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NATURAL VENTILATION STUDIES WITHIN THE FRAME OF PASCOOL PROJECT

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ABSTRACT

Natural ventilation studies were carried out within the frame of PASCOOL EC Research Project. Research on this topic included experimental and modeling work aiming to fill the existing gaps in our knowledge of indoor air conditions in naturally ventilated buildings. Experiments were carried out in full scale and test cell facilities during the summer period. Single sided and cross ventilation as well as air flow through large internal openings were the basic topics that were studied. Existing models were validated and new ones were developed. A new computational tool for ventilation prediction was developed, based on the airflow network modeling. An intermediate approach, between network and CFD was proposed to take into account the impact of non-homogeneity on the indoor air motion.

1. INTRODUCTION

Natural ventilation is a very important strategy for the reduction of the cooling load and the improvement of indoor comfort, especially in the Mediterranean countries, where air conditioning systems do not represent a realistic alternative. Prediction of the ventilation rates for design assessment purposes is a complex problem and various methods and models have been proposed. However, very few experimental studies are available and validation of the existing models is limited. Natural ventilation studies were carried out in the framework of PASCOOL programme, which was partly financed by the European Commission, DG XII for Research.

Extensive experimental activities were carried out in full scale buildings and test cell facilities during summertime. The purpose of these experiments was to study three different aspects of natural ventilation:

• single sided ventilation • cross ventilation and • air flow through large internal openings

Tracer gas experimental techniques were used in order to derive natural ventilation airflow rates and some limitations in their use were identified. Alternative methods to measure air flows in buildings were proposed. A new algorithm was developed for the computation of experimental airflow rates through large internal openings, when the tracer gas decay technique is used.

Data from the experimental programme were used in order to validate existing models and develop new ones. Further research was undertaken in order to fill the gaps that were identified. Knowledge acquired from experimental and modeling activities was incorporated in a new computational tool for the prediction of natural ventilation rates. Finally, an intermediate approach, between network and CFD, was proposed in order to take into account the impact of non-homogeneity on the indoor air motion.

This paper presents the natural ventilation research activities undertaken within PASCOOL as well as a brief presentation of their outcome.

2. SINGLE SIDED VENTILATION

Single sided ventilation was studied experimentally in full scale buildings and in test cell facilities. Experiments in full scale buildings were carried out in Athens (Greece) and in Madrid (Spain). The test cells are fully equipped, two room outdoor facilities for thermal and solar monitoring. The ones located in Athens and BBRI (Belgium) had been developed within the frame of PASSYS, EC Research Project [1]. Test cell experiments were also carried out in Porto (Portugal). Data from a total of 76 different configurations were gathered to compose the biggest and most important existing database on single sided ventilation. All the experiments were carried out using the tracer gas decay technique, with the exception of those in BBRI, where the constant injection technique was followed. N_2O, SF_6 and CO_2 were used as tracer gases. Two different approaches were used in order to derive the air flow rates in the case of the Belgian experiments: the tracer gas and the heat balance approach. The latter was found to provide a less fluctuating and more accurate flow [2].

Simplified methods were used in order to calculate the air flow rate for some of the experiments. The following simplified methods that were used:

- de Gids and Phaff [3]
- BS [4]
- University of Athens method [5]

Comparison of predicted and measured air flow rates has shown that, in general, simplified methods do not predict the air flow accurately, especially in the cases where the wind forces are dominant. The main reason for this is the fact that the impact of the wind is not correctly taken into account in combination with the flow due to temperature difference.

Five air flow network models were used in order to simulate the experiments that were carried out in Athens:

- COMIS [6]
- BREEZE [7]
- AIRNET [8]
- ESP [9]
- PASSPORT-AIR [10]

All tools gave similar predictions for the air flow rates. Further analysis using Warren plots has proved that these experiments were inertia dominated. As network modeling practically disregards the wind effect in the case of single sided ventilation simulation, a disagreement was observed between predicted and measured air flow rates, the correlation coefficient between the two sets of data never exceeding 0.4. To mend for this inaccuracy, a new model was developed and validated: the CF model.

According to the model, the network model predictions are multiplied by a "correction factor", CF, to yield more accurate air flow rates:

$$Q_{predicted} = CF x Q_{network(Cd=1)} \qquad (1)$$

$$CF = 0.08(Gr / Re_D^2)^{-0.38} \qquad (2)$$

where:

$Q_{network(Cd=1)}$: air flow rate predicted by a network model, taking the discharge coefficient equal to unity (Cd=1)

Re_D : Reynolds number (=UD/ν)

Gr : Grashof number (=g ΔT H^3 / T ν^2)

U : wind speed at 10 m (m/s)

ΔT : indoor-outdoor temperature difference (^oK)

T : mean indoor-outdoor temperature (^oK)

ν : air viscosity (m^2/s)

H : vertical size of the opening (m)

D : room "depth" (m), defined as the distance from the wall where the opening(s) is (are) to the wall opposite to it in the studied zone.

If the resulting value from eqn. (2) is less than 0.6, the CF=0.6.

The above described model has been validated with success using data from other single sided ventilation experiments. It was found to improve the accuracy of network models, especially in the cases of important wind speed and small temperature difference. Validation has been done for wind speed ranging from 2 to 10 m/s, temperature difference from 0.5-8 ^oC and room depth varying from 3-7 m.

Based on the BBRI PASSYS Test Cell experiments a "multi-term" model was developed:

$$Q = \sqrt{Q_{network}^2(Cd, \Delta T...) + (\alpha AV)^2 + (\beta A)^2}\ , \ m^3/s \qquad (3)$$

where:

$Q_{network}$: air flow rate calculated by network models using Cd=0.66

A : opening surface (m2)

V : wind speed at 10m (m/s)

α, β : wind and turbulent term parameters related to the investigated environment

The multi-term model was derived from a particular experimental condition and this fact restricts the limits of its applicability.

3. CROSS VENTILATION

An extensive literature survey on reduced order models predicting air flow in naturally ventilated buildings revealed that the limits of applicability of most of the existing models are not well defined; therefore, it is very difficult to apply them with confidence.

Three different kinds of experiments have been carried out in Greece, Spain, Belgium and Switzerland, following the decay and the constant injection technique. The Aynsley[11] model was used in order to derive the discharge coefficient for a single zone cross ventilation configuration in Athens. The discharge coefficient was found equal to 0.2 and did not seem to be influenced by the indoor-outdoor temperature difference. In a two-zone cross ventilation experiment held in Athens, the mixing of the tracer gas in the room space was found to be very good and no stratification was observed. This was not in agreement with Murakami's report [12] that an inertial flow would be expected in the room. This was verified in the case of the Mendillori apartment in Spain, where cross ventilation experiments were carried out using constant injection and decay techniques. As the air tightness of the studied space was not good, the decay technique proved to be more appropriate. Analysis of the results showed the existence of a virtual stream tube in the center of the room, which prevented the homogenous mixing of the gas. Cross ventilation experiments were also carried out in a test cell facility, using two tracer gases, namely: SF_6 and N_2O. Air velocities measured near the exterior opening of the test cell were correlated to wind speed data at 18m according to Givonni's model [13]:

$$V_i = 0.45\,(1-\exp(-3.84X))V_z,\quad X=4 \tag{4}$$

The main result of the study in this topic was that the hypothesis of homogeneity which is adopted by all existing models is no longer valid. The absence of homogeneity imposes the necessity of concentration field measurement, which, at the moment, is restrained by the characteristics of existing gas analyzers. Further research in this topic of ventilation will require the design of experiments and the development of new measurement techniques for specific experimental facilities permitting a rigorous control of the boundary conditions.

4. LARGE INTERNAL OPENINGS

Research activities in this topic focused on two goals:

- to check whether the global value of discharge coefficient equal to 0.4 is valid in the case of a real scale building. This value had been derived from experiments in Liege and in Minibat [14], characterized by a strong stratification and an important boundary layer flow.
- to check whether the air flow resistances formed by open doors in series can be predicted by a simple Bernoulli model and usual discharge coefficients.

For the investigation of the discharge coefficient value, the air flow through a doorway was experimentally studied in a controlled climatic environment, the Optibat test cell in Lyon as well as in a PASSYS test cell in Athens. Two new software tools developed within PASCOOL were used: EXAC 1.0 [15] for the calculation of the experimental and PASSPORT-AIR [10] for the calculation of the theoretical air flow rates. The discharge coefficient was calculated by the ratio:

$$\mathrm{Cd} = \frac{\text{Experimental air flow rate}}{\text{Theoretical air flow rate (computed by PASSPORT-AIR for Cd=1)}} \qquad (5)$$

The discharge coefficient was found to vary between 0.47±0.06 and 0.67±0.09 (mean: 0.59±0.08), when the temperature difference varied from 1 to 3.7 $^{\mathrm{o}}$C. The following correlation was derived:

$$C_d = 0.563 + 4.11\frac{\Delta T}{T} \qquad (6)$$

Thus the derived value of the discharge coefficient was different from the one proposed by IEA/ECB Annex 20. However, it was in very good agreement with the global Cd value of 0.6 proposed by the Canadian Group of Wilson [16].

Air flow through internal openings in series was studied in the LESO building in Lausanne, using the constant injection technique under conditions of buoyancy dominated flow. The Bernoulli model was found to predict the air flow rates with sufficient accuracy. The discharge coefficient is defined as the product of the velocity and the contraction coefficients, C_v and C_c respectively. In this series of experiments a value of C_v=0.7 was derived from velocity measurements. Smoke visualization has shown that the contraction coefficient, C_c, has a value greater than 0.6 for low velocities in large openings. In the case of cross ventilation with several openings in series, C_v approaches unity, especially in the case where the distance between the openings is smaller than 10 times the opening size. During these experiments, the flow was underestimated when a value of C_d=0.6 was used for each of the openings in series.

5. AIR FLOW PREDICTION

Two approaches have been studied within the frame of PASCOOL regarding air flow modeling : Network and Zonal modeling. A new air flow computational tool was developed based on the network concept: PASSPORT-AIR. Research activities on the second approach lead to the developments of a primary zonal model: a Stratification Predictive Model.

5.1 PASSPORT-AIR : A multizone air flow model

This computational tool, based on the principles of network modeling, calculates the air flow rates through building openings, such as windows, doors and cracks, based on a power-law formula. According to the concept of the network approach each zone is represented by a pressure node. Boundary nodes of known pressure are also used in order to represent the outdoor environment. The unknown pressures at the interior nodes of the network are derived from the solution of a non-linear system of equations, which is formed from the requirement of mass balance at every node:

$$\sum_{j=1}^{m} \rho Q_{ij} = 0 \qquad (7)$$

where m is the number of zones that are adjacent in the flow direction. An iterative Newton-Raphson method is used in order to solve the system.

PASSPORT-AIR was validated using data from the experiments carried out in PASCOOL. Table 1 summarizes the predicted and measured air flow rates for the experiments carried out in LESO under conditions of buoyancy driven flow. As shown, there is a good agreement between the two sets of data.

LESO building	MEASURED (kg/s)		PREDICTED (kg/s)	
Experiment No	INFLOW	OUTFLOW	INFLOW	OUTFLOW
1	2.03	1.90	1.91	1.92
2	1.10	1.16	1.07	1.07
3	1.39	1.41	1.09	1.09
4	1.00	1.16	0.91	0.92
5	1.01	1.13	0.82	0.83
6	1.64	1.76	1.66	1.68

Table 1: Measured and predicted air flow rates during cross ventilation buoyancy dominated experiments.

The CF model which was developed for single sided ventilation (section 2) was incorporated in PASSPORT-AIR to improve its accuracy in predicting the air flow rate in this mode of ventilation.

5.2 Zonal Modeling for natural ventilation

This modeling approach is an intermediate step between network and CFD modeling. Pressure network models calculate inter-zone air flow rates through cracks and large openings but they do not predict indoor air patterns. Such a prediction is very important when investigating the impact of ventilation on thermal comfort and indoor air quality.

Like CFD modeling, zonal modeling is based on a macroscopic division of the enclosures in subzones. The difference between the two approaches lies in the size of the control volumes, which are larger in the case of zonal modeling, using a typical size in the order of one meter. In each of the subvolumes that are created the conservation equations are formulated, namely:

- The total mass balance
- The enthalpy balance
- The momentum balance along each of the three space coordinates

The unknowns of the problems are:

- The normal heat fluxes (or velocities) on each boundary between the suibvolumes
- The static pressure and temperature in each subvolume

This modeling approach is a very promising one, yet further research effort is required in its computational translation for the model to reach a safe convergence to a unique solution.

6. CONCLUSIONS

A large research effort has covered a wide range of aspects in the field of natural ventilation. Practical answers have been given, following the goal of producing new design methods or empirical knowledge suitable to design purposes. Results and experience gained from the PASCOOL research activities lead to perspectives for future work in both the experimental and the theoretical level. There is an important lack of knowledge, equipment and facilities in order to characterize a non homogenous indoor environment and especially the air flow patterns in naturally ventilated buildings. The intermediate approach of zonal modeling proves to be a promising way to fill the gap between the well mixed hypothesis and the CFD approaches. However, much more effort is required in order to transform the research models developed so far into efficient tools for designers or architects.

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