TWO- AND THREE-DIMENSIONAL FINITE-VOLUME PREDICTIONS OF FLOW IN A STAIRWELL AND COMPARISON WITH EXPERIMENT

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ABSTRACT

The paper describes a numerical study of three-dimensional buoyancy-driven flow in a stairwell. The HARWELL-FLOW3D computer program which uses the finite-volume method and incorporates the $k-\varepsilon$ turbulence model was employed. The thermal boundary conditions at the walls are those measured by the authors. The radiation exchanges between surfaces are calculated separately and then incorporated in the numerical computation via the boundary conditions. Two- and three-dimensional predictions of the temperature and velocity fields are presented and the results are compared with experimental data. Comparisons have also been made with two-dimensional predictions.

KEYWORDS Numerical Modelling, Flow, Buoyancy, Stairwell, Building

1. INTRODUCTION

In recent years there has been an increased interest in the study of mass and energy transfer between different zones of buildings. The study of air movement in stairwells is a good example in this respect. A number of studies have been reported. These are the works of Feustel et al. (1985), Reynolds (1986), Zohrabian et al. (1989a,b) and Riffat et al. (1988). The above studies have been mainly of experimental or analytical nature. Studies of such processes based on the application of Computational Fluid Dynamics are those of Simcox and Schomberg (1988), who used the HARWELL-FLOW3D code to study the fire at King's Cross station, and of Zohrabian et al. (1988), who used their own finite-volume program to predict the two-dimensional buoyancy-driven flow in a stairwell model.

Related to buildings in general, there are now numerous publications available on computation of air flow. Some examples are air flow in cavities (e.g., Mokhtarzadeh-Dehghan et al. 1990), in rooms (e.g., Murakami et al. 1990; Haghighat et al. 1989), in atriums (e.g., Alamdari et al. 1991) and also the work of Yau et al. (1991) on air flow in an airport terminal building.

The main focus of the existing literature is on the prediction of the flow field without detailed comparison with experimental data. Such comparisons are needed in order to improve the existing predictive procedures. We address this issue in this paper.

2. THE EXPERIMENTAL DATA AND BOUNDARY CONDITIONS

The boundary conditions and the experimental data used for comparison with the predicted results were obtained using a half-scale stairwell model. A schematic diagram of the rig is shown in Figure 1. The walls were made of Perspex, except those indicated by A to K, which were made of plywood. The air velocity and temperature were measured using an omni-directional probe and platinum resistance thermometers, respectively. The heater was an electric panel radiator used, for example, in houses or in offices. It was located in the lower compartment. Further details of the experimental set-up and its instrumentation can be found in Zohrabian et al. (1989b).

direction, except in regions close to the side wall (see (c) in Figure 2), where the flow pattern is markedly different. Here the air flows downwards along the side wall, an effect which is enchanged as a consequence of the heat loss, to the wall, except in the central region where the effect of the rising warm air is still strong. The flow behaviour described above can also be seen from the velocity fields in the y-z planes shown in Figure 2 (d). In all three planes the magnitude of the velocity component in the y- direction is small. This indicates that the flow in the x-z plane is dominant.

Figure 3 (a to c) shows the temperature distributions in the three x-z planes. The results (a) and (b) show that the hot air flowing along the ceiling of the lower compartment forms a hot plume when it enters the stairway area and then the upper compartment. Its temperature gradually decreases and a region of hot air forms in the upper part of the upper compartment where the temperature varies only by about 1 °C. Comparing Figure 3 (a) and (b) indicates the spreading of the plume in the y- direction. The effect of this rising hot air can still be seen in Figure 3 (c), but the hot region is now limited to the middle parts of the stairway.

The lower part of the upper compartment is occupied by a region of colder air (by about 2 °C). In the central part of the stairwell, the formation of the cold stream flowing down the stairs can be seen clearly in Figure 3 (a). The lateral extent of this cold stream is reduced further from this middle region (see Figure 3 (b)), because of the spreading of the hot air towards the stairs. Considering the side-wall temperature, it can be seen that the main temperature gradient between the air and the side wall is limited to a narrow region of about 0.05 m width. This is a direct result of the stairwell geometry and the position (and width) of the heater which produces a stong flow in the x-z plane.

The two-dimensional predictions of the velocity and temperature distributions are shown in Figures 4 (a and b). These results should be compared with the three-dimensional results in the mid-region of the stairwell (Figure 2 (a)), where the assumption of two-dimensionality is more acceptable. The two-dimensional results are included here to indicate the degree of accuracy which may be achieved from a less costly (in terms of computer time and memory) computation. Generally higher temperatures are predicted in the two-dimensional case. The velocity field shown in Figure 4 (a) has the same overall features as the three-dimensional predictions. However, the hot plume to spread more rapidly and this results in more uniform velocities in the upper compartment. The results are somewhat different from the two-dimensional results obtained by Zohrabian et al. (1988). In their computations the effects of heat losses from the side walls were excluded. This was achieved using boundary conditions which were obtained for a stairwell with insulated side walls. Their results therefore approximated more closely to the two-dimensional situation. However, their velocity field is qualitatively more like to the three-dimensional results obtained here.

Comparison of the two- and three-dimensional vector plots shows that the general features of the flow in the stairway are the same, although, in the former case,there is more interaction between the hot and cold regions in the stairway. This can also be seen from the temperature distribution. Some differences between the flow patterns in the lower compartment can also be distinguished. In the two-dimensional results, the cold air penetrates deeper into the lower compartment, while in the three-dimensional results the cold air tends to rise earlier.

Comparisons of the experimental results with the predicted ones are shown in Figure 5 (a and b). The overall pattern agrees with flow visualization tests (not included here). The three-dimensional calculations lead to better agreement with experiments. In the upper parts of the throat area, the agreement between the predicted and measured temperatures is good. However, in the lower parts there is a difference of about 5 % between the two results. There are larger differences in the central region of the throat area. This is expected, because the presence of the counter-flowing and interacting hot and cold streams makes computation (and measurements) more difficult. Higher predicted temperatures have also been reported by Alamdari et al. (1986) and Zohrabian et al. (1988). The behaviour may be attributed to the turbulence model and to the wall function method.

The predicted velocity profiles show good agreement with experiment, especially in the upper parts of the throat area. The three-dimensional results are closer to experimental values than the two-dimensional results, except in the lower part, where the maximum velocity is underestimated. The relatively large difference between the velocities in the lower part of the throat area can be attributed to the fact that the flow is particularly difficult to model (and also to measure) in this region, because of the presence of the stairs.

7. CONCLUSIONS

A buoyancy-driven flow within the rather complex geometry of a stairwell model was computed numerically. Two- and three-dimensional computations predicted the overall features of the flow satisfactorily. The experimental data were also predicted with reasonable accuracy, considering the many factors (such as the turbulence model and wall functions, experimental errors and boundary conditions) which affected the accuracy of the results. Although the particular geometry of the modelled stairwell tended to produce a weak three-dimensional flow, a better agreement with experiment was achieved with three-dimensional simulations and resulted in a better understanding of the flow behaviour in the third direction and near the side walls.

8. ACKNOWLEDGEMENT

S. Ergin-Özkan gratefully acknowledges the financial support of Çukurova University, Turkey during her PhD study.

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Table 1. Thermal boundary conditions.

Surface	A	B	C	D	E	F	G	H
Temperature (°C)	50.9	38.4	37.8	36.4	31.6	32.0	31.0	31.1
Surface	I	J	K	L1	L2	L3	M	N
Temperature (°C)	32.9	33.8	37.4	31.3	32.0	33.7	-	-
Heat Flux (W m^{-2})	-	-	-	-	-	-	213.0	295.0

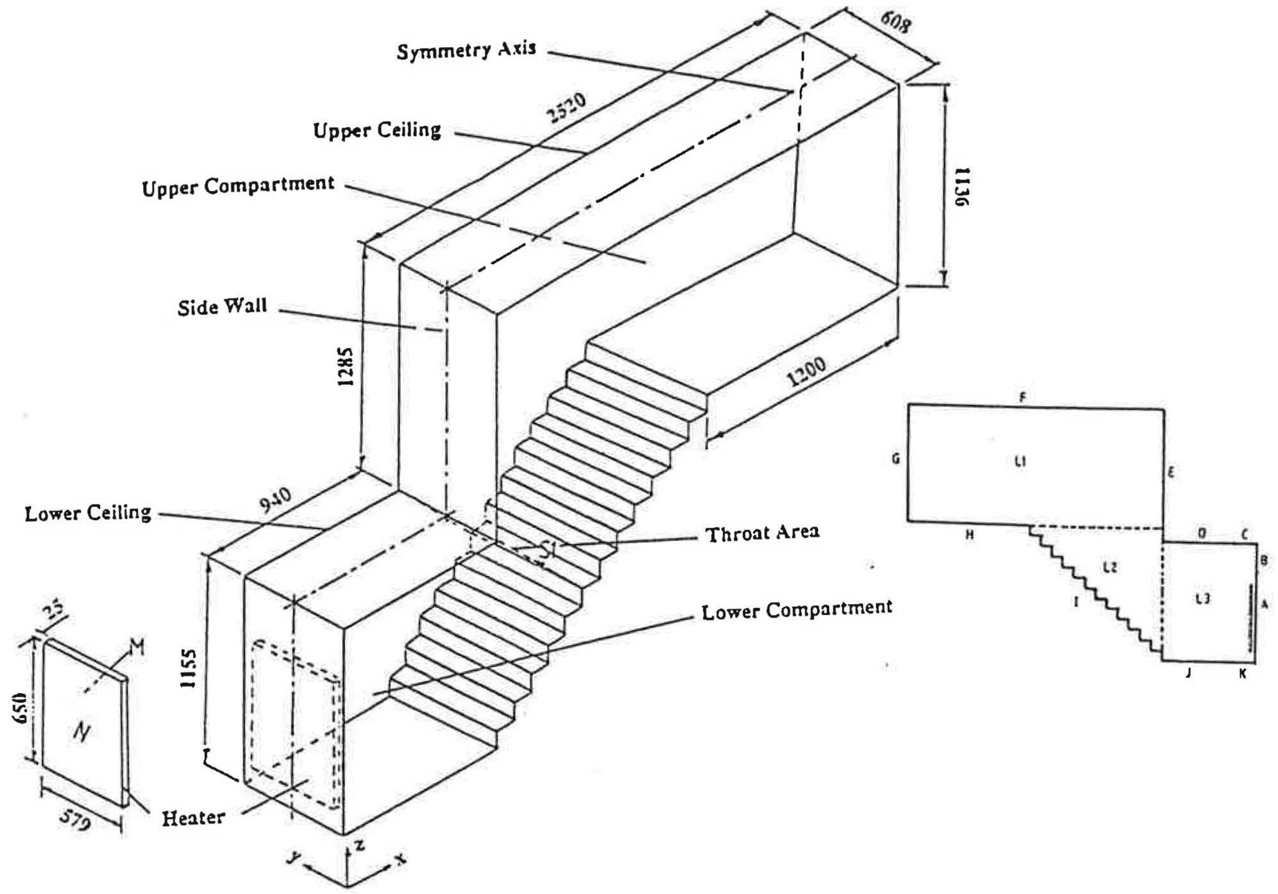

Figure 1. The Schematic diagram of the stairwell (Dimensions are in mm).

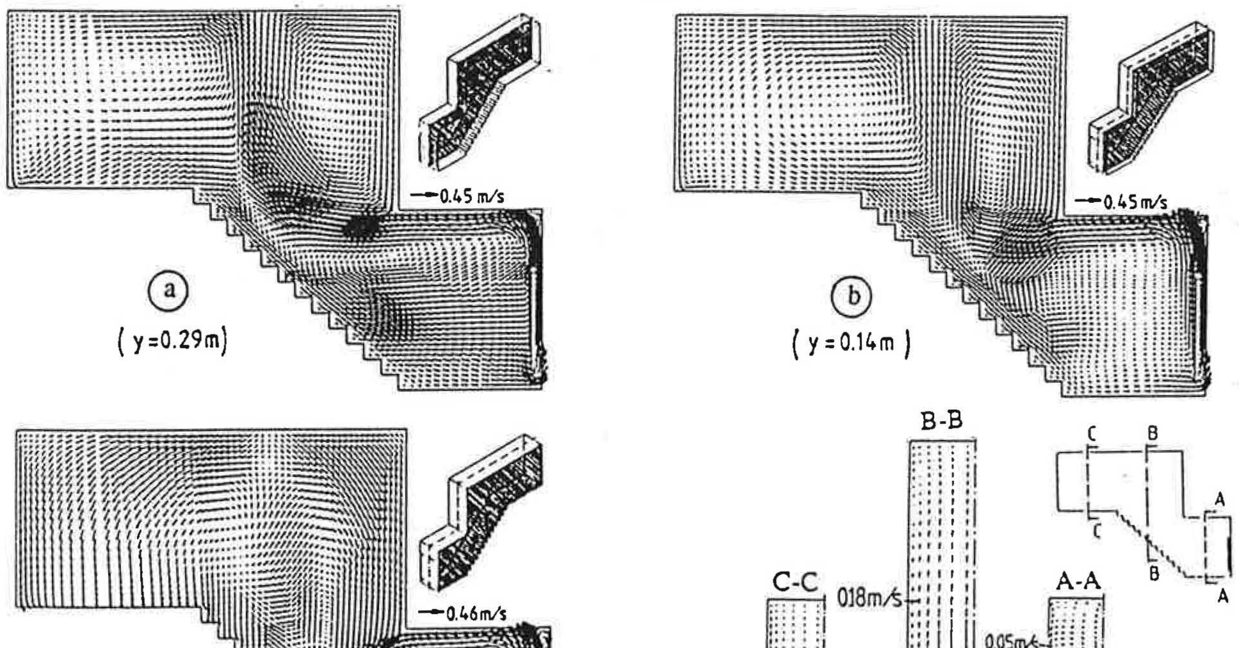

Figure 2. Three-dimensional predictions of velocity.

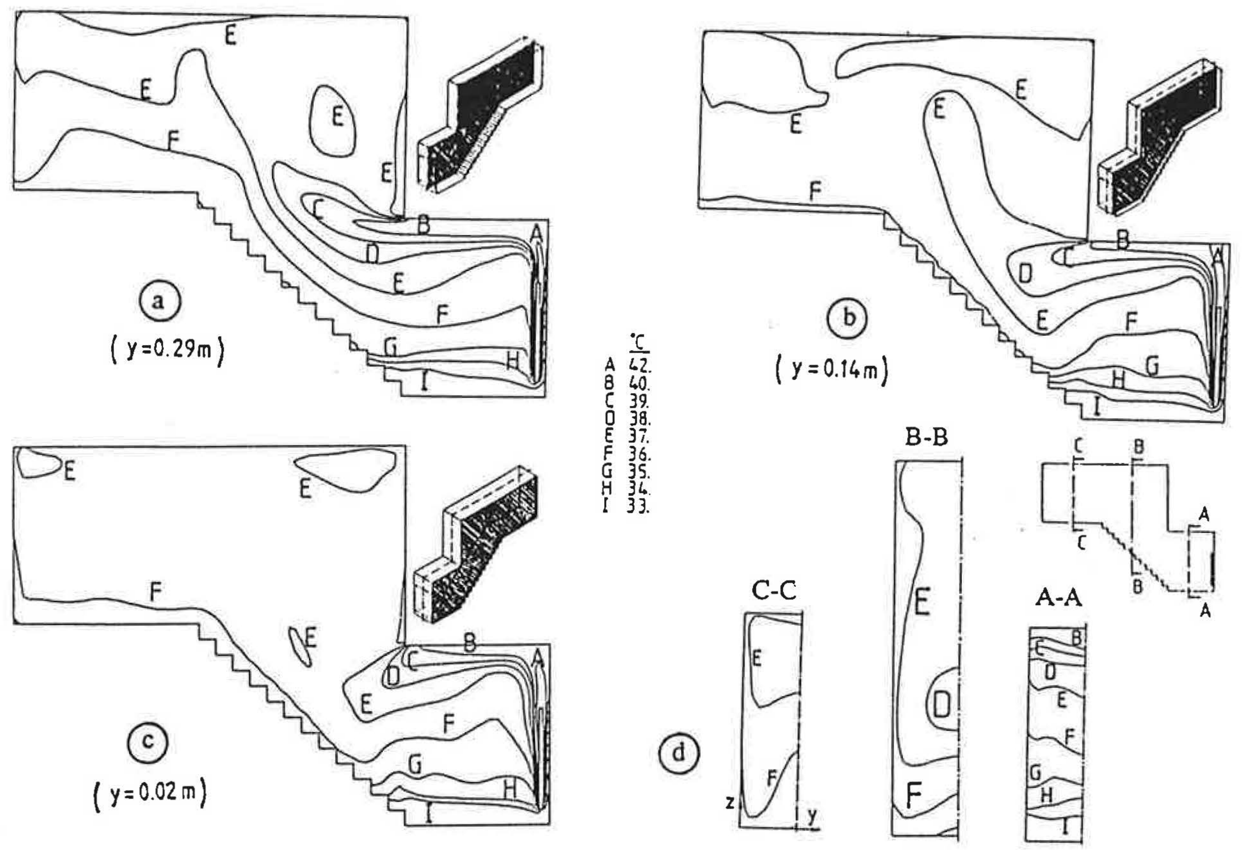

Figure 3. Three-dimensional predictions of temperature.

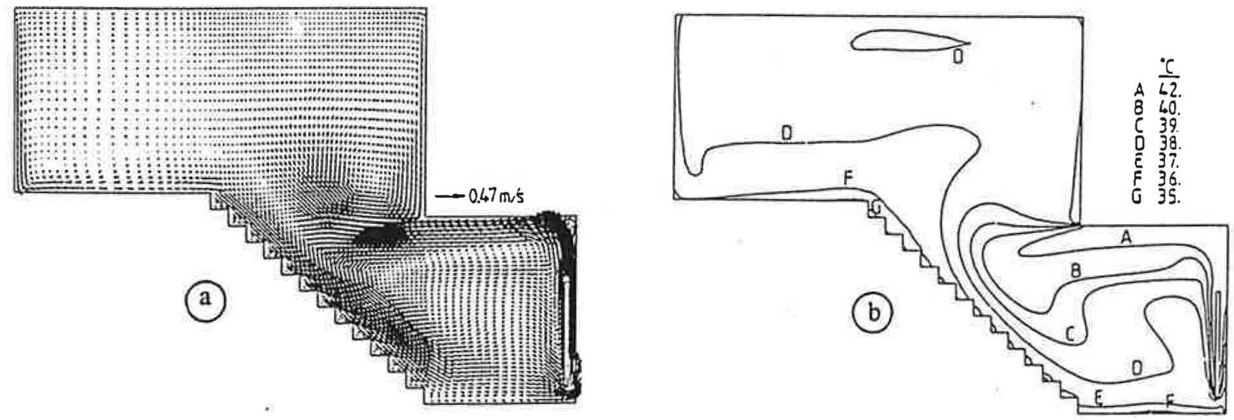

Figure 4. Two-dimensional predictions of velocity and temperature.

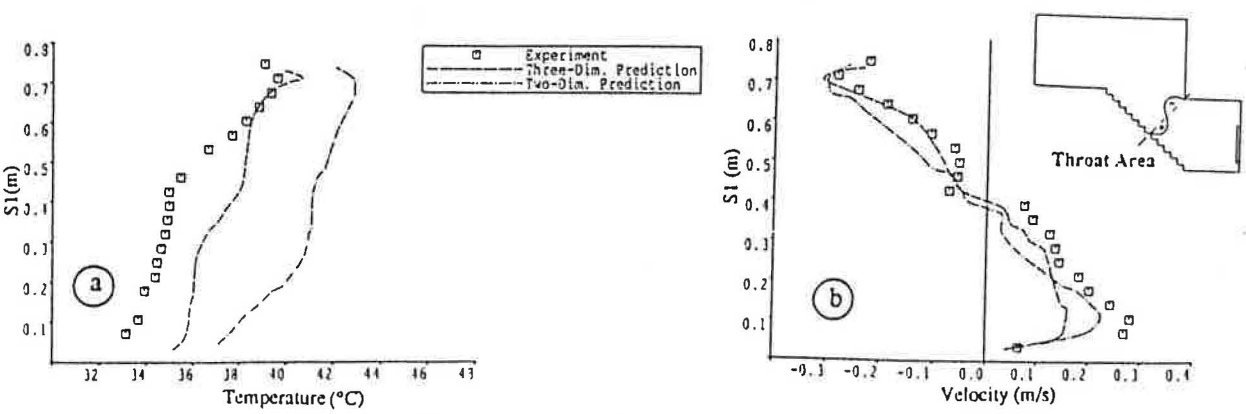

Figure 5. Velocity and temperature profiles at the throat area.