Zonal model based on airflow partitioning

S. Guernouti[1], M. Musy[1], L. Mora[2], and G. Hégron[1]

[1] CERMA-UMR CNRS 1563, Ecole d'Architecture de Nantes, rue Massenet BP81931, 44319 Nantes Cedex 3-France
Email: sihem.guernouti@cerma.archi.fr http://www.cerma.archi.fr
[2]LEPTAB, University of La Rochelle, Av.M.Crépeau, 17042 La Rochelle Cedex- France

Summary: *We present in this paper an advanced formulation of zonal models for calculating room air temperature and airflow distributions. It is based on a new way of sub-dividing the room usings the Octree method. It allows us to obtain a partitioning based on airflow patterns. The behaviour of the room is represented by the connection of SPARK calculation objects according to its partitioning. The SPARK's objects represent sub-zones of the room or interfaces between sub-zones. We developed an automatic generator of zonal models. This generator performs partitioning of a room and assembles the appropriate SPARK objects to construct a zonal model of a room. Then SPARK solves the resulting set of equations and the airflow and temperature distributions are obtained.*

Keywords: Zonal model, Octree, Airflow, Partitioning.
Category: Modelling techniques

1. Introduction

The request of comfort, and indoor air quality became increasingly important. To answer this request and determine comfort conditions, zonal models were developed.

These models are intermediate between single-air-node models, which give no information about airflow patterns, and CFD models, which give detailed temperature and flow distributions but are extremely computationally intensive. Furthermore, solving zonal models is faster than solving CFD models by one order of magnitude. It makes zonal models still very interesting for long time analysis such as annual or seasonal analysis.

Currently, the use of zonal models requires an important modelling expertise and experimentation in the building. Especially, the user of zonal models has to choose empirical models to implement in order to represent driving airflows. This choice is crucial because in zonal models, the quality of the airflow representation strongly depends on the use of particular models [1,2,3]. Therefore, we developed a tool to generate automatically the zonal model with the minimum user's expertise.

2. Zonal model

The principle of zonal method is to divide the considered room into a number of sub-zones in which temperature and density are assumed homogeneous, while pressure varies hydrostatically.

Generally, the room's subdivision is performed according to the type of flow, in order to treat each sub-zone with the appropriate method: For dominant airflows (plumes, jets and boundary layers), specific laws are applied; outside this range, the laws are simplified ones.

So, the macroscopic character of partitioning is compensated by an accurate description of driving airflows.

We started from the zonal model concept proposed by Wurtz [3] that introduced the "cell" and "interface" notions for the sub-zones and their boundaries respectively.

In this case, in a general way, mass and heat balance equations (1) are applied to cells and exchanges are calculated in interfaces.

$$\frac{dM_i}{dt} = \sum_{j=1}^{n} m_{ij} + m_{source} + m_{sink}$$
$$\frac{dQ_i}{dt} = \sum_{j=1}^{n} q_{ij} + q_{source} + q_{sink} \quad (1)$$

2.1. Room partitioning

Zonal models usually encountered in literature are based on a cartesian partitioning.

For reasons detailed in [4], we propose to use a partitioning of the room based on the Octree method. This method is one of the most common hierarchical representations based on a recursive and regular 3D space partitioning. It is derived from *quadtree* (2D representation). It has been used as a domain decomposition method for computer graphics and solid modeling [5].

The octal tree is built from a box that encompasses the entire domain of the problem; in our model the box represents the room located at the root of the tree. The room is recursively divided into eight similar cubes or octants. An example of partitioning is shown on figure (Fig.1.), which represents the octree partitioning of a room with an isothermal plane jet. The relationship between the octants is represented by a tree structure. Each octant (cell) is assigned an identification tag that gives it level in the tree (level of sub-dividing), so, it gives it exact location in the octree [4].

The subdivision process continues as far as a stopping criterion is reached.

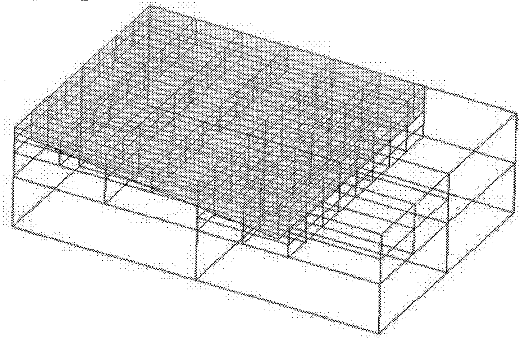

Fig. 1 Octree partitioning of a room with ceiling jet.

2.2. Airflow model

As mentioned before, ordinary cells represent sub-zones where no driving flow occurs. The ordinary airflow model between adjacent cells is based on a power-law formulation. The airflow rate dm_{ij} across the common surface between the cells i and j depends on the pressure difference between the two zones. We can represent the airflow rate by the expression:

$$dm_{ij} = C_d \rho_{i,j} w \left(\frac{2}{\rho_{i,j}} \left| \Delta P_{i,j} \right| \right)^{1/2} \varepsilon_{i,j}(\Delta P_{i,j}) dz \qquad (2)$$

Where:

$$\Delta P_{i,j} = (P_i - \rho_i g z_i) - (P_j - \rho_j g z_j), \qquad (3)$$

$\varepsilon_{i,j}$ is sign from $\Delta P_{i,j}$, And C_d is an empirical coefficient analogue to discharge coefficient, in common practice C_d=0,83.

For driving airflows, we use empirical laws. For example, in the case of the two-dimensional isothermal ceiling jet we will represent in the following application, we retain the laws proposed by Rajaratnam [6].

The jet width $b_u(x)$, the longitudinal velocity profile U(x) and the velocity amplitude $U_m(x)$ are given by:

$$b_u(x) = 2{,}36 C_u x \qquad (4)$$

$$\frac{U(x)}{Um(x)} = \exp\left[-0.937 \left(\frac{y}{C_u x} - 0{,}14 \right)^2 \right] \qquad (5)$$

$$\frac{U_m(x)}{U_{in}} = K_v \sqrt{\frac{h_0}{x}} \qquad (6)$$

Where, x is the coordinate along the jet axis, y is the distance to wall, U_{in} and h_0 are the inlet velocity and diffuser height respectively.

Rajaratnam recommends a value of 3,5 for the empirical decay constant K_v and the value of 0,068 for the empirical coefficient C_u.

From these laws, we calculate the airflow rate q(x) in the jet verticals interfaces (portions of a jet section in which the wall distance ranges from y1 to y2) by:

$$q_m(x) = \int_{y1}^{y2} \rho U(x) l dy \qquad (7)$$

The flow rate entrained by the jet is calculated by applying the mass balance equation to the jet cells.

3. Zonal model generator

The automatic generator of zonal models is divided into five parts: analysis tool, database of analytical models, partitioning tool, flow solution and visualization tool [4].

The analysis tool allows interpreting the boundary conditions and foreseeing the flows which are dependent on them. The most adapted analytical model is chosen automatically in the database to represent the expected airflow. After the phase of analysis and choice of the models, we obtain a file containing the geometrical and physical characteristics of the models.

The partitioning tool is based on the octree method. The terminal octants (cells of the room) at the leaves of the tree represent either specific homogeneous zones containing plume, jet or boundary layer airflow or ordinary homogeneous zones containing ambient air. In short, the partitioning tool returns the list of the cells and for each cell the list of its neighbouring cells.

In each ordinary homogeneous octant (where no specific flow occurs), mass and heat balances will be written. In the other octants, the specific empirical law will be considered.

For the flow simulation tool, we choose to implement our zonal model in the object-oriented simulation environment SPARK to solve the resulting set of equations.

So, we take advantage of the library developed for existing zonal models [7, 8, 9]. We just have to re-write the model generator and add some models in the library to meet the requirement of our partitioning.

3.1. Spark environment

The simulation Problem Analysis and Research Kernel (SPARK) is a general modular simulation environment that automates writing code for systems of non-linear equations and supports a robust differential and algebraic equation solver.

In SPARK, the smallest object is an *atomic class*. It characterizes one equation and its variables. At the higher level, macroscopic objects or *Macro classes* bring together several atomic classes and/or other macro classes.

Problem models are described, using a combination of the different necessary objects.

Its output is a C++ program, which is compiled, linked and executed to solve the problem for given boundary and initial conditions (input data).

To generate the C++ program, SPARK uses graph-theoretic techniques to decompose the problem into a series of smaller problems, called components, thus reducing the size of equations sets and small cut sets are determined, thereby reducing the number of iteration variables needed to solve each equations set [10].

3.2. Implementation of octree zonal model in Spark

In classical zonal models, a cell always has six neighbors while in our approach each cell may have more than six neighbors. The number of neighbors for each cell can range from 6 to 4^N x 6 where N is the level of the partitioning.

This implies a major difficulty because, in current cells models; the term "n" in equation (1) is set to 6. It is not realistic to create a cell model for each of the other cases.

For this reason, we introduced a new object called *filter*. When a cell has more than one neighbor on one of its face, a filter is used to link the cell to its neighbors. The main task of the filter is to sum the airflow rates and the heat flux of the smallest cells and then to transmit them to the adjacent largest cell. To satisfy all the partitioning cases, we can stack filters (see Fig.2.).

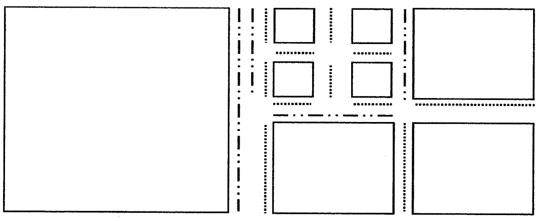

Fig. 2. Example of implentation of zonal model based on octree method in Spark (Cell/interface/filter)

Knowing the neighbors of each cell, the zonal model can be generated by linking cell's variables to interfaces or filters ones and conversely.

Figure (Fig.5.) represents the way of linking two cells of identical size, while figure (Fig.6.) show how a filter is introduced when the cell has four neighbors on its face

4. Application

To valid a proposed approach, we used a zonal model based on octree method to automatically generate a Spark model in a simple case of a room with two-dimensional isothermal jet. We will show the preliminary results obtained by comparison with experimental and classical zonal models results.

Nielsen and Restivo (1978) have performed velocity measurements in a rectangular parallelepiped scaled model of room (H=89,3 mm) where the isothermal airflow is two-dimensional (see Fig. 3). The inlet velocity Uin is imposed on 15,02 m/s (Re = 5000). Detailed measurements of airflow velocity profiles are provided through the central vertical plane located at y = W/2, along two vertical lines (at x = H and x = 2H) and two horizontal lines (at z =0,972 H and z =0,028H) [11].

We performed simulation of airflow using our zonal model in full-scale geometry (H = 3m) equivalent to Nielsen's cavity, the inlet velocity is imposed on Uin = 0.447 m/s [11].

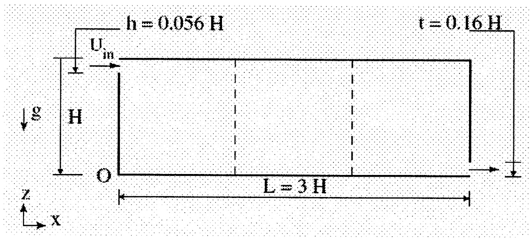

Fig. 3. Description of the experimental model [11]

We subdivide Nielson cavity into 64 cells like presented in Table 1.

Table 1: Distribution of the cells in Nielsen cavity.

Level	Ordinary cells	Jet cells
1	4	0
2	16	12
3	16	16

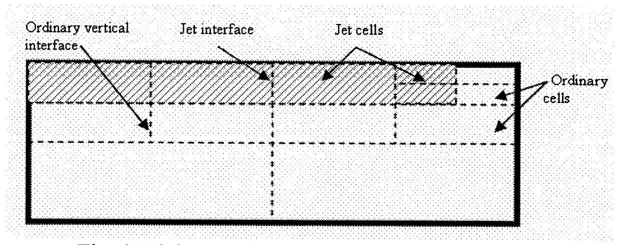

Fig. 4. Nielsen cavity's octree partitioning

In figure (Fig.8., Fig.7.), we present the prediction of airflow pattern obtained by Mora et al. and by the proposed model respectively.

Each arrow represents the velocity vector interpolated in the centre of each cell. Note that the scale is not the same in the two schemas.

Considering our partitioning of the jet, it is difficult to analyze velocity in the cell. Indeed, they are mean velocities calculated on a whole section of the jet except in the end of the jet where its section is subdivided in several jet interfaces. We see, that the entrainment of the ambient air into the jet is well predicted.

In the end of this paper, we provide the comparison of the velocity profiles through the central vertical plane obtained with our model and by Mora [12] to experimental ones. In our case, the zonal model does not calculate velocities in the planes X=H and X=2H. It is the reason why we perform interpolations between values obtained in the interfaces (three kinds for the profile X=H and two for the profile X=2H).

We can see that the results given by the two zonal models are quite similar, the differences in the jet region being due to the fact that the velocity is averaged on more or less the height of interface.

In the plane X=2H, we note that the vertical subdivision of the jet allows a better estimation of the velocity within the jet but the velocity obtained is still a mean and for this reason underestimates the velocity measured by Nielsen.

5. Discussion

In the whole, the results are promising; we could improve them in the start zone of the jet with a better adapted partitioning. This will not modify the airflows in the room because the entrained airflow rates will be the same ones.

If we want a better representation of the jet, we could thinly partition it and conserve a coarse grid in the other zones. In this case, we just have to change the stopping criterion in the partitioning tool.

6. Conclusions

In this paper, we have presented an automatic generator of zonal model based on an adaptive space partitioning method. As conventional zonal models, the proposed model can estimate airflows and heat transport rapidly. Note that the preliminary results obtained are similar to those given by classical zonal models because we use the same laws.

The interest of this approach is the local refinement of the partitioning notably in particular airflows.

Another interest that has not yet been exploited and which is the basis of ongoing work is the inheritance principle of the octree method, which will allow the dynamic management of a set of flows varying and interacting over time.

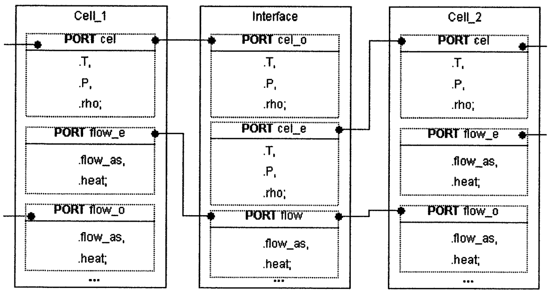

Fig. 5. Classical zonal model's objects links [9].

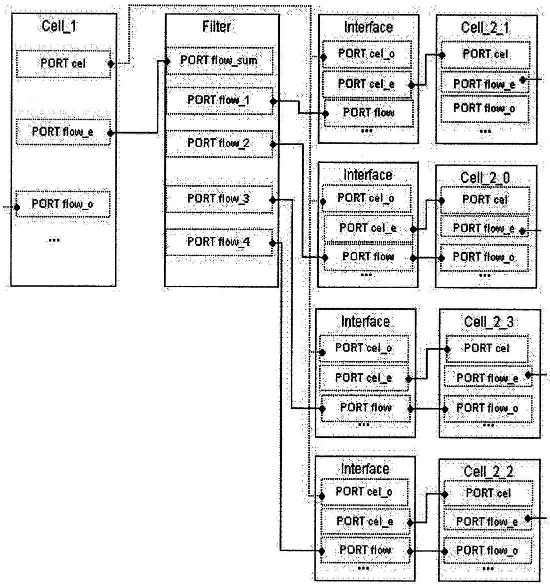

Fig. 6. Octree based zonal model's objects links

7. Nomenclature:

Mi: mass in the zone i [kg/s]

mij: rate of mass flow from zone i to zone j[kg/s]

msource: rate of mass supplied by the source in the zone [kg/s]

msink: rate of mass removed from the zone [kg/s]

Qi: the heat energy in zone i [W]

qij: the rate of heat energy from zone I to zone j [W]

qsource: the rate of heat energy supplied by the source in the zone [W]

qsink: the rate of heat energy removed from the zone[W].

8. References

[1] C.Inard.

Contribution à l'étude du couplage thermique entre une source de chaleur et un local, Thèse de Doctorat, INSA Lyon, France, 1988.

[2] H. Bouia.

Modélisation simplifiée d'écoulement de convection mixte interne: Application aux échanges thermo -aérauliques dans les locaux, Thèse de Doctorat, Université de Poitiers, France, 1993.

[3] E.Wurtz.

Modélisation tridimensionnelle des transferts thermiques et aérauliques dans le bâtiment en environnement orienté objet, Thèse de Doctorat, ENPC, France, 1995.

[4] S.Guernouti, M.Musy, G.Hégron.

Automatic generation of partitioning and modelling adapted to zonal method. Ibpsa conference, pp.427-434, Eindhoven, Netherlands, 11-14 August 2003.

[5] E.F. Charlton, K.G. Powell.

An octree solution to conservation-laws over arbitrary regions (OSCAR), AIAA paper 97-0198. 1997.

[6] N.Rajaratnam.

Turbulent jets. Elsevier Scientific Publishing Co. Amsterdam, 1976.

[7] M. Musy., F.Winkelmann, E.Wurtz, A.Sergent. Automatically generated zonal models for building air flow simulation: principles and application Building and environment 37 (2002).873-881.

[8].K.C.Mendoça, C.Inard, E.Wurtz, F.C.Winkelmann, F.Allard.

A zonal model for predicting simultaneous heat and moistures transfers in buildings. Proceedings of 9th International Conference on Indoor Air Quality and Climate, pp.518-523, Monterey,CA,USA.

[9] L.Mora, K.C.Mendoça, E.Wurtz, C.Inard. SimSpark: an object-oriented environment to predict coupled heat and mass transfers in buildings. Ibpsa conference, pp.903-910, Eindhoven, Netherlands, 11-14 August 2003.

[10] SPARK 1.0.2 Reference Manual, Simulation Problem Analysis and Research Kernel.

Lawrence Berkley National Laboratory, 1997-2002.

[11] P.V.Nielsen, A. Restivo.

The velocity characteristics of ventilated rooms. Journal of Fluids Engineering.100. (1978) 291-298.

[12] L. Mora , A.J. Gadgil, and E. Wurtz.

Comparing Zonal and CFD Model Predictions of Isothermal Indoor Airflows to Experimental Data, International Journal of Indoor Environment and Health (Indoor Air), 13(2) (2003) 77–85.

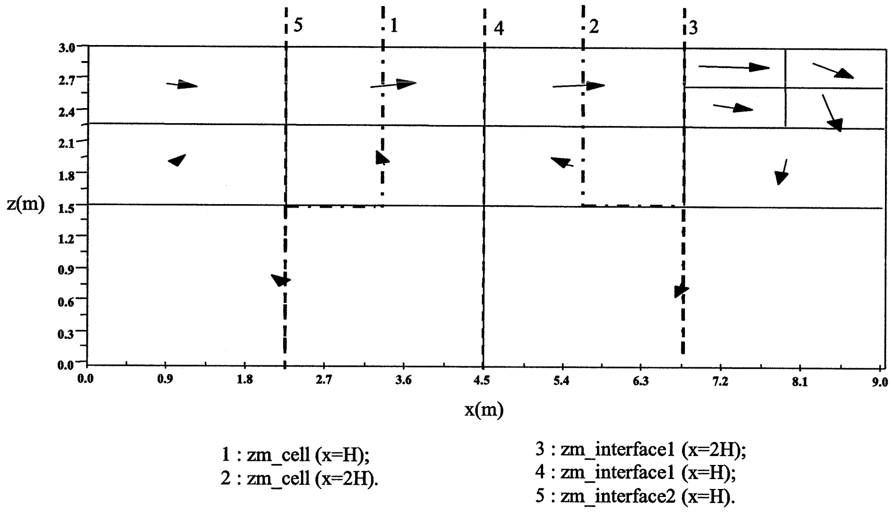

Fig. 7. Airflow pattern in Nielsen cavity with zonal model based on octree partitioning

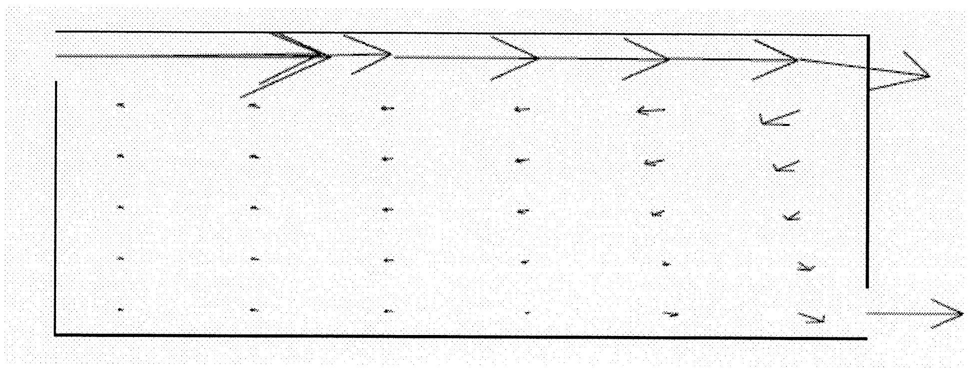

Fig. 8. Airflow pattern in Nielsen cavity with classical zonal model [12]

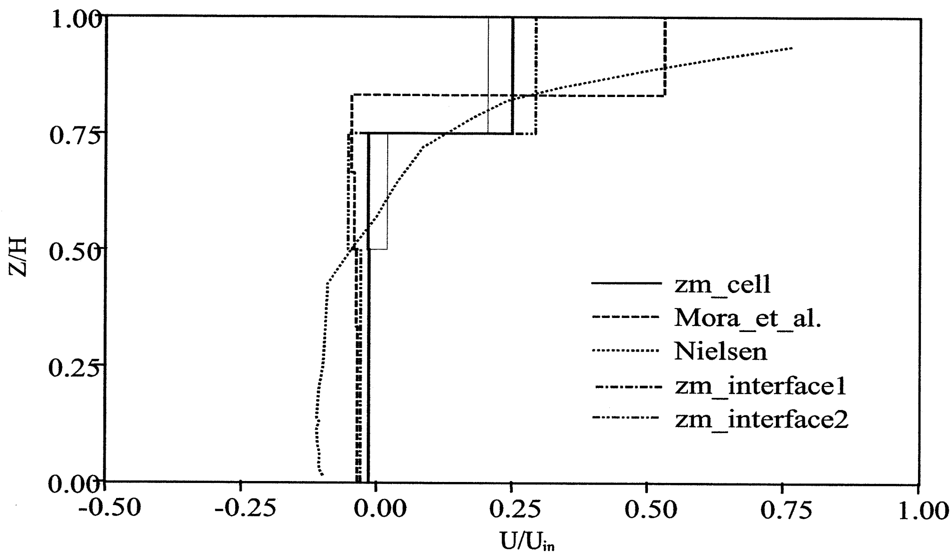

Fig. 9. Velocity profiles predicted by zonal models and experimental data in the central vertical plan at x= H

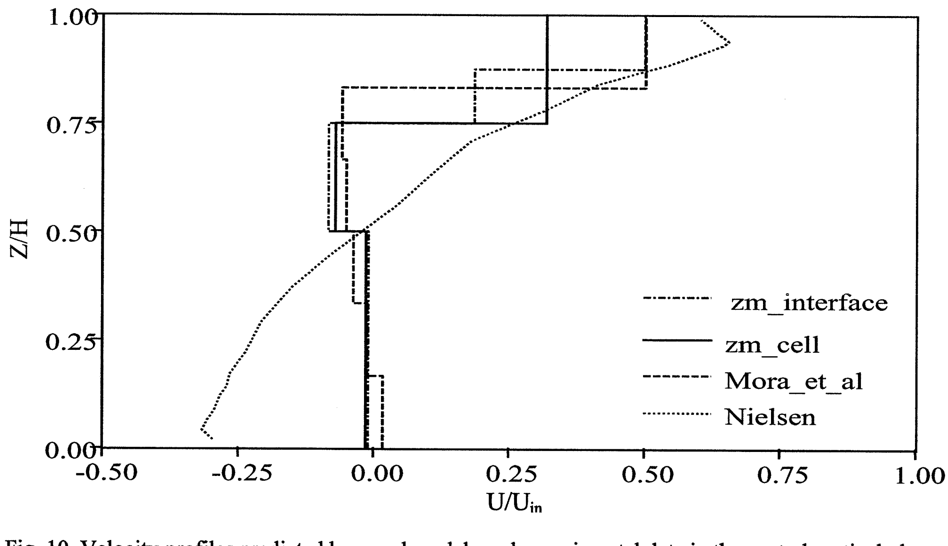

Fig. 10. Velocity profiles predicted by zonal models and experimental data in the central vertical plan at x= 2H