COMPUTER ANALYSIS OF THE AIR POLLUTION IN THE MYCEANE HALL OF THE ARCHAEOLOGICAL MUSEUM OF ATHENS

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ABSTRACT

The paper presents a mathematical model, implemented in a general computer code, that can provide detailed information on velocity and temperature fields as well as pollutants concentrations prevailing in three-dimensional buildings of any geometrical complexity, for given external meteorological conditions. The model involves the partial differential equations governing flow and heat transfer in large enclosures containing heat sources. Turbulent flow is simulated and buoyancy effects are taken into account. The model allows for such practical aspects of the problems under consideration as blockages, internal heat and contaminant loads, external weather conditions, the presence of people, etc. The model is used to assess the environmental conditions inside the main Hall of the National Archaeological Museum of Athens (Myceane Hall) with external conditions corresponding to Ministry of Environment spring-autumn, summer and winter days.

KEYWORDS

Air quality; CFD; contamination sources; thermal comfort; turbulent buoyant convection.

INTRODUCTION

The purpose of studying the environmental conditions inside buildings is to provide comfortable and healthy conditions for the people in them, both in terms of air temperature, velocity and pollutants concentrations. The problem of thermal comfort in rooms gives rise to questions concerning the arrangement of fresh air supply. It is important to get adequate mixing of the inlet air with the room air, to obtain a uniform temperature and fresh air distribution. At the same time the mixing should not be so intense that people present in the room feel the draught. These requirements are often opposite in such a way that intense mixing gives rise to large velocities and velocity fluctuations. It is therefore of great importance to be able to predict the flow and mixing conditions before the installation of the ventilation as well as heating equipment. Furthermore, for achieving and maintaining a high level of cleanliness in the so-called clean-rooms, highly filtered air is directed through all critical zones of these spaces, carrying out the airborne contaminants. Control over the contaminants distribution can only be achieved by regulating the way air flows throughout these rooms. Therefore, the importance of predicting the air flow patterns is obvious.

Predictions are often obtained by setting up the flow configuration in a model or full scale room. Flow visualisation and measurements are used to get a picture of the flow. Such investigations are often very expensive in terms of man power and experimental equipment and it can be difficult to alter geometry, and inlet conditions. A numerical computation model of the flow behaviour in the room will therefore make a helpful tool to predict heating, ventilation and cooling processes of rooms. To alter the flow conditions in the computer model only means to change the boundary conditions.

This paper reports on some of the results of the development of a numerical computation procedure for three dimensional turbulent flow. The technique can be used with confidence at least for checking the relative advantages and disadvantages of various design alternatives in construction as well as in instrumentation of these spaces. This modelling procedure is intended to contribute to the effort towards designing and instrumenting buildings that provide cleaner and more comfortable environment. Furthermore it is able to give reasonable solutions for the design and the selection of the mechanical equipment (heating, cooling and ventilation systems) of a building, avoiding the incorrect choices which could lead to the expense of a great amount of energy, without having the demanded thermal comfort as well as the proper healthy environment.

Although computation procedures for flow have been available for some time, relatively few applications to thermal comfort and indoor pollution problems have appeared. Holmberg et al. (1975) indicated that these methods cannot be extended to three dimensional flows because of the formulation of the equations. However, it is feasible and preferable in three - dimensional rooms to solve equations for the primitive variables, the three velocity components, the pressure and the temperature.

A computer model of this kind will provide the architects, heating and ventilation and environmental engineers with powerful and economical means of evaluating alternative building designs and energy sources.

The model is used to assess the environmental conditions inside the main Hall of National Archaeological Museum of Athens (Myceane Hall) with external conditions corresponding to Ministry of Environment, spring-autumn, summer and winter days (1996).

Three different cases are considered, to demonstrate the capabilities of the present model, according to the meteorological conditions and the required human interventions. For all cases, a thermal source by the museum visitors per square unit is considered. The program calculates the velocity, the pollutants concentration and the temperature fields, throughout the three-dimensional configurations, and the results are presented in the form of velocity, temperature and concentration contours. The air pollutants considered, are: O_3, CO, SO_2, NO_X, Pb and CO_2. This model is based on a previous work done by Patrikiou (1992).

MATHEMATICAL FORMULATION AND APPLICATION OF THE MODEL

The Differential Equations

For steady flow, the equations for continuity, velocity components, temperature and chemical concentrations can be expressed in the following general conservation form (Markatos and Spalding, 1983) :

$$\mathrm{div}\left(\rho\bar{u}\varphi - \Gamma_{\varphi}\,\mathrm{grad}\varphi\right) - S_{\varphi} = 0 \qquad (1)$$

where ρ = density

$\bar{u}$ = velocity vector

Γ_{φ} = effective exchange coefficient of φ

S_{φ} = source rate per unit volume

The source rate and the effective exchange coefficient corresponding to each φ solved for in this study are given in Table 1.

Table 1 Source rate and effective exchange coefficient for each φ

Equation	φ	S_{φ}	Γ_{φ}
continuity	1	0	0
x-momentum	u	$-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)$	μ
y-momentum	v	$-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right)+\rho g\frac{T-T_0}{T_0}$	μ
z-momentum	w	$-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu\frac{\partial w}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial w}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial w}{\partial z}\right)$	μ
energy	h	q_{com}	μ/σ_h
kinetic energy of turbulence	k	$G-\rho\varepsilon$	μ/σ_k
eddy dissipation rate	ε	$C_1\frac{\varepsilon}{k}G-C_2\rho\frac{\varepsilon^2}{k}$	μ/σ_{ε}
concentration	m_{co}	0	μ/σ_{co}
concentration	m_{co_2}	m	μ/σ_{co_2}
concentration	m_{so_2}	0	μ/σ_{so_2}
concentration	m_{no}	0	μ/σ_{no}
concentration	m_{no_2}	0	μ/σ_{no_2}
concentration	m_{o_3}	0	μ/σ_{o_3}
concentration	m_{pb}	0	μ/σ_{pb}

where :

μ = viscosity

σ = Prandtl number for variable φ

g = gravitational acceleration

T_0 = ambient temperature
T = temperature
G = turbulence production rate
The values of the constants C_1 and C_2 are 1.44 and 1.92, respectively.

The Solution Method

To solve the set of the model differential equations together with their boundary conditions, a finite-domain technique is used which combines features of the methods of Patankar and Spalding (1972), and Spalding (1980) and a whole-field pressure-correction solver (Markatos and Pericleous, 1984). The space dimensions are discretised into finite intervals and the variables are computed at only a finite number of locations, at the so-called "grid points". These variables are connected with each other by algebraic equations derived by their counterparts by integration over the control volumes defined by the above intervals. The pressure-correction equation is deduced from the finite-domain form of the continuity equation. The source terms are linearised. To solve the 3-D flow equations the "SIMPLEST" practice of Spalding is followed, in which the finite-domain coefficients of the momentum equations contain only diffusion contributions, the convection terms being added to the linearised source term. Hybrid-differencing for convection and harmonic averaging for diffusion are used. The momentum equations are solved by a point-by-point procedure. The present model is implemented in the general computer program PHOENICS (Markatos and Spalding, 1983).

Test Cases Considered

The simulation is concerned with the flow and heat as well as contaminants transfer, in large enclosures, containing heat and contaminant sources. Three cases are considered, referring to the main Hall of National Archaeological Museum of Athens (Myceane Hall) for three different seasons, spring-autumn, summer and winter. The external climatic conditions correspond to Ministry of Environment (Directorate of Environmental Planning, DEP). The Hall configuration is given at Figures 1, 2, 3. The three different cases demonstrate the capabilities of the present model according to the meteorological conditions and the required human interventions. At all the cases outdoor air is brought into the Hall through two opposite doors. This air gets heated by the heat released by the lights, the visitors and the heating units (in winter case), and rises towards the ceiling where it

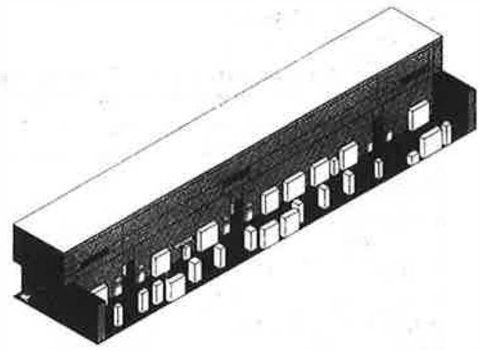

Figure 1. View of the small Hall.

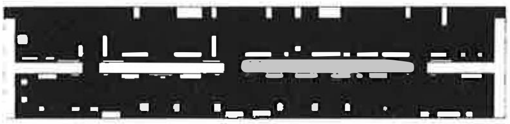

Figure 2. Ground plan of the Myceane Hall.

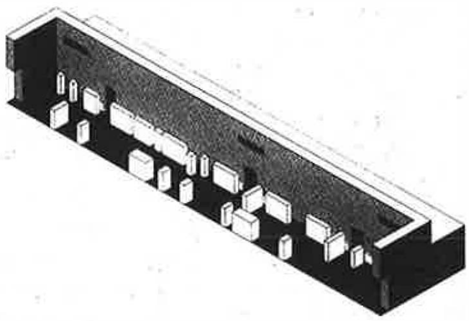

Figure 3. View of the main Hall.

is extracted through different, for each case, windows. The outdoor contaminants which get into the Hall through the two doors are, CO, NO, NO_2, SO_2, O_3, Pb. The values of the contaminants are given by measurements of Ministry of Environment for the atmospheric pollution in Athens for year 1995. The CO_2 which due to people breathing is considered as an internal source of pollution.

Table 2 Input data used in computations

Data	Test case 1 *Spring-Autumn*	Test case 2 *Summer*	Test case 3 *Winter*
Outdoor air temperature (K)	288.15	303.15	278.15
Indoor air temperature (K)	291.15	291.15	285.15
Wall temperature (K)	288.15	288.15	283.15
Outdoor air velocity (m/s)	3.0	1.5	4.0
Air flow (m^3/s)	22.2	11.1	29.6
Wind direction	West		
Air density (kg/m^3)	1.189		
Air viscosity (kg/ms)	10^{-5}		
Heat released by each light at central/small Hall (W)	50/20		
Number of lights central/small Hall	10/25		
Heat realised by each heating unit at central/small Hall (W)	3500/1630		
Number of heating units at central/small Hall	6/6		
Number of visitors	350		
Heat released by each visitor (W)	100		
CO concentration (kg/s)	$115.44\ 10^{-6}$	$62.16\ 10^{-6}$	$198.32\ 10^{-6}$
Pb concentration (kg/s)	$22.20\ 10^{-6}$	$11.10\ 10^{-6}$	$29.60\ 10^{-6}$
SO_2 concentration (kg/s)	$488.40\ 10^{-6}$	$271.95\ 10^{-6}$	$991.60\ 10^{-6}$
NO concentration (kg/s)	$3263.40\ 10^{-6}$	$1631.7\ 10^{-6}$	$6985.60\ 10^{-6}$
NO_2 concentration (kg/s)	$1847.04\ 10^{-6}$	$1101.12\ 10^{-6}$	$2581.12\ 10^{-6}$
O_3 concentration (kg/s)	$333.00\ 10^{-6}$	$271.95\ 10^{-6}$	$236.80\ 10^{-6}$
CO_2 concentration (kg/s)	$3840\ 10^{-6}$		

Other input information are given in Table 2. The statues blocks as well as the heating units inside the Hall are modelled by use of "porosities" (Markatos and Mukerjee, 1981). The program calculates the velocity, temperature and contaminants concentration fields throughout the three-dimensional configurations described above.

Boundary conditions

Boundary conditions are specified as follows. At the two inlets (doors) a fixed mass flow rate is specified as well as the values of velocity, temperature and contaminants concentrations that this flow rate is bringing into the domain. At the walls, wall functions (Patankar and Spalding, 1972) are used to calculate the wall shear stress. The walls are assumed isothermal. Finally the CO_2 concentration and the heat sources released by visitors, heating units and lights are added.

Grid dependence

The reported results have been obtained using a non - uniform grid consisting initially of 18 cells in the x-direction, 20 cells in the y-direction and 82 cells in the z-direction. Then a 36x20x105 cells grid was used, whose solutions are grid independent, as proved by repeating the run with even more cells.

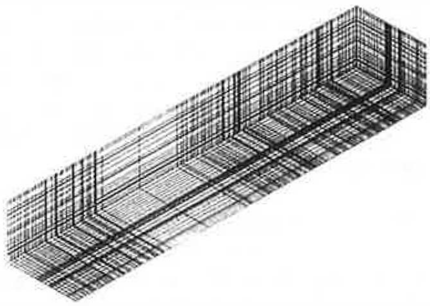

Figure 4. A 36x20x105 cells grid.

Computer storage and time requirements

The calculations have been performed on an O2 Workstation (Silicon Graphics), CPU R 10000 processor and main memory 64 Mbytes. A typical CPU time for a run with the above grid (75600 cells) is 20 hs for full convergence.

RESULTS AND DISCUSSION

Some of the results of the study are presented in the next figures in the form of isolines.

Figures 5 to 15 refer to the winter case for the main Hall and figures 16 to 26 refer to the beside small Hall respectively.

Figures 5 to 7 presents the velocity of the three co-ordinates isolines on the z-y plane passing through the cell 9 (the middle of the main Hall). It is seen that the outdoor air penetrates in the Hall with a 4 m/s near the inlet door an then the velocity values decrease gradually. The velocities values can be considered as been in acceptable levels for the visitors. An increment of these values near the ceiling maybe is caused of the heated temperature

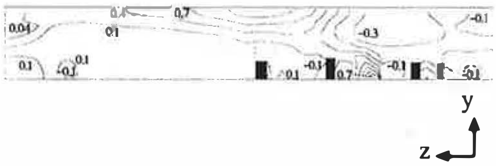

Figure 5. The u-velocity component at the main Hall (m/s).

of air due to the existence of lights but this values, near 1.2 m/s, do not really effect the visitors.

Figure 6. The v-velocity component at the main Hall (m/s).

Figure 7. The w-velocity component at the main Hall (m/s).

Figure 8 presents temperature contours at same z-y plane as above. The temperature of the outdoor air is 278 K but entering in the Hall an increment is observed due to the heating unit, the visitors and the lights. The lower values of the temperature are observed near the two doors.

Figure 8. Temperature contours at the main Hall (K).

Figures 9 to 15 refer to the iso-concentrations of the outdoor and indoor air pollutants, CO, NO, NO_2, O_3, SO_2, Pb and CO_2. As it is shown in figures 9 to 13, for steady state conditions, the pollutants concentrations increase near the middle of the Hall and towards the ceiling, as the air moves to the upper levels of the room where higher velocities occur.

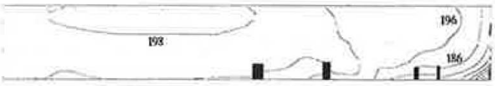

Figure 9. CO concentration contours at the main Hall (μg/s).

Figure 10. NO concentration contours at the main Hall (μg/s).

Figure 11. NO_2 concentration contours at the main Hall (μg/s).

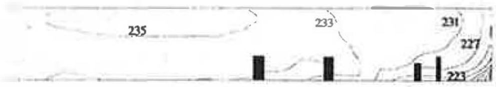

Figure 12. O_3 concentration contours at the main Hall (μg/s).

Figure 13. SO_2 concentration contours at the main Hall (μg/s).

Figure 14 refers to Pb concentration, and as it is indicated, this pollutant follows a different distribution due to the significant difference of its Schmidt number (2.7 10^{-6}) in comparison with the other compounds (their Schmidt numbers being between 0.476 and 0.833). As it is shown the Pb concentration decreases rapidly after the pollutant entry in the Hall. It is due to the lead deposition on the solid surfaces.

Figure 14. Pb concentration contours at the main Hall (μg/s).

Figure 15 presents the CO_2 concentration contour caused by the visitors breathing. As an indoor source, the CO_2 concentration increases at the level of the visitors head and decreases at higher levels. Some high CO_2 concentrations which are observed at particular sites, are due to the complexity of geometry of the Hall and the site of statues blocks.

Figure 15. CO_2 concentration contours at the main Hall (μg/s).

Figures 16 to 26, give similar patterns of velocities, temperature and pollutants concentrations for the small Hall, as those referred to the main Hall. It is obvious, however, that the air velocities are smaller, their magnitudes being in the range 0.1-0.7 m/s, because no additional currents are created due to the lack of openings in the room.

Figure 16. The u-velocity component at the small Hall (m/s).

Figure 17. The v-velocity component at the small Hall (m/s).

The same behaviour is also observed for the pollutant concentrations, which are higher than those in the main Hall.

Figure 18. The w-velocity component at the small Hall (m/s).

Figure 19, which represents the small Hall isotherms, enforces the above remarks. As it is seen the temperature fields also increase (280 K - 289 K), especially near the ceiling, due to the lights .

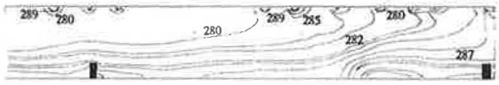

Figure 19. Temperature contours at the small Hall (K).

Figure 20. CO concentration contours at the small Hall (μg/s).

Figure 21. NO concentration contours at the small Hall (μg/s).

Figure 22. NO_2 concentration contours at the small Hall (μg/s).

Figure 23. O_3 concentration contours at the small Hall (μg/s).

Figure 24. SO_2 concentration contours at the small Hall (μg/s).

Figure 25. Pb concentration contours at the small Hall (μg/s).

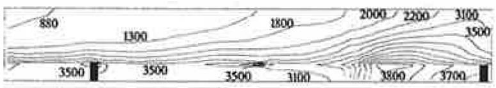

Figure 26. CO_2 concentration contours at the small Hall (μg/s).

Analogous conclusions are derived for the two other seasons, spring and summer. Some typical results are given in figures 27 to 30 for the summer case at the z-y plane,

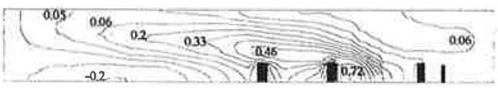

Figure 27. The w-velocity component at the main Hall in summer (m/s).

Figure 28. Temperature contours at the main Hall in summer (K).

for x-cells 9 and 25, respectively, representing the w-velocity component and temperature contours.

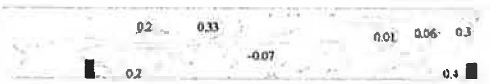

Figure 29. The w-velocity component at the small Hall in summer (m/s).

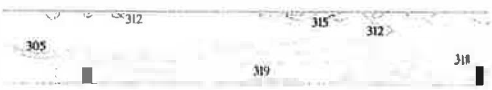

Figure 30. Temperature contours at the small Hall in summer (K).

CONCLUSIONS

This paper presents an attempt to bring the buildings atmosphere to the attention of a wider group of architects, heating and ventilation engineers and environmental scientists, through the description of a computational method. The work demonstrates that numerical solutions for such problems can be obtained quickly and economically. Results have been presented and appear physically plausible. Further work is still required, basically comparisons between predictions and experimental measurements. In the specific case of museums, there is much work to be done, if we are to understand how well to protect artefacts that form such an important part of our cultural heritage. Furthermore, this modelling procedure is applicable to any problem of heating, cooling, insulation and ventilation of domestic, commercial, industrial and public buildings, predicting, within practical resources, the thermal and fluid-dynamics behaviour of the relevant systems. It is intended to contribute to the effort towards designing and instrumenting buildings that provide cleaner and more comfortable environment, and for obtaining maximum energy savings.

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