models are summarised in another appendix of this report. Data like these for a much wider range of building materials are highly necessary.

Notwithstanding there are still uncertainties in the theories, attempts have recently been made to apply them in investigations of simultaneous heat and moisture transport in buildings. Among various attempts made, the lumped parameter approach appeared to be a popular choice due to its simplicity and analytical solution can be obtained in some simple cases (e.g. Becker & Jaegermann 1982, Cunningham 1983). Tsuchiya (1980) developed a simple model for indoor humidity analysis which was an early attempt. In his model, assumption was made that moisture adsorption and desorption took place only in a thin layer at the building fabric surface. The humidity ratio in the air film at the room fabric surface was related to the moisture content at the surface layer of the material by a simple equation which actually was a piecewise linear fit of the sorption isotherm of the material. The average moisture content at room surfaces however need to be determined experimentally. Kohonda (1983) developed a surface probe for measuring the coefficients for use with Tsuchiya's model. This model is an attractive one due to its simplicity but unfortunately, not much corresponding materials data have been published.

The approach of using a Fick's Law like equation to relate moisture flux to either a moisture concentration or a vapour pressure gradient has been applied in studies on effect of moisture storage of walls on indoor air latent load (e.g.Isetti et al 1988, Wong 1990 and Wong & Wang 1990). Cunningham (1990) has also developed recently a 3-D model using vapour pressure gradient as the driving potential for moisture movement in solids. Problem with this approach is in availability of appropriate data of diffusivity or permeability and they are strongly dependent on the moisture content. Often, constant values were assumed in analyses (e.g. Wong & Wang 1990).

Fairey & Kerestecioglu (1985) have developed a finite element model called MADAM, based on Luikov's differential equations (1964, 1966, 1975), for simulation of simultaneous heat and moisture transfer in building materials. The model is an elaborated one and has been validated against some experimental data. Unfortunately, due to the use of 'Mass Transfer Potential' (Luikov 1964) as the driving protential for moisture movement, not much transport data of materials are available for use with this model. Kerestecioglu, Swami & Kamel (1990) further proposed the 'Effective Moisture Penetration Depth' (EMPD) theory to simply the analysis. With it, the simple lumped parameter approach can be used and thus would require less effort in the solution process. Unfortunately, the effort for obtaining appropriate values of EMPD could be substantial. Further, as the authors themselves remarked, this concept need to be used with caution and good judgement and different values of EMPD may be required for different operating conditions.

The evaporation and condensation theory has been adopted to formulate mathematical models for describing moisture transport in building materials. Such a model has been proposed by Kerestecioglu & Gu (1990), as an alternative to the Luikov's theory. The equation to be solved is slightly more complex than those of Luikov's theory but more material properties data are available for this type of model (Kerestecioglu et al 1988). Harmathy (1969) derived a set of partial differential equations for simulation of simultaneous heat and moisture transfer in a porous medium during the pendular stage (no bulk liquid movement) and used them to study drying of a piece of brick. Huang (1979) and Huang et al (1979) also presented similar equations (see next section) and used them to simulate drying of a concrete slab and a slab of cement paste. Their equations were derived based on conservation of mass of vapour moisture and dry air and conservation of energy, resulting in three non-linear partial differential equations. Moisture transport was assumed to take place only in the vapour phase but liquid moisture content within the porous medium would vary due to evaporation or condensation and would affect the rate of vapour transport. Vapour transport mechanisms modelled included vapour diffusion, convective flow, evaporation and condensation and effect of a temperature gradient. The sorption isotherm of the material was employed to relate liquid moisture content to thermodynamic states of the water vapour/air mixture within the pores of the medium and thus provided a closed set of equations.

THE HEAT AND MOISTURE TRANSFER SIMULATION PROGRAM DEVELOPED

General Features

A simulation program is being developed at the Hong Kong Polytechnic for dynamic modelling of simultaneous heat and moisture transport in buildings. At present, the program can be used to simulate variations of indoor temperature and humidity in a simple rectangular room due to the heat and moisture exchanges between the room air and the enclosing walls and slabs (a single-zone model). Simultaneous effects of outdoor weather and air-conditioning on the room fabric and indoor air conditions can be simulated. The room comprises four walls, one ceiling slab and one floor slab. One of the walls can be an external wall with a window on it (see Figure A), which is exposed to incident solar radiation and outdoor air. The wall opposite to the external wall is assumed to be a partition wall separating the room and a corridor with contant air temperature and humidity which may be different from those in the room. The room being modelled is assumed to be a typical cell in a building with idential cells at both sides and at above and below.

Mathematical Models

Wall/Slab Model In the simulation program, heat and moisture transport in individual layers of materials within the walls or slabs are modelled based on the set of non-linear partial differential equations developed by Huang (1979) based on Harmathy's theory (1969). This model is chosen due to its sound theorectical grounds, the variables chosen as heat and moisture transfer driving potentials are continuous across adjoining layers of different materials (and hence the model is readily adaptable to multi-layer analysis), and data for use with this model is relatively more easy to obtain from literatures (Keresteciogiu et al 1988). The equations of the model are of the form as follows:

$$A_i \frac{\partial \phi}{\partial t} + B_i \frac{\partial P}{\partial t} + C_i \frac{\partial T}{\partial t}$$

$$= D_i \frac{\partial^2 \phi}{\partial x^2} + E_i \frac{\partial^2 P}{\partial x^2} + F_i \frac{\partial^2 T}{\partial x^2} + G_i \left(\frac{\partial \phi}{\partial x}\right)^2 + H_i \left(\frac{\partial P}{\partial x}\right)^2 + I_i \left(\frac{\partial T}{\partial x}\right)^2 +$$

$$J_i \left(\frac{\partial \phi}{\partial x} \cdot \frac{\partial P}{\partial x}\right) + K_i \left(\frac{\partial \phi}{\partial x} \cdot \frac{\partial T}{\partial x}\right) + L_i \left(\frac{\partial P}{\partial x} \cdot \frac{\partial T}{\partial x}\right)$$

for $i = 1, 2$ & 3, denoting respectively conservation equations for mass of vapour, mass of air, and energy; where ϕ is the mole-fraction of vapour in the moist air; P is the moist air pressure; and T the temperature. A_i to L_i are coefficients with values dependent on the local state of the medium, the transport properties of the medium, and the local equilibrium moisture content as governed by the sorption isotherm of the material. Mathematical expressions for evaluation of these coefficients are detailed in Huang's paper (1979).

The set of non-linear partial differential equations has been discretised into a set of algebric equations using an implicit, backward-in-time finite difference scheme. The set of nodal equations (three algebric equations for each nodal point) constitutes a finite difference model for the room envelop. The finite difference model has been formulated to enable multi-layered walls and slabs be simulated using the program.

Convective Heat and Moisture Transfer at Wall/Slab Boundary Surfaces Rate of convective heat exchange between the outdoor or room air and the boundary surface of a wall or slab is evaluated using the Newton's Law of Cooling. The convective heat transfer coefficient is determined by using equations given by ASHRAE (1975). For the outdoor side of the external wall, the coefficient is evaluated with reference to the wind speed and direction whereas the indoor side coefficient is determined with reference to the direction of heat flow. Similar to heat transfer, moisture exchange at wall surfaces is calculated based on the surface to air vapour mole fraction difference and a mass transfer coefficient which is determined based on the convective heat transfer coefficient and the Lewis' relationship (Keresteciogiu et al 1988).

Solar Radiation Model Intensities of direct and diffuse solar radiation incident upon the external wall and window is determined based on global solar radiation (total horizontal intensity) data contained in the weather data file. The global solar radiation is first decomposed into direct normal and diffuse components using Kimura's model (1977) and intensities on the external wall are then calculated based on the incident angle at the corresponding time.

Internal Surfaces Radiation Exchange Long wave radiation exchange among internal surfaces in the room are modelled following basic principles of radiation heat transfer among gray surfaces (Incropera and DeWit 1985). To simplify the calculation, both direct and diffuse solar radiation transmitted through the window is assumed to be diffuse radiation which will be distributed to other internal wall or slab surfaces according to the radiation shape factor between the window and individual wall/slab surfaces, as for the long wave radiation.

Window Model The window glass is modelled by a lumped equation (an ordinary differential equation) derived from heat balance at the window glass and backward-in-time finite difference was applied to obtain a numerical model for the window.

Air-conditioning System Model In the program, the air-conditioning system model includes a cooling and dehumidifying coil model, a control valve model and a simple pipe flow model. The coil model was developed based on detailed theory of heat and moisture transfer between the air stream through the coil and the surface in a finned coil (McQuiston 1989, ASHRAE 1988). Effects of heat capacitance of the coil material and water held in the tubes are at present neglected. Options are available for the valve to be either controlled by an ON/OFF or a Proportional controller. In the present version of the program, time-lag in controller output is also neglected. When proportional control is used, the valve characteristics is assumed to be an equal percentage valve. Flow rate of chilled water through the cooling coil is determined based on hydraulic principles under the condition of a given pump head and pressure losses through the chiller, the pipings, the coil and the control valve corresponding to the flow. Supply chilled water temperature is assumed constant.

Air-node Model The room air condition is also modelled by a lumped parameter approach. Two ordinary differential equations, one for the air-node temperature and the other for the humidity ratio, that were derived respectively from heat and moisture balance in the room air, are used to simulate the air-node condition changes. They are both discretised into finite difference form by backward-in-time finite difference and solved in conjunction with equations for the walls and slabs, the window and the air-conditioning system.

Weather Data A weather data file containing actual hourly records of Hong Kong weather data in Year 1980 has been prepared for use with the simulation program. Outdoor weather parameters include temperature, relative humidity, wind speed and direction and global solar radiation intensity.

Other modules of the program include those for calculating radiation shape factors, radiation heat exchanges among internal wall and slab surfaces, those for psychrometric calculations and general mathematical routines for solution of a non-linear equation, a system of equations and for interpolation of weather data and materials' sorption isotherm data. Cubic spline functions are used in such interpolations.

Numerical Solution of the Mathematical Models

Numerical Solution Scheme Guass-Seidal iteration scheme with under relaxation is employed to solve simultaneously the set of coupled equations for the walls, slabs, the window, the air-conditioning system and the air-node.

Time Step Size Control The equations to be solved by the numerical scheme is a set of highly non-linear equations. Although an implicit finite difference scheme has been used, there is still a limit on time step size (and grid size in walls and slabs) whereas the criterion for its determination is not easy to work out and it also changes with progress of simulation (Huang 1979). In the program, a variable time step control scheme has been incorporated into the program to minimize chances of divergence and to speed up the calculation when the conditions become stablised. From trial runs with the program, it was found that the time-step size needs to be small at the start of a simulation or after the occurrence of a change of condition like starting/stopping of the air-conditioning system (in the order of minutes when the room is air-conditioned and in the order of seconds when the system is shut-down) but can be larger as the simulation proceeds. In the program, the time step can be lengthened during the simulation run at the user specified rate until the time step reaches the maximum value specified b user. When convergence is not achieved after a maximum number of iterations, the time step size will be halved and this continues until convergence is achieved or when the time step size is reduced to the minimium size in which case simulation time will be brought backward by a number of time steps and simulation will be resumed from there starting with the minimum time step size. This adaptive time step size control worked reasonable well in the trial runs.

SIMULATION STUDIES USING THE PROGRAM

General

The simulation program had been used to model dynamic heat and moisture transfer in a typical room at the perimeter of a hypothetical building situated in Hong Kong. Geometric configuration of the room was as shown in Figure A.

Construction, Material Properties and Initial and Operation Conditions The model room was 3m (W) x 3m (D) x 3m (H) in size with a 3m (W) x 1.5m (H) window at the South-facing external wall (wall 1). All walls and slabs were composite walls, each constructed of 100mm thick concrete with 13mm cement plastering at each side. The window was of 6mm thick single pane glass. Properties and initial conditions of the wall/slab materials and window glass used in the calculations were as summarized in Table 1.

The indoor set-point conditions, conditions in the corridor (outside of Wall 3, fixed) and indoor design parameters were assumed to be:

Room air set-point condition	temperature	:	298 K
	rel. humidity	:	50%
Corridor air condition (fixed)	temperature	:	300 K
	rel. humidity	:	65%
Number of occupanct :	1 person		
Ventilation rate :	7 l/s		
Infiltration rate :	1/2 air-change per hour (continuous)		
Lighting load :	225 W		
Air conditioned hrs. :	8:30 to 17:00		
Occupied hrs. :	9:00 to 17:00 (cccupants in and lights on)		

Discretisation of Walls/Slabs In the numerical simulation study with the model room, the external plastering, the concrete core and the internal plastering layer of each wall and slab were discretised respectively into 5, 15 and 5 sub-layers resulting in a total of 26 nodal points for each wall/slab and a total of 156 wall nodes for the entire room. Node number 1 and 26 are surface nodes whereas node number 6 and 21 are interface nodes between the plastering layers and the concrete core.

Design Cooling Load of the Room Design cooling load of the model room had been calculated according to ASHRAE's cooling load calculation method (ASHRAE 1989) and design data for Hong Kong. U-values used in the calculation were determined based on thermal conductivities of the wall and slab materials, with liquid moisture content as given in Table 1. This effective thermal conductivity was evaluated based on Kingery' empirical formula (see Huang's paper 1979).

Results of the calculation were as follows:

Peak Time : 14:00 Oct.

Peak Cooling Load (W):

Components	Sens.	Lat.	Total
Solar	783	0	783
Conduction (Glass)	175	0	175
Conduction (Wall)	263	0	263
Occupants	65	55	120
Lighting	225	0	225
Infiltration	33	129	162
Room Total	1544	184	1728
Ventilation	61	240	301
Block Total	1605	424	2029

Air Conditioning System Based on the design load calculation result, a fan-coil unit was selected for the model room. Charateristics of the selected unit were as follows:

Supply air flow rate :	0.125 m^3/s
Chilled water supply flow rate (valve open) :	0.12 kg/s
Chilled water supply temperature (assumed) :	280 K

Coil characteristics:-
No. of rows : 3
Fin spacing : 2 mm
Face area : 0.12 m^2 (600 mm x 200 mm)
No. of circuits : 1.5
No. of tubes per row : 10
Dia. of tubes : 9.53 mm / 8 mm (outer/inner)
Tube spacing : 20 mm / 20mm (transverse/longitudinal)
Fin thickness : 0.15 mm
Rated sensible cooling capacity : 1684 W
Rated total cooling capacity : 2196 W

Table 1 Properties and initial conditions of wall materials of the model room

Properties	Concrete	Plastering	Glass
Dry density (kg/m^3)	2600	2200	2500
Dry thermal conductivity (W/mK)	1.44	1.44	1.05
Porosity (m^3/m^3)	0.3	0.43	-
Dry specific heat (J/kgK)	879	879	750
Permeability of air at dry state (m^2)	2.5×10^{-14}	2.5×10^{-14}	-
Initial moisture content (m^3/m^3)	0.05	0.15	-
Initial temperature (K)	300	300	300
Emmisivity of surface (long wave radiation)	0.8	0.8	0.8
Absorptance (short wave radiation)	-	-	0.2
Transmittance (short wave radiation)	-	-	0.4
Shading coefficient	-	-	0.53

Fresh air supply at outdoor condition was assumed to be ducted to the return plenum of the fan-coil units at which it would mix with the return air. Chilled water flow through the fan-coil unit was assumed to be controlled by an ON/OFF controller with on/off settings at ± 1 °C about the set-point.

Simulation Results

Results of three simulation runs are presented here. Before that, a simulation run had been performed over the period of 0:00 on 1st July to 8:30 on 4th of July, with the room air conditions fixed at the set-point conditions, to allow the room fabric to attain relatively steady conditions. The first simulation run started from 8:30 on 4th July till 17:00 of the same day but with the room air-conditioned by the fan-coil system with ON/OFF control. This was for investigating effect of air-conditioning on the indoor conditions during the normal operating hours. The second run started from 17:00 till 8:30 on 5th July with no air-conditioning, for investigating rate of moisture build-up during the shut-down period. The third run continued from ending time of the second run till noon time of the same day, for investigating effectiveness of the air-conditioning system during the pull-down operation.

Run No.1 (Normal Operation) During the normal operating hours, the air-conditioning system was able to limit the room temperature from rising or falling outside of the control differential of 298 $\pm$ 1 K (Figure B.1) while the moisture content in indoor air was kept rather steadily at a level of about 0.0105 kg/kg (Figure B.2). Expanding the time scale showed that both the room temperature and moisture content actually were not as steady but were fluctuating due to the effects of ON/OFF control (Figure B.3 & B.4).

Run No.2 (Shut-down Period) When the air-conditioning system was shut-down, the room temperature quickly rose to about 302 K in 15 minutes (Figure C.1). The indoor air moisture content also started to rise but at a rate that was much slower than temperature (Figure C.2). The increase in room temperature steadied-down in about an hour after air-conditioning was stopped (Figure C.3) but indoor moisture content continued to rise steadily to about 0.0125 kg/kg just before re-starting time of the air-conditioned period in the following day (Figure C.4). Due to sun rise in the early morning whilst air-conditioning was only started at 8:30, the indoor temperature further rose to above 303 K during this period (Figure C.3).

Run No.3 (Pull-down Period) When air-conditioning resumed in the next day, the room temperature dropped quickly from around 303 K back to within the controlled range but fluctuated rather rapidly, which was the result of the ON/OFF control (Figure D.1). The moisture content also dropped rather rapidly at the start but it slowed down after the first several minutes from re-starting of the air-conditioning system (Figure D.2). In contrast to the room temperature which remained rather steady after the first 30 minutes (Figure D.3), it took about two hours for moisture content to attain a steady level (Figure D.4).

DISCUSSIONS

From the simulation results, the effects of moisture storage at building walls and slabs were found to be significant. In the shut-down period, the results (run No.2) demonstrated that the indoor moisture content only rised by a small extent. Had there been no adsorption of moisture at wall surfaces, the indoor moisture should have risen quickly to a level close to the outdoor condition due to the continued infiltration of humid outdoor air into the room. The adsorbed moisture were released from wall surfaces back into the room air when the air-conditioning was re-started in the next day. As opposed to thermal storage, effects of moisture storage on indoor air moisture content was much slower and the pull-down period required to bring indoor conditions back to the desired range took a much longer time than to bring temperature alone back to the controllable range (run No.3). If this moisture adsorption and desorption effect is not accounted for in predicting indoor conditions and evaluating performance of the air-conditioning system, erroneous results will be obtained.

The results demonstrated that analyses of indoor air humidity transients can be carried-out with the program developed and further analyses including conditions in days with more humid or colder weather, effects on energy for air-conditioning, effects of other type of control systems etc. can also be investigated by using the program. The method adopted in describing the moisture adsorption and desorption effects of the walls and slabs (Huang's equations) however appeared to be too complicated for long term simulation analysis as it took a very large computational effort in the simulation calculations. In the simulation studies reported here, the CPU time required (using a 486 machine) was as long as the simulated time. A simplier model for use in year-round simulation studies is therefore necessary but the detailed model is still a valuable tool for detailed, storter term studies and could serve as a reference model for checking accuracy of the simplier model.

ACKNOWLEDGEMENT

The work reported here was sponsored by the Hong Kong Polytechnic as a staff development program for the author. The work was registered as a research degree programme at the Newcastle Upon Tyne Polytechnic, UK. The author thanks Dr. C. P. Underwood, Dr. A. J. Newall, Dr. W. K. Chow, Dr. J. Burnett and his colleagues in the Department of Building Services Engineering, Hong Kong Polytechnic, for their kind support towards his work.

REFERENCES

ASHRAE (1975) Subroutine Algorithms for Heating & Cooling Loads to Determine Building Energy Requirements, ASHRAE, USA.

ASHRAE Handbook (1988) Equipment, ASHRAE, USA.

ASHRAE Handbook (1989) Fundamentals, ASHRAE, USA.

Becker, R and Jaegermann, C (1982) The Influence of Permeability of Materials and Absorption on Condensation in Dwellings, Bldg. Envir. 17(2) pp.125-134.

Berger, D, and Pei, D C T, (1973) Drying of Hygroscopic Capillary Porous Soilds - A Theoretical Approach, Int. J. Heat Mass Transfer, Vol.16, pp.293-302.

Bomberg, M (1974) Moisture Flow Through Porous Building Materials, Report 52, Division of Building Technology, Lund Institute of Technology, Sweden.

CIBSE (1986) Guide Vol. A. The Chartered Institution of Building Services Engineers, UK.

Clarke, J A (1986) Simulation of Building Energy Systems, Proc. CIB 5th Int. Sym., Bath, 1986, pp.118-133, CIBSE, UK.

Cunningham, M J, (1983) A New Analytical Approach to the Long Term Behaviour of Moisture Concentrations in Building Cavities - I Non-condensing Cavity, Bldg Envir. 18(3), pp. 109-116.

Cunningham, M J, (1990) Modelling of Moisture Transfer in Structures - I. A Description of a Finite-Difference Nodal Model, Bldg Envir. 25(1), pp. 55-61.

Davies, M G, (1990) Mean Radiant Temperature in the CIBSE Guide, BSER&T 11(2), pp.69-71, CIBSE, UK.

Fairey, P W, and Kerestecioglu, A (1985) Dynamic Modelling of Combined Thermal and Moisture Transport in Buildings: Effects on Cooling Loads and Space Conditions, ASHRAE Trans. V.91, Pt.2A, pp.461-472.

Fanger, P O (1970) Thermal Comfort Analysis and Applications in Environmental Engineering, McGraw-Hill Book Company.

Harmathy, T Z, (1969) Simultaneous Moisture and Heat Transfer in Porous Systems with Particular Reference to Drying, I&EC Fundamentals, 8(1), pp. 92 - 103.

Huang, C L D, (1979) Multi-phase Moisture Transfer in Porous Media Subjected to Temperature Gradient, Int. J. Heat Mass Transfer, Vol. 22, pp. 1275 - 1307.

Huang, C L D, Siang, H H, and Best, C H, (1979), Heat and Moisture Transfer in Concrete Slabs, Int. J. Heat Mass Transfer, Vol.22 pp. 257-266.

Isetti, C, Laurenti, L and Ponticiello, (1988) Predicting Vapour Content of the Indoor Air and Latent Loads for Air-conditioned Environments: Effect of Moisture Storage Capacity of the Walls, Energy and Buildings, 12(1988), pp.141-148.

Incropera, F P and DeWitt, D P, (1985) Fundamentals of Heat and Mass Transfer, 2nd ed., John Wiley & Sons.

Ker ecioglu, A, Swami, M, Dabir, R, Razzaq, N and Fairey, P, (1988) Theoretical and Computational Investigation of Algorithms for Simultaneous Heat and Moisture Transport in Buildings, Final Report

US DOE Cotract #DE-FC03-865F16305 and GRI Contract #5087-243-1515, FSEC-CR-191-88.

[illegible], A. Swami, M. and Kamel, A (1990) Theoretical and Computational Investigation of Simultaneous Heat and Moisture Transfer in Buildings: "Effective Penetration Depth" Theory, ASHRAE Trans. V.96, Pt.1, ASHRAE USA.

[illegible], A. and Gu, L. (1990) Theorectical and Computational Investigation of Simultaneous Heat and Moisture Transfer in Buildings: 'Evaporation and Condensation' Theory, ASHRAE Trans. Vol.96, Pt.1, ASHRAE USA.

[illegible] (1977) Scientific Basis of Air-conditioning, Applied Science Publishers Ltd., London.

[illegible] (1983) Indoor Humidity Calculations, ASHRAE Trans. V.89 Pt.2, ASHRAE, USA.

[illegible] A V (1964) Heat and Mass Transfer in Capillary Porous Bodies, Advances in Heat Transfer, V.1, Academic Press.

[illegible] A V (1966) Heat and Mass Transfer in Capillary Porous Bodies, [illegible] Press.

[illegible] A V (1975) Systems of Differential Equations of Heat and Mass Transfer in Capillary Porous Bodies (review), Int. J Heat Mass Transfer, V.18, pp.1-14.

[illegible], R C and Galbraith, G (1988) Interstitial Condensation: Applicability of Conventional Vapour Permeability Values, BSER&T 9(1) pp.29-34, CIBSE, UK.

[illegible], F C and Parker, J D (1988) Heating, Ventilating, and Air-conditioning Analysis and Design, 3rd ed., John Wiley & Sons.

[illegible] J R, and DeVries, D R, (1957) Moisture Movement in Porous Media under Temperature Gradients, Trans. Am. Geophisical Union, 38(2), pp.222-232.

[illegible]legger, A E, (1974) The Physics of Flow Through Porous Media, 3rd Ed., University of Toronto Press, Toronto.

[illegible], A D and Simpson, A (1986) Moisture Factors and Thermal Conductivity of Concrete, BSER&T 7(2), pp.73-77, CIBSE, UK.

[illegible], T (1980) Infiltration and Indoor Air Temperature and Moisture Variation in a Detached Residence, JSHASE Japan, 54(11), pp.13-19.

[illegible]aker, S (1977) Simultaneous Heat Mass and Momentum Transfer in Porous Media: A Theory of Drying, Advances in Heat Transfer, Vol 13, pp.119-203.

[illegible], P, Russman H D, and Bishop, J D, (1977) Porosity of Building Materials - a Collection of Published Results, Building Research Establishment Current Paper, CP21/77, Building Research Establishment, Department of the Environment, UK.

[illegible], S P W, (1990) Simulation of Simultaneous Heat and Moisture Transfer by Using the Finite Difference Method and Verified Tests in a Test Chamber, ASHRAE Trans. V.96, Pt 1, ASHRAE, USA.

[illegible], S P W, and Wang, S K, (1990) Fundamentals of Simultaneous Heat and Moisture Transfer Between the Building Envelop and the Conditioned Space Air, ASHRAE Trans. V.96, Pt 2, ASHRAE, USA.

[illegible]enbroeck Ir. J (1990) Building Heat Loss Calculations: Choice of Internal Temperature and of Heat Exchange Coefficient hi, BSER&T 11(2), pp.49-56, CIBSE, UK.

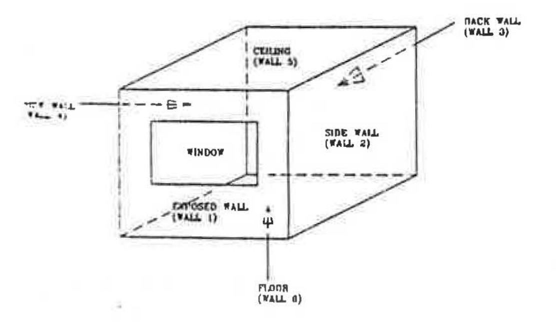

Figure A

Figure B.1 Air-conditioned Period

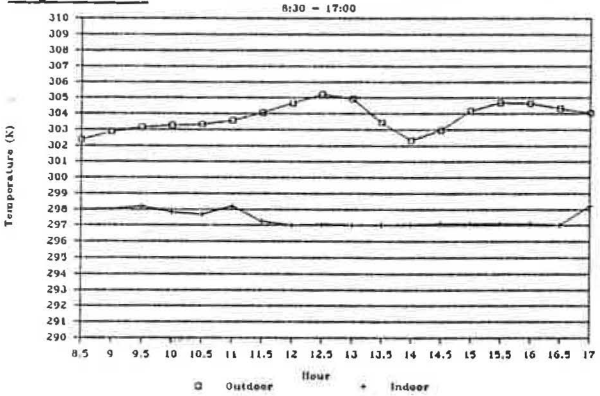

Figure B.2 Air-conditioned Period

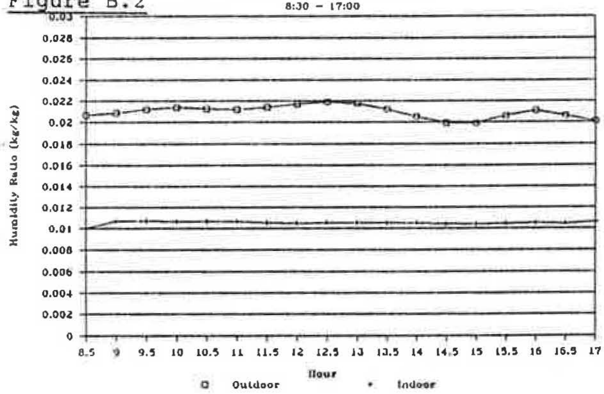

Figure B.3 Air-conditioned Period

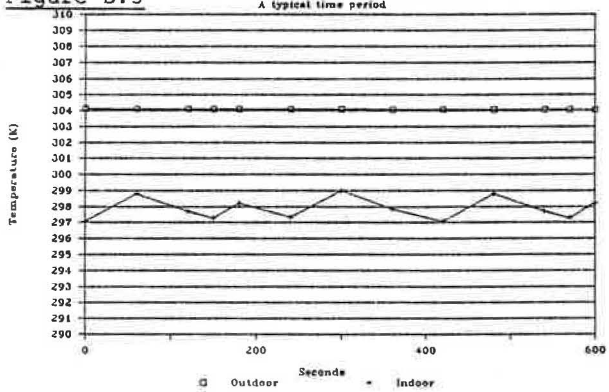

Figure B.4 Air-conditioned Period

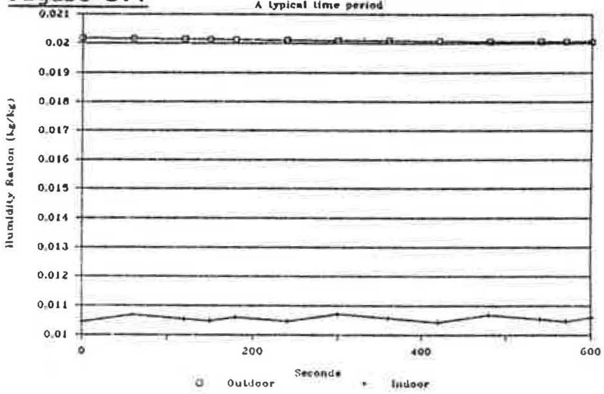

Figure C.1

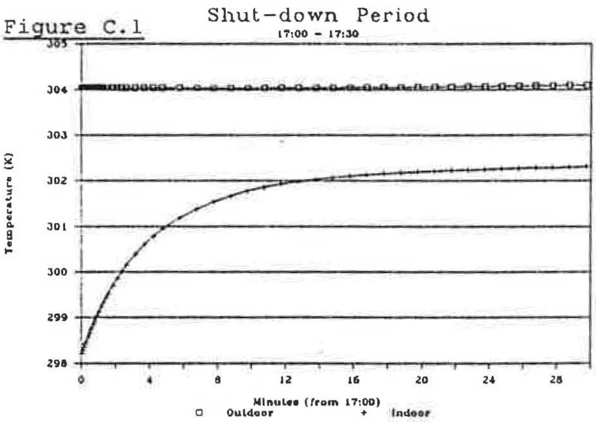

Figure D.1

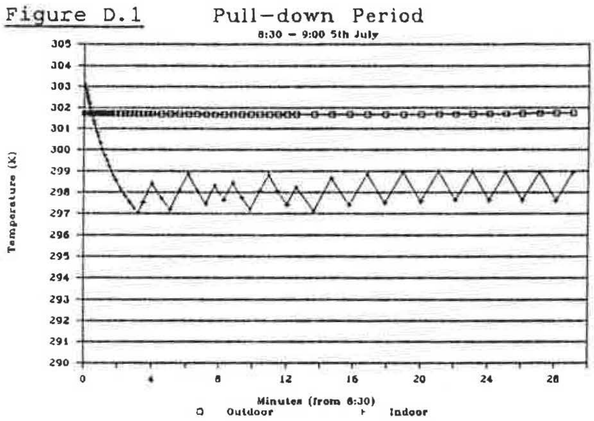

Figure C.2

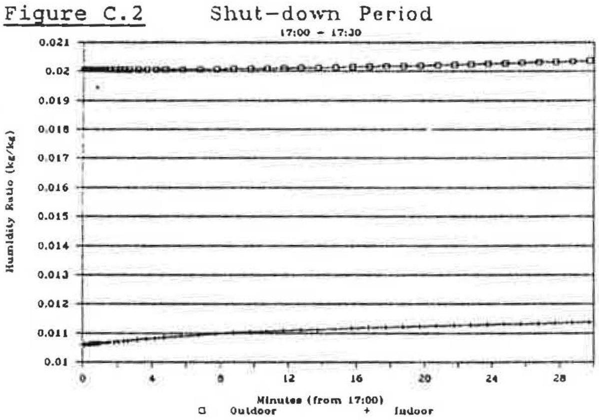

Figure D.2

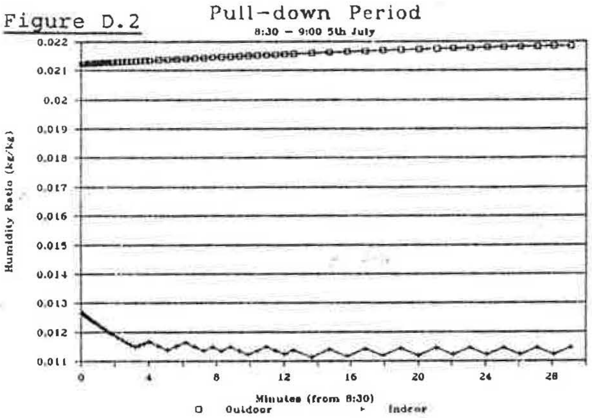

Figure C.3

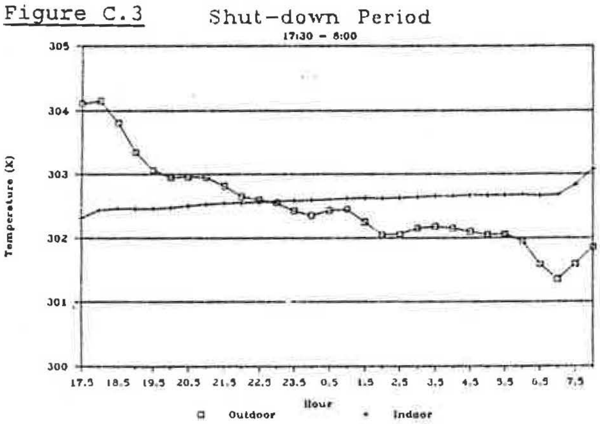

Figure D.3

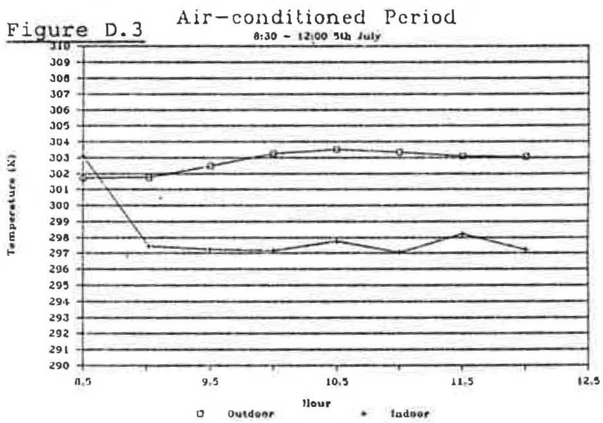

Figure C.4

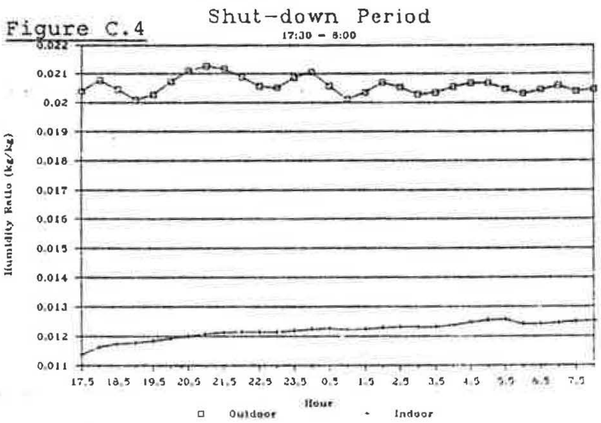

Figure D.4