INNOVATIONS IN VENTILATION TECHNOLOGY

21ST ANNUAL CONFERENCE

THE HAGUE, NETHERLANDS, 26-29 SEPTEMBER 2000

Design of Ventilation Systems in Industrial Buildings. A Computational Approach of Displacement Ventilation in Paper Industry

K. A. Papakonstantinou, C.T. Kiranoudis and N. C. Markatos

Department of Chemical Engineering, National Technical University of Athens, GR-15780, Athens, Greece

DESIGN OF VENTILATION SYSTEMS IN INDUSTRIAL BUILDINGS. A COMPUTATIONAL APPROACH OF DISPLACEMENT VENTILATION IN PAPER INDUSTRY

K. A. Papakonstantinou C.T. Kiranoudis N. C. Markatos

Department of Chemical Engineering, National Technical University of Athens, GR-15780, Athens, Greece

ABSTRACT

In this paper, the ventilation of a "crêpe" paper-processing workshop containing dryers, which generate a high thermal load, is considered. Displacement ventilation has been used for many years in industries with high thermal load. The main ventilation design problem is to find the appropriate ventilation flow that guarantees that the interface between the fresh air zone and the hot air zone is located above the occupied region of the room. The paper presents a mathematical model, implemented in a general computer code that can provide detailed information on the velocity, temperature and moisture fields in three-dimensional buildings of any geometrical complexity.

The simulation results could be used as a base for further analysis for ventilation design for other industrial processes producing high levels of thermal loads and moisture, intending to a proper ventilation system selection for a more healthy and comfort environment in a building.

NOMENCLATURE

Latin Symbols

h enthalpy (J kg^{-1})

k kinetic energy of turbulence J kg^{-1}

P pressure, Pa

R gas constant, J mol^{-1} K^{-1}

S_φ source rate per unit volume

T temperature, K

$\vec{u}$ velocity vector components, m s^{-1}

<u>Greek Symbols</u>

Γ_{φ} effective exchange coefficient of φ

• eddy dissipation rate, J s^{-1} kg^{-1}

μ viscosity, kg m^{-1} s^{-1}

ρ density, kg m^{-3}

σ Prandtl number for variable φ

1. INTRODUCTION

Displacement ventilation has been used for many years in industries with high thermal load. It was rediscovered for the ventilation of office rooms with low thermal loads in the last ten years. The principles on which the displacement ventilation is based are the following: the room contains dryers which generates plumes and the fresh airflow to the room is supplied into the occupied zone by low velocity diffusers. The plume from the dryer entrains air from the surroundings in an upward movement and the airflow is extracted from the room by return openings located in the ceiling. The main ventilation design problem is to find the appropriate ventilation flow that guarantees that the interface between the fresh air zone and the hot air zone is located above the occupied region of the room.

The paper presents a mathematical model, implemented in a general computer code that can provide detailed information on the velocity, temperature and moisture fields in three-dimensional buildings of any geometrical complexity. The model allows for such practical aspects of the problems under consideration as blockages, internal heat and humidity loads. The program calculates the velocity, the temperature and the moisture fields, throughout the three-dimensional configuration, and the results are presented in the form of velocity vectors, temperature and moisture contours. To solve the 3-D flow equations the "SIMPLEST" practice of Spalding (1980) is followed, using the k-• turbulent model as a closure relation for estimating turbulence.

Control over the temperature and moisture distribution can only be achieved by regulating the way air flows throughout the buildings. 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 manpower and experimental equipment and it can be difficult to alter geometry, and boundary conditions. A numerical computation model of the flow behavior in the room will therefore make a helpful tool to predict the velocity fields as well as the distribution of the thermal loads and the moisture, which are generated during the paper drying process. To alter the flow conditions in the computer model only means to change the boundary conditions.

The evolution, during the last decade, of a large number of multidimensional, multiphase models and solution techniques for simulating fluid flow and transport processes, coupled with the development of modern high speed/low cost computers and work stations has made it possible to use new computational fluid dynamics methods to assess the effectiveness of ventilation provisions in industrial and other buildings (Broyd et al, 1983).

In this study we consider a workshop containing three dryers processing “crêpe” paper. The workshop is 20 m long, 18 m wide and 7 m high. The ventilation system is based on displacement. Two cases are considered to demonstrate the capabilities of the present model. In the first case, the heat power generated from the process is estimated to 450 kW and the simulations are done before the use of a ventilation system and after the use of an effective ventilation system. The model developed is used in conjunction with a general - purpose CFD code, PHOENICS that can provide detailed information on the velocities as well as temperature and moisture fields. In the second case the heat power generated from the process is estimated to 300 kW. A parametric study is carried out and the interface height is studied as a function of the ventilation flow rate and of the heat power. Results are compared to those obtained from the Plume Box Model. Two ventilation flow rates and two heat powers are considered, to demonstrate the capabilities of the present model.

This study 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.

2. MATHEMATICAL FORMULATION OF THE MODEL

2.1. The Differential Equations

For steady flow, the equations for continuity, velocity components, temperature and moisture can be expressed in the following general conservation form (Markatos et al. 1983):

$$\frac{\partial}{\partial x_i}(\rho u_i \varphi) = \frac{\partial}{\partial x_i}\left(\Gamma_\varphi \frac{\partial \varphi}{\partial x_i}\right) + S_\varphi \tag{1}$$

where ρ is the density, u_i the velocity vector components, Γ_φ the effective exchange coefficient of φ and S_φ the 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, where μ the viscosity, σ the Prandtl number for φ and $G = \mu_l(\partial u_i/\partial x_j + \partial u_j/\partial x_i)\partial u_i/\partial x_j$ the turbulence production rate. The values of the constants C_1 and C_2 are 1.44 and 1.92, respectively (Markatos et al. 1983).

Table 1. Source rate and effective exchange coefficient for each φ

Equation	φ	S_φ	Γ_φ
continuity	1	0	0
momentum	u_i	$-\frac{\partial p}{\partial x_i} + \rho g_i \left(\frac{T - T_o}{T_o}\right)$	•
energy	h	Q	• /• $_h$
kinetic energy of turbulence	k	$G - \rho\varepsilon$	• /• $_k$
eddy dissipation rate	•	$C_1 \frac{\varepsilon}{k} G - C_2 \rho \frac{\varepsilon^2}{k}$	• /• .

2.2. The Solution Method

In order to solve the set of the above mentioned seven differential equations, the finite-domain technique is used that combines features of the methods proposed by Patankar and Spalding (1972), Spalding (1980) and a whole-field pressure-correction solver (Markatos et al. 1984). The space dimensions were discretized into finite intervals and the variables were computed at a finite number of grid centroid locations. These variables are connected to each other through algebraic equations derived by utilising their counterparts through integration over the control volumes defined by the above intervals. This leads to equations of the form:

$$\sum_n (A_n^\varphi + C)\varphi_P = \sum_n A_n^\varphi \varphi_n + CV \tag{2}$$

where the summation n is over the cells adjacent to a defined point P. The coefficients A_n^φ, accounting for convective and diffusive flux across the elemental cells, are formulated using the "upwind interpolation" scheme. The source terms can be written in the linear form:

$$S_\varphi = C(V - \varphi) \tag{3}$$

where C, V stand for a coefficient and a value of the variable φ. Pressure values were obtained from a pressure correction equation yielding the pressure change necessary to procure velocity changes that satisfy the mass continuity equation. To solve the 3-D flow equations, the SIMPLEST algorithm of Spalding is followed (Patankar and Spalding, 1972), in which finite-domain coefficients of the momentum equations contain only diffusion contributions, the convection terms being added to the linearised source term. The momentum equations were solved by a point-by-point procedure. The pressure-correction equation was solved over the whole-field (Spalding, 1980). The present model was implemented in the general computer program PHOENICS (Markatos et al., 1983).

3. APPLICATION OF THE MODEL

3.1. Test Cases Considered

The most common drying system in the paper industry is a single- or multi-cylinder section, where the paper is threaded through internally heated cylindrical dryer drums (Polat and Mujumdar, 1995). A workshop containing three dryers processing "crêpe" paper is examined in this study. The paper is impregnated with ink and then is rolled on heated cylinders. The workshop is a parallelepiped which dimensions are: 20 m long, 18 m wide and 7 m high (Figures 1a, 1b). The dryers are modeled by three pairs of parallelepiped obstacles which dimensions are: 2.5 m long, 1 m wide and 2 m height.

3.1.1. First case considered (A)

The heat power generated from the process is estimated to 450 kW. Eight planar diffusers are used which dimensions are: 1.5 m high and 0.5 m wide and they are located near the walls. Five planar diffusers are used which dimensions are: 2 m high and 1.3 m wide. Three of them are located near the dryers and the others are located near the walls. Three air exhausts are located on the ceiling above the dryers which cross section are 0.5 m x 0.5 m. The inlet velocities are horizontal, perpendicular to the diffuser and uniformly distributed on the surface of the inlet. For the first 8 inlets, the velocity intensity varies with the ventilation flow rate: 0.6 m/s and 0.2 m/s. For the 2 other inlets the velocity values varies : 0.5 m/s and 0.2 m/s respectively. The three diffusers located near the dryers have a velocity value of 0.29 m/s. The velocity vectors are oriented towards the dryers.

The program calculates the velocity, temperature and moisture fields throughout the three-dimensional configurations described above.

3.1.2. Second case considered (B)

The heat power generated from the process is estimated to 300 kW. Twelve planar diffusers are used which dimensions are: 1.5 m high and 0.5 m wide. Eight of them are located near the walls and the others are located near the machines. Five planar diffusers are used which dimensions are: 2 m high and 1.3 m wide. Three of them are located near the machines and the others are located near the walls. Three air exhausts are located on the ceiling above the machines which cross section are 0.5m x 0.5 m. Two ventilation flow rates are considered: 37000 m^3/h and 50000 m^3/h. The inlet velocities are horizontal, perpendicular to the diffuser and uniformly distributed on the surface of the inlet. For the first 12 inlets, the velocity

(a) (b)

Figure 2. Plan view of the drying room

(a) First case considered (b) Second case considered

intensity is 0.46 m/s. For the 5 other inlets the velocity values varies with the ventilation flow rate: 0.5 m/s and 0.75 m/s. The velocity vectors are oriented towards the machines, except for the four diffusers located near the machine whose velocity vectors are oriented towards the walls.

3.2. Boundary Conditions

Boundary conditions are specified as follows. At the inlets a fixed mass flow rate is specified as well as the values of velocity and the air temperature. At the walls, wall functions are used to calculate the wall shear stress (Patankar and Spalding, 1972). Finally the heat power released by the dryers and the humidity released by the paper dehumidification are added.

The main assumptions that are made are:

(a) No outside wind effect are taken into account.

(b) The air coming into the cavity is totally free of humidity.

(c) The test room walls are considered isothermal.

3.2. Grid Dependence

3.3.1. First case considered (A)

The reported results have been obtained using a non - uniform grid consisting of 32 cells in the x-direction, 14 cells in the y-direction and 39 cells in the z-direction. The solutions for the two cases are grid independent.

3.3.2. Second case considered (B)

The reported results have been obtained using a non - uniform grid consisting of 41 cells in the x-direction, 28 cells in the y-direction and 44 cells in the z-direction. The solution is grid independent.

3.4. Computer Storage - Time Requirements

3.4.1. First case considered (A)

The calculations have been performed on an ORIGIN 200 Workstation (Silicon Graphics), 4 CPU R 10000 processor and main memory 256 Mbytes. A typical CPU time for a run with the 32x14x39grid (17472 cells) is 13.5 hrs for full convergence.

3.4.2. Second case considered (B)

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 41x28x44 grid is 31.2 hrs for full convergence.

3.5. Convergence

A converged solution was defined as one that met the following criterion for all dependent variables:

$$\max\left|\varphi^{n+1}-\varphi^{n}\right|\leq 10^{-3} \tag{4}$$

between sweeps n and n+1. To improve convergence underrelaxation was used. Relaxation of the "false transient" type was used for the three velocity components and the moisture. For pressure and enthalpy, "linear" relaxation was used.

4. RESULTS AND DISCUSSION

4.1. First case considered (A)

Space restrictions dictate that only some indicative results may be given in Figure 2 through to 6. In Figure 2(a) the velocity field of the z-y plane for the no ventilation case is presented. In Figure 2(b) the velocity field of the z-y plane for the case of 0.6 m/s ventilation rate, at the x-axis site of 7.5 m is given. In Figure 3 temperature contours for both the cases are presented again in the z-y plane, at the x-axis site of 7 m. In Figure 4 the effect of ventilation on the moisture distribution is presented for both cases. Finally in Figure 5 the moisture distribution versus height and versus z-axis distance is given, for both the ventilation rates.

The velocity fields of the z-y plane, at x equal to 7.5 m for both cases, without and with ventilation system is presented, in Figure 2. It is observed that in the first case, where there is

(a) (b)

Figure 2. Velocity vectors at 7.5 m

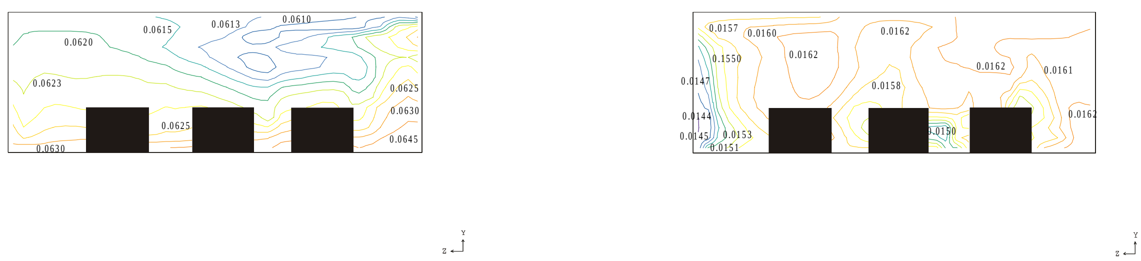
not a ventilation system, except of an air entrance and three outlets on the ceiling, the velocity vectors have large values near the floor and near the ceiling at the second half of the room. In the second case, where an efficient ventilation system operates, a more smooth air distribution is observed, as is shown in Figure 2b.

The temperature contours are presented in Figure 3, for both cases, without and with operation of ventilation system. It is obvious in the first case, that hot air occupies all the room with a temperature value of 318 K and only near the outdoor air entrance the temperature values decreases, without any significant result. On the contrary, after the use of an efficient ventilation system, like this one of Figure 3b, the temperature values range between 293 K and 296 K and a quite good temperature distribution is succeeded.

(a) (b)

Figure 3. Temperature contours at 7 m

In Figure 4, the effect of ventilation system on the moisture distribution is presented for both cases, at the x-axis site of 8.3 m. The important effect of ventilation is presented in these two moisture isolines. The humidity levels in the first case are very high and there is a great problem for the people occupied zone. In the second case, where the ventilation system is considered, the humidity levels are low enough and a thermal and moisture comfort is succeeded. The humidity range is between 0.0144 and 0.0162 and the lower values are observed near the occupied zone.



(a) (b)

Figure 4. Moisture contours at 8.3 m

Finally in Figure 5 the moisture distribution versus height and versus z-axis distance is given, for both the ventilation rates. As it is presented in these diagrams, the room humidity decreases with the increase of ventilation rate, and for this case the three times higher ventilation rate gives significant lower humidity values and results to a thermal and moisture comfort environment.

(a) (b)

Figure 5. Moisture distribution for different ventilation rates.

4.2. Second case considered (B)

The definition of Mierzwinski for the interface height h is adopted. The interface height is the height at which the air temperature has increased by 30% of the difference between outlet and inlet temperatures.

Table 2 presents a comparison between the values of h, computed by the CFD and by the Plume Box models. As it is observed there is a good agreement between the two models. The CFD model is more conservative, stratification occurs at lower height, but for all examined cases, an interface height above the occupied regions of the room has been succeeded for both of the models.

Table 2. Interface Height as a Function of Ventilation Flow Rate and Heat Power of the Process

Configurations	Interface Height (CFD) (m)	Interface Height (PBM) (m)
A1 (50000 m^3/h – 450 kW)	2.125	2.228
A2 (50000 m^3/h – 300 kW)	2.325	2.536
A3 (37000 m^3/h – 150 kW)	3.125	3.183

Figure 6 presents the temperature field for the A1 case. As it is seen the stratification takes place at an interface height of 298 K.

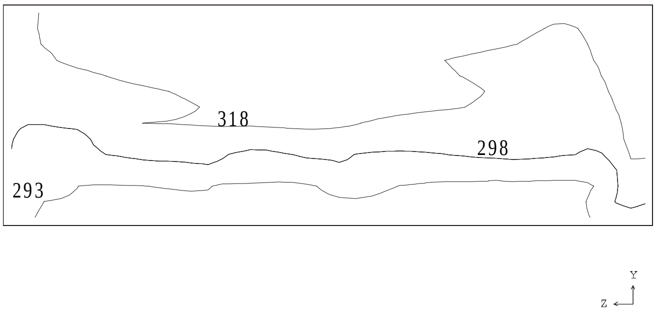


Figure 6. Temperature field for A1 case.

5. CONCLUSIONS

This paper demonstrates a CFD method for the description of the flow field when the displacement ventilation is applied. It is also an attempt to bring the CFD methods to the attention of a wider group of ventilation engineers and environmental scientists. The work demonstrates that numerical solutions for such problems can be obtained quickly and economically. Results have been presented and are physically plausible (Papakonstantinou et al., 1999, Markatos, 1984, Fontaine et al., 1998). General computer programs (like PHOENICS) are very useful tools for evaluation and analysis of existing ventilation equipment. In addition they can dictate new designs for an optimal operation, from the point of view of safety and hygiene.

6. REFERENCES

1. BROYD, T. W., DEAN, R. B., OLFIELD, S. G. and MOULT, A.
'The use of computational method to assess the safety and quality of ventilation in industrial buildings'
Proc. I. Mech. E. conference Heat and Fluid Flow in Nuclear and Process Plant Safety, London, 17-18 May 1983.
2. FONTAINE J.R. and ROUSSEAU R.
'Design of ventilation systems in large halls - Displacement ventilation in industry' Proceedings of 4th ECCOMAS CFD Conference, Athens, Greece, September 7-11, 1998.
3. MARKATOS, N.C. and SPALDING, D.B.
'Computer simulation of fluid flow and Heat/Mass Transfer Phenomena - The PHOENICS Code system'

A Lecture Course, School of Mathematics, Thames Polytechnic, London, 1983.

4. *MARKATOS, N.C.*
'Computer analysis of building ventilation and heating problems'
Passive and Low Energy Architecture, Pergamon Press, 1983, pp667-675.

5. *MARKATOS, N.C. and PERICLEOUS, K.A.*
'Laminar and turbulent natural convection in an enclosed cavity'
Int. J. Heat Mass Transfer, 27, No. 5, 1984, pp755-772.

6. *PAPAKONSTANTINOU, K. A., KIRANOUDIS, C. T. and MARKATOS, N. C.*
'Mathematical modelling of environmental conditions inside historical buildings. The case of the Archaeological Museum of Athens'
Energy and Buildings, accepted 2000.

7. *PAPAKONSTANTINOU, K. A., KIRANOUDIS, C. T. and MARKATOS, N. C.*
'Computational analysis of thermal comfort. The case of the archaeological museum of Athens'
Applied Mathematical Modelling Journal, accepted (2000).

8. *PAPAKONSTANTINOU, K. A., KIRANOUDIS, C. T. and MARKATOS, N. C.*
' Numerical Simulation Of Volatile Organic Compounds Dispersion Emitted From Flooring Materials In Buildings'
Drying Technology, accepted (2000).

9. *PAPAKONSTANTINOU, K. A., KIRANOUDIS, C. T. and MARKATOS, N. C.*
'Mathematical Simulation of Air Flow Field in Single-sided Ventilated Buildings' Proceedings of 6th National Conference of IHT, 3-5 November 1999, Volos, Greece.

10. *PATANKAR, S.V. and SPALDING D.B.*
'A calculation procedure for heat, mass and momentum transfer in parabolic flows'
Int. J. Heat Mass Transfer, 21,1972, pp1565-1579.

11. *POLAT, O. and MUJUMDAR, A.S.*
' Drying of pulp and paper'
Handbook of Industrial Drying (ed. A.S. Mujumdar), Marcel-Dekker, NY,1995, pp861-898.

12. *SPALDING, D.B.*
'Mathematical modelling of fluid mechanics, heat transfer and chemical-reaction processes'
A Lecture Course, Imperial College, London, CFDU Report No. HT5/80/1, 1980.