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A Simulation Approach to the Evaluation of Coupled Heat and Mass Transfer in Buildings

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ABSTRACT

This paper describes the techniques used within the *ESP* environment[#] to simulate coupled heat and mass flows in integrated building and plant systems. In particular, it describes the equation-sets used to represent inter-zonal (building) and inter-component (plant) fluid flow, the method used for the simultaneous solution of these non-linear equations, and the solution coupling of the heat and mass conservation equation-sets. By means of a brief description of a case study, the application in a real building performance evaluation context is demonstrated.

INTRODUCTION

In buildings, and the HVAC systems which services them, fluid flow phenomena are encountered in four principle areas:

- air flow through cracks and openings in the building structure, that is infiltration and natural ventilation;
- the flow of air through the distribution network designed to satisfy thermal comfort and air quality demands;
- the flow of heating/ cooling fluids within the plant;
- and the 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 building/ plant performance assessment, the sophistication of its treatment in many modelling systems has tended to lag the treatment applied to the other important energy flow paths. The principal reason for this would appear to be the inherent computational difficulties and the lack of sufficient data. In recent times more emphasis has been placed on fluid flow simulation with two approaches extant:

Computational Fluid Dynamics (CFD); in which the conservation equations for mass, momentum and thermal energy are solved for all nodal points of a two- or three-dimensional grid inside or around the object under investigation. A well known example of a CFD model is PHOENICS (Spalding 1981). While in theory the CFD approach is applicable to any thermo-fluid phenomenon, in practice, and in the building physics domain in particular, there are several problematic issues of which the amount of necessary computing power (Chen 1988), the nature of the flow fields and the assessment of the complex, occupant-dependent boundary conditions are the most problematic. This has often led to CFD applications being restricted to the steady-state case which, in many building performance contexts, is atypical. Application examples in the field of building energy simulation are the prediction of temperature and velocity fields inside large or technically complex enclosures such as atria and television studios (Markatos 1984), the simulation of the effects of wind (Bottema et al. 1989), and the prediction of the pressure field around a building (Haggkvist et al 1989).

The Zonal Method; in which a building and its plant are treated as a collection of nodes representing rooms, parts of rooms and plant components, with inter-nodal connections representing the distributed flow paths associated with cracks, doors, ducts and the like. The assumption is made that there is a simple, non-linear relationship between the flow through a connection and the pressure difference across it. Conservation of mass for the flows into and out of each node leads to a set of simultaneous, non-linear equations which can be integrated over time to characterise the flow domain.

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 the *ESP* system. The reasons for this are threefold. Firstly, there is a strong relationship between the nodal networks which represent the fluid regime and the corresponding networks which represent its thermal counterpart. This means that the information demands of the energy conservation formulations can be directly satisfied. Secondly, the technique can be readily applied to combined multi-zone buildings and multi-component, multi-network plant systems. And finally, the number of nodes involved will be considerably less than that required in a CFD approach and so the additional CPU burden is minimised.

It is the zonal method then which has been employed for several years as the basis of the building side air flow module of the *ESP* system and which

In this context, the term ESP refers to the research version of the system as currently under development at various centres throughout Europe including the Universities of Strathclyde and Eindhoven. A separate version of the system is being commercialised by a private company, ABACUS Simulations Limited.

underpins recent developments which have led to an improved equation solver and extensions of the technique to plant systems in general. Within *ESP* these developments are made available to a user via the mass flow network solver *ESPmfs* for use in cases where buoyancy effects are time-invariant, and as an integral encapsulation within *ESPbps*, the main building and plant simulation module, for use in cases where buoyancy has a strong temporal dimension.

This paper describes the theoretical basis of the *ESP* approach to simulation of coupled heat and mass transfer in buildings. Firstly, the approach to fluid flow simulation is outlined in terms of the flow equation types used and the numerical solution strategy employed. A more rigorous description may be found elsewhere (Hensen 1990; Clark and Hensen 1990; Hensen and Clark 1990). The paper then describes the integration of the flow algorithm within the *ESPbps* numerical processing scheme to enable combined heat and fluid flow in building/ plant systems. Finally, and briefly, the paper illustrates the application of the approach in practice.

THE APPROACH IN OUTLINE

Within the *ESP* approach, during each simulation time step, the problem is constrained to the steady flow (possibly bi-directional) of an incompressible fluid along the connections which represent the building/ plant mass flow paths network when subjected to certain boundary conditions regarding pressure and/ or flow. The problem reduces therefore to the calculation of fluid flow through these connections with the nodes of the network representing certain pressures. This is achieved by an iterative mass balance approach in which the unknown nodal pressures are adjusted until the mass residual of each internal node satisfies some user-specified criterion.

Information on potential mass flows is given by a user in terms of node descriptions, fluid types, flow component types, interconnections and boundary conditions. In this way a nodal network of connecting resistances is constructed. This may then be attached, at its boundaries, to known pressures or to pressure coefficient sets which represent the relationship between free-stream wind vectors and the building external surface pressures to 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.

Nodes may represent rooms, parts of rooms, plant components, connection points in a duct or in a pipe, ambient conditions and so on. Fluid flow components correspond to discrete fluid flow passages such as doorways, construction cracks, ducts, pipes, fans, pumps,

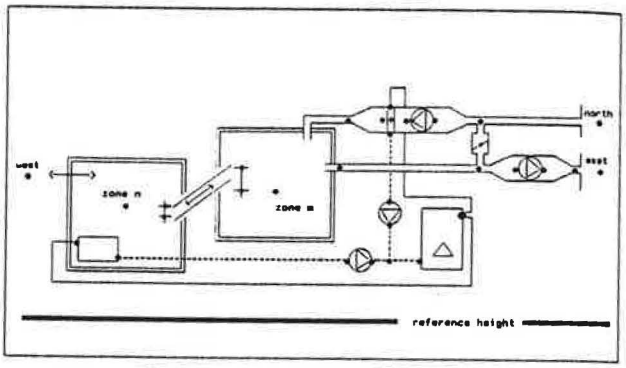

Figure 1 Example building and plant schematic

etc. As an example Figure 1 shows a schematic of part of a building consisting of two rooms, air flow connections between these rooms, a radiator heating system connected to one zone and an air heating system connected to the other zone. In this case the building and plant configuration contains two mass flow networks - one for the air and one for the water. One possibility with respect to the translation of this configuration into a fluid flow nodal scheme is indicated by the dots.

In an *ESP* model. nodes are characterised by several data items, including
an identifier, the fluid type, the node type, the height above some arbitrary datum, temperature and several supplementary parameters which depend on the node type. The nodes of the network represent either internal or boundary pressures with only internal nodes being subjected to mass balance tracking. Note that in the present context 'internal' is not necessary equivalent to 'inside' nor does 'boundary' necessarily equate to 'outside'. Usually the pressure at an internal node is unknown, although it may be treated as a known parameter as could be required, for example, in the case of an expansion vessel in a hydronic radiator system.

Flow components are characterised by an identifier, a type code (indicating duct, pipe, pump, crack, doorway, etc.) and a number of supplementary data items defining the parameters associated with a specific component type. When a certain flow component is repetitively present in the network, it need only be defined once. The currently supported fluid flow component types are summarized in Table 1. Within *ESP* each flow component has a subroutine counterpart which is used to generate the flow and flow derivative at each iteration. As an example, the power law component type is elaborated in the next section. Detailed information on all component types can be found elsewhere (Hensen 1990).

A flow network is defined by connections. Each connection is described in terms of the name of the node on its (arbitrarily declared) positive side, the height of the positive linkage point relative to the node on the positive side, the name of the node on the (arbi-

Table 1 Currently supported fluid flow components

Code	Type
10	Power law volume flow resistance element
15	Power law mass flow resistance element (definition 1.)
17	Power law mass flow resistance element (definition 2.)
20	Quadratic law volume flow resistance element
25	Quadratic law mass flow resistance element
30	Constant volume flow rate element
35	Constant mass flow rate element
40	Common orifice flow element
50	Laminar pipe flow element
110	Specific air flow opening
120	Specific air flow crack
130	Specific air flow door
210	General flow conduit (duct or pipe)
220	Conduit ending in converging 3-leg junction & C = f(q/qc)
230	Conduit starting in diverging 3-leg junction & C = f(q/qc)
240	Conduit ending in converging 4-leg junction & C = f(q/qc)
250	Conduit starting in diverging 4-leg junction & C = f(q/qc)
310	General flow inducer (fan or pump)
410	General flow corrector (damper or valve)
420	Flow corrector with polynomial local loss factor
450	Ideal (frictionless) flow controller

tranly declared) negative side of the connection, the height of the negative linkage point relative to the node on the negative side, the name of the connecting flow component and supplementary data which depends on the flow component selected. Note that more than one connection may exist between two nodes. The concept of a connection having a positive side and a negative side is used to keep track of the direction of fluid flow. For most mass flow component types, uni-directional fluid flow will result (in either direction). However, some component types may represent bi-directional fluid movement - for example in the case of a doorway where, due to the action of small density variations over the height, bi-directional flow may exist.

THE CALCULATION PROCESS

Consider Figure 2 which shows two zones connected by some fluid flow component. It is assumed that each volume can be characterised by a single temperature and a single static pressure at some height relative to a common data plane. The inlet and outlet of the connecting component are at different heights relative to each other and relative to the nodes representing the volumes. Analysis of the fluid flow through a component i is based on Bernoulli's equation for one-dimensional steady flow of an incompressible Newtonian fluid including a loss term:

$$\Delta P_i = (p_1 + \frac{\rho v_1^2}{2}) - (p_2 + \frac{\rho v_2^2}{2}) + \rho g (z_1 - z_2) \; (Pa) \qquad (1)$$

where ΔP_i is the sum of all friction and dynamic losses (Pa), p_1, p_2 are entry and exit static pressures (Pa), v_1, v_2 are entry and exit velocities (ms^{-1}), ρ is the density of the fluid flowing through the component (kgm^{-3}), g is the acceleration of gravity (ms^{-2}) and z_1, z_2 are the entry and exit elevations (m).

Bernoulli's equation can be simplified by combining

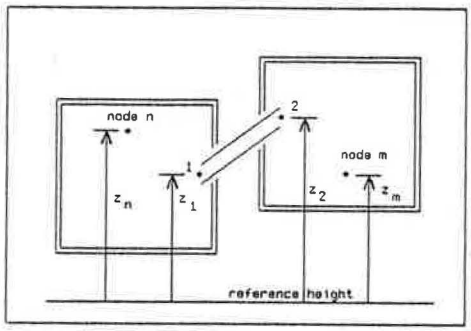

Figure 2 An example two zone connected system

several related terms. Stack effects are represented by the $\rho g (z_1 - z_2)$ term in equation (1). Dynamic pressures are the $\rho v^2/2$ terms, and total pressure is defined to be the sum of static pressure and dynamic pressure; that is $P = p + \rho v^2/2$. If nodes n and m represent large volumes (for example a room), the dynamic pressures are effectively zero. If the nodes represent some point in a duct or pipe network, there will be a positive dynamic pressure. Equation (1) thus reduces to:

$$\Delta P = P_n - P_m + PS_{nm} \; (Pa) \qquad (2)$$

where P_n, P_m is the total pressure at nodes n and m (Pa), and PS_{nm} is the pressure difference due to density and height differences across connection $n-m$ (Pa). Equations (1) and (2) define a sign convention for the direction of flow: positive from point 1 to point 2 (or n to m). The flow within each fluid flow component is described by a relation of the form $\dot{m} = f(\Delta P)$. The partial derivatives needed for the establishment of the Jacobian matrix (representing nodal pressure corrections in terms of all branch flow partial derivatives) are thus related by $\partial \dot{m} / \partial \Delta P_{nm} = -\partial \dot{m} / \partial \Delta P_{mn}$.

Flow Calculation

Within *ESP* each flow component has a subroutine counterpart which is used to generate flow and flow derivative at each iteration. As an example, consider the power law component types (10, 15, or 17). These flow components use one of the following relationships between flow and pressure difference across the component:

$$type\ 10: \; \dot{m} = \rho\, a\, \Delta P^b \; (kg/s) \qquad (3a)$$

$$type\ 15: \; \dot{m} = a\, \Delta P^b \; (kg/s) \qquad (3b)$$

$$type\ 17: \; \dot{m} = a \sqrt{\rho}\, \Delta P^b \; (kg/s) \qquad (3c)$$

where $\dot{m}$ is the fluid mass flow rate through the component (kg/s), a is a flow coefficient, expressed in: $m^3/s/Pa^b$ (type 10), $kg/s/Pa^b$ (type 15), or $(kg\ m^3)^{1/2}/s/Pa^b$ (type 17). ΔP is the total pressure loss across the component (Pa), and b is the flow exponent (-).

As can be seen, the difference between the three sub-

types is only in the dimension of the flow coefficient a. Although in the literature all three forms can be found, the first one is the most commonly encountered. The value of ρ depends on the type of fluid and on the direction of flow. If the flow is positive (that is when $\Delta P \geq 0$) then the temperature of the node on the positive side is used to evaluate the fluid density. Likewise, for a negative flow the temperature of the node on the negative side of the connection is used. Theoretically, the value of the flow exponent b should lie between 0.5 (for fully turbulent flow) and 1.0 (for laminar flow). The power law relationship should, however, be considered a correlation rather than a physical law. It can conveniently be used to characterize openings for building air infiltration calculations, because the majority of building fabric leakage description data is available in this form (AIVC 1986). The power law relationship can also be used to describe flows through ducts and pipes, albeit to a lesser accuracy than by the technique as incorporated in the flow component type 210. The primary advantage of the power law relationship for describing fluid flow components, is the simple calculation of the partial derivative needed for the Newton-Raphson approach:

$$\frac{\partial \dot{m}}{\partial \Delta P} = \frac{b\,\dot{m}}{\Delta P} \quad (kg/s/Pa). \tag{4}$$

There is a problem with this equation however: the derivative becomes undefined when the pressure drop (and the flow) approach zero. This is handled in *ESPmfs* by switching to numerical approximation of the partial derivative in cases where the pressure drop is smaller than a certain threshold (say $10^{-20}\,Pa$):

$$\frac{\partial \dot{m}}{\partial \Delta P} \approx \frac{\dot{m} - \dot{m}^*}{\Delta P - \Delta P^*} \quad (kg/s/Pa) \tag{5}$$

where * denotes the value in the previous iteration step.

Network Solution

Each fluid flow component, i, thus relates the mass flow rate, $\dot{m}_i$, through the component to the pressure drop, ΔP_i, across it. 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 non-linearly 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 technique employed by *ESP* is to assign an arbitrary pressure to each internal node to enable the calculation of each connection flow from the appropriate connection equation. The internal node mass flow residuals are then computed from:

$$R_i = \sum_{k=1}^{K_{i,i}} \dot{m}_k \quad (kg/s) \tag{6}$$

where R_i is the node i mass flow residual for the current iteration (kgs^{-1}), $\dot{m}_k$ is the mass flow rate along the kth connection to the node i (kgs^{-1}) and $K_{i,i}$ is the total number of connections linked to node i.
The nodal pressures are then iteratively corrected and the mass balance at each internal node is re-evaluated until some convergence criterion is met. The method used in *ESP* is based on an approach suggested by Walton (1989a, 1989b). This approach was implemented and tested in an earlier version of *ESP* and shown to result in considerable speed improvements as evidenced in Table 2 (Clarke & Hensen 1988).

Table 2 Bench-mark results. All runs were performed on a SUN 3/50 and correspond to a one day (24 hour) simulation

Problem	Original Solver		New Solver		Iteration Ratio	CPU Ratio
	CPU Seconds	Iterations 1st hr - 24 hrs	CPU Seconds	Iterations 1st hr - 24 hrs	24 hrs	24 hrs
1. atria	3087	6363 - 152117	55	137 - 522	291	56
2. house 1	377	374 - 27863	17	29 - 459	60	21
3. house 2	48	146 - 2510	23.2	11 - 105	23	2
4. 2 zone	9	309 - 2376	3.6	16 - 287	8	2
5. 3 zone	3	27 - 358	2.5	4 - 90	3	1
6. Trombe	2168	14009 - 122754	50.2	29 - 474	258	43
		1st hr - 2nd hr		1st hr - 2nd hr	1st - 2nd hr	
7. large		13270 - 25318		24 - 1	552 - 25318	

The latest *ESP* model has a further enhanced solver which has resulted in additional iteration reductions. However, at the time of writing no bench-mark results were available. The solution method suggested by Walton is based on a simultaneous whole network Newton-Raphson technique which is applied to the set of simultaneous nonlinear equations. With this technique a new estimate of the nodal pressure vector, $\mathbf{P}^*$, is computed from the current pressure field, $\mathbf{P}$, via:

$$\mathbf{P}^* = \mathbf{P} - \mathbf{C} \tag{7}$$

where the pressure correction vector, $\mathbf{C}$, is computed from the matrix product of the current residuals $\mathbf{R}$ and the inverse $\mathbf{J}^{-1}$ of a Jacobian matrix which represents the nodal pressure corrections in terms of all branch flow partial derivatives:

$$\mathbf{C} = \mathbf{R}\,\mathbf{J}^{-1} \tag{8}$$

where $\mathbf{J}$ is the square Jacobian matrix (N*N for a network of N nodes) whose diagonal elements are given by:

$$J_{n,n} = \sum_{k=1}^{K_{n,n}} \left[\frac{\partial \dot{m}}{\partial \Delta P}\right]_k \quad (kg/s\,Pa) \tag{9}$$

where $K_{n,n}$ is the total number of connections linked to node n and ΔP_k is the pressure difference across the kth link. The off-diagonal elements of $\mathbf{J}$ are given by:

$$J_{n,m} = \sum_{k=1}^{K_{n,m}} -\left[\frac{\partial \dot{m}}{\partial \Delta P}\right]_k \quad (kg/s\,Pa) \tag{10}$$

where $K_{n,m}$ is the number of connections between node n and node m. This means that - for internal nodes - the summation of the terms comprising each row of the Jacobian matrix are identically zero.

Conservation of mass at each internal node provides the convergence criterion. That is, if $\sum \dot{m}_k = 0$ for all internal nodes for the current system pressure estimate, the exact solution has been found. In practice, iteration stops when all internal node mass flow residuals satisfy some user defined criteria.

INCORPORATION OF *ESPmfs* IN *ESP*

ESPmfs may be used in stand-alone mode (assuming that flows are predominantly pressure driven) or as an integral part of *ESPbps*, the main 'engine' of *ESP* which permits combined heat and flow simulation of building/ plant configurations. In this case, the building/ plant system is divided into a large number of finite volumes. Then, at each time step as a simulation proceeds, an energy and mass balance is applied for all volumes, giving rise to a differential matrix equation for the entire system. This is then solved by a customised matrix processing technique which operates in terms of user-imposed control statements.

Incorporating the flow simulation capability within *ESPbps* necessitated the development of several new functions:

- a fluid mass flow network set-up routine
- a fluid mass flow calculation control routine which for each simulation time step: (1) sets temperatures for nodes corresponding to building energy zones; (2) sets temperatures for nodes corresponding to plant energy components; (3) sets boundary nodes temperature and pressure; (4) solves the fluid flow network mass balances; (5) transfers flow simulation results to a results file; and (6) invokes one or both of the following subroutines
- a results conversion routine which transfers building-side air flow results to the energy equation set-up module in the form of zone infiltration and ventilation conductances. This routine also updates the building-side zones moisture balance information. To do this it is necessary to establish the air moisture content x_j at each mass flow network node (that is including those nodes which do not correspond to a building zone). Within *ESP*, it is assumed that the water vapour is distributed through the flow network proportional to the air mass flow; that is any moisture storage effects are disregarded at present (recently two research projects were initiated aimed at eliminating this limitation). Then, for each node j, a linear equation can be established:

$$x_j = \sum_{i=1}^{n} \dot{m}_i^{+} x_i \; / \; \sum_{i=1}^{n} \dot{m}_i^{+} \quad (kg/kg) \qquad (11)$$

where n denotes the number of nodes connected to node j, and $\dot{m}_i^{+}$ is the mass flow rate from node i to node j (only 'positive', or receiving, air flow is taken into account). In cases where node j represents ambient air or a building zone, the moisture content is obviously known. The relations above can be combined into the matrix equation:

$$\mathbf{x} = \mathbf{A}^{-1}\,\mathbf{b} \qquad (12)$$

where $\mathbf{A}^{-1}$ is the inverse of a matrix holding the mass flow vector, and $\mathbf{b}$ is a vector holding the known nodal moisture contents.

- a results conversion routine which transfers plant-side mass flow results to the main energy simulation modules by assigning fluid mass flows to plant component inter-connections.

COMBINED 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 (Clarke 1985). (Note that in the case of building-side flows and for some plant, two flow balance matrix equations will be required to represent the two fluids present; air and water vapour for example). While in principle it is possible to combine all six matrix equations into one overall 'super-matrix', this is not done within *ESP*, 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 - indeed *ESP* never forms a two dimensional array but instead holds matrix topology and topography as a set of vectors. 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 considerations, plant + flow, and so on. A third advantage is that, potentially, different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on. This is the approach adopted within *ESP*.

It is recognised 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 zone) depends on a variable of state solved within an partition (say the temperature of a radiator), it is important to ensure that both values match in order to preserve the thermodynamic integrity.

What follows is a brief description of how this issue is currently handled in *ESP*; for a more detailed description the reader is referred elsewhere (Clarke 1985 and Hensen 1991).

The current status with respect to the general lay-out of *ESPbps*'s main numerical controller MZNUMA is visualized in Figure 3. As indicated in this diagram, the overall simulation time increment may be smaller than one hour. A complete configuration time-step involves the evaluation of all building-side zones followed by the processing of the plant system equations. If a mass flow

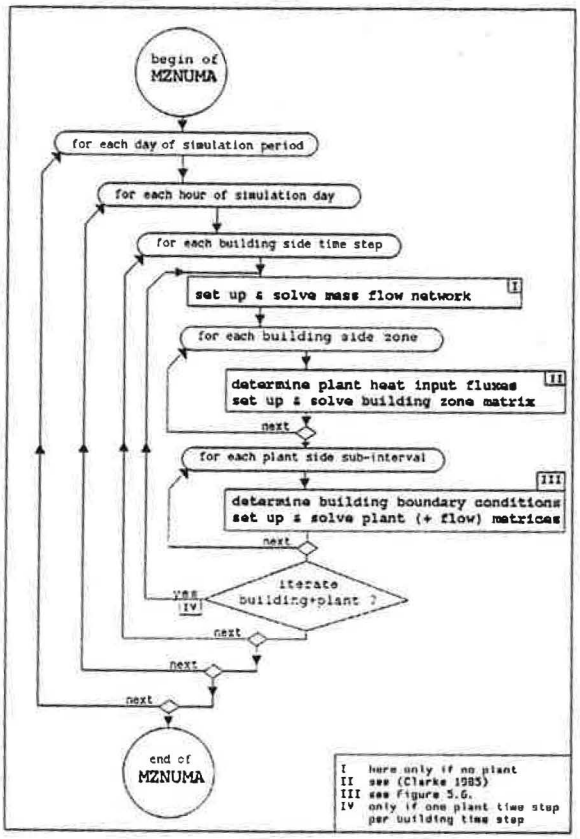

Figure 3 Indicative flow chart showing the main loops in the simulation process for a combined building and plant configuration

network is defined to exist, this is processed together with the plant system network. In cases where the user defines a building-only configuration, the mass flow network is processed prior to the building zones.
At each overall simulation time-step the building- and plant-side state-space equations, and the mass flow network equations are generated and solved as separate partitions. The building-side solution process is invoked once per user-specified time step. This process uses a matrix partitioning technique in which one partition is formulated per building zone (in *ESP* a zone does not necessarily equate to a physical space). For the building, heat interaction with the plant is regarded as a known boundary conditions.
The plant-side partition is then established and solved (by a sparse matrix method) repeatedly at some smaller time-step interval in order to cater for the different time constants. This is done in terms of the now known excitations from the building-side.

This division of the overall problem into a building- and plant-side may lead to coupling problems. For example, when processing the building-side partition, plant heat inputs/ extracts will be one time-step in arrears. In similar manner problems may arrise when plant-side control is dependent on building-side inputs which, in turn, correspond to plant inputs which relate to the immediate past time-row.
ESP offers two methods to deal with such problems. The first involves the use of a time-step control facility in which simulation time-steps are successively halved on the basis of compared state variables at the end of each user-defined time-step. This algorithm is so designed that the time-stepping scheme always attempts to return to that initially specified. Using this facility it is possible to separately control the building- and plant-side time-steps and to vary the control criteria temporally (on the basis of boundary condition look-ahead for example). A second method is to make use of the mechanism indicated in Figure 3. At some arbitrary time-step, the plant heat
input as assumed in processing the building side is compared with the plant heat emission as calculated when processing the plant side. If the difference exceeds some user specified value, the whole building and plant solution process is repeated based on the newly calculated values. If either the absolute or the relative difference between assumed and newly calculated building/ plant heat exchange satisfies the user specified tolerances, the model proceeds with the next time-step. While this approach will solve the problem, acceptable simulation times cannot be guaranteed. (It is probably worth making the point in this context that in the authors' opinion the effects of the one time-step in arrears assumption is at least an order of magnitude less than the effect of the variety of other assumptions which represent today's state-of-the-art.)

A CASE STUDY

In Eindhoven, The Netherlands, a major alteration of the inner-city is in progress. In this context, an extensive shopping mall, the "Heuvel Galerie", is being build. This 4-level complex incorporates a 220 metre long shopping arcade, interspersed with atria and dome-shaped roofs, ≈ 20,000 m^2 shops, 8,600 m^2 theatre, 3,000 m^2 restaurants, a 1,200 units car park, offices, and appartments.
It will be apparent that such a building is a highly complicated system. The manner in which air will flow depends on external pressures on entrances and domes, temperature differences inside and with respect to ambient, and impulses by the ventilation system. For this building *ESP* was used to make predictions with respect to the indoor environment (Wisse and Pernot 1990, Pernot and Hensen 1990). To give an idea of how part of the building was abstracted for this study, Figure 4 shows a sketch of the mass flow network representing the main flow paths through the shopping arcades of the mall. Table 3 summarizes some informative data related to user effort involved in this study. It is apparent that now - unlike with previous flow simulation models - most effort is related to input preparation

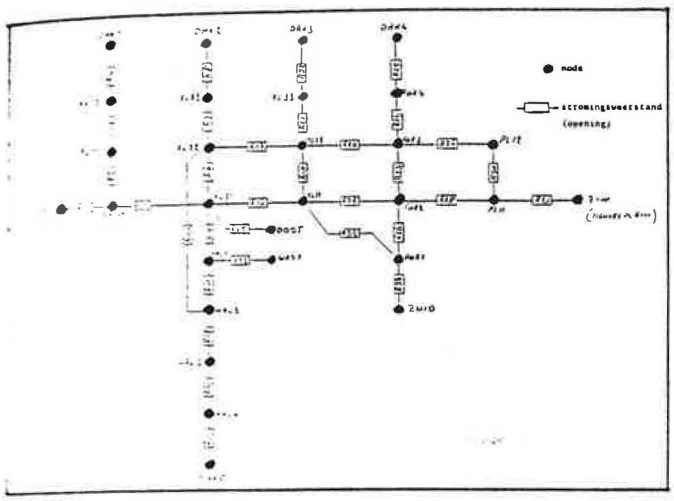

Figure 4 Sketch of mass flow network representing main flow paths through shopping arcades

and results manipulation, as opposed to the actual simulation time.

Table 3 Some data related to user effort

data preparation starting from architectural drawings etc	≈ 1 *day*
number of nodes for the shopping arcades	29
number of flow components	33
number of studied design alternatives; ie ESP runs	> 100
typical system time requirement per ESP run (1 simulation day)	≈ 1 min
typical system time requirement per design alternative for results manipulation using standard UNIX tools	≈ 5 min

The basic results emerging from the simulation incorporate nodal pressures and flow rates. These may

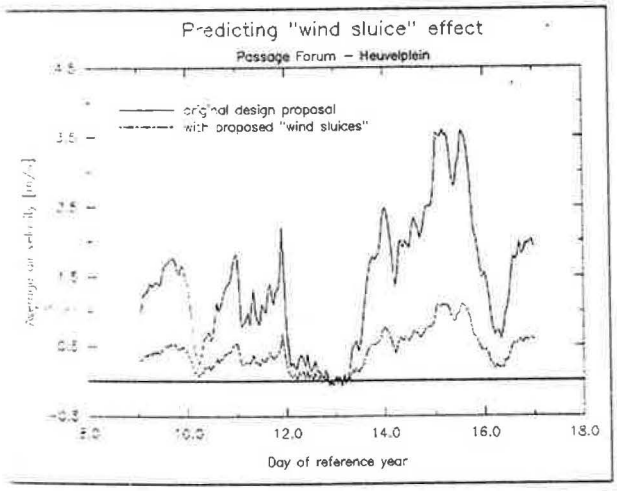

Figure 5 Predicted effect of proposed "wind sluice" to decrease the air velocities in the pedestrian entrance area

then be transformed to eg average connection air velocities. As an example, consider Figure 5 which shows results with respect to the air velocities which may be expected in the pedestrian entrance area. For commercial reasons, the architects and the developers want the entrance areas to be as open as possible. From the first results it was clear however that the original design proposal would lead to unacceptably high air velocities. One of the main conclusions was that the (open) cross-section of the main entrance should be limited to about 6 m^2 and that in unfavourable weather conditions this should be further restricted to about 40% of the cross-section.

CONCLUSIONS

This paper has described a "modular-simultaneous" technique for the simulation of combined heat and fluid flow in a building/ plant context. The present performance of the model indicates that it is practical to solve the building/ plant heat and mass flow network in detail. Moreover, the solution of complex fluid flow networks in the transient state is now feasible on inexpensive computers.

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 component models (especially improved large opening models), the development of additional plant component models in the 'state-space' format required by *ESP*, expansion of the system's wind pressure database and experimental validation of the simplifying assumptions in the component models.

Acknowledgements

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