Energy and Buildings, *19* (1993) 297–302

Towards an integral approach of building and HVAC system

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(Received July 22, 1991; accepted in revised form January 15, 1993)

Abstract

The dynamic thermal interaction between a building and the HVAC systems which service it is still difficult to predict. As this thermal interaction becomes more critical in practice, related knowledge and evaluation tools become increasingly important. It is argued why these need to be based on an integral approach of the overall problem.

A research project aimed at development and/or enhancement of building performance evaluation tools for this field of interest is outlined. The work involved expansion of an existing building energy simulation environment on the fluid flow and plant simulation side. Application of this integral simulation system is demonstrated by means of a case study.

Keywords: computer simulation, energy, fluid flow, building, systems, design evaluation tool.

Introduction

Due to the highly diverse dynamic properties involved, the thermal interaction between building and heating, ventilating and air-conditioning (HVAC) system — under the influence of occupant behaviour and outdoor climate — is often difficult to predict. In practice this may result in non-optimal, malfunctioning, or even 'wrong' building/system combinations.

There is a large class of problems which really need an integral approach of the complete technical system consisting of building structure, occupants and HVAC system. Typical examples are: development of Building Energy Management Systems, passive solar applications, HVAC system and (intelligent) control development, extraordinary building/system combinations (e.g. re-destination of historical buildings), integrated building/system combinations (e.g. floor heating, a swimming pool, etc.), and (transient) thermal comfort studies involving building/system thermal interaction.

Early research in this area focused on the relation between building design and energy consumption. Only later was more attention directed to the plant side of the overall problem domain. In the former approach the influence of the HVAC system was more or less neglected by over-simplification. In the latter approach the complex building energy flow paths were usually grossly simplified.

In the current research (detailed by Hensen [1]) we started from the principle that neither approach is preferable for the majority of problems indicated above: both building and plant have to be approached on equal levels of complexity and detailedness.

Outline of the approach

The objective is development/enhancement of building performance evaluation tools addressing the dynamic thermal interaction between a building and its HVAC system. In this context, thermal comfort and energy consumption are the objective functions.

The current research started from the energy simulation research environment ESP-r [2, 3] which is currently under development and subjected to a rigorous validation programme [4] at various research institutes throughout Europe. Starting from such a platform offers vast advantages for any individual research group. The most important ones are:

(1) as an individual group it is not necessary to have expertise in all areas;

(2) areas not addressed within a specific research project will still be state of the art;

0378-7788/93/$6.00

(3) as more people are using the system, any bugs or flaws are likely to surface sooner;

(4) results transfer to the international research community is implicit and therefore very efficient.

At the project commencement, ESP-r was already very mature in terms of building energy simulation. However there was a clear need to expand the fluid flow and the plant simulation side, and to enable better integration with the building side.

Fluid flow simulation

In the current context, fluid flow phenomena are encountered in four principal areas:

(1) airflows through cracks and openings in the building structure, i.e., infiltration and natural ventilation;

(2) the flow of air through the distribution network designed to satisfy thermal comfort and air quality demands;

(3) flow of heating/cooling fluids within the plant;

(4) convective fluid flows within interior building spaces and plant components.

Some knowledge of the magnitude of these flows is necessary for load and energy calculations, system control analysis, thermal comfort assessment and contaminant/moisture dispersal estimation. Although fluid flow is demonstrably an important aspect of combined building and plant simulation, its analysis has considerably lagged the modelling of other energy flow paths. The main reasons for this would appear to be the lack of sufficient data and the inherent computational difficulties.

In recent times more emphasis has been placed on fluid flow simulation with two approaches extant: computational fluid dynamics (CFD) and the zonal network method. In the context of combined heat and mass flow simulation in buildings, it is the zonal method which has proved (for the present at least) to be most commensurate with the modelling approach adopted by ESP-r. The reasons for this are:

(1) there is a strong relationship between the nodal networks which represent the fluid regime and the corresponding networks which represent its thermal counterpart, implying that the information demands of the energy conservation formulations can be directly satisfied;

(2) the technique can be readily applied to combined multi-zone buildings and multi-component, multi-fluid, multi-network plant systems;

(3) the number of nodes involved will be considerably less than that required in a CFD approach and so the additional CPU burden is minimized.

Within the network approach, during each simulation time step, the problem is constrained to the steady flow (possibly bi-directional) of an incompressible fluid along the branches of network which represent the building/plant mass flow paths. Information on potential mass flows is given by a user in terms of node descriptions, fluid types (currently air and water are supported), flow component types (e.g., power law, orifice, vent, crack, door, duct, pipe, valve, pump, etc.), interconnections and boundary conditions. In this way a nodal network of fluid flow resistances is constructed. This may then be attached, at its boundaries, to known pressures or to, for instance, pressure coefficient sets which represent the relationship between free-stream wind vectors and the building external surface pressures which result. The flow network may consist of several decoupled sub-networks and is not restricted to one type of fluid. However, all nodes and components within a sub-network must relate to the same fluid type.

Each flow component has a subroutine counterpart which is used to generate flow and flow derivative at each iteration. Conservation of mass at each internal node is equivalent to the mathematical statement that the sum of the mass flows must equal zero at such a node. Because these flows are nonlinearly related to the connection pressure difference, solution requires the iterative processing of a set of simultaneous non-linear equations subjected to a given set of boundary conditions. The solution method in use is based on an approach suggested by Walton [5], and employs a simultaneous whole network Newton-Raphson technique which is applied to the set of simultaneous nonlinear equations.

The current fluid mass flow simulation module has a further enhanced solver. This module may be operated in stand-alone mode (e.g., to prove integrity of a defined flow network). However, it appears to fuller advantage when it is used in tandem with the main building and plant energy simulation modules. This enables energy, air quality and comfort studies to be made of combined building and plant configurations in which the fluid flow rates may vary with time due to changing temperatures, pressures or flow path characteristics.

Plant simulation

With respect to dynamic plant simulation techniques, two main approaches can be distinguished: (1) the sequential modelling technique, of which TRNSYS [6] is a well-known representative, and (2) the simultaneous modelling technique, which is used in the current research. Here HVAC system modelling is achieved by a modular, component-wise approach. Each plant component model consists of one or more finite volume, state-space equations, representing the conservation of heat and mass. The overall system is a combination of component models resulting in a complete set of state-space equations for the whole system. At run time, each component has a corresponding subroutine whose mission is to generate the coefficients of these matrix equations. Examples of currently supported plant component models are: junctions, adiabatic humidifier, fan, heating or cooling coil, ducts, plate heat exchanger, boilers, radiators, pipes, thermostatic radiator valves, room thermostats, etcetera.

Given the problem domain context, a selection criterion for plant component models is that they need to be as comprehensive as deemed necessary to guarantee thermodynamic integrity. On the other hand, the component models will have to be as simple as possible (especially with regard to usage of descriptive parameters) to enable the user to extract the necessary data from available sources (i.e., literature, manufacturers data, etc.).

Although it may appear that there are many plant component models readily available from literature, this is deceptive to say the least. The reasons for this are:

(1) most models encountered are described in an analytical fashion (i.e., no numerical formulation);

(2) almost all numerical models encountered are geared at the sequential modelling technique;

(3) most models encountered are steady-state approaches;

(4) (almost) same model descriptions re-occur.

No model was found in literature which could readily be used as it was. Developing or adjusting models is often difficult and time-consuming. Only recently incentives have taken place to facilitate this process by, for instance, establishment of a database of component models [7], development of a "neutral format model" which should be usable for various simulation environments [8], or development of other concepts to ease the reuse of models [9].

Combining heat and mass flow

Coupling of building and plant in a mathematical/numerical sense, effectively means combining the energy and flow balance matrix equations for both the building and its plant [2]. While in principle it is possible to combine all building/plant and heat/fluid flow matrix equations into one overall 'supermatrix', this is not done primarily because of the advantages which accrue from problem partitioning.

The most immediate advantage is the marked reduction in matrix dimensions and degree of sparsity. A second advantage is that it is possible to easily remove partitions as a function of the problem in hand; for example when the problem incorporates building-only considerations, plant-only consideration, plant + flow, and so on. A third advantage is that different partition solvers can be used which are well adapted for the equation types in question – highly non-linear, differential and so on.

It is recognized however that there are often dominating thermodynamic and/or hydraulic couplings between the different partitions. If a variable in one partition (say air temperature of a building zone) depends on a variable of state solved within another partition (say the temperature of a radiator), it is important to ensure that both values match in order to preserve the thermodynamic integrity of the system. Without going into details, two methods are offered to handle these couplings: (1) a time step control facility, and (2) iteration mechanisms.

Case study

A typical example of a problem, for which an integral approach is necessary, is performance evaluation of a room thermostat. This case study was inspired by findings from pilot experiments in a relatively small flat with a wet central heating system, controlled by a (still widely in use) mechanical room thermostat. It should be noted though that the investigated problems are of importance for electronic room thermostats too.

Technical considerations led to some modifications of the heating system during the measurements, one of which was disabling the thermostat's acceleration heating (which is used to raise the temperature of the sensitive element more rapidly towards the switch-off temperature in order to decrease the room air temperature differential). The acceleration heating is very important with respect to the boiler switch frequency. In this specific case and given the prevailing environmental conditions, the burner cycle time (burner-on till burner-on) was about 90 times longer when the acceleration heating was disabled. The total burner-on time – for an equal period of time – was approximately 50% shorter, suggesting a strong decrease in fuel consumption. It should be noted, however, that in this specific case both the number of cycles per hour (at average heating season conditions ≈ 30) and the boiler stand-by heat losses may be regarded as well above average.

A longer cycle time has consequences also with respect to the fluctuation of the air temperature. Without the acceleration element, the fluctuation of the mean room air temperature during one cycle is much larger. Whether the resulting conditions would be acceptable to the occupants was investigated by means of a literature study on thermal comfort in transient conditions [10].

The objective of the present case study was to see whether the above observations can be repeated – by computer simulation – for a more general case, and to investigate whether decrease of thermostat acceleration heating might be a potential energy conservation strategy.

Imagine a building and plant configuration as schematically shown in Fig. 1. The room is part of a reference house for energy-related research, in this case representing a typical Dutch terraced house. The exterior envelope is insulated according to prevailing regulations. For the present study, the air temperatures of the spaces adjoining the living room are kept at constant values as indicated. The living room is serviced by (part of) a wet central heating system, comprising: a (two-node model) radiator, a (two-node model) high efficiency condensing boiler (scaled down to accommodate the current single radiator system), a pump delivering a fixed water flow rate, piping as indicated, and a mechanical room thermostat located in the living room.

Two plant control loops were defined to drive the system: (1) to actuate the boiler on the basis of the temperature sensed by the room thermostat, and (2) to simulate the acceleration heating of the room thermostat.

The degree of heat input is the primary parameter to be considered in the following. To illustrate the influence of the degree of acceleration heating, Fig. 2 shows some simulation results comprising a two-hour period of a climatic reference year. The simulations were performed for two values of thermostat heat input: 0.05 and 0.10 W. For the given conditions, this gives either approximately 1 or 2 cycles per hour, resulting in air temperature differentials of approximately 1 and 2 K respectively. Figure 2 also indicates the set-point differential. It may be seen that in the 0.05 W input case, the sensed temperature still rises even after the burner is switched off. This is due to the fact that at those points in time the room air temperature is actually higher than the thermostat set point. Note that there are two transient factors which play a role in the time lag and damping of the sensed temperature when compared to the room air temperature: (1) the sensed temperature depends on both air temperature and building construction temperatures (which lag behind because of thermal inertia of the building materials), and (2) thermal inertia effects of the heating system itself.

To investigate whether the overall gas consumption is also affected, several simulations – comprising the period January 12 to January 15 inclusive – were performed for various degrees of acceleration heating. From results not presented here it is clear that when the simulations would start from a constant thermostat set point, this would lead to different average room air temperatures. Obviously the results would then be incomparable. Therefore

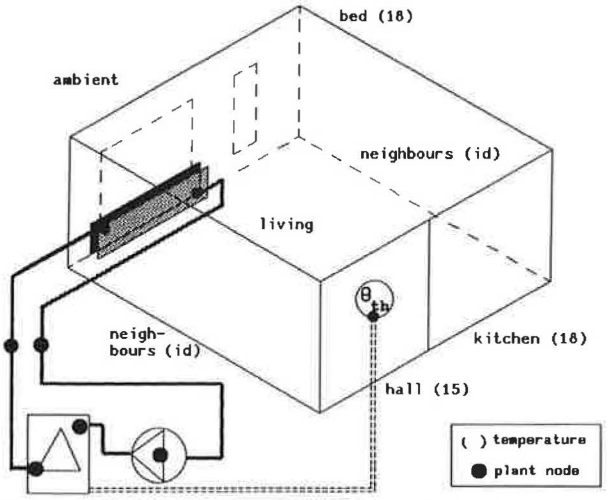

Fig. 1. Schematic representation of a building and plant configuration comprising a living room serviced by (part of) a wet central heating system.

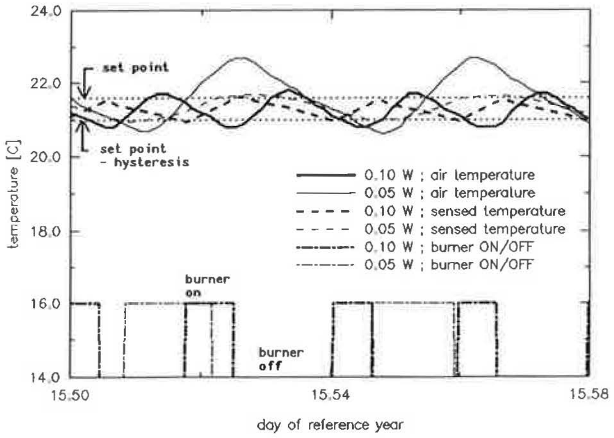

Fig. 2. Influence of acceleration heating on fluctuation of mean living room air temperature and on temperature as sensed by the room thermostat during a two-hour simulation period.

TABLE 1. Results of simulations during January 12 to January 15 inclusive for various degrees of acceleration heating applied to the mechanical room thermostat

Description	Parameter value or result				
Acceleration heating (W)	0.20	0.10	0.05	0.01	0.01
Set point (°C)	22.4	21.5	21.5	21.5	20.8
Overall average air temperature (°C)	20.6	20.7	21.1	21.5	20.8
Idem but Jan 13 only (°C)	20.4	20.7	21.1	21.3	20.4
Idem but Jan 15 only (°C)	21.3	21.3	21.6	22.0	21.3
Average cycle freq. Jan 13 only (h^{-1})	4.0	1.8	1.0	0.8	0.8
Average cycle freq. Jan 15 only (h^{-1}	4.5	2.0	1.1	0.9	0.9
Air temp. differential Jan 13 only (K)	0.3	1.3	2.3	3.3	3.3
Air temp. differential Jan 15 only (K)	0.3	1.0	2.1	3.0	3.0
Total gas consumption (m_0^3)	16.1	16.0	16.6	17.1	16.0
Idem but Jan 13 only (m_0^3)	4.9	5.0	5.2	5.4	5.1
Idem but Jan 15 only (m_0^3)	2.9	2.7	2.9	3.0	2.7

some of the thermostat set points were chosen (by trial and error) such that the resulting average room air temperature (for January 15) would be equal. The most important simulation results — with respect to the investigated problem — are collected in Table 1. When the cycle frequencies and the corresponding air temperature differentials are compared with the thermal comfort criteria for transient conditions, all cases presented in Table 1 fall within the comfort limits.

When comparing the gas consumption results for the cases with equal average air temperature, Table 1 indeed evidences that it is possible to conserve energy — while maintaining thermal comfortable conditions — by decreasing the burner cycle frequency. Lowering the cycle frequency from 4.5 to 2.0 h^{-1}, results in a gas consumption reduction of only 1% when the whole period is taken into account, but in a 7% reduction when just the "average heating season day" (i.e., January 15) is taken into account. This suggests that the optimal strategy is to apply the "cycle frequency control" strategy selectively; i.e., weather dependent.

Obviously the above has to be investigated further with respect to what is the optimal strategy (i.e., development of knowledge for intelligent controllers), and for which type of systems is it applicable. In the present context, this case study should be regarded merely as a demonstration of applying our approach.

Conclusions

This paper has described a "modular-simultaneous" approach for the simulation of combined heat and fluid flow in a building/plant context. The present performance of the model indicates that it is now practical to simulate building/plant configurations in the transient state and on equal levels of detailedness.

While the model is robust and well adapted for its task, several future developments have been identified. These include the development of additional fluid flow components (especially improved large opening models), the development of additional plant component models in the required state-space format, and experimental validation of the simplifying assumptions in the component models.

Acknowledgements

The author is deeply indebted to Professor J.A. Clarke of the University of Strathclyde in Glasgow for his continuing support.

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