Dynamic Modelling of Both Thermal and Air Quality Conditions in Houses

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ABSTRACT

In this study the COwZ model (COMIS with sub-zones) was modified to allow dynamic simulations of indoor thermal conditions, humidity and pollutant transport and concentrations throughout whole buildings. The new version of COwZ may be used to predict the impact of heat supply and ventilation options on indoor conditions, particularly temperature and humidity, over extended periods, with dynamic weather conditions and varying occupant activities.

KEYWORDS

COwZ, dynamic modelling, ventilation, thermal modelling, indoor humidity.

INTRODUCTION

Air flows in buildings form a dynamic system with hundreds of flow paths linking indoor spaces and indoors to outdoors, where external conditions are continually changing. There is also a significant interaction between air flows and thermal conditions. In designing buildings and their heating and ventilation systems it would be useful to be able to take all these interacting processes into account. It would be impractical to use CFD for such complex, dynamic scenarios, but in recent years a number of building thermal models have been developed including ESP-r, TRNSYS and EnergyPlus (see Weber *et al.* 2003).

Our research focuses on developing new models for predicting indoor air flows, temperatures and heat loads, pollutant emission and dispersion, occupant exposure and the effectiveness of heating and ventilation systems. We have developed the COwZ model (Ren and Stewart 2003, Stewart and Ren 2005), based on the public domain multizone air flow and pollutant transport model COMIS, to which we have added many facilities including: zonal modelling (to resolve air velocities, temperatures and pollutant concentrations within rooms); a quasi-steady state thermal model; and a range of source emission models (Ren 2002). In the work described here, we investigate the responses of indoor thermal conditions and moisture to transient external weather and occupant activities. A dynamic thermal model has been developed and integrated into COwZ to predict building performance over periods from a few hours to many days.

METHODOLOGY

COwZ nests a sub-zonal model within a multizone model (COMIS). In COwZ critical rooms in a building are sub-divided into a relatively small number of sub-zones. All other well-mixed rooms are treated as single zones. Two types of sub-zone are used: standard sub-zones – where flows are driven by pressure gradients; and, flow element sub-zones – where flows are driven by inlet ducts, fans or temperature gradients associated with heaters or warm surfaces (Ren 2002).

The solution of the system of equations, based on the laws for conservation of air flows, thermal energy and mass of each contaminant species in each zone (sub-zone), provides air flows, temperatures and pollutant concentrations. As COMIS does not include thermal balance equations these had to be added. The transient energy balance can be expressed by:

$$\rho_i C_p V_i \frac{dT_i}{dt} = \sum_{j=0}^{j=Nz}\sum_{l=0}^{l=Nl} m_{jil} C_p (T_j - T_i) + \sum_{k=0}^{k=Nf} \alpha_{ik} A_{ik} (Tw_{ik} - T_i) + q_{s,i} + m_{s,i} C_p T_{s,i} \quad (1)$$

where ρ, C_p, V, T and t are respectively the air density, specific heat, zone volume, temperature, and time. N_z and N_l are the total number of sub-zones and flow paths between sub-zones j and i respectively. α_{ik} and A_{ik} are convective heat transfer coefficient and surface area between solid surface k and sub-zone i respectively. Tw_{ik} is the temperature of the solid surface k. N_f is the total number of solid surfaces in sub-zone i. $q_{s,i}$ is internal gain of energy due to heaters, equipment, lights and people. $m_{s,i}$ is an airflow source in zone i. $m_{s,i} > 0$ if it is a source, and $m_{s,i} < 0$ if it is a sink. $T_{s,i}$ is air temperature of source or sink airflow in zone i. In the case of a sink, $T_{s,i}$ is equal to the temperature of zone i. In the case of a source, $T_{s,i}$ is equal to the temperature of the air supplied in zone i.

For steady state, the left side of Eqn. 1 is equal to zero, and this equation has been successfully integrated into COwZ (Ren 2002). For transient conditions, Eqn. 1 is solved numerically using a suitable finite volume method. The specific heat C_p is assumed to be constant. By using a purely implicit finite difference scheme to integrate Eqn. 1 over time, under matrix notation we obtain:

$$[A]\{T_{ip}^{t+\Delta t}\} = \{B\} \quad (2)$$

With:

$$A(i,j) = \sum_{l=0}^{l=N_l} - m_{jil}(t+\Delta t) C_P \qquad i \neq j$$

$$A(i,i) = \frac{\rho_i (t+\Delta t) V_i C_P}{\Delta t} + \sum_{j=0}^{j=N_Z} \sum_{l=0}^{l=N_l} m_{jil}(t+\Delta t) C_P + \sum_{k=0}^{k=N_f} \alpha_{ik} A_{ik}$$

$$B(i) = \frac{\rho_i (t) V_i C_P}{\Delta t} T_i(t) + \sum_{l=0}^{l=N_O} m_{oik}(t+\Delta t) C_p T_O(t+\Delta t) + \sum_{k=0}^{k=N_f} \alpha_{ik} A_{ik} T_{ik}(t+\Delta t) + q_{s,i}(t+\Delta t) + m_{s,i}(t+\Delta t) C_P T_{s,i}(t+\Delta t)$$

In the source term $B(i)$, the subscript o represents outside characteristics. For building simulations there are generally three types of thermal boundary conditions. For the first type, solid surface temperatures T_w are known (perhaps determined by experiment); for the second type, solid surfaces are assumed to adiabatic (by setting the *α* coefficients to zero). Vector B includes all the known heat sources and solid surface temperatures Tw_{ik}. Eqn. 2 can be solved directly. But for the third type, the solid surface temperatures T_w are unknown. Vector B includes all the known heat sources and unknown solid surface temperatures Tw_{ik}. At each time step, the solid surface temperature Tw_{ik} must be determined, making the solution more complex.

When a building is furnished and occupied, there are various room surfaces, furniture, and appliances. It becomes difficult (if not impossible) to determine each solid surface temperature. In this study, for external walls, roof, floors, and windows, the heat transfer between indoor and outdoor air through the building fabric can be expressed as:

$$q_{i,o} = U_i A_i (T_o - T_i) \tag{3}$$

For typical British buildings, the U-value can be obtained from published sources such as Energy Efficiency Best Practice in Housing (EST, 2004).

The effects of internal thermal mass (such as internal walls, furniture, appliances, internal concrete partitions, etc.) were modelled using a weighting factor method in which the rate of heat storage or release is assumed to be η ($\rho C_p V \frac{dT}{dt}$). Using the weighting factor method and introducing Eqn. 3 into Eqn. 1, the energy balance equation becomes:

$$(1+\eta)\rho_i C_p V_i \frac{dT_i}{dt} = \sum_{j=0}^{j=Nz}\sum_{l=0}^{l=Nl} m_{jil} C_p (T_j - T_i) + \sum_{m=0}^{m=N_E} U_{im} A_{im} (T_O - T_i) + q_{s,i} + m_{s,i} C_p T_{s,i} \tag{4}$$

and then for Eqn. 2, *A(i,i)* and *B(i)* become:

$$A(i,i) = (1+\eta)\frac{\rho_i (t+\Delta t) V_i C_P}{\Delta t} + \sum_{j=0}^{j=N_Z}\sum_{l=0}^{l=N_l} m_{jil}(t+\Delta t) C_P + \sum_{m=0}^{m=N_E} U_{im} A_{im}$$

$$B(i) = (1+\eta)\frac{\rho_i (t) V_i C_P}{\Delta t} T_i(t) + \sum_{l=0}^{l=N_O} m_{oik}(t+\Delta t) C_p T_O(t+\Delta t) + \sum_{m=0}^{m=N_E} U_{im} A_{im} T_o(t+\Delta t) + q_{s,i}(t+\Delta t) + m_{s,i}(t+\Delta t) C_P T_{s,i}(t+\Delta t)$$

where N_E is the total number of external walls, roof, floor and windows in sub-zone *i*.

The weighting factor η is dependent on the features of the room and internal thermal mass (such as room size, furniture size and materials, etc.). Balaras (1996) and Yam *et al*. (2003) reviewed a large number of previous studies on thermal mass effects in buildings and provided procedures for estimating the effective heat storage capacity. A set of weighting factors is determined by heat balances (Eqn. 4) and then used during the entire simulation period, assuming that the weighting factors will not change during the period of the simulation (Al-Homoud 2001, ASHRAE 1997).

Because the coefficient matrix *A* is symmetric ($A(i,j) = A(j,i)$) and diagonally dominant ($|A(i,i)|>\Sigma|A(i,j)|$; *sum for all* $j \neq i$), it is positive definite and we can obtain a unique value for T from Eqn. 2.

CASE STUDY

In this section we present some comparisons with experimental data collected from a three-storey house to demonstrate some of the capabilities of COwZ. On the ground floor the house has a living room, kitchen and entrance hall, on the first floor two bedrooms and a bathroom, and on the second floor is a bedroom.

The input data were provided from a local weather station and from an assumed schedule of occupant activity and moisture emission rates (Table 1). Thermal input from the central heating was estimated by an iterative process where the energy supplied was adjusted until the predicted room temperatures matched the measured values. The temperature predictions are therefore not independent and cannot be used to evaluate the model. However, there is much less dependence for the relative humidity predictions and the good level of agreement between the simulation and the measurements gives a high level of confidence in the model.

Figures 1, 2 and 3 show a comparison for temperature and relative humidity between COwZ and measurements for the living room, kitchen and bedroom over a 33 hour period. The match between simulated and measured temperature for the each room is very close, all simulated data falling within 0.5 °C of measurements. This reflects the iterative matching process described in the previous paragraph. The agreement is also good for relative humidity. In each room the simulated data lie within ±9% (but mostly ±5%) of measurements. Towards the end of the simulation the gap between simulation and measurement in the bedroom widens to 14%.

Overall, the agreement between the model and the measurements is remarkably good, especially considering the level of assumptions on occupant activity which were made.

TABLE 1 Moisture emission rate from various occupant activities (Pretlove, 2000)

Occupant/activity/location	*Emission rate (kg/hr)*
Seated person	0.0432
Sleeping person	0.0374
Kitchen (cooking, washing, etc.)	0.1667
Bathroom	0.0500

CONCLUSION

A new dynamic thermal model, which represents a compromise between simpler methods that ignore building mass effects (such as steady-state methods), and the more complex methods (such as complete heat balance calculations), has been developed and incorporated into COwZ. It has been demonstrated that COwZ can be used to predict building dynamic thermal performance and relative humidities through whole buildings. Additional comparisons are required to further evaluate the new program.

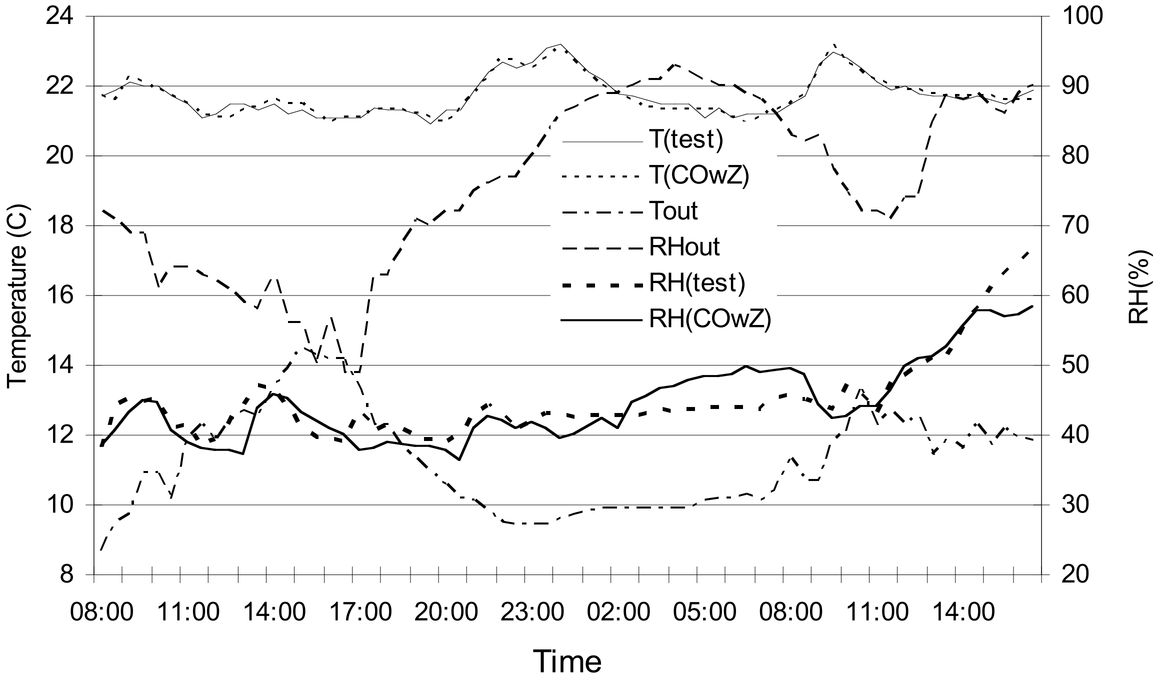

Figure 1 Comparison between COwZ modelling and measurement for living room

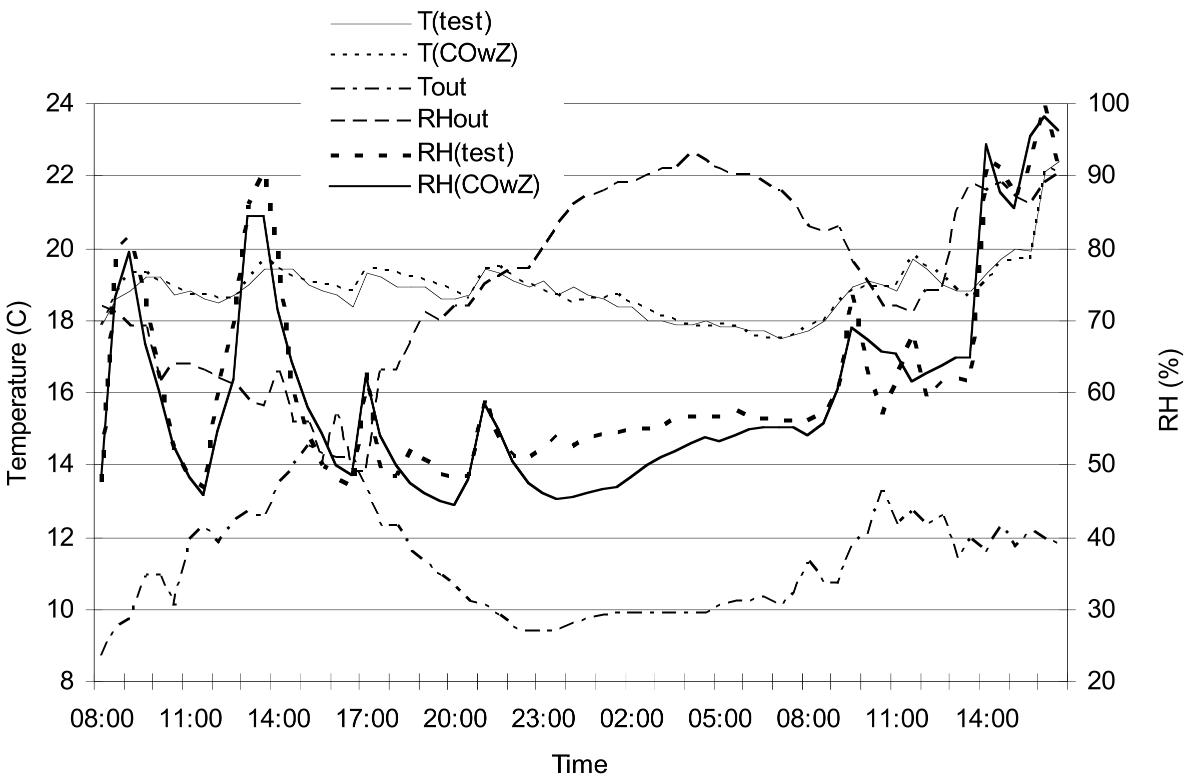

Figure 2 Comparison between COwZ modelling and measurement for kitchen

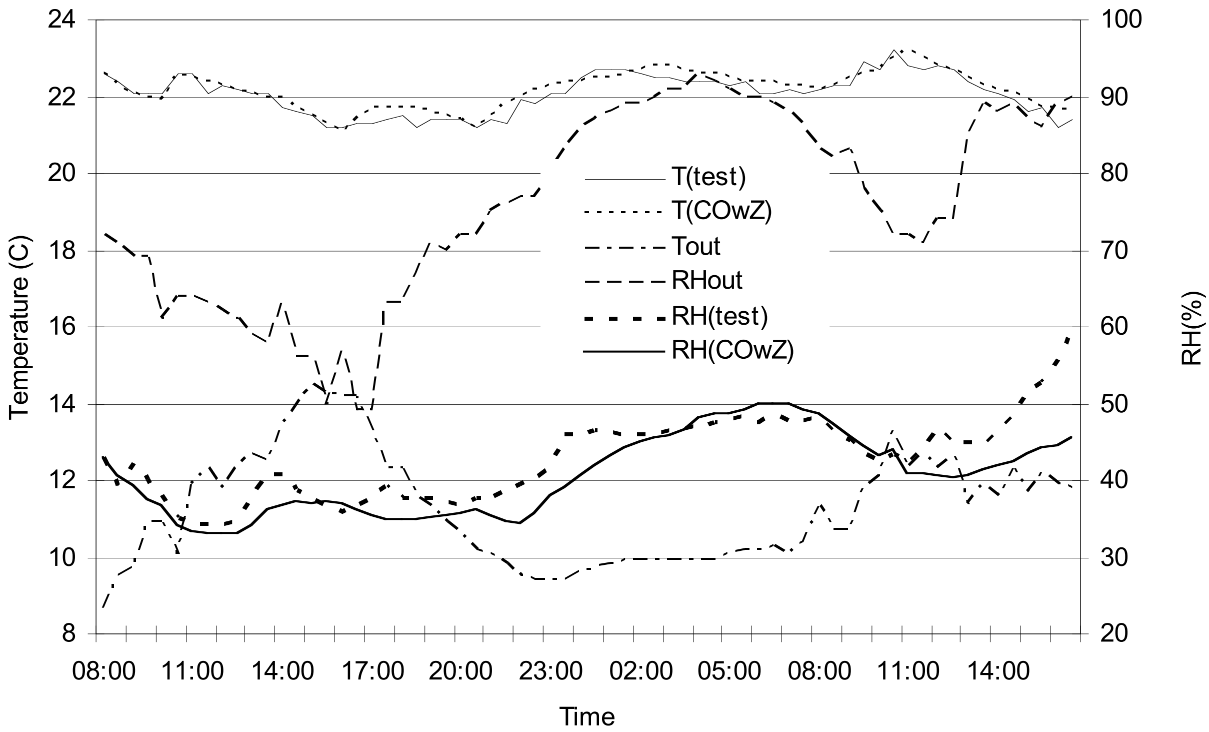

Figure 3 Comparison between COwZ modelling and measurement for bedroom

ACKNOWLEDGMENTS

This project is funded by a grant from the Northern Ireland Housing Executive.

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