An intermediate model to predict thermal comfort and air quality in a building

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ABSTRACT

In this paper, a zonal model used to predict the air movement, temperature distribution and air quality in a room is presented. It is based on a rough partitioning of the room: it is an intermediate approach between one-node models (that consider an homogeneous temperature in each room, and, for that reason, do not permit to predict the thermal comfort in a room) and CFD models (that require great amount of simulation time). Where plumes, jets or thermal layers occur, air flow is described by empirical laws. In low velocity domains, flow rates are calculated in respect to the pressure distribution. This air flow model is coupled with a building envelope model including the calculation of radiant and conductive exchanges. The complete model is implemented in an object oriented environment, SPARK, in which modelling a room consists in connecting the different pre-design elementary models. Hence , the way of modelling is very modular, so that the zonal model can now be applied to a very large field of configurations. The strict syntax of SPARK permits having the simulation automatically generated. Now, imagining the creation of a very flexible tool that allows to represent a whole building is realistic.
Results of simulations in a 3D-room will be given and it will be shown that this model yields rather accurate results even with a rough partitioning.

INTRODUCTION

Room convection models are needed that are intermediate between single-air-node models, which give no information about air flow pattern, and CFD models, which give detailed temperature and flow distributions but are extremely computer intensive. Such intermediate models execute much faster than CFD calculations but provide temperature and flow distributions that are accurate enough to predict thermal comfort.
One such approach is the so-called 'zonal model'. In zonal models, the inside of a room is divided into a small number of 'cells' which are rectangular parallelopipeds. Mass and heat balance equations are applied to them, the exchanges are calculated between them. The solution of the resulting set of equations gives the air flow and temperature distribution.
The first zonal models [1-4] were based on fixed air flow directions and on the application of specific flow laws for plumes, jets and boundary layers. Assuming fixed air flow directions obviously restricts the field of application of these models. Other models [5,6] made the inter-cell air flow rates a function of pressure distribution. It has been shown that this approach cannot represent correctly the driving flows [7]. Later, hybrid models were formulated that applied specific laws for driving flows and a power-law pressure distribution everywhere else [8,9]. However, they were applicable only to a few simple configurations.
In the present work, we present an advanced formulation of a zonal model extended to pollutants transport simulation and, to achieve a complete calculation, connected with conduction through the rooms walls and radiant interchanges between them. The resulting set of equations is solved with the Simulation Problem Analysis and Research Kernel (SPARK).

Using this object oriented environment allows the simulations to be constructed by assembling calculation elements from a model library.

METHODS

A zonal model for a room involves mass and heat balance equations for each cell into which the room air has been partitioned. Additional equations describe conduction through the walls, convection and long-wave and short-wave radiant interchange among the inside wall surfaces.

1. Air flow model

In the zonal air flow model, four different types of cells are considered: basic cells (with low air flow), plume cells, jet cells and boundary layer cells, which has a different set of equations. Cells are connected to their neighbour using interfaces. As there is different types of cells, there are different types of interfaces, where the exchanges are calculated. A jet model will be outlined in the following. Plumes and boundary layers are similarly built. First, the air will be a single gas, afterwards, we will consider it contains several gaseous species.
Assuming that the air is incompressible, the sum of the mass flows across the faces of a cell must be zero. Similarly, the net heat transferred into the cell across its faces must equal the heat stored in the volume of air in the cell. This yields the following mass and heat balance equations:

$$Q_{mWest} - Q_{mEast} + Q_{mSouth} - Q_{mNorth} - Q_{mTop} + Q_{mBottom} = 0 \quad (1)$$

$$\Phi_{East} - \Phi_{West} + \Phi_{North} - \Phi_{South} + \Phi_{Top} - \Phi_{Bottom} = \Phi_{source} - h.w.L.c_p.\rho_i.\frac{\partial T_i}{\partial t} \quad (2)$$

where Q_{mWest}, Q_{mEast}... are the air flow rates (kg/s) crossing the west, east... faces of the cell, Φ_{West}, Φ_{East}... the net heat transferred. h, w and L are the cell height and width. c_p is the specific heat of air at constant pressure, ρ_i and T_i the air density (kg/m^3) and temperature (K) in the cell.
Finally, we assume that the relationship between the air pressure, density and temperature in a basic cell is given by perfect gas law.
Heat and mass transfers are calculated between the cells, within the interfaces. For vertical ones, the mass flow rate is assumed to be proportional to the pressure difference across the face. For horizontal ones, the hydrostatic variation of pressure is taken into account. Therefore, the mass flow rate across the east and the bottom faces, for example, are given by:

$$Q_{mEast} = -C(P_i - P_{East}) \quad (4)$$

$$Q_{mBottom} = -C\left((P_i - P_{Bottom}) - \frac{1}{2}g(\rho_{Bottom} h_{Bottom} + \rho_i h_i)\right) \quad (5)$$

where C is an empirical coefficient (kg/m^2.s.Pa), P_{east}, P_{bottom}, ρ_{East}, ρ_{Bottom}, are the pressure and air density in East and Bottom cells and g is the gravitational acceleration.
The overall heat exchange across a face is the sum of the enthalpy flux and conductive flux, giving, for example, for the east face:

$$\Phi_{East} = \left(T_{East} Q_{mEast}^{+} + T_i Q_{mEast}^{-}\right) - \frac{\lambda h L}{c_p w}(T_{East} - T_i) \quad (6)$$

where λ is the air thermal conductivity, T_{east} the temperature in East cell.

A jet cell contains two subcells, one containing air belonging to the jet itself and one containing air from the surroundings. for this reason, the jet objects consist of equation that are reused from basic cells objects (to represent the surrounding air) plus equations that are specific to the jet. Note that the jet is contained in rectangular parallelopipeds set side by side (figure 1). This simplifies the partitioning of rooms that have jets since it make it easy to line up the jet cells with the other cells.

In the following, we describe the characteristics of a two-dimensional isothermal ceiling jet using the equation of Schwarz et al[10] and Rajaratnam[11]. The jet width, *h(x)*, the maximum jet velocity *Um(x)*, and the air flow rate, *Qm(x)*, are:

$$h(x) = 2.36Cx \quad (7)$$

$$Um(x) = Um_0 K_v \sqrt{\frac{h_0}{x}} \quad (8)$$

$$Q_m(x) = 1.054 C K_v Q_{m0} \sqrt{\frac{x}{h_0}} \quad (9)$$

Um_0 and Q_{m0} are the velocity and the air flow rate in the diffuser, h_0 the diffuser height. K_v and C are empirical coefficients, they are respectively set to 3.5 and 0.068.

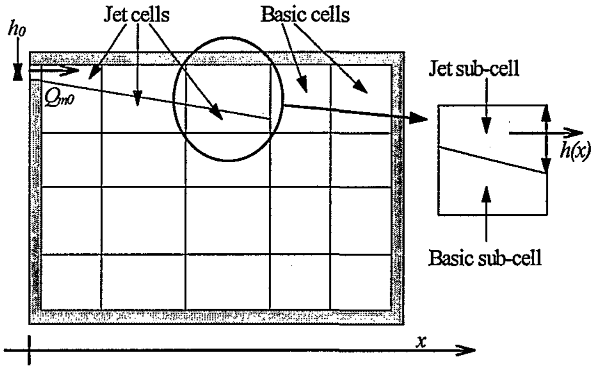

Figure 1: Cells associated with the jet model.

These equations are the additional equations of vertical jet interfaces.
The mass balance equation, applied to the jet part of the cell allows the flow rate of air entrained by the jet to be calculated. The end of the jet is the interface in which *Um(x)* becomes less than a threshold value. In this interface and in the following ones *h(x)* and *Qm(x)* are set to zero and the cells revert back to basic cells. Therefore, it is not necessary to know *a priori* how long the jet will reach: the simulation will automatically convert jet objects.

Now, if we consider that the air consists of several gaseous species, mass balance equation must be written for each of them:

$$Q_{mWest\_j} - Q_{mEast\_j} + Q_{mSouth\_j} - Q_{mNorth\_j} - Q_{mTop\_j} + Q_{mBottom\_j} = Q_{mBottom\_j} - \rho hLw \frac{dX_j}{dt} \quad (10)$$

X_j is the ratio of the specie density and the air density which is equal to the sum of the species' densities. The source term, $Q_{msource\_j}$ can be an input data or calculated by using laws describing the chemical kinetic of the reactions between the different species.
The movement of the species in the room is governed by the two phenomena that are transport and diffusion. Mass flow rates are the sum of two terms corresponding to both of them. Therefore, the mass flow rate of specie 'j' across the east face, for example is given by:

$$Q_{mEast\_j} = -Lh\left(CX_{i\_j}(P_i - P_{East}) + 2D_j \frac{X_{i\_j} - X_{East\_j}}{l_{East} + l_i} \right) \quad (11)$$

D_j is the specie's diffusion coefficient (for the solvent its value is zero).
Perfect gas law is kept as well as equations about heat exchanges.

2. Wall model

Wall conduction, assumed to be one dimensional, is calculated with finite difference equations. The convective flux at the inside wall surface, Φ, is:

$$\Phi = hS(T_i - T_{si}) \quad (12)$$

where S and T_{si} are the interface area and surface temperature.
The convective heat transfer coefficient, h, depends on the surface-to-air temperature difference according to:

$$h = C(T_i - T_{si})^n \quad (13)$$

for which the values of the coefficient, C, and exponent, n, are given by Inard et al[12].
From the heat transfer coefficient, the mass transfer ones, h_j, are calculated using the relations given by Webb[13] and Holman[14]:

$$h_j = \frac{h}{\rho c_p}\left(\frac{D_j}{\alpha}\right)^{2/3} \quad (14)$$

where α is the air thermal diffusivity.
Then, the air flow rates are :

$$Q_{m\_j} = \rho S h_j \left(X_j - X_{s\_j} \right) \quad (15)$$

where X_{s_j} is the concentration of the specie at the wall surface.
We use Walton's method [15] to calculate long- and short-wave radiant exchanges among the inside room surfaces. In this method each room surface is assume to radiate to a fictitious surface whose characteristics give about the same heat transfer from the room surface as in the actual multi-surface case. The advantage of the method is that it considerably reduces the number of interchange equations.

3. Object-oriented simulations

To solve the zonal model equations we use SPARK[16], a modular simulation environment that automates writing code for systems of non-linear algebraic and differential equations. SPARK allows to build complex simulations by connecting atomic objects (single equations) or macro-objects (sets of equations). Using graph-theoretic techniques, SPARK reduces the size of the equations system by determining a near-minimum set of iteration variables from which the other unknowns can be calculated. It uses Newton-Raphson iteration to solve this reduced system and, after convergence, solves for the remaining unknowns. SPARK can automatically generate computer code for objects from equations expressed symbolically.

We grouped the zonal model equations into cell macro-objects (basic, plume, jet, boundary layer), interface macro-objects (basic horizontal and vertical, plume...), and a radiant exchange macro-object. They were stored in a library for later use. To build a simulation, cell and interface objects are instantiated as many times as required by the partitioning of the rooms and they are linked (the links being the variables shared by the equations corresponding to the objects). Next, the wall interfaces are linked to the radiant exchange macro-object. Finally, input values are specified and SPARK is allowed to determine the unknown variables.
A pre-processor code was written that automates the above procedure. To create this code, the variables of each macro-object were categorised as either local variables shared with neighbouring cells, or as global variables appearing in the cells only or in both the cells and interfaces... Then, based on the partitioning of the room, on the kind of cells and interfaces involved and on the number of gaseous species, the code automatically creates and instantiates the needed macro-objects and links them.

RESULTS

The simulation results will be compared with measurements from the CETIAT experimental room, MINIBAT [17], equipped with a ventilation device. Figure 2 shows the room geometry and partitioning into cells, and the location of the diffuser. The inputs to the simulation are the inside surface temperatures, the entering air flow rate, and a pollutant source (SF6) in the middle of the room (Table 1).

	Floor	Ceiling	East	South	North	West	Inlet	Pollutant
Temperature(°C)	19.4	21.	20.	18.9	20.	19.9	33.5	
Air flow rate (kg/s)							8.32^e-3	2.943^e-3

Table 2. Input values for inside surface temperature, inlet air and pollutant source.

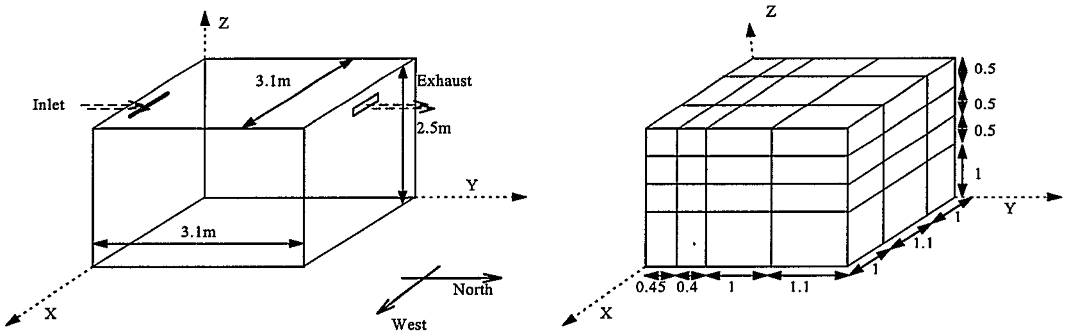

Figure 2: The MINIBAT experimental room partitioned into 4x3x4 = 48 cells. Three of these are jet cells.

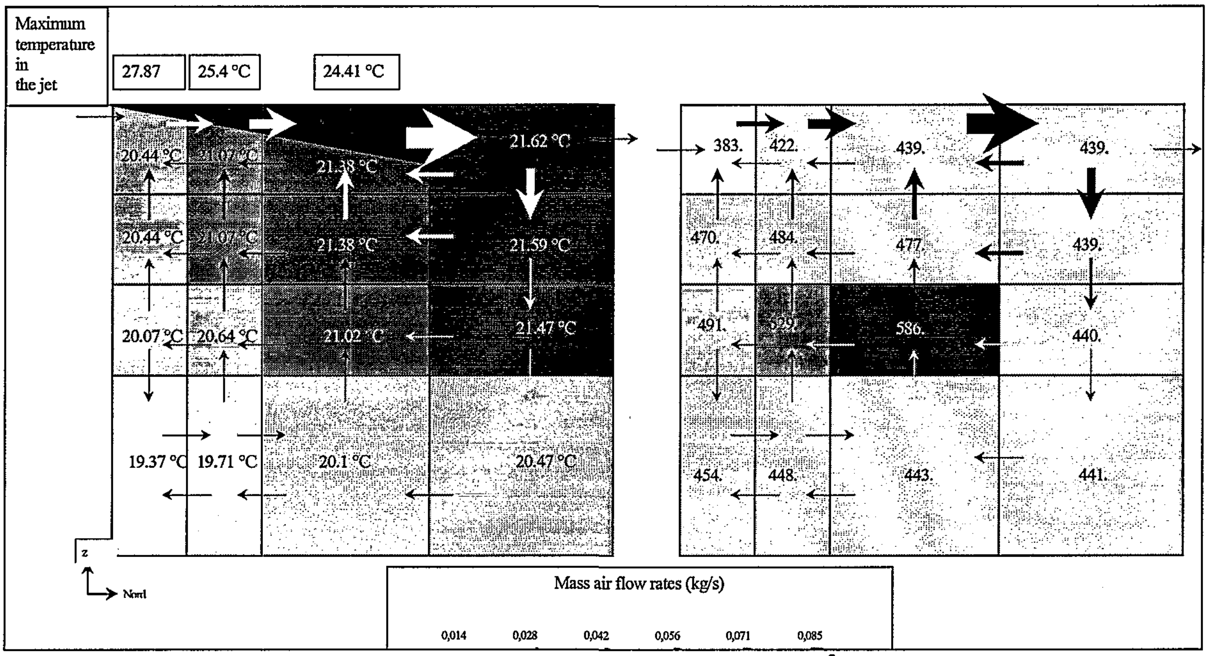

Figure 3 : Calculated temperature and SF6 concentration (mg/m^3) in the South-North vertical plane passing through the jet Shading shows the different temperature or pollutant density levels. Air flow rate is proportional to arrow thickness.

The simulation results were compared with measurements from the CETIAT experimental room. Temperatures agree with measurement to within 1°C in the three bottom layers and to within 1.3°C in the top layer. Pollutant concentration is too low excepted near the source. This could be attributed to the fact that for the moment, the model doesn't take into account a turbulent diffusion coefficient that can in some place of the room be high compared to molecular diffusion coefficient.

DISCUSSION

We have shown how a zonal model can be used to calculate room air temperature and air flow distributions. In the case studied, dividing the room air volume into 48 cells was sufficiently fine-grained to allow thermal comfort and air quality to be determined without excessive calculation time or machine capacity.

Two levels of automation were used to generate models in the SPARK environment:

- Generating equation objects using symbolic processing.
- Automatic generation of zonal model for a room.

We are currently working on integrating other models and on completing the pollutant models by taking into account heterogeneous and homogeneous reactions. We are also working on fully automatic generation of a zonal model of multiple rooms and their associated heating and cooling systems. This will make it possible to generate a complete simulation of a building given only the building geometry and properties of the heating and cooling systems.
So far, the comparisons we have made with experimental measurement have been encouraging. We are currently making additional comparisons to further validate our zonal model approach.
It is important to note that the simulation approach that we have developed can be applied to all types of thermal and air-flow problems: it is not restricted to simple configurations nor is it required that the flow distribution be known *a priori*.

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