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THREE-DIMENSIONAL NATURAL CONVECTION IN ROOMS CONNECTED TO THE OUTSIDE THROUGH LARGE OPENINGS

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Summary

The growing interest in the study of natural convection in geometrically complex enclosures with restricted communication has been stimulated by applications involving energy-efficient passive-solar buildings, natural convection cooling of electronic equipment and room heating and ventilation. Airflow through doorways, windows and other large openings are significant ways in which air, pollutants and thermal energy are transferred from one zone of a building to another or to outside.

The present paper describes a numerical method for analysing three-dimensional natural convection in rooms connected to the outside through large openings. The calculations made use of a Computational Fluid Dynamics (CDF) procedure taking into account the effects of buoyancy, heat sources, thermal radiation heat transfer and air flow turbulence. The CFD predictions agree with the experimentally observed features of the flow field, including the vertical air temperature stratification, with a reasonable degree of accuracy.

Introduction

Airflows through doorways, windows and other large openings are significant ways in which air, pollutants and thermal energy are transferred from on zone of a building to another or to outside. The subject of airflows through large openings includes a large number of different problems, ranging from steady gravitational flows to fluctuating flows due to wind turbulence, and including recirculating flows caused by boundary layer effects in a thermally driven cavity.

Purpose of the paper

Our contribution here is to describe the various physical problems of the first category, including the effects of gravitational flows due to density gradients and the effects of boundary layer flows developed in a cavity, review the solutions developed in the literature and describe a numerical method for analysing 3D natural convection in rooms connected to the outside through large openings. The calculations made use of a Computational Fluid Dynamics (CFD) procedure.

Short Review of the Literature

Air may flow differently at the top of a doorway than at the bottom. This flow characteristic of large opening behaviour has a variety of causes that contribute to the high number of parameters and the complexity of the physical phenomena. It becomes virtually impossible to arrive at a general solution of the problem. Feustel (1985) pointed out that no code was able to solve this problem other than by dividing the large opening into a series of small ones described by crack flow equations.

Before proposing a CFD prediction tool to the problem, we will review the literature describing the main physical phenomena and the existing solutions.

Gravitational flows through vertical openings

The classical approach of the gravitational flow problems assumes airflows through large openings to be driven by density fields on both sides of the opening. Each side is considered as a semi-infinite reservoir with no boundary layer flows and each streamline is supposed to be horizontal (Fig. 1). Many authors have dealt with this approach (Shaw and Whyte, 1974; Lidwell, 1977; Kiel, 1985) and provided elementary solutions developed analytically of purely natural convection or mixed convection using Bernoulli' s equation.

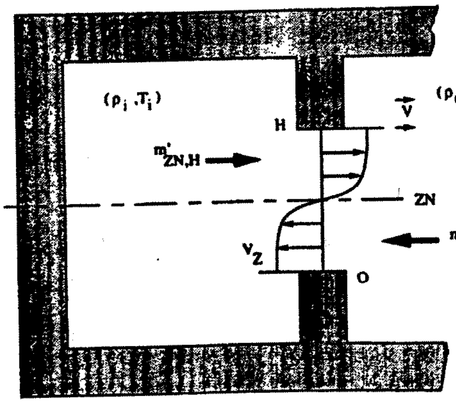

Fig.1: The classical problem of the gravitational flow through a vertical opening

Coupling with vertical thermal gradient in each zone

In the preceding problem the air density in both zones is presumed to be uniform. In fact, because of thermal stratification, or gradients of concentration of any species, this assumption is restrictive and does not allow for the general behaviour of a large vertical opening. Several authors dealing with airflow circulation in passive solar buildings have pointed out the effect of density gradients. The main consequence of density gradients, when they exist, is that various neutral levels may appear in the height of the opening for small values of temperature difference. In the various experimental studies developed by Balcomb *et al.* (1983), Hill *et al.* (1986) and Pelletret (1988), it appears that most of the configurations can be represented quite well by uniform density gradients.

It becomes clear that more precision is needed in the definition of the physical modelling and in the experimental conditions of its determination. However a precise determination remains very difficult.

Computational Fluid Dynamics Algorithm

The main objective in proposing a solution for large openings is to fit it easily into the network definition and to go as far as possible in the modelling of the various phenomena influencing the behaviour of large openings.

The equations that describe the flow of a fluid and heat transfer within an enclosure are all based on the conservation of mass, momentum and thermal energy within the enclosure. In most cases, the indoor airflow encountered in rooms is turbulent. The mathematical modelling of turbulent flow is within the capabilities of modern mathematical and numerical methods. Among the turbulent models, the k-ε two-equation buoyancy-extended turbulence model, based on eddy-viscosity/eddy-diffusivity concepts (Launder and Spalding, 1984), seems most widely used for airflow studies in rooms.

Since the temperature difference in room air is relatively small compared to the mean Kelvin temperature, it is a common practice to use the Boussinesq approximation

Airflow and heat transfer models

The density in the transport equations is represented by the equation of state and the governing equations are represented by the continuity equation, the incompressible Navier-Stokes equations, the energy conservation equation, the turbulence energy conservation and the dissipation rate of turbulence energy.

The governing equations for the averaged steady flow can be written in the general elliptic form for an incompressible fluid as:

$$\frac{\partial\left(U_j\phi\right)}{\partial x_j}-\partial\left(\Gamma_\phi\frac{\partial\phi}{\partial x_j}\right)/\partial x_j=S_\phi \qquad (1)$$

where Γ_ϕ and S_ϕ are identified for each governing equation (Ramos, 1997; Carvalho and Ramos, 1998).

Boundary conditions

The accuracy of the solution of the discretization equations presented in the previous section will depend on the accuracy of specifying the physical quantities at the boundary of the flow domain and on the method of linking these quantities to the bulk of the flow.

Wall Boundary:

Because of the damping effect of the wall, the transport equation for the turbulence quantities does not apply close to the wall. The alternative is to extend the Couette flow analysis and apply algebraic relations, the so-called logarithmic laws or wall functions for momentum and heat fluxes (Launder and Spalding, 1984), for the calculation of the velocity parallel to the boundary components and the heat flux through the boundary. The problem presents a conjugate heat transfer problem. Unlike the convection-conduction problem, the radiation-convection-conduction interactions at the air-wall interface give rise to complexities in the numerical method, which requires special treatment.

Free Boundary:

For economical reasons, the calculation domain does not extend all the outside the room. The flow is linked to the outdoor conditions by an adequate treatment of the boundary conditions using a free boundary. A free boundary is not a physical boundary, but is a limit that imposes on the domain of calculation, a surface where the pressure is prescribed. At this free boundary, the fluid is entrained at an unknown rate. Thus, the boundary condition consists of prescribing the pressure equal to the atmospheric value sufficiently far from the door opening.

Numerical solution procedure

The general partial differential equation (1) has been discretized by means of a finite volume method, i.e., by integration of the equations over a control volume on a mesh to yield finite difference equations (Patankar, 1980).
A staggered non-uniform grid with velocity nodes offset from scalar nodes is used in the present computations. The continuity equation is rewritten into an equation for the pressure correction and the pressure-momentum linked equations are solved by the SIMPLE algorithm (Patankar and Spalding, 1972). The resulting algebraic equations are solved in an iteration sequential manner by using the TDMA (tri-diagonal matrix algorithm) line-by-line method (Carnahan *et al*, 1969).

Study Case

The investigation has been carried out by means of physical measurement and numerical prediction of the environment in a naturally ventilated office room communicating with a 2.5 m high corridor via a doorway 0,78 m wide and 2 m high (Fig. 2).

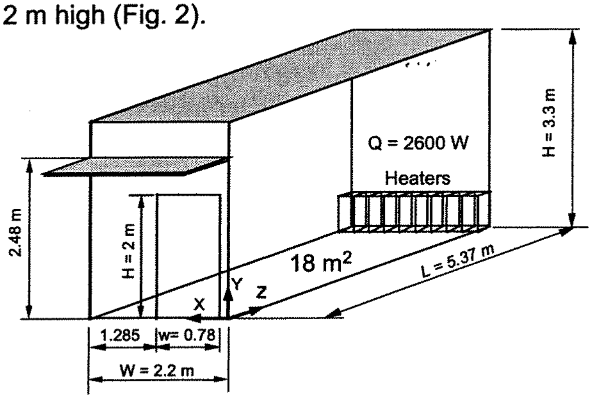

Fig.2: Schematic of the room configuration

Inside room, near the front wall, there are 4 electric air heater radiant units. Two of them were 500 W and the other were 800 W, each. Experimental techniques are used to measure the air temperature distributions, to measure the velocity airflow pattern and to have flow visualizations (Ramos, 1997).

Solution and Validation

In this section, comparisons between the predicted and measured behaviour of the flow field and the air heat transfer are presented and discussed. Experiments include measurements of mean air velocity and mean air temperature distribution, that allow testing the numerical model performance.
Fig. 3 and 4 shows the predicted air temperature distribution and the mean air velocity components profile on a longitudinal plane.

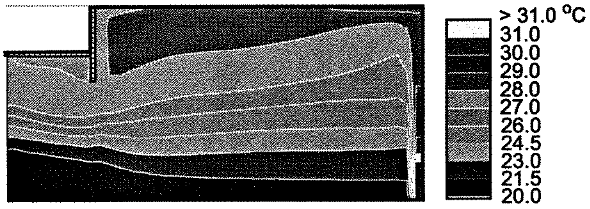

Fig.3: Predicted air temperature distribution

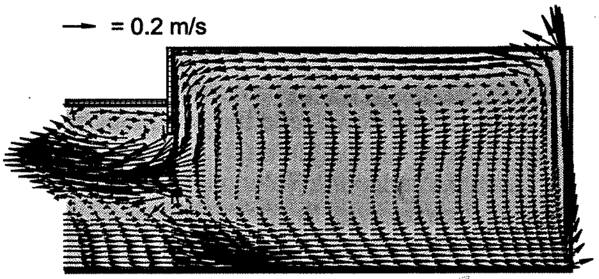

Fig.4: Predicted mean air velocity components

Fig. 5 shows the comparisons between the air velocity longitudinal component calculated by analytic model using Bernoulli's equation, prediction by CFD and its experimental data, on the same plane, in the doorway section. The comparisons between the measurements and the predictions are indicated that predicted flow pattern follows closely the experimental values. The incoming air flows from the corridor through the lower half-height doorway and then takes the form of a gravity current flowing horizontally along the floor in the direction of the air heaters. Beyond, due to buoyancy effect, the air goes up to the ceiling. The outgoing air flows to the doorway direction where leaves the room to the corridor (cold zone) by the upper half-height, as a turbulent jet.

The measurements of air temperature distribution and the vertical temperature stratification inside room are also consistent with the CFD predictions (Ramos, 1997).

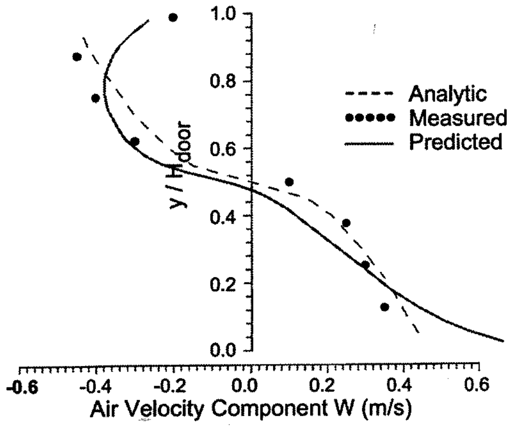

Fig.5: Comparison between the air velocity longitudinal component in the doorway section

Conclusions

In the literature the prediction of gravitational flows through vertical openings in steady-state configurations used Bernoulli's equation. Nevertheless, it becomes clear that more precision is needed in the definition of the physical modelling and in the experimental conditions of its determination. A real lack of knowledge exists on the behaviour of openings in thermally driven flows, and the coupling with the flow patterns existing in each zone is not really taken into account. Taking into account the whole complexity of the problem, we proposed a three-dimensional CFD tool to predict the airflow pattern and the heat transfer within a heated office room connected to a corridor via a doorway. The results have been compared to experimental data obtained in full-scale.

The air flow pattern, the temperature distribution and the radiation heat transfer has been predicted solving the equations for the conservation of mass, momentum and thermal energy, taking account of the effects of buoyancy, airflow turbulence, transfer of thermal radiation and thermal conduction through the walls, heat sources and obstacles in the room. The k-ε model had modelled the turbulence parameters. The validation of the ventilation model has show that 3D CFD code is a useful tool to predict the airflow and the heat and mass transfer in rooms connected to the outside through large openings.

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