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MEASUREMENT AND CFD MODELING OF AIRFLOW THROUGH STAIRWELLS

A.A.Peppes , M. Santamouris and D.N.Asimakopoulos

Department of Physics, Division of Applied Physics,
University of Athens, Building PHYS-V, GR-BES
GR - 157 84, Athens, Greece

ABSTRACT

The present paper deals with one of the most important mechanisms of inter-zone mass and energy transfer, namely the buoyancy-driven flows through stairwells that connect the floors of buildings. To further investigate these phenomena, experimental as well as theoretical studies have been carried out. A series of experiments have been performed in order to study the airflow through a typical stairwell that connects the two individual zones of a two-storey house. Airflow rates between the two zones were measured using a single tracer gas decay technique. The analysis of results provided relations which can predict the volumetric flow rate as a function of the interzonal average temperature difference between the two floors. Simulations of these experiments were carried out , using validated CFD algorithms. Airflow rates estimated by these simulations showed good agreement with experimental values despite the difficulties related to the applicability of CFD to model the buoyancy driven flows. Finally the paper discusses the airflow patterns through the stairwell.

KEYWORDS

Buoyancy-driven airflow, stairwell, tracer gas techniques, volumetric flow rate, Computational Fluid Dynamics, turbulence model, simulations.

INTRODUCTION

In recent years there has been an increased interest in the study of airflow through large internal openings. This issue is of great importance due to its implication on energy saving, adequate ventilation, thermal comfort, pollutant transfer and dispersion of smoke in the interior of buildings. However, little work has been done on the airflow through horizontal openings, such as ventilation shafts and stairwells. Indeed, very few authors have studied these phenomena and very few systematic experimental data are available in the literature.

A number of studies have been reported. Brown (1962) has investigated air flow through small square openings in horizontal partitions. Reynolds (1986) and Zohrabian et al (1989) have conducted experiments in a reduced scale model of a typical stairwell. Reynolds et al (1988), have developed a model for buoyancy-driven flow in a stairwell. Riffat (1989) has studied the energy and mass transfer through a staircase in a two-floor house. Other laboratory experiments were carried out by Klobut and Siren (1994), to explore the influence of several parameters on combined forced and density-driven air flows through large openings in a horizontal partition. In other studies Zohrabian et al (1989) and Riffat et al (1994) used CFD modeling and compared predictions with experimental data.

In real buildings, buoyancy-driven flows occurring in stairwells that connect the storeys of buildings are caused by density differences due to temperature differences. This is considered as the most common process of air movement through horizontal openings, encountered in the interior of buildings. Tracer gas measurement techniques and recent research in CFD permit the analysis of these airflow phenomena by conducting measurements and applying extensive modeling. The purpose of this study is to expand the existing knowledge on these physical phenomena and to compare the CFD predictions and measurements and consequently to provide foundations for improving the existing predictive procedures.

EXPERIMENTAL PROCEDURE AND INSTRUMENTATION

A series of experiments have been performed in a two-storey building , in order to study the buoyancy-driven airflow through a typical stairwell that connects the two zones. The stairwell extends to a height of 6.3 m, while the lower and upper zone have an effective volume of 29.1 m^3 and 35.8 m^3 , respectively.
Since the geometry is rather complex, figures can describe the building in a more effective way. Figure 1, shows a schematic diagram of this specific experimental building with the main dimensions and the locations of the instruments.

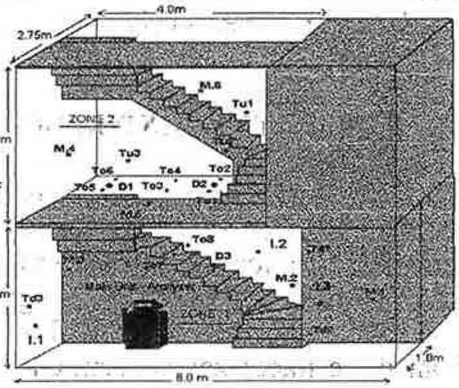

Figure 1: Schematic diagram of the stairwell and instrumentation.
(T : temperature sensor, D : air velocity sensor,
M: measuring point and I : injection point).

The entrance door, the doors connecting the stairwell with the apartments located in the two floors and the top windows were kept closed and sealed during all the experiments. Some small openings and cracks were also sealed in order to reduce the infiltration as much as possible. The airflow rate between the two zones is mainly determined by the size and geometry of the opening connecting the two floors. This horizontal opening is defined by the stairwell geometry. Furthermore, an additional obstacle was placed suitably across this opening, decreasing its size. Under this modified configuration, additional experiments were performed in order to study this dependence. Hereafter, the experiments characterized by the original configuration, will be referred as runs with opening A, while the others will be referred as runs with opening B. Opening A has dimensions of 1.5m by 2.7m while opening B has dimensions of 1.5m by 2.15 m. The airflow rate between the two zones is also affected by the temperature difference of these zones. The temperature difference between the zones was defined as the difference of average zone temperatures. In order to investigate this dependence, the lower zone was heated at various temperatures. This was done by using thermostatically controlled heaters.

A single tracer gas technique -using N_2O- was adopted in order to estimate the airflow between the two storeys. The concentration of gas was measured using an infrared gas analyzer (accuracy:± 1%). At the beginning of each experiment the opening between the two floors was closed by a PVC sheet and every gap between this sheet and the adjacent surfaces was sealed. This prevented heat transfer and tracer gas exchange prior to starting each experiment. Tracer gas was released in the lower floor (zone 1), where it was mixed with air. This was accelerated by using small fans near the injection points of gas. After a uniform concentration had been achieved in zone 1, the PVC sheet was removed and the evolution of tracer gas concentration in both zones, was monitored. Some tracer gas was carried into the second floor (zone 2) and some returned back to the first floor (zone 1). Applying the tracer material balances in each zone and with the inclusion of continuity, we resulted in a series of equations (Riffat (1989)). These equations are valid, provided that a steady state exists and that the concentration of tracer gas in the ambient air is negligible. This system of volumetric-balance equations can be solved using the theoretical technique based on the Sinden (1978) method. A similar method was adopted by Afonso and Maldonado (1986). According to this method, a multizone system may be represented by a series of cells of known and constant volume that are all connected to a cell of infinitely large volume (outside). Equations were integrated using Simpson's rule and the final system was solved numerically by Gauss elimination.

The thermal performance of the stairwell was constantly monitored. The air temperature was monitored by thirteen sensors (accuracy: ± 0.2 ° C) which had already been calibrated (Fig. 1). Surface temperatures on almost all the internal surfaces were measured by an infrared thermometer (accuracy: ± 0.1%). Air velocity measurements were also provided by three air velocity sensors (accuracy:± 0.01 m/sec ± 5%) located in three specific points of the stairwell for all the experiments (Fig. 1).

MEASUREMENTS, CFD SIMULATION AND RESULTS

Eleven experiments were carried out in the building described above, under various temperature differences between the two zones. In these experiments the lower floor was heated to various temperatures for a long time before the beginning of monitoring so as to reach thermal equilibrium. Figure 2a shows the tracer gas concentration in zones 1 and 2 against time during the second experiment. The airflow volumetric rates between the two zones were estimated from these tracer gas concentration data using the method described above. Since infiltration and exfiltration of air ((Q_{01}-Q_{10}) and (Q_{02}-Q_{20})), due to the temperature difference between the inside and outside of the building and the wind speed can affect the interzonal airflow, the induced flow was subtracted from the total airflow between the two floors.The estimated volumetric flow rates between the zones and the average temperature difference between them for the duration of each run are given in Table1.

Table 1

Experiment	Configuration	Average Temperature Difference between zones 1 and 2 (°C)	Volumetric flow rate between zones 1 and 2 (m^3 / sec)
1	opening A	6.2	0.170
2	opening A	0.5	0.070
3	opening A	0.2	0.060
4	opening A	3.3	0.130
5	opening A	1.1	0.094
6	opening B	4.9	0.121
7	opening B	3.4	0.104
8	opening B	0.7	0.060
9	opening B	2.4	0.099
10	opening B	0.1	0.039
11	opening B	2.7	0.101

These experiments verified that the airflow rate between the two zones is a function of the temperature difference and of the size of the opening.

Applying Bernoulli's equation [1], the volumetric flow rate through a horizontal opening separating two zones can be given approximately by :

$$Q = A\ C\ \sqrt{\Delta T\, g\, H / T} \qquad (1)$$

where A is the cross-sectional area of the opening, C is the coefficient of discharge, ΔT is the average temperature difference between the zones, T is the mean absolute temperature of the two zones and H is the thickness of the partition separating the zones. This equation was adopted despite the complex geometry of the specific building. It yields the theoretical value of volumetric flow rate through the opening connecting the two floors. It is also notified that this opening is not easily determined as it is bounded by the stairwell geometry. To evaluate the coefficient of discharge for this opening, the measured airflow rate was divided by the theoretical one, given by equation (1). It was found that the coefficient of discharge was rather independent of the opening size. It was also found to decrease from about 0.76 to 0.34 as the temperature difference between the two floors increased from 0.2 to 6.2 °C (Figure 2b). This decrease in the coefficient of discharge may be due to an increase in interfacial mixing as a result of the direct transfer of some cold air from the upper zone into the inflowing warm air from the lower zone. Furthermore, the increase in density difference can increase the turbulence in two zones. This may affect the value of discharge coefficient. These results were correlated very well with r-squared value equal to 0.96 (Fig. 2b):

$$C = 0.147\,(\Delta T/T)^{-0.2} \tag{2}$$

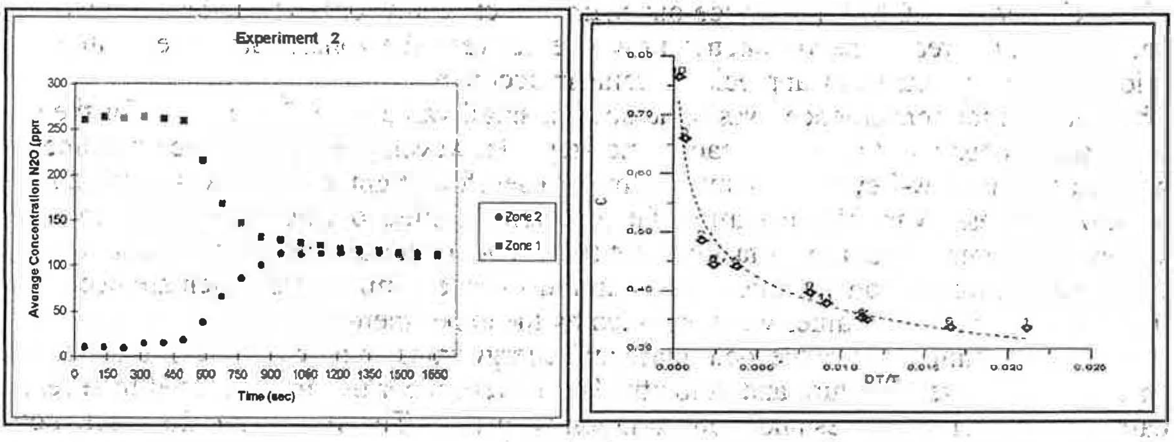

Figure 2: (a) Variation of concentration of N_20 with time (exper.2)
(b) Variation of coefficient of discharge with $\Delta T/T$.

Neglecting the runs characterized by near isothermal conditions (low temperature difference), the coefficient of discharge decreased from about 0.48 to 0.34. It also appeared to stabilize close to 0.34 for high temperature differences. Brown (1962) and Riffat (1989) investigated similar phenomena and suggested comparable values for this coefficient. From equations (1) and (2), the volumetric flow rate between the two zones can be given by:

$$Q = 0.147\,A\,\sqrt{gH}\,\left(\Delta T/T\right)^{0.3} \tag{3}$$

This equation indicates that the volumetric flow rate increases linearly with $(\Delta T/T)^{0.3}$ for each opening configuration.

A computational fluid dynamics method was used to simulate the cases corresponding to the eleven experiments, described before. It must be noted that buoyancy driven flows are difficult to model using CFD techniques. The main reasons are the following: small driving forces can lead to numerical instabilities; selection of the most accurate turbulence model determines the final predictions; the flow is implicitly specified since the velocity field is calculated by the buoyancy sources; the definition of boundary conditions is not usually accurate and complete. However, a series of simulations were carried out. These simulations were performed, applying CFD algorithms which had already been developed and extensively validated.

The algorithms generate approximate solutions to the Navier-Stokes equations, which are considered universally valid to describe the flow of a fluid, heat and concentration in a specific field. These equations are based on the conservation equations of mass, momentum, thermal energy and concentration species. In particular, they were transformed to the algebraic ones through the Finite Volume method, based on a Cartesian grid and the power–law interpolation scheme. To derive the pressure the SIMPLE algorithm was used. Finally, these equations were solved numerically using the Tri-Diagonal Matrix algorithm. To numerically simulate turbulent flow, this study used the more recent RNG k-ε model based on Renormilized Group theory established by Yakhot and Orszag (1992). The advantage of this model is that it is valid for a very wide range of flow types including both high and low Reynolds number flows. Computations were time-dependent to deal with the concentration decay and the highly transient flow field. Small time steps of around 1/10 of the characteristic time scale were used in order to improve the accuracy of results. The computations were performed over the whole period of each experiment. Computations were also three-dimensional since the flow had been expected to be highly asymmetrical due to complex geometry of the building. For simplicity, an orthogonal, equally spaced grid system was used to cover the domain. Five different grid sizes were investigated to determine the necessary resolution for grid-independent solutions. These grid sizes ranged from 2160 cells (15x9x16) to 35280 cells (42x20x42). Comparison of simulated volumetric flow rate between the zones showed that a grid-independent solution was achieved by using a 30x14x30 mesh (12600 cells). Since our main objective was only to model the general flow patterns and to predict the volumetric flow rate between the zones, further refinement of the grid would not produce any appreciable gains in accuracy.

The criterion for convergence was to achieve a small value (~ 10^{-4} kgr sec^{-1}) for the sum of the mass residuals at the end of each time step. However, the convergence becomes quite problematic in low-Reynolds number flows. Therefore tight control was required in the solution process. Variable relaxation factors were applied during simulations in order to achieve convergence. Care was taken to set the boundary conditions and the initial conditions of each zone, for the concentration level, air and surface temperature which are necessary for the simulations. These values were provided by the experiments.

As the simulation proceeded, mass and energy transfer between the two zones caused variations in air temperature and velocity. These were recorded and analyzed to reveal flow patterns air exchange rates and their variation with time. The volumetric flow rates between the two zones, were calculated at the end of each time step and averaged over the whole duration of each experiment. The final values were compared with experimental measurements, presented in Table 1. The relative difference between the simulated predictions and experimental estimations ranged from about 2.0 % to 11.6 %, with an average value equal to 5.5 % for all the experiments. This is a very good agreement, considering the many factors such as the turbulence model, experimental errors and boundary conditions, which affected the accuracy of results.

Simulations revealed the airflow patterns in the zones as well as in the opening connecting the two zones. Figure 3 shows examples of the predicted air movement in the opening and in the individual zones, at a moment 360 sec into the fourth experiment.

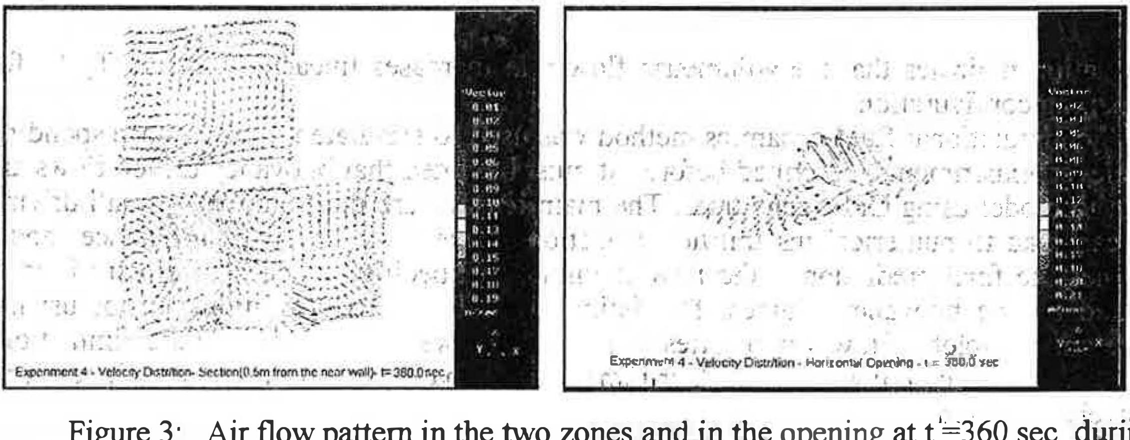

Figure 3: Air flow pattern in the two zones and in the opening at t =360 sec during experiment 4.

It was found that these patterns are affected mainly by the temperature difference between the zones and by the stairwell geometry. The flow pattern in the lower zone was dominated by many vortices which promoted heat transfer and uniformity. The situation in the upper zone is similar but to a lesser extent. The higher the temperature difference was, the more intense the eddies are. In addition these flow patterns varied with time.

CONCLUSIONS

The volume flow rate through the opening connecting the two zones was a function of the interzonal average temperature difference and of the size of the opening. This rate increased significantly with increasing temperature difference. The coefficient of discharge, appeared to be dependent only on the interzonal average temperature difference. Further experimental work is required to investigate the possible effect of stairwell geometry and size of the opening on the value of this coefficient.

CFD simulations of buoyancy-driven flow through a typical stairwell, were carried out. These simulations revealed the general airflow patterns in the zones. Comparison of the simulated volumetric airflow rates between the two zones and those based on experimental measurements, showed very good agreement, despite the difficulties related to turbulence models, geometry, simplifications, experimental errors and boundary conditions. Investigation of these factors is required so as to enhance the effectiveness of these algorithms to model these airflow phenomena.

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