ELSEVIER

Energy and Buildings 33 (2001) 245–250

ENERGY AND BUILDINGS

www.elsevier.com/locate/enbuild

About the construction of autonomous zonal models

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1. Introduction

Because of the first petrol crisis in 1973–1974, the management of energy consumption becomes an absolute necessity for occidental states. For example, 50% of houses in France at this period were heated with fuel heating systems [1]. At this moment, new regulation concerning building insulation and energy management have been taken.

Even though research about physical phenomena in buildings has begun a long time before this crisis, it became urgent to evaluate the energy needs.

At this time a very strong effort has been carried out to develop numerical tools to predict quickly and cheaply the global thermal behavior of buildings and their energy needs.

In these general "energy codes", the system to be evaluate is the building itself and the study concerns the global energy exchange between the building as a whole and the outside. [2,3].

As the insulation levels were increasing, the ventilation became an important part of the energy consumption of buildings, so that it has been necessary to study more specifically the mass transfers of air between the building and outdoor and in order to control more specifically heating and ventilating systems, between the different zones of a building. These approaches have been called multizone modeling. In case of multizone models, the building is divided in several zones connected each other with different methods [4].

Then from 1980s, the demand of indoor quality and comfort became more and more important. The existing tools were no more sufficient various research teams developed the use of Computational Fluid Dynamics codes in order to answer the new questions. These simulation codes propose a detailed description of indoor air behavior. They are based on the construction of a grid for a room and the solving of the coupled energy and Navier and Stokes equations with iterative methods. These models allow numerical simulations and are able to calculate physical parameters which are not measurable. No doubts, they are a source of qualitative and quantitative knowledge for building conception. But the grid construction, the description of the boundary conditions and the mathematical representation of unsteady turbulent flows make the numerical model very difficult to implement and requires considerable computational resources. If these models are necessary in order to improve our knowledge of the global behavior of indoor climates, at these stage obviously they cannot be used as design tools.

In order to fill the gap between the scientific knowledge and the need of operational design tools, an intermediate approach between CFD codes and multizone models has been invented: the so-called zonal models.

The first studies are lead by Lebrun [5] since the 1970s. The aim is to describe thermal stratification in dwelling room taking into account the heating and ventilating systems, to predict the thermal needs and the system efficiency, the thermal comfort and the air quality.

The domain is divided in zones like in the multizone approach. But this time, zones correspond to elementary flows expected in the rooms that is expertised by the conceptor. Then, to each zone, energy and mass balance, eventually state equations are provided and solved. Concerning the first works, the partitioning and the models construction are based essentially on experimental knowledge [6–8]. More recently, research leads to simplified models more general so that an expert knowledge is not a necessity any more [9,10]. Despite of correct qualitative results, one can remark that these models fails to represent properly zones with plumes, jet or boundary layers [10,11].

At present, the use of zonal models requires a large competence in modeling and experiments in buildings. Moreover, for each different problem, a new analysis is necessary to build a new grid and to solve new equational system again, so that any parametric study is practically excluded. So, an important work remains to decrease the intervention of the model developer.

Our contribution to this general problem aims to generate zonal models with a minimum expertise of the modeler by putting this expertise within the code. Following the example of expert system techniques, we propose to constitute a database with qualitative knowledge about elementary flows encountered in dwelling rooms (jet, plumes, boundary layer) and modeling knowledge (experimental correlations and

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PII: S0378-7788(00)00088-8

Nomenclature

Ar	Archimede number
b_u, b_T	characteristic thickness of the jet (m)
h	dimension of the jet inlet (m)
K_v, K_T	empirical constants
L	length of the wall (m)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (K)
T_m	maximal temperature (K)
T_0	jet temperature (K)
U	axial component of the velocity (m/s)
U_m	maximal velocity (m/s)
U_0	jet velocity just after the inlet (m/s)
x_0	virtual origin

models, numerical or analytic solutions issued from experiments, numerical solutions code and literature). Then we propose to build an engine in charge of using these data to deduce the expected flows behavior and thermal transfer. From this analysis based on expert rules, the code proposes a partitioning with respect to the flow pattern and constructs an appropriated simplified model.

2. A general presentation of the automatic generation of zonal model

The tool we are developing is part of a future automatic simulation tool of dynamical and thermal phenomena in buildings (cf. Fig. 1).

The generator of zonal models after its own expertise provides an equational system. These equations may be transmitted to a generator of code in order to be solved by a solver. Then, in the future way of a dynamical solving, the results may be transmitted again to the generator of zonal model. The process stops when hypothesis and solutions are coherent.

2.1. The functions

The generator of zonal models has to use a set of physical knowledge and modeling knowledge about air flow patterns in buildings.

Four functions characterize the tool:

1. Identification of elementary flows thanks to expert rules.
2. The determination of the limits of the elementary flo which represent the validity domains of empirical la
3. The selection of the appropriate analytical local mo in a library for each elementary flow.
4. The correction of the local models, so that the heat a mass transfers continuity are simplified.

2.2. The structure

The conception of the tool is based on several necessit on the one hand, the structuration and the specification of problem, on the other hand, the modularity and the ext sibility to be able to adapt to various boundary conditi and geometry.

The analysis process has two levels:

1. The first level is the problem structuration. For problem, the tool has to answer these seven question the following order:
   Which are the causes of the flows? Which are main flows? Which is the nature of the elementary fl issued from the main causes? Which are the bound of the elementary domains? Which is the r appropriate model for the elementary flow? Whic the solving method? Which are the new boun conditions for the problem?
2. The second level is the specification of the diffe elementary flows. When the nature of the main flo identified among the main families of flows like boundary layer or jet, the tool has to determine i flows is turbulent or laminar, if the flow is warm or versus the indoor climate, if the flow is horizont vertical and its direction, if the flow is free o because of wall proximity.

Hence, the information is stored in a string which ca read at any time during the execution of the computa

The structure of the tool has to conserve the mo aspect of zonal model. The domain under study is di in sub-domains. Even though zones are connected other, the flow in each zone has a specific beh represented by a local model with its own boundary c tions. But we can find several similar zones in a dom in different problems. So, we try to define eleme qualitative rules, sufficiently general to be used w Moreover, four entities corresponding to four fun seen above can be distinguished, so that each entity be improved and extended without rewriting the program.

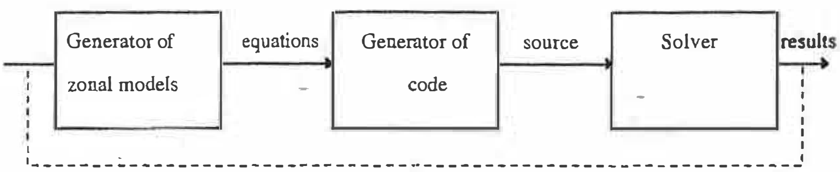

Fig. 1. Automatic simulation tool.

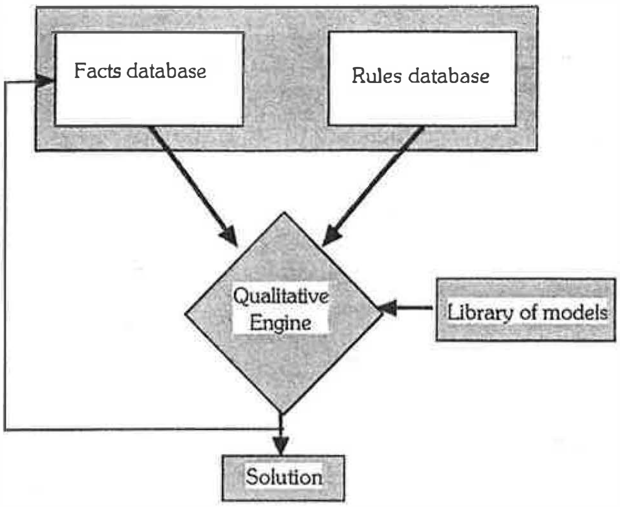

Fig. 2. Structure of the generator of zonal models.

These four parts are illustrated in Fig. 2, where the facts database contains the expert rules describing the problem (geometry and physical boundary conditions); the rules database sets the expert rules using the facts in order to deduce other facts; the library contains the analytical models and the empirical laws; and the qualitative engine applies the rules and determines the partitioning and chooses the local analytical models.

The use of analytical models involves the derivation and the handling of symbolic expressions. We need to manipulate different types of objects like lists, strings, numbers, equations but also points, lines, vectors. Computer algebra system are both a programming language and a tool to make computation easier thanks to a large database of mathematical functionality. Hence, we use Maple V to develop the qualitative engine and to implement the analytical models [12].

3. The generator of zonal model in details

We carry our effort to generate automatically a partitioning and a simplified model for two-dimensional and steady-state problems. Two illustrations of these cases have been presented in previous papers [13,14] related to the academic natural convection window problem in one hand and to a bi-dimensional ventilated enclosure in the other hand. Both illustrations follow the same analysis process, in five main steps.

3.1. The definition of the main driving flow

First, the fact database allows to interpreting the boundary conditions of the problem defined by the user in order to find, for example, the main driving flows. Hence, we assume that all computational domains could be represented by a set of the line segments. Walls and internal boundaries are modeled as a list of descriptors:

- the coordinates of segment extremities;
- the dynamical and thermal conditions on the segment;
- a string distinguishing a wall from a fictitious frontier.

Then, the program is able to deduce from these symbolic data other facts: a wall segment associated with an heat flux condition implies an heat source, a wall segment associated with a non null velocity through the segment implies a jet, a cool or a warm wall segment implies a natural convection flow.

When several main driving flows exist simultaneously, more refined rules are devoted to manage conflicts between them. For example, in the case of the window problem, a criterion based on the Rayleigh number determines if the two boundary layers along the opposite walls are separated or not.

3.2. The definition of the specific elementary flow to be generated

An other set of qualitative rules specifies as much as possible the nature of the elementary flow induced by the source.

In case of boundary layer, the program tests its position of the wall segment in the enclosure, its temperature versus the reference temperature estimated from an global energy balance on the enclosure. The program calculates non dimensional number and determine if the flow is turbulent or laminar.

In case of a jet, the program specify if the jet is horizontal or vertical, if it is a free or a wall jet, if the jet is warm or cool versus the reference temperature (it is seen above) and evaluates its penetration depth thanks to empirical correlation.

All this information is contained within a string available for consultation at each step of the partitioning process.

3.3. The definition of the boundaries of the zone

Once the nature of the local flow is known, the generator of zonal models has to determine the boundaries of the zone where the detected elementary flow is available.

As said before each validity domain can be represented in a first approximation by a polygon. Hence, a boundary layer zone is a rectangle whose dimensions are given by the wall and the maximum boundary thickness (cf. Table 1).

Table 1
Empirical laws for the maximal boundary layer thickness

	Maximal laminar boundary layer thickness (δ)	Maximal turbulent boundary layer thickness (δ)	References
Natural convection	$5L\,Ra^{-1/4}$	$0.527LR_L^{-1/10}P_r^{-11/30}$	[15]
Forced convection	$\dfrac{5L}{\sqrt{Re_L}}$	$5(0.37L\,Re^{-1/5})$	[16]

Table 2
Velocity profiles, temperature profiles and depth penetration laws

	Velocity and temperature characteristic laws of the jet	Jet penetration depth (D_p)	References
Isothermal free jet	$U = U_m \exp\left(-0.693\left(\frac{y}{b_u}\right)^2\right)$ $U_m = K_v U_0 \sqrt{\frac{h}{x}}$ $b_u = 0.1x$		[16]
Anisothermal horizontal free planar jet	$U = U_m \exp\left(-0.693\left(\frac{y}{b_u}\right)^2\right)$ $\Delta T = \Delta T_m \exp\left(-0.693\left(\frac{y}{b_T}\right)^2\right)$ $U_m = K_v U_0 \sqrt{\frac{h}{x}}, \qquad \Delta T_m = K_T \Delta T_0 \sqrt{\frac{h}{x}}$		[18]
Anisothermal vertical free planar jet	$U = U_m \exp\left(-0.693\left(\frac{y}{b_u}\right)^2\right)$ $\Delta T = \Delta T_m \exp\left(-0.693\left(\frac{y}{b_T}\right)^2\right)$ $U_m = K_v U_0 \sqrt{\frac{h}{x}}\left[1 \pm 1.8\left(\frac{K_T}{K_v^2}\right) Ar_0 \left(\frac{x}{h}\right)^{3/2}\right]^{1/3}$ $\Delta T_m = K_T \Delta T_0 \sqrt{\frac{h}{x}}\left[1 \pm 1.8\left(\frac{K_T}{K_v^2}\right) Ar_0 \left(\frac{x}{h}\right)^{3/2}\right]^{1/3}$	$\frac{D_p}{h} = 0.68\left(\frac{K_v^{4/3}}{K_T^{2/3}}\right) Ar_0^{-2/3}$	[17]
Isothermal wall jet	$U = U_m \exp\left(-0.937\left(\frac{\delta}{b_u} - 0.14\right)^2\right)$ $U_m = U_0 3.5 \sqrt{\frac{h}{x}}$ $b_u = 0.068(x - 10h)$	With an opposite air extract $D_p = 0.9L$ With air entrance and extract at the same side: $D_p = 0.64L$	[16,20,21]
Anisothermal horizontal wall jet	$U = U_m \exp\left(-0.937\left(\frac{y}{b_u} - 0.14\right)^2\right)$ $\Delta T = \Delta T_m \exp\left(-0.937\left(\frac{y}{b_T} - 0.14\right)^2\right)$ $b_u = \frac{0.069(x + x_0)}{h}$ $b_T = \frac{0.075(x + x_0)}{h}$ $U_m = U_0 \overline{U} Ar_0^{1/3}, \qquad \Delta T_m = \Delta T_0 \overline{\Delta T} Ar_0^{1/3}$ $\overline{U} = \frac{U_m}{U_0} Ar_0^{-1/2}, \qquad \overline{T} = \frac{\Delta T_m}{\Delta T_0} Ar_0^{-1/2}, \qquad \overline{X} = Ar_0 \frac{(x + x_0)}{h}$	$\frac{D_p}{h} = \frac{0.4 K_v^{4/3}}{\sqrt[3]{(K_T Ar_0)^2}}$	[18,19]
Anisothermal vertical cold wall jet	$U = U_m \exp\left(-0.937\left(\frac{y}{b_u} - 0.14\right)^2\right)$ $\Delta T = \Delta T_m \exp\left(-0.937\left(\frac{y}{b_T} - 0.14\right)^2\right)$ $b_u = \frac{0.069(x + x_0)}{h}$ $b_T = \frac{0.075(x + x_0)}{h}$ $U_m = U_0 \overline{U} Ar_0^{1/3}, \qquad \Delta T_m = \Delta T_0 \overline{\Delta T} Ar_0^{1/3}$ $\overline{U} = (K_v^3 \overline{X} - A K_v K_T)^{-1/3}$ $A = 4.841 - 1.995 \overline{X}^{3/2}$ $\overline{X} = Ar_0^{2/3} \frac{x + x_0}{h}$	$\frac{D_p}{h} = 4.4 Ar_0^{-0.389}$	[18,19]

Table 3
References of the models used by the zonal model generator

Models	References
Boundary layer	[15]
Isothermal free jet	[16]
Anisothermal free jet	[17–19]
Isothermal wall jet	[16,20,21]
Anisothermal wall jet	[18,19,22,23]
Plumes	[24]

The width of a jet or a plume zone defined by an experimental expansion law. To estimate the maximal thickness of the jet, we suppose the jet velocity limit is equal to 1% of its maximal value like it is reported in Table 2. The length by the penetration depth estimation is issued from experimental studies. The correlations implemented in our program are summed up in the Table 2.

3.4. The definition of the appropriated model

For each zone, the choice of appropriated model in the library is done with rules testing the string about the qualitative specifications of the flow, the geometric descriptors and the boundary conditions.

The outputs are the new boundary conditions on each border, the calculus of heat and mass flows and the local analytical solution. These operations are performed with the computer algebra system: Maple V.

All of the models implemented in our program are referenced in Table 3.

3.5. The updating of the data and the connection between zones

The partitioning of the enclosure is performed step by step. After the first zone is defined (the geometry and the nature of the local flow), there are new boundary conditions based on the adjacent solution just determined for the new unknown domain. Then, the zone just created is taken away from the empty zone that remains to be filled. The same iteration is performed until the whole initial domain has been filled with local solution.

The connection between zones is checked by the continuity of mass and heat flow rate but also, from time to time, the continuity of the velocity and the temperature. Because of the diversity of the local models, the connection is a real difficulty, particularly if two directed momentum zones are joined.

Many studies have been lead about analytic connection methods. But these methods, very difficult to implement involve an accurate computational level higher than the one of our modeling method. Hence, to avoid these situations, we have implement, first, qualitative rules in charged to give the priority to a main driving flow over the others. Second, we do the partitioning so that directed momentum zone have no shared borders. Transition zones are defined where heat and mass flux balance are only provided.

4. Conclusion

We present results for the window problem and the bi-dimensional ventilated enclosure in papers [13,14]. The generator of zonal models give a good qualitative representation of the flow dividing the enclosure in a few number of zones. The qualitative results are quite satisfactory.

The ongoing work concerns anisothermal bi-dimensional and tri-dimensional problems. The qualitative knowledge issued from empirical studies allows to build the partitioning without difficulties. In tri-dimensional case, the segments are replaced by rectangular areas. The descriptors and the analysis process are still the same. The rules database just requires more rules and the solving of the equational system seems to be more complex but without formal difficulty.

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