

Simulations of integrated airflow-energy-moisture behavior of multizone buildings

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ABSTRACT. The global thermal behavior of buildings is very difficult to model, because of its complex geometry and of the numerous interacted phenomena, such as heat and mass flows, moisture transfers, etc. In this paper, a general numerical strategy based on splitting into blocks is proposed to solve the steady state of airflow-energy-moisture (AEM) model. Simulations of a complex configuration show a good reliability of the block method. Also the observed impact of model components on the numerical convergence is in good agreement with predicted effects. This block strategy shows its good adaptation to the AEM models and therefore it will be implemented in *CLIM2000* simulation environment to improve its capacities for the simulations of global models.

1. Introduction

The main objectives of building physics are to reconcile user's comfort and energy efficiency in the design of buildings. As these two criteria lead to contradictory recommendations, the numerical simulations are often the only way to predict thermal behavior of a building. The modeling of global behavior is important for the correct thermal design of new buildings and becomes essential in some special fields such as for example health care or electronic industry.

The global thermal behavior of buildings is very difficult to model. Firstly, the geometry of a building is in general sole and complex. Therefore often simplified, lumped models are used in order to bypass a detailed description of building's geometry. Secondly, numerous coupled phenomena influence the thermal behavior, such as heat and mass flows, moisture transfers, etc. For comprehensive simulations of building's behavior, the interactions between these phenomena must be represented. Such global, integrated models generate ill-conditioned and hard to solve systems of equations.

We are interested here in the integrated airflow-energy-moisture (AEM) multizone models, where one 'zone' corresponds to one room. These models are implemented in *CLIM2000* building simulation environment, developed by Electricité de France [1]. For numerical computations *CLIM2000* uses *ESACAP* [2], general solver of algebro-differential equations, developed by StanSim (Denmark).

This work is a part of a research project devoted to the development of a reliable method enabling easy simulations of buildings' thermal behavior using global models. The aimed method should be very general in order to allow for simulations of very different configurations of AEM models without any intervention of the user: building physicist and not numerical analyst. Some preliminary results showed that block methods need to be used in order to solve simple configurations of the integrated AEM model. The aim of this paper is then to check the reliability of the block method to

solve complex configurations. First, the fundamental principles of the AEM models are introduced, and commonly met numerical problems are discussed. Then, using previously published results, a general numerical strategy to solve AEM models is proposed. In the second part of this paper, proposed method is applied to a complex configuration. On this example the relationship between different model's components and the performance of the numerical strategy is analyzed.

2. Airflow-energy-moisture modeling

2.1. General presentation

The objective of airflow-energy-moisture modeling is to represent heat and mass transfer inside the buildings in order to predict both indoor climate (temperature and moisture content) and energy consumption. The fundamental equations of the AEM model are mainly three types of balances:

- dry air mass balance : determining air movements (variable: air pressure at ground level),
- vapour mass balance : describing moisture transfers in a multizone space (variable: air moisture content),
- enthalpy balance : determining energy consumption and inside temperatures (variable: air temperature).

In more complex configurations additional equations may be introduced to describe the transfers through building envelope, the heating system, the moisture storage, etc. The different equations are strongly coupled together, following the relationships presented in figure 1.

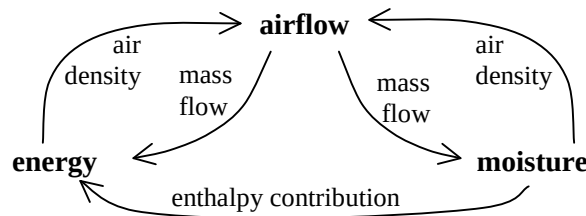


Figure 1. Main couplings between different balance equations

The resulting mathematical model has strong algebraic non-linearities, mainly due to two factors :

- airflow equations, linking pressure difference (ΔP , [Pa]) and the mass flow (Q , [kg/s]) using the power law: $Q = K \Delta P^n$, (K and n : power law real coefficients),
- perfect gas relationship: $PV = MrT$; linking pressure (P , [Pa]), temperature (T , [K]) and mass (M , [kg]) with air volume (V , [m³]) and perfect gas constant (r , [J/(kg K)]).

2.2 Numerical difficulties

The integrated AEM model is expressed as a system of algebro-differential equations. However, in most configurations, this system of equations turns out to be impossible to solve using general purpose solvers, such as *ESACAP*. Let's consider for example the

situation presented in Figure 1, describing steady-state moist airflow between two rooms (including two-way flow through the open door). It is represented using 6 algebraic non-linear equations (see [3] for details). This model is very simple from the physical point of view (represents only balance equations of the inside air, no heat sources or transfers through the envelope are described), however its numerical behavior is typical of all encountered difficulties. In a set of 60 different simulations of this configuration (varying: parameter values, external climate, starting points, solving algorithms), using general numerical algorithms, only 1 computation converges.

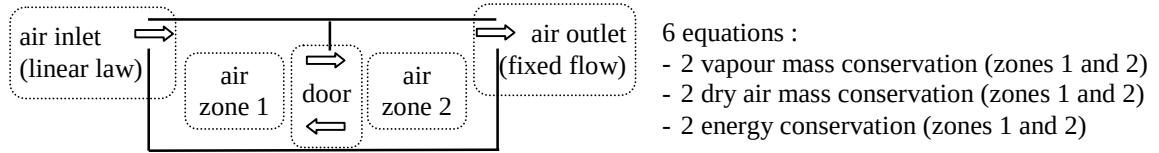


Figure 2. Example 1: Moist air flow in a two-room configuration

In order to improve the performance of the numerical algorithm it is important to understand the origin of encountered convergence difficulties. Most of the popular non-linear solvers (including *ESACAP*) are based on Newton's direction [2], [4], [5], [6], where at each non-linear iteration we need to solve the linear system (1).

$$J(x) dx = - F(x) \quad (1)$$

In the AEM models, the jacobian matrix, $J(x)$, is ill-conditioned. Even for very small systems, such as the example 1, the associated matrix has the condition number of about 10^9 . This high condition number expresses the physical sensitivity of the coupled model to variations of boundary conditions. It is mainly due to the representation of the airflow through large openings (such as doors). We use here the popular simplified expression based on Bernoulli equation [7]. In such configurations different flow directions are possible : $1 \rightarrow 2$, $2 \rightarrow 1$ and even a two-way flow : $1 \leftrightarrow 2$. Integration of different possibilities and of their transitions into the airflow model introduces situations difficult to solve. The airflow model is very sensitive to even small variations of the inside temperature or moisture content. Typically, an important difference of the mass flow of about 100 kg/h can be introduced by a very small difference of pressures of about 10^{-2} - 10^{-3} Pa. At the moment, no robust method to compute the solution of the complete problem exists [3], [8] and [9].

2.3. Adapted numerical method

2.3.1. General principles

In building physics, the steady state computations are extremely important. The knowledge of the steady state of the AEM system is in general needed before the analysis of its dynamical behavior. This is essential for the airflow inside the building. Therefore, in this work we concentrate on the steady state behavior, that is on the solving of a non-linear algebraic system $F(x)=0$.

As the simultaneous resolution of the complete system of equations failed on our problem, an adapted numerical approach must be used. In order to achieve numerical convergence, the complete model have to be divided into smaller blocks. The splitting into blocks should be based on general criteria, in order to allow for an automatic use of

the splitting. A good way to fulfill this requirement is to follow the physical form of the system. In our case, two splittings can be performed:

- (R) into 'Rooms' (*multizone* modeling), by regrouping balance equations of each zone of the partitioned space, (2 blocks of 3 equations each for example 1)
- (S) into 'sub-Systems' (*coupled* airflow-energy-moisture modeling), by regrouping balance equations of the same type (dry air mass, vapour mass, energy), (3 blocks of 2 equations each for example 1).

Practical application of both possibilities showed that the splitting (S) is far more efficient (see [10]). Additional benefit from the (S) splitting is that basic equations of each physical sub-system are mainly linear and therefore easy to solve. However, the correct splitting is not sufficient to ensure reliable convergence. The strategy to update values of variables during the iteration process needs as well to be adapted to physical interactions represented in the model. A hybrid Gauss-Seidel – Jacobi update strategy, adapted to the high sensitivity of the airflow model proved to be the most effective (see [11]).

2.3.2. Resulting algorithm

The final block algorithm, proposed for simulations using coupled AEM models is presented in figure 3. It takes into account the (S) splitting. 3 blocks solved separately are the 3 physical sub-systems: airflow, energy and moisture. The hybrid update strategy from [11] is included in each global iteration. Its main role is to maintain the flow values independent from temperature and moisture content variations during the resolution of the energy and moisture blocks.

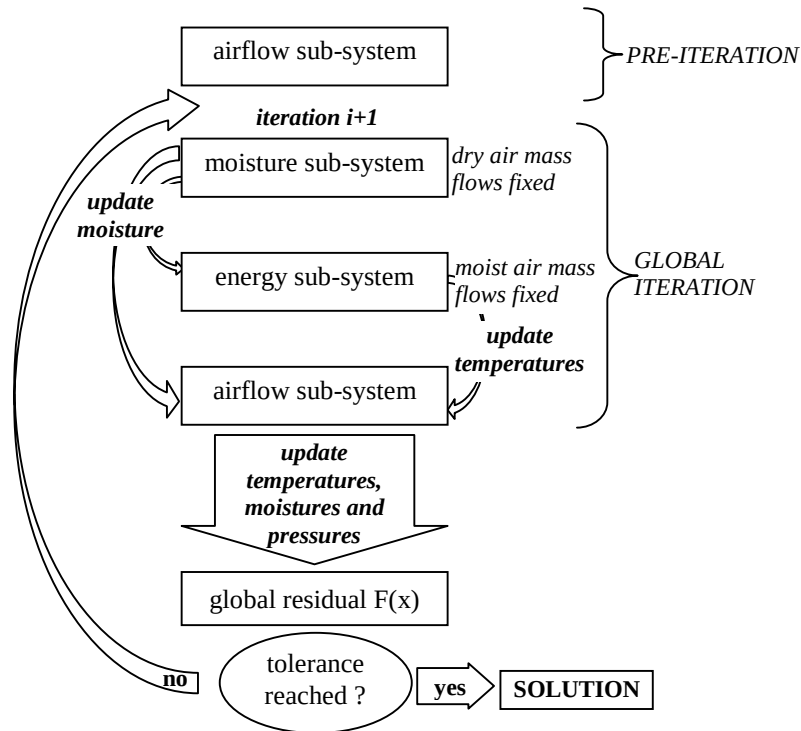


Figure 3. Block algorithm for AEM simulations

Initial vector is the nil vector. Each block is solved using Newton method (also called Newton-Raphson method), associated with a line search procedure to globalize convergence (both algorithms are described in [6]). Jacobian matrix is computed using a divided differences first order approximation. At the end of each global iteration, the global residual, $F(x)$, is computed using ℓ_2 norm. Global residual expresses the non-balance of mass or heat conservation equations, it is very well adapted to the physical problem. This iteration procedure ensures the achievement of the solution of the coupled system. The algorithm is implemented in a standard windows PC environment. The results presented in the following are obtained using a tolerance of 10^{-9} for the resolution of each block and of 10^{-6} for the global solution. All calculations are performed using double precision numbers.

2.3.3. Application on the example 1

The algorithm presented above is applied to solve the example 1. The progress of the iteration process can be seen in Table 1.

global iteration	moisture sub-system		energy sub-system		airflow sub-system	
	number of iterations	global residual	number of iterations	global residual	number of iterations	global residual
0	-	-	-	-	3	0.1
1	1	0.5	2	0.4	3	$3 \cdot 10^{-9}$

Table 1. Application of block method. Iterations needed to solve one block and global residual

In the table 1, the global residual is given after the resolution of each block. The residual at the end of each global iteration is represented only by the values in the last column (after the resolution of the airflow block, see also figure 3). From the results in table 1, a very good performance of the numerical method can be seen. Only one global iteration is needed to achieve convergence. This good performance is not surprising, because the numerical resolution is based on physical interactions for moist air flow model.

3. Simulations of an individual house

3.1. Comprehensive AEM model

The proposed numerical strategy is used to inquire the behavior of an individual house, in order to check its performance to simulate real life situations. The individual house is presented in figure 4. The AEM model of the house includes the following elements:

- mass and enthalpy balances of all air zones,
 - moist air infiltration and mechanical exhaust,
 - inter-room moist air transfers through open internal doors,
 - thermal transfer through the envelope,
 - regulated heating system composed of individual convectors in each zone.
- All convectors are equipped with individual regulation, the aimed temperature is settled at 19°C.

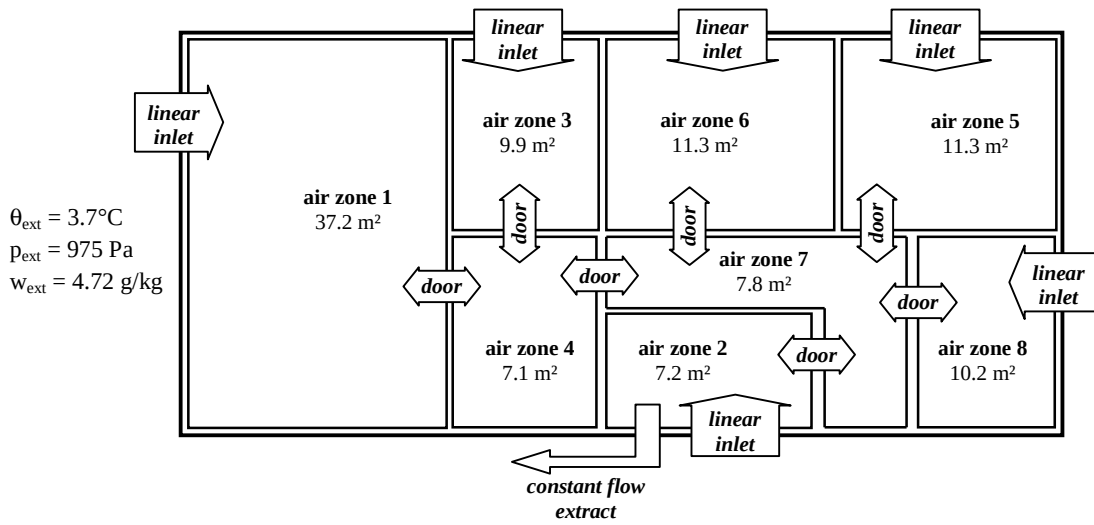


Figure 4. Example 2: Individual house.

The first 3 elements of the model are similar to the ones used in the example 1. However, as the number of rooms and open doors is more important (8 rooms and 7 doors in the example 2 against 2 rooms and 1 door in the example 1) the mathematical model more complex. Moreover, the last two elements (envelope and heating system) are not represented in the example 1.

The mathematical AEM model of the example 2 comprises 196 equations:

- moisture sub-system : 8 equations (1 mass balance for each of 8 rooms),
- energy sub-system : 180 equations (1 energy balance for each of 8 rooms, 1 equation for the regulation of each of 8 convectors and 166 energy balances describing heat transfer through the envelope).
- airflow sub-system: 8 equations (1 mass balances of the dry air for each room).

3.2. Numerical simulations

3.2.1. Results from the comprehensive AEM model

The simulations are performed using the numerical strategy presented in the section 2.3. The main results obtained are presented in figure 5.

Figure 5 shows the importance of the mixing of the air through the open doors in the simulated house. The mixing flow is much more important than the net flow. This has very important impact on the repartition of the heating power and on the air temperatures inside the house. The results show the importance of the interactions between the energy and the airflow and prove the importance of integrated modeling.

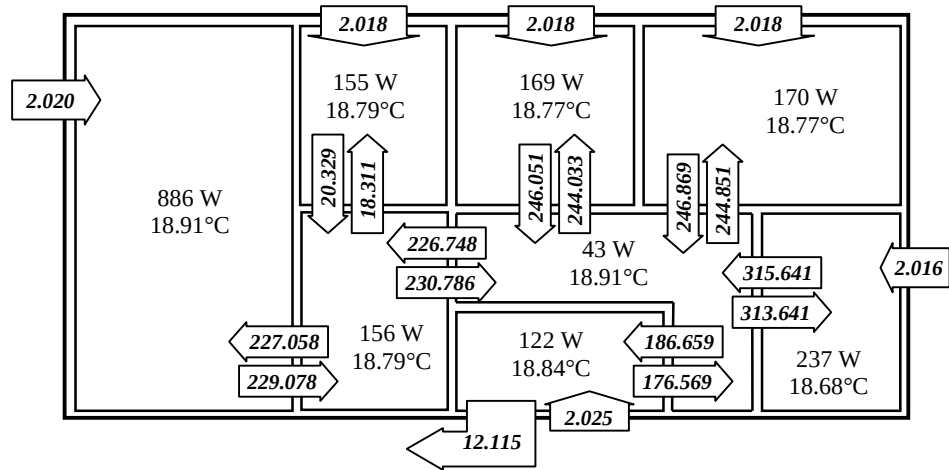


Figure 5. Elements of the solution : interzonal mass flow (kg/h) and in each room : heating power of each convector (W) and air temperature (°C)

3.2.2. Impact of different model components on numerical convergence

Another important point is the analysis of the numerical performance of the block algorithm. The progress of numerical iterations is represented in the table 2.

global iteration	moisture sub-system		energy sub-system		airflow sub-system	
	number of iterations	global residual	number of iterations	global residual	number of iterations	global residual
0	-	-	-	-	3	$1 \cdot 10^4$
1	1	$1 \cdot 10^4$	25	40	5	0.1
2	1	0.1	2	25	6	0.01
3	0	0.01	2	4	6	$3 \cdot 10^{-3}$
4	0	$3 \cdot 10^{-3}$	2	.8	2	$6 \cdot 10^{-4}$
5	0	$6 \cdot 10^{-4}$	1	.1	2	$1 \cdot 10^{-4}$
6	0	$1 \cdot 10^{-4}$	1	.03	2	$2 \cdot 10^{-5}$
7	0	$2 \cdot 10^{-5}$	1	$5 \cdot 10^{-3}$	1	$4 \cdot 10^{-6}$
8	0	$4 \cdot 10^{-6}$	1	$1 \cdot 10^{-3}$	1	$7 \cdot 10^{-7}$

Table 2. Application of block method. Iterations needed to solve one block and global residual.

The results in table 2 show that in the example 2 8 global iterations are needed to achieve global convergence, against only 1 for the example 1. This is not a surprising result, because of the example 2 is clearly more complex than the example 1. However, in order to check the adaptation of the block method to AEM simulations the impact of each component of the model should be precisely analyzed. Therefore, some additional simulations are done using some simpler models of the example 2. The models used are:

- 2a: the simplest AEM configuration, representing only moist air flow (balance equations, interzonal airflow and ventilation),
- 2b: 2a + thermal envelope,

- 2c: 2b + the simplest heating system (constant power: no regulation),
- 2d: 2c + proportional regulation of the heating system (this is the model used in the section 3.2.1).

The main elements of the numerical resolution are given in table 3.

model		number of equations				iterations in energy block	global iterations
name	main characteristic	total	A	E	M		
2a	basic	24	8	8	8	2	1
2b	+ envelope	188	8	172	8	2	1
2c	+ heat source	188	8	172	8	2	17
2d	+ regulation	196	8	180	8	25	8

Table 3. Impact of different model elements on the numerical resolution

Table 3 shows clearly that the description of building envelope has an important impact on the size of the system of equations but does not affect the iteration process. In both, 2a and 2b cases, the energy block is solved in 2 Newton's step and the global convergence is met after one global iteration. This is in good agreement with the model, composed mainly of linear equations. On the other hand, the energy source has no effect on the size of the system, but causes an important rise in the number of global iterations. The reasons of this behavior are easy to explain. A heat source in one room has an important impact on the inside temperature, which affects the mass flow. Modification of the mass flow affects the air temperature, etc.

As the energy balance equations for the inside air and for the thermal envelope are linear, the energy block is easily solved in the cases 2a, 2b and 2c. The regulation of convectors is described by non-linear equations and therefore it affects the resolution of the energy block. On the other hand, the stabilizing effect of the regulation on the number of global iterations can be clearly seen (cases 2c and 2d). This is also in good agreement with the physical model. The regulation of air temperature "smoothes" the impact of air temperature on the interzonal airflow.

Using the results presented in Table 3, the convergence rate of the block method can be estimated. In the case when no enthalpy sources are present, the convergence is instantaneous. In the cases 2c and 2d, convergence rate can be computed using the equation (2):

$$\tau = \frac{\|\vec{x}_{i+2} - \vec{x}_{i+1}\|}{\|\vec{x}_{i+1} - \vec{x}_i\|} \quad (2)$$

where i is the number of Newton iteration. The convergence rate for the cases 2c and 2d is shown in figure 6 below.

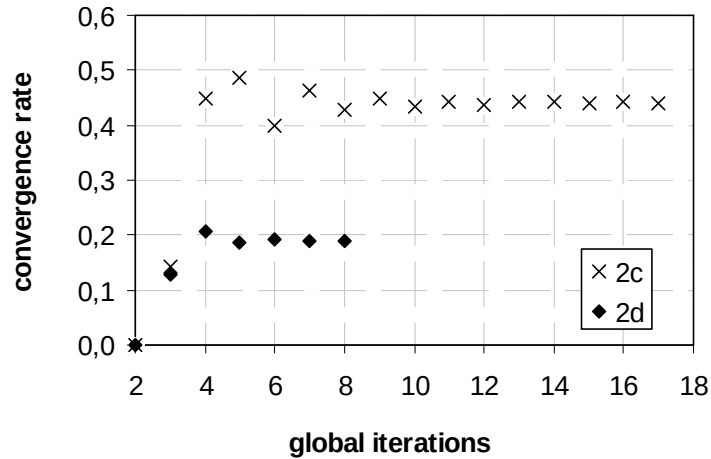


Figure 6. Convergence rate.

From figure 6 it can be clearly seen that in both cases the convergence is linear with a constant rate. This result is a good, it indicates that even if the convergence is not very rapid, it is effective.

4. Conclusions and future works

A general numerical strategy based on splitting into blocks is proposed in this paper to solve the steady state of airflow-energy-moisture model. This method is based on previously published results for the moist airflow models. It is successfully applied here to a comprehensive model of an individual house.

The convergence is reached in all performed calculations, showing reliability of the proposed block method to solve AEM models. Additionally, in the most complex configurations the convergence is at least linear. Moreover, the impact of different model components on the numerical convergence is studied. A good agreement is found between the observed behavior and the expectations based on the physical model. These results prove the adequacy of the proposed block method to solve complex AEM models. Considering these conclusions, the block method is now being implemented in the *ESACAP* solver. This should enable easy simulations of global behavior of buildings using *CLIM2000* code.

Moreover, use of the block methods offers some very interesting possibilities for time-domain calculations. In a building, different phenomena have very distinct time constants, for example less than one minute for mass transfer through an open door and several hours for heat flow through a concrete wall. Adapting time steps to different phenomena, can significantly diminish computing time, maintaining high numerical precision. Preliminary tests have given some interesting conclusions [12], and future work should develop practical recommendation concerning the splitting into blocks in the time domain.

Also, some additional improvements are still possible, for example representation of the thermal control system increase the number of Newton iterations needed to solve the energy block (25 iterations with control system, against 2 without). This increase can be

limited (down to 8), through controlling the size of Newtonian step. It is also necessary to analyze more in detail the impact of moisture models, such as moisture storage and phase change, on the numerical resolution.

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