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Air transfer, natural convection
Air transfer between rooms

DEVELOPMENT AND VALIDATION OF NEW AERAULIC MODEL DESIGNED FOR THERMAL COMPUTATION WITH PARTICULAR ATTENTION TO THE PROBLEMS OF AIR QUALITY

Roger Pelletret and Hala Khodr

Roger Pelletret, a research engineer in charge of research into Energy Conservation in buildings at the Centre Scientifique et Technique du Bâtiment, CSTB, and Hala Khodr briefly describe the research and experiments at Service Thermique et Techniques Avancées, TTA. The paper describes the new aeraulic model and focuses on its limits and the importance of vertical temperature gradients.

Roger Pelletret, ingénieur chargé de la recherche sur la maîtrise de l'énergie dans les bâtiments au CSTB (Centre Scientifique et Technique du Bâtiment) décrit, avec Hala Khodr, les travaux de recherche et d'expérimentation menés au service Thermique et Technique Avancées. Ils présentent, en particulier, le nouveau modèle aéraulique en insistant sur ses limites et sur l'importance des gradients verticaux de température.

Context

The main aim of this reserch is to evaluate the effect of internal partitions of buildings on the computation of thermal performances, either for the building envelope components or for heating system components.

Until recently, performance was computed by using building zone models. A building was described as an isothermal single volume; the free gain (solar gains, heat losses of systems, etc.) were assumed to be uniformly distributed.

Taking into account the true internal divisions of buildings leads us into non-uniform temperature fields. For instance, overheating in some places can be more mportant than with a unizone hypothesis. The computed rate of recovery of the free gains is lower when the nternal partition is taken into account (refs 1–4).

To compute with some accuracy the thermal performance of the building envelope, or heating sysem components in a multizone environment, the heat transfers between rooms have to be computed as accurately as possible. The main difficulty is the modelization of the heat transfers, due to aeraulic transfer. To compute with accuracy the aeraulic heat transfer, it is logical to use a model based on the computation of the pressure fields. For thermal computations (single goal of the aeraulic model: to provide thermal conductances due to air movements) an aeraulic model based on the computation of pressure fields is too complicated. To use such a model leads to excessive running times, if annual simulations are required. Problems of non-convergence occur sometimes (refs 5 and 6).

A new model, adapted to thermal computation codes, has been developed. The application field of this new model has been defined in the framework of a global classification method for the various kinds of aeraulic models. The architecture of the new model is described below. To validate this new model, an experiment has been designed, the main characteristics of which are given under Experiments. In addition to the main aim of

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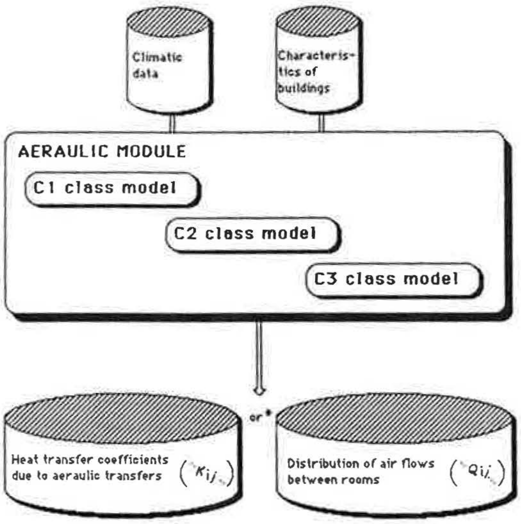

*Using a C2 or a C3 class model

Fig. 1. Aeraulic module

this new model, it could be used (as a simplified model) to compute the air flow rates between zones. The limits of validity of this model, in particular the problems of multiple neutral plan in an aperture are discussed in the Main Results section.

Architecture of the new aeraulic model

Classification of aeraulic models

A classification of the various aeraulic models has been designed. The models are classified depending upon their main application field. The different classes are:

- C1 Class Models with fixed scenarios for air movement between zones.
- C2 Class Models taking into account at each time step the evolution of the temperature in the different rooms, but without computing the pressure fields.
- C3 Class Sophisticated models based on the computation of the pressure fields.

C1 class models are the simplest models and the most commonly used for thermal computations. Their application field is restricted to thermal computation codes. In a C1 class model, the air flow rate distribution between rooms (including the outside of the building) is defined before starting transient simulations. The air flow rate distribution can be defined by the software user or can be computed using a C2 or C3 class model. In any case, the air flow rate distribution will change all along the simulation. At best, it is possible to define periodical time dependent scenarios.

C2 class models are designed to be used mainly for thermal computations. Nevertheless, with some restrictive conditions, they can be used to compute air flow rates. The new model we have developed is a C2 class model. At each time step, this model allows an accurate enough computation of the heat conductances due to air movements between rooms.

C3 class models are designed to compute with accuracy the air flow rates. They take into account the wind effects, the air leakage, the buoyancy effects, the ventilation systems, etc. C3 class models are used in thermal computation codes (CSTBât(1); ESP(2)) to compute heat transfers coefficients between rooms.

A complete aeraulic module (Fig. 1) would involve the different classes of aeraulic models, as each one is adapted to a specific problem.

Architecture of a C2 class model

To calculate thermal performances for a whole heating period, it is more important to take into account the variations of the internal air movements than the variations of the air leakage and of the ventilation. For thermal computations, average values for the exchanges of air between the outside and the inside of a building can be used. Eventually, different average values will be used for winter, and for autumn and spring (only if a climatic analysis would show that there are big differences between the average values of air leakage, because o different average wind speed and direction and airtight ness in the building). In addition, mechanical ventilatio can be defined, as a periodical time dependent function

The aeraulic model involves a pre-processor to con pute average distributions of air flow rates due to a

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(1) CSTBât: Code de Simulation de la Thermique du Bâtime
CSTB Sophia Antipolis, France

(2) ESP: Environmental Systems Performance; University Strathclyde, Department of Architecture

leakage and ventilation. These calculations must be made for all the possible configurations, i.e. depending upon the possible status of the doors (open or closed). The computations can be easily made with a C3 class model, assuming that all the temperatures in the rooms are equal (because with this last hypothesis, the present C3 model runs very well, calculating quickly).

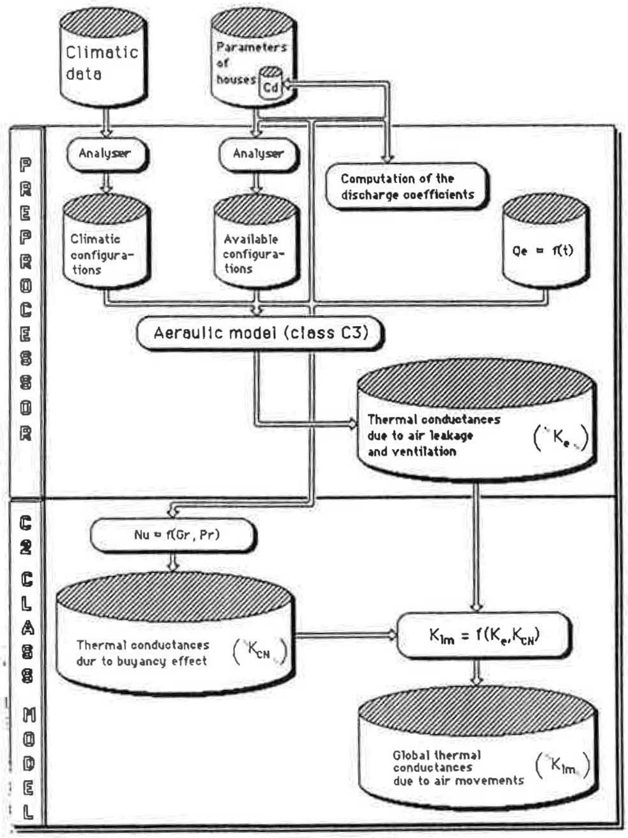
Finally, the results are translated in terms of thermal conductances (named $Ke_{l,m}$) between rooms. The values of $Ke_{l,m}$ are stored in a matrix (named D(*i*, *j*, *k*, *l*, *m*)),

Index i is for the different periods of the heating season (if necessary) (in general $i=1$ or 2).
Index j is used if daily scenarios for the mechanical ventilation are defined.
Index k is to differentiate the various configurations (combination of all the possibilities to have open or close doors). The maximum value of index *k* depends upon the number of rooms and the hypothesis concerning the doors between rooms (behaviour of inhabitants).
Indexes l and *m* are to point out the rooms between which the conductance Ke(*i*, *j*, *k*, *l*, *m*) occurs.

When this initialized phase is complete (i.e. when the D matrix is full), the transient computations can be run. The air movement between rooms is due, on one hand, to air leakage and ventilation and, on the other, to buoyancy effect. The thermal conductance due to air leakage and ventilation are extracted from D matrix. The thermal conductance due to buoyancy effect is computed through a simplified model; this model can be shown as $Nu=f(Gr, Pr)^*$; such a model defines the temperature dependent conductance between two nodes, representing two adjacent rooms.

The global thermal conductance is computed by using a coupling model. The coupling model consists of a simplified relationship to calculate the global thermal conductance between two rooms knowing the thermal conductance due to air leakage and ventilation and the thermal conductance due to buoyancy effect.

The architecture of a C2 model is summarized in Figure 2.



'ig. 2. *Architecture of a C2 class aeraulic model*

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* Nu Nusselt's number
Gr Grasshof's number
Pr Prandlt's number

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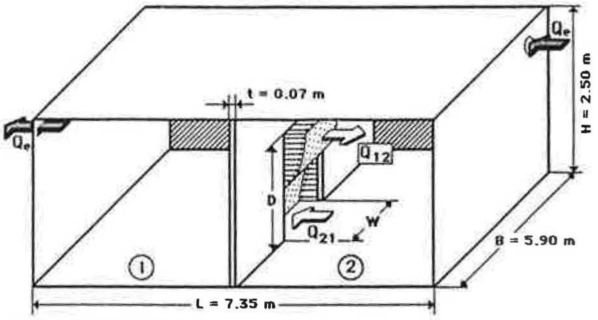

Fig. 3. Experiment

Important points

The aeraulic model of C2 class involves several sub-models:

- A model to compute discharge coefficients as a function of opening characteristics;
- A model to compute the D matrix (i.e. the thermal conductances due to air leakage and ventilation);
- A model to compute the thermal conductances due to buoyancy effect;
- A coupling model to compute the global conductances.

These diferent models are described in detail in ref. 7.

To identify the parameters of these models, an experiment, which takes into account the results of the previous work (refs 8 and 9), has been designed.

Experiment

This experiment takes place in the DESYS test cell which is built within the area of the CSTB in Sophia-Antipolis. The DESYS test cell is described in detail in ref. 10. The design, instrumentation and data acquisition system concerning the experiment about air transfers are described in detail in paragraph 6 of ref. 5.

Nevertheless, we give below some important information concerning the experiment. The aims are:

- To provide some elements of reflection about the physical aspects of convection through a large opening;
- To identify the parameters of reduce order models (as for example, a Nu=f(Gr, Pr) relationship);
- To provide experimental data to validate the whole C2 model.

The experiments aim to measure the heat transfer between two rooms (Figure 3) under various conditions. Heat transfer can be calculated, either by using the measured speed and temperature fields in the aperture, or with a method of thermal balance.

The various conditions which can be applied are:

- Fixed values for the heat fluxes in the two rooms (these fluxes can be *positive*, i.e. a heated room, *negative*, i.e. an air-cooled room, or *equal to zero*, i.e. no heating or cooling system in the room;
- Different heating or cooling systems (convection, which depends on the system, inside one room can influence the air flow between the two rooms);
- Air flow rate due to mechanical ventilation (there is an air-inlet in room 2 and an air-outlet connected to a fan in the room 1, the rotation speed of the fan is adjustable);
- The dimensions of the opening (the surface area of the opening can be changed from some cm^2 to about 2 m^2. The position of the opening can be changed as well).

Air speeds in the opening are measured with nine anemometric probes (DANTEC, n. 54R10). These probes are attached to a movable cane (cf. Figure 4).

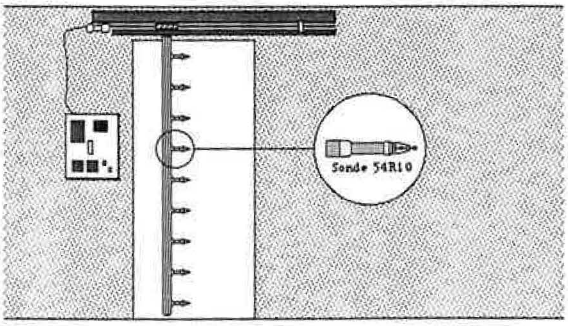

Fig. 4. Movable cane with its nine anemometric probes

Main results

A model to compute the heat transfer due to the buoyancy effect has been validated. This model (relationship Nu=f(Gr, Pr)) uses as characteristic temperature difference the difference between the average temperature of the rooms. At the moment, the range of validity is $1.8\ 10^9 < Gr_D < 2.5\ 10^9$ and $D/H \geq 0.84$. This model is not very well adapted if a heating or cooling system incorporating pulsed air is used. The model is:

$$Nu_D = 0.4\ Gr_D^{0.5}\ Pr$$

By comparison with the previous similar models, the main advantage of this model is that the characteristic difference of temperature is really the difference between the average temperature of the rooms. This is an advantage because in the aeraulic, or thermal compu-

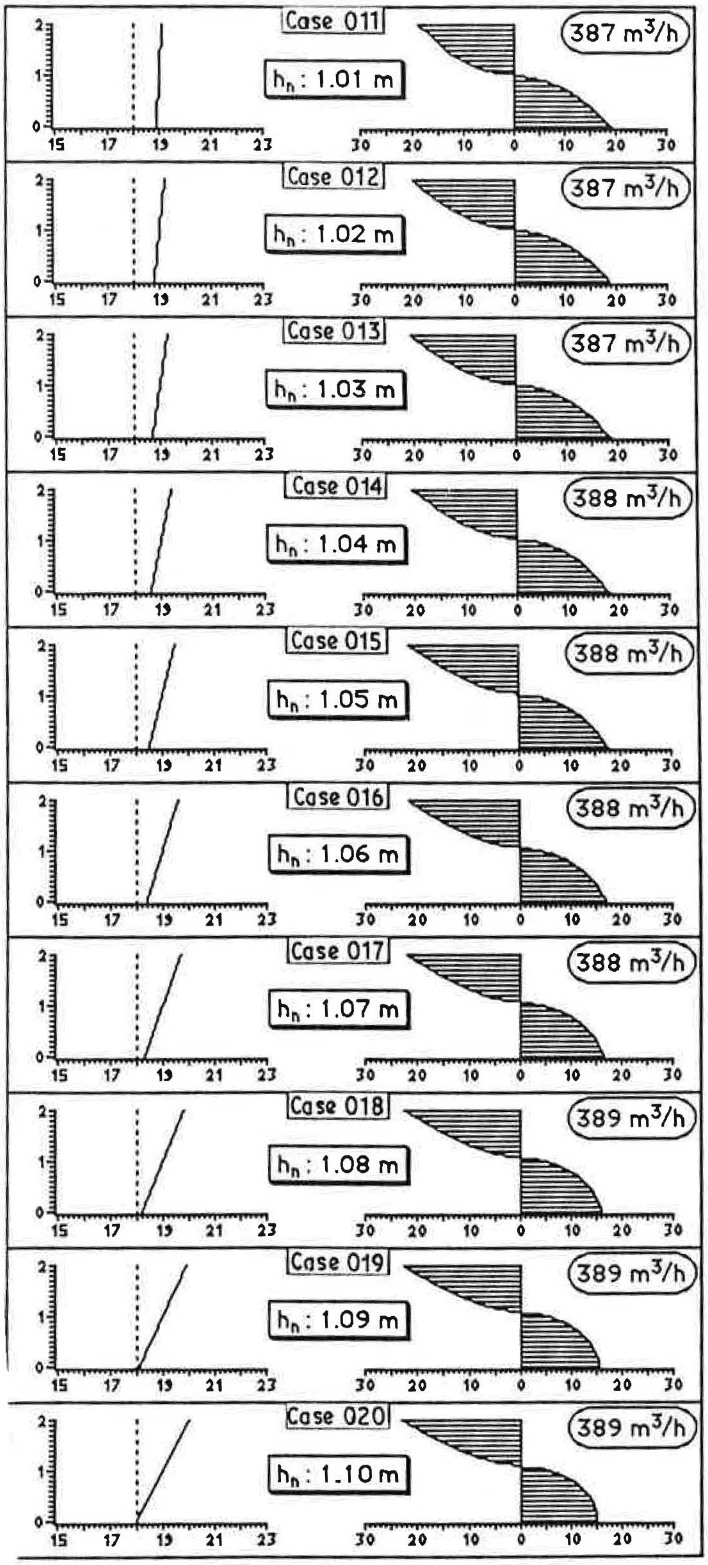

Fig. 5. Computed speed profile in the opening and air flow rate as a function of the temperature profile in room 2

Consider two air-tight rooms connected by a large opening (0.9 m×2.0 m).

The temperature of room 1 is represented by the dotted line, the temperature of the room 2 is represented by the full line (look at left side of the pictures).

In this sequence, the temperature of room 1 is constant, equal to 18 °C. The temperature gradient in room 2 increases gradually. At the beginning (case 011), the gradient is 0.1°/m; at the end (case 020) the gradient in room 2 is 1°/m.

The neutral plane (hn) is over the middle of the opening. The neutral plane goes up when the gradient in room 2 increases.

The air flows do not change a lot although the gradient in room 2 is very different between case 011 and case 020. This happened because the temperature profiles are linear. It would be different if they were not so.

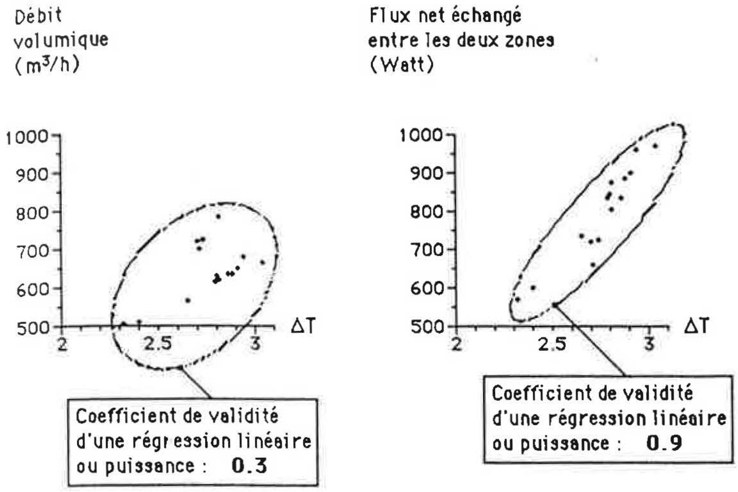

Fig. 6. ***Heat transfers*** **(Φ)** ***and air flows*** **(Q)** ***as a function of the difference between the average temperature of the rooms***

tation codes, the only available temperature is the average temperature of the rooms (for experimental reasons, most of the previous similar models used the difference between the average temperatures of the opposite walls).

In addition to evaluating heat transfer between rooms, the relationship Nu=f(Gr, Pr) can be used very easily to evaluate the air flow rate between two rooms, knowing only the average temperatures of the rooms. But this calculation will give an accurate enough result; if the temperature profiles in the two rooms are almost linear (without leading to a phenomena of multiple neutral plan, cf. Figure 7).

To study the relationship air flow rate = f(profiles of temperature) a C3 class model can be used (this model is described in detail in ref. 7. The C3 model we have developed is able to take into account any temperature profile. If, using the C3 model, it is proved that the temperature profiles have no effect (or a negligible one) on the computation of the air flow rates (for given average temperatures), a C2 model can be used. The computations made with the C3 model have been validated by comparison with the measures made in the DESYS test cell.

For w=0.90 m and D=2.00 m, we have shown that for some temperature air flow rates profiles in the opening do not depend upon the temperature gradient in the rooms (Fig. 5).

On the other hand, if the temperature profiles are of different linear profiles, the air flow rates depend upon the temperature gradients and this is what the measurements made in the DESYS test cell have shown (Fig. 6).

Comparing the two samples in Fig. 6, we notice that the experimental points representing the relationship $\Phi=f(\Delta T)$ are closer together than the points representing the relationship $Q=f(\Delta T)$. For the same difference of average temperatures, the air flows between the two zones can be very different, but the corresponding heat transfer is unchanged. This means that air flows can depend upon the temperature gradients (but, as it has been shown in Figure 5, the dependence can be very slight if the gradient is constant, and if there is only one neutral plane).

In case of double neutral plane

Even if the temperature profiles are linear, a C2 class model cannot be unstable to compute air flow rates. It is, however, as soon as multiple neutral plane appears in the opening.

Let us consider the simple case of a double neutral plane as illustrated in Figure 7.

With this example, it is clear that although the temperature profiles are linear, it is not possible to compute the air flow rates by using a C2 class model. Moreover, to compute the air flow rates with a C3 class model, the model must take into account at least a certain temperature stratification. Such a model has been defined in ref. 7.

Conclusions

The air flows in large openings, due to the buoyancy effect, can reach high values in comparison with the values of the air flows due to air leakage and ventilation. For example, through a 'standard' opening (about 0.9 m×2 m), a difference of temperature 0.1° creates a circulation of air of about 120 m³/h. A difference of 1° in temperature creates an air circulation of about 390 m³/h. The buoyancy effect plays a major role in the diffusion of pollutants.

To model the influence of the buoyancy effect, simplified models (C2 class) can sometimes be used. Such a model has been designed and partially validated. Its application field for the computation of air flows is limited to the case when the temperature profiles in the rooms are almost linear, and there is no multiple neutral plane. If there is a multiple neutral plane (this can happen with very simple temperature profile), the air flow rates can be very important although the average temperature of the rooms are equal (for instance, about 200 m³/h through a 'standard' opening for equal average temperatures (18°C) but with gradients of 1°/m in one room and 2°/m in the other).

If a C2 class model is inapplicable, a C3 model must be used. But, to be very accurate, the C3 model has to take

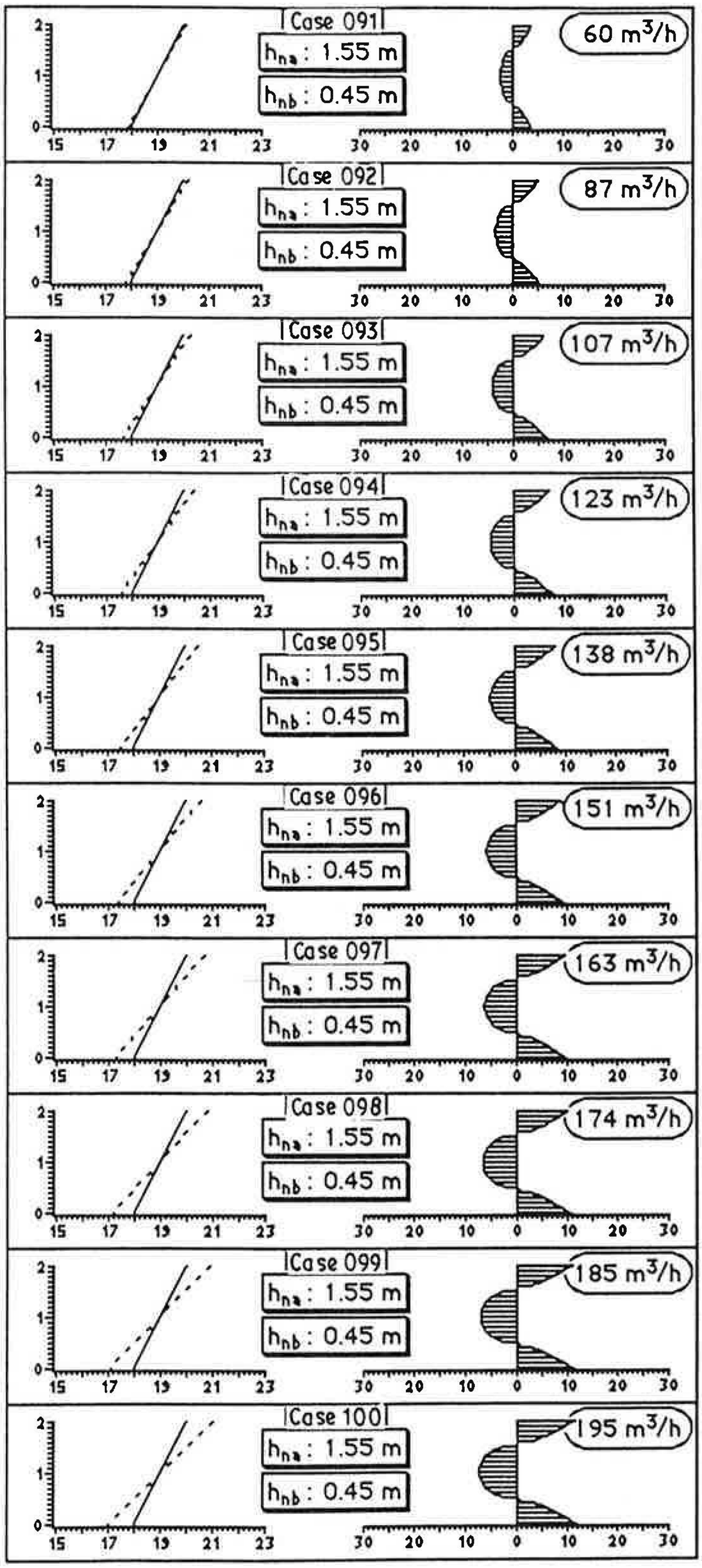

Fig. 7. ***Air exchanges between rooms with a phenomena of double neutral plane***

In this sequence, the temperature of room 2 (full line) does not change (average value 18°C with a vertical gradient of 1°/m).

The average temperature of room 2 is equal to the average temperature of room 1. Moreover, the average temperature of room 1 does not change but the vertical gradient does change (from 1.1°/m in case 091 to 2°/m in case 100).

A double neutral plane appears in the opening. Although the average temperatures are equal, the air flows are not equal to zero. The air flows depend upon the temperature gradient in the two rooms.

into account the vertical temperature gradients in the rooms. This kind of computation is not very complicated if the temperature profiles are known (inputs of the problem) but it becomes complicated if temperature profiles are variables.

In addition, the on-going experimental study would provide some data to validate a model to compute the discharge coefficient of the large openings. Some elements of reflection could be provided about the physical mean of the discharge coefficient and its relevant use.

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