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PAPER 5

MODELLING OF LARGE OPENINGS

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SYNOPSIS.

The subtask 2 of Annex XX (Optimization of Air Flow Patterns Within Buildings) involved a research project called "Air Flows Through Large Openings In Buildings". The scope of this project was to test the range of validity of available algorithms, and where possible to develop new ones. This paper focuses on the new interzonal airflow studies which have been carried out in this frame. The research was based on three test rooms (respectively at the University of Liège, at INSA Lyon and at CSTB Sophia Antipolis) and mainly focused on natural convection ; the aim was to improve the knowledge and the numerical prediction of heat and mass transfer through doorways. This goal was achieved through a joint research effort which was based on the comparison of our experimental results. Moreover, these experimental results have been used to validate a C.F.D (Computational Fluid Dynamics) model developed at Concordia University.

The main result consists of validated models to compute the mass flows in large openings assuming either isothermal air volumes or linear temperature profiles in both rooms ; the discharge coefficient that has been found is about 0.43. Local discharge coefficients have also been determined but this topic needs more studies ; C.F.D models, as those developed at Concordia University, seem well adapted to fulfill this task as long as they are validated.

LIST OF SYMBOLS.

$\dot{m}_h$	Mass flow in the upper part of the opening	(kg/s)
$\dot{m}_c$	Mass flow in the lower part of the opening	(kg/s)
$\dot{m}_{measured}$	Measured mass flow	(kg/s)
$\dot{m}_{computed}$	Computed mass flow	(kg/s)
z_b	Height of the bottom of the opening	(m)
z_n	Height of the neutral plane	(m)
z_t	Height of the top of the opening	(m)
Cd	Discharge coefficient	
W	Width of the opening	(m)
ρ_h	Density of hot air	(kg/m^3)
ρ_c	Density of cold air	(kg/m^3)
ΔP	Pressure difference	(Pa)
g	Acceleration of gravity	(m/s^2)
$V(z)_{measured}$	Measured air velocity	(m/s)
$V(z)_{computed}$	Computed air velocity	(m/s)

1. INTRODUCTION.

Numerous studies have been performed on the subject of "Airflow Through Large Openings" connecting two zones at different temperatures. Literature surveys (Barakat 1985, Sandberg 1989, Vandaele and Wouters 1989) have shown that the developed models, to compute heat and mass transfer through a large opening, generally assume that the flow is one-dimensional and that the interconnected rooms are isothermal ; the only free parameter is the discharge coefficient. The three dimensional nature of the flow and the presence of a vertical temperature gradient are then neglected and the discharge coefficient appears to vary from experiment to experiment (the discharge coefficient reported in the literature varies between 0.3 and 0.8 and it is not clearly understood where the difference comes from).

The scope of subtask 2.1 of Annex XX was to test the range of validity of available algorithms, and where possible to develop new ones. This subtask was coordinated by Dr. van der Maas from LESO-EPFL, Lausanne, Switzerland ; it involves three laboratories in Europe with each a different experimental set-up : the "MINIBât" test cell at INSA Lyon, France, a climatic test cell at University of Liège, Belgium, and the DESYS test cell at CSTB Sophia Antipolis, France. It involves also a laboratory from the Concordia University, Montréal, Canada, which has developed a C.F.D code and wanted to try to validate it by comparison with experimental results.

This paper focuses on the new interzonal airflow studies which have been carried out in this frame. The research was based on the three test rooms above-mentioned and mainly focused on natural convection ; the aim was to improve the knowledge and the numerical prediction of heat and mass transfer through doorways. This goal was achieved through a joint research effort which was based on the comparison and the analysis of the experimental results.

In this paper, we present first the various laboratory set-ups (§ 2), then the typical experimental rough results (measured velocities profiles in the doorways) (§ 3). The experimental results are analyzed in order to validate models based on Bernoulli's equation ; two models have mainly been validated : a model based on the assumption of isothermal air volumes and a model based on the assumption of linear temperature profiles in both rooms (§ 4). An example of the comparison between the Concordia University's C.F.D model with some of our experimental results is detailed in § 5.

2. EXPERIMENTAL SET-UPS.

The three set-ups are described below (see figure 1) ; their main common characteristic is to be real scale experiments. The test rooms at University of Liège and at INSA Lyon are climatic test rooms ; the CSTB's set-up is in natural environment.

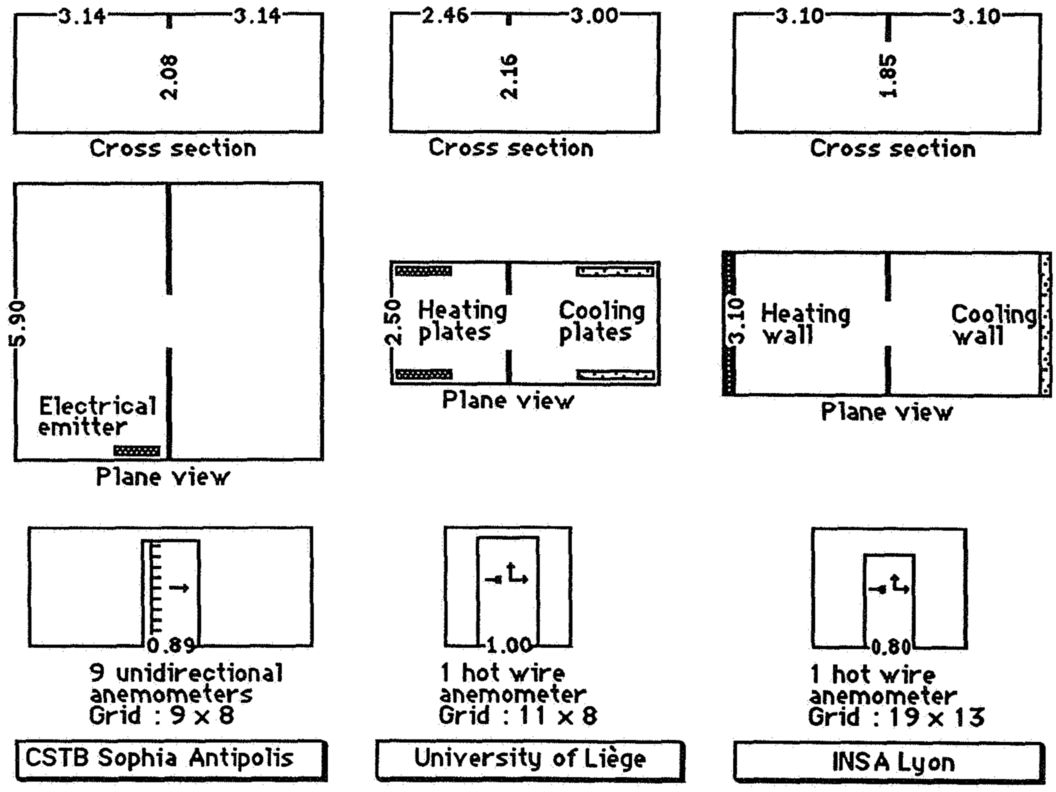

Fig. 1 : The three laboratory set-ups.

The CSTB's test cell is called the DESYS test cell ; the DESYS test cell is a 86 m^2 house built with industrial envelop components and of which the detailed thermal characteristics have been carefully measured (Pelletret 1987). The test cell area is partitioned in three main zones ; the partitions between the zones are very well insulated ; one of these zones is divided into two symmetric rooms connected with a large opening.

The experimental studies, carried out at University of Liege, started with a set of experiments in a calorimetric chamber (Lebrun and Liebecq 1987) ; then a new set of experiments has been performed to better understand the influence of the width of the door on the heat and mass transfer (Baranowsky 1989). The calorimetric chamber is bounded by a double envelope through which the air temperature is controlled. In the hot zone, heating films were mounted to raise the air temperature as well as cooling plates were placed in the cold zone to cool it.

The basis of the experimental facility at INSA Lyon is the MINIBât test cell (Allard 1987) built in a controlled environment (each of the two zone is bounded on five sides by air volumes controlled at a constant temperature, the sixth side is submitted to controlled climatic conditions ; a solar simulator and electrical heating films located along the surfaces on the internal side of the walls of the two rooms complete the set-up and enable to generate a wide range of boundary conditions.

3. VELOCITY PROFILES.

In the CSTB's test cell, about hundred experiments with various heights and positions of the opening have been performed. Some experiments have been made with none of the rooms heated or one heated with an electrical emitter but not the other one or both heated or one heated and the other one cooled with a cooling air system ; but, in general, the experiments were performed with only one room heated as shown in figure 1 ; twenty experiments of this kind have been made with an opening's height of 2.08 m and fifteen experiments with an opening's height of 1.56 m. Figure 2 shows an example of a velocity profile measured with these typical experimental conditions (one room heated but not the other one) and an opening's height of 2.08 m.

In the test cell of the University of Liège, five experiments with an opening's height of 2.16 m have been performed. These experiments aimed to approximate the experimental conditions to fit as well as possible with the hypothesis of the mathematical model (which is based on Bernoulli's equation) : with symmetrical heating and cooling plates, located as shown in figure 1, it was possible to minimize the effect of air movements in the rooms due to the thermal devices. The five measured profiles are very similar and the profile shown in figure 2 is really a typical one.

In the INSA's test cell five experiments with an opening's height of 1.85 m have been performed including two experiments with a cooling wall and a heating wall, two experiments with a single cold active surface and one experiment with a single hot active surface. With two active walls, the neutral plane is close to the mid height of the opening ; this fits very well with the symmetric boundary conditions.The other profile shown on figure 2 was measured when only the cooling wall was active ; this boundary condition leads to a different airflow pattern within the cooled room and the displacement of the neutral plane (which, in this case, is below the mid height of the opening) is only the result of this fact.

Our goal is to facilitate the comparison between the typical velocity profiles measured in the three test cells. To reach this goal, the velocity profiles are plotted in the same way : the velocity profiles are plotted as a function of the ration z/H where H is the opening's height ; then, for all the experiments, the ration z/H varies between 0 and 1 (see figure 2). The velocity profiles are specific for each experimental set-up ; the various heating or cooling devices explain why the shapes are different :

- in the CSTB's experiments, the neutral plane is approximately located at the two thirds of the opening's height ; this is because the electrical emitter creates a specific air movement in the heated room and then a typical vertical temperature profile with a 2 K/m gradient ;

- in the Liège's experiments, the neutral plane is sightly above the mid height of the opening ; this results fits well with the INSA's experiments when the opposite walls are active ;

- in the INSA's experiments with only the cooling wall active the velocity profile is asymmetric and the neutral plane is below the mid height of the opening ; this result is symmetrical of the one of CSTB's experiments and strengthens previous experiments performed in the Liège's test cell with non symmetrical devices : the cooling plates were close to the opening and faced it, then the neutral plane was greatly below the mid height of the opening.

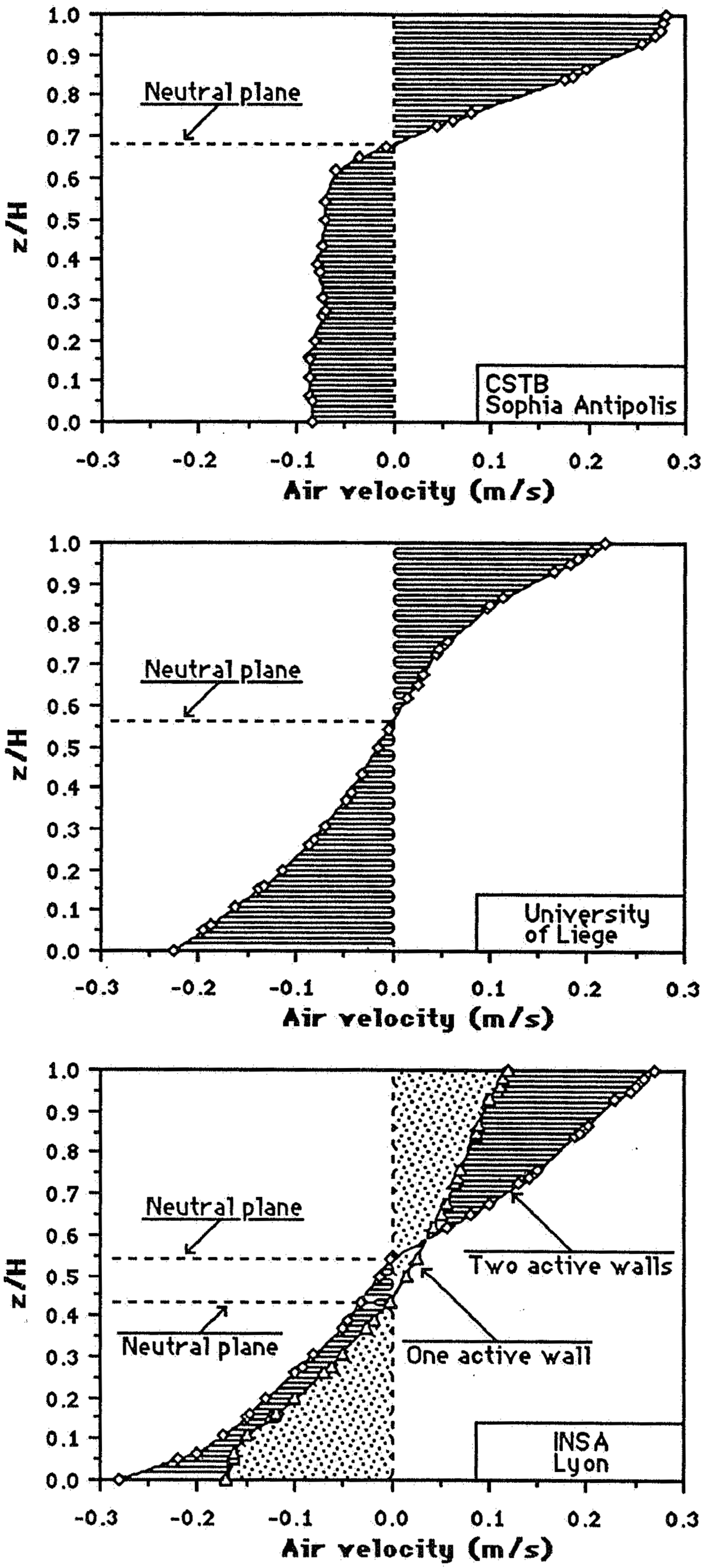

Fig. 2 : Typical velocity profiles (the plot symbols do not indicate the points where the velocities were measured but only the points were the experimental results have been interpolated in order to plot them in the same way).

4. MASS TRANSFER MODELLING.

Both CSTB and INSA calculated the experimental mass flows by integration of the measured velocity profiles. University of Liège calculated the experimental mass flows both integrating the measured velocity profiles and computing it from the heat balance of the test rooms but concluded that to compute them with a heat balance was more accurate in their case.

4.1. Assumption of isothermal air volumes.

With this assumption of isothermal, the theoretical mass flows are computed as :

$$\dot{m}_h = Cd\ (2/3)\ W\ (2\ \rho_h)^{0.5}\ \Delta P(z_t)^{3/2}\ /\ [g\ (\rho_c - \rho_h)] \qquad \text{(Eq. 1)}$$

$$\dot{m}_c = Cd\ (2/3)\ W\ (2\ \rho_b)^{0.5}\ \Delta P(z_b)^{3/2}\ /\ [g\ (\rho_c - \rho_h)] \qquad \text{(Eq. 2)}$$

In natural convection, $\dot{m}_h = \dot{m}_c$. Equations 1 and 2 are equivalent to equations 3 and 4 when replacing the pressure differences by their expressions as a function of the differences between the heights at the top and at the bottom of the opening and the neutral plane :

$$\dot{m}_h = Cd\ (2/3)\ W\ [2\ \rho_h\ g\ (\rho_c - \rho_h)]^{0.5}\ (z_t - z_n)^{3/2} \qquad \text{(Eq. 3)}$$

$$\dot{m}_c = Cd\ (2/3)\ W\ [2\ \rho_b\ g\ (\rho_c - \rho_h)]^{0.5}\ (z_n - z_b)^{3/2} \qquad \text{(Eq. 4)}$$

with : $z_n = [\rho_h^{1/3}\ z_t + \rho_c^{1/3}\ z_b]\ /\ [\rho_h^{1/3} + \rho_c^{1/3}]$ (Eq. 5)

The Cd coefficient is computed with : $Cd = \dot{m}_{measured} / \dot{m}_{computed}$

To compare our results, the Cd coefficients are plotted versus the difference between the rooms average temperatures but for the INSA's experiments for which it is computed as the difference between the two central air temperatures measured in each room (see Figure 3).

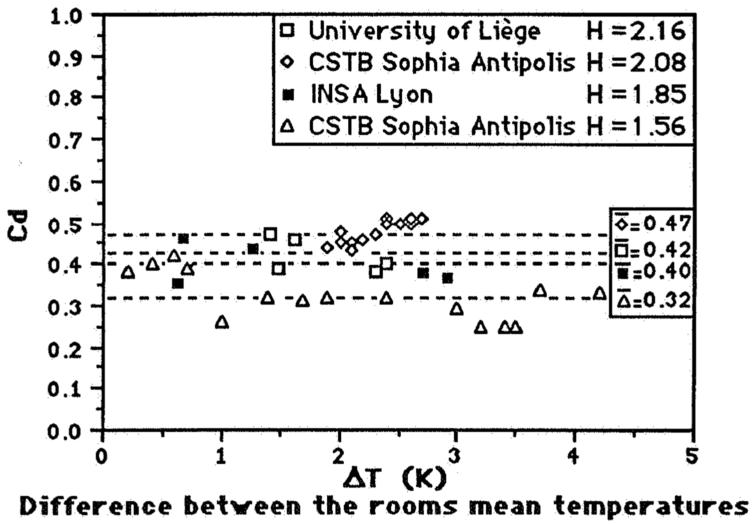

Fig. 3 : Discharge coefficients with an assumption of isothermal air volumes.

As shown on figure 3, the results obtained from the three experiments fit quite well :

- the discharge coefficient decreases with the opening's height
- the Cd mean value computed from the CSTB's experiments is slightly higher than the Cd mean value computed from the Liège's experiments though the openings' heights are similar (2.08 m and 2.16 m) ; of course this can be explained because of problems of uncertainty in the measurements but, presumably, this is also because, in the CSTB's set-up, the air movement in the heated zone (due to the electrical emitter) influences the air movement in the opening. And this assertion is strengthened by the INSA's results : for the asymmetric experiments (with only a cooled wall), the Cd coefficient is about 0.45 (close to the mean value of the CSTB's experiments), this value is 20% higher than the Cd mean value computed with symmetric boundary conditions.

4.2. Assumption of linear temperature profiles.

Similar computations to determine Cd values have been made assuming that the temperature profiles in each room were linear. The new Cd values are very close to the Cd values computed with an assumption of isothermal air volumes for the computation of the theoretical mass flows with an assumption of linear temperature profiles give quite the same results than with an assumption of isothermal air volumes. When there are differences they can be explained because, with a linear approximation of the real temperature profile, the mean value of the temperature can be different from the mean value directly computed from the rough results.

4.3. Local discharge coefficients.

Taking into account the measured temperature profiles in each room and using a model based on Bernoulli's equation, it is possible to compute a theoretical velocity profile in the opening and to compare it to the measured velocity profile ; then one can define local discharge coefficients as : $Cd(z) = V(z)_{measured} / V(z)_{computed}$.

Figure 4 shows the typical Cd(z) profiles found with the INSA's experiments and with the CSTB's experiments ; each profile depends on the boundary conditions. On these figures, we plotted only three Cd(z) profiles for the CSTB's experiments but the seventeen others are very similar to these threes. For the INSA's experiments, one profile is obtained in a symmetric case (two active walls), for the other comparable experiment which has been made at INSA the Cd(z) profile is very close to the one displayed on figure 4 ; in this case, it is very interesting to note how much the Cd(z) profile is symmetric. The other plotted Cd(z) profile is for a single cold active wall, the Cd(z) computed for the two other experiments made with only one active wall are quite different from the example plotted on figure 4 ; in this case, the discrepancy is greater than with the symmetrical cases or with the CSTB's cases.

Nevertheless, these specific studies have demonstrated that it was possible to define Cd(z) profiles, adapted to a specific configuration, and then the models using these Cd(z) profiles enable an accurate calculation of the mass flows and the velocity profiles (including, of course, the height of the neutral plane).

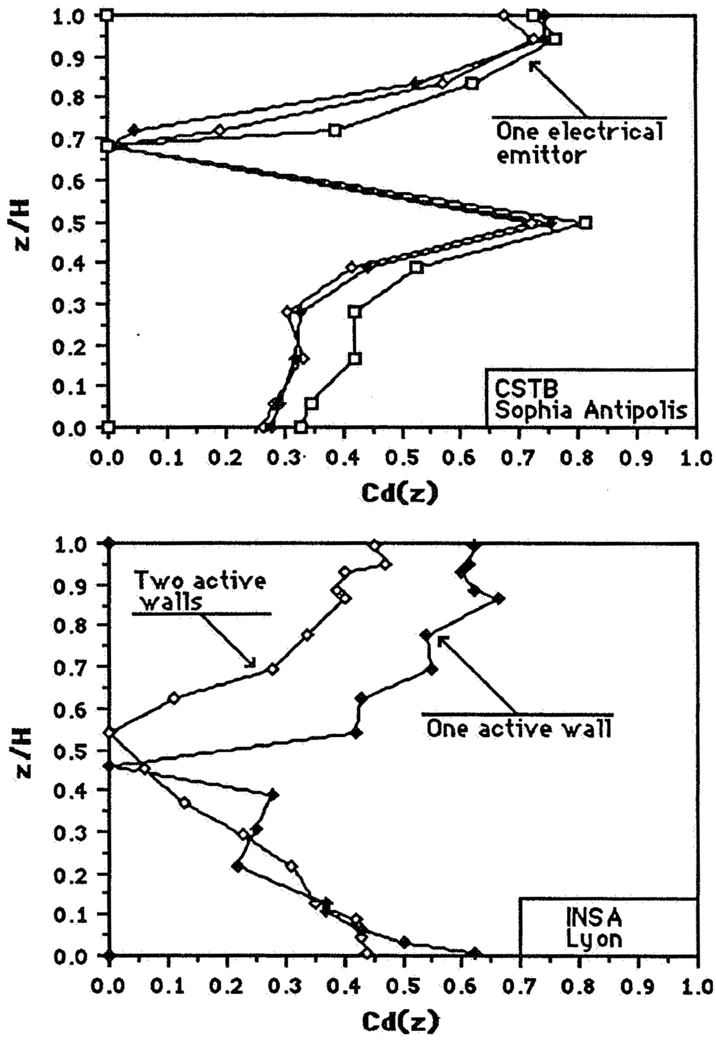

Fig. 4 : Local discharge coefficients.

5. COMPARISON WITH A COMPUTATIONAL FLUID DYNAMICS CODE.

5.1. Brief description of "Concordia" code.

This code employs a finite-difference method and the K-ε two-equation model of turbulence to obtain the approximate solution of governing equations for the three-dimensional turbulent flow in rectangular enclosures. At the region near a solid surface, where the viscosity effects become important, the wall function method is adopted to modify the K-ε two-equation model.

More details are given in the final report of Annex XX and in "Haghighat 1989".

5.2. Validation.

Some comparisons with experimental results from Liège or from INSA have been made. As an example of these comparisons, the measured and the computed velocity profiles are plotted in figure 5 :

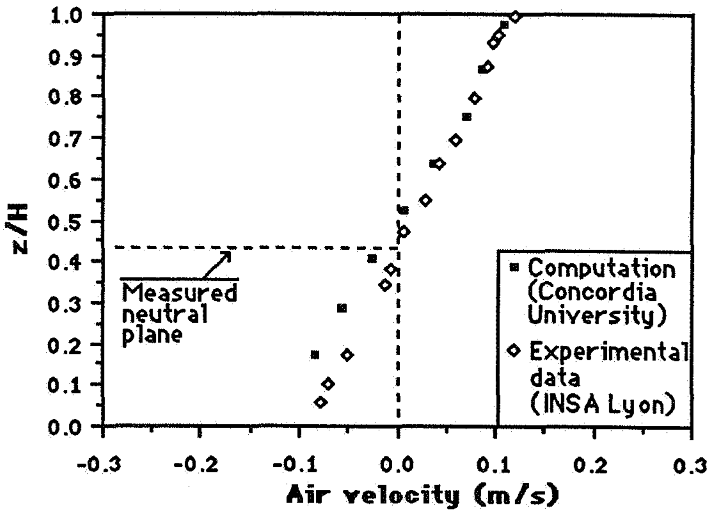

Fig. 5 : Velocity distribution at the center of door opening in comparison with measurements.

Discrepancy is observed in the low region of the door opening. This can be explained because, in this experiment, there was a 0.08 m step on the floor of the door opening and this step is neglected in the computation with the "Concordia" code because it is too small to be considered in a uniform mesh system adopted. In the east part of the door opening, the predicted velocity distribution is in very good agreement with experimental data.

6. CONCLUSIONS.

The joint research effort led to validate models based on the Bernoulli's equation assuming either isothermal air volumes or linear temperature profiles. The discharge coefficients in both case are quite similar ; Cd varies from 0.37 in case of pure natural convection to 0.51 if a (cold or hot) plume exists. An average value of 0.45 seems adequate to correctly model a large variety of configurations such as non heated rooms, or one room heated not the other one or both heated and for an opening's height higher than 2 m. The discharge coefficient decreases with the opening's height ; a very simple relation as $Cd = 0.21\ H$ fits well our experimental results in the range $H \in [1.5\ m ; 2\ m]$.

The vertical Cd distribution seems to be strongly related with the boundary conditions. Further studies are necessary to define average Cd distribution corresponding to typical boundary conditions or real flow patterns observed in buildings in case of heating or air conditioning.

More experiments are obviously necessary although experiments are expensive, heavy to carry out , time consuming and , furthermore, in most cases, it is hard to change significantly the design parameters of the experimental set-ups ; that is why airflow modelling using computational fluid dynamics could be useful as long as the code is validated ; we have began to make progress in that direction trying to validate the "Concordia" code ; this task is not yet achieved but this is a promising way for general parametric studies.

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