SIMULAR AIR
A THREE DIMENSIONAL TRANSIENT AIR FLOW PROGRAM

R. Mohr, J. Fuerst
ROM, System Development
Tilsiterstr. 162
2000 Hamburg 70, FRG

ABSTRACT

SIMULAR AIR is a computer code for calculating the three dimensional transient indoor air flow using a k,e - turbulence model. It solves the nonlinear partial differential equations for momentum, energy, continuity, turbulence and air purity by an implicit time marching technique. The equations are modeled by a finite volume procedure. The model handles a variety of flow, temperature and heat flux boundary conditions including prescribed inflows and outflows. All boundary conditions can be defined time dependent. The computer code is able to handle obstacles in the flow region to simulate furniture. The results are presented graphically on the screen or as numerical output on a printer or a file.

SIMULAR AIR is available for workstations but can also be run on a standard PC with an 80386 processor and either an Intel 80387 or a Weitek coprocessor under an extended DOS operating system. All modules of the program (preprocessing, calculation and graphical output) are menue driven and provide online help.

The program has been used to calculate air movement, distribution of temperature and fraction of fresh air in a three dimensional model room with alternating air supply and exhaust. Results of two calculations on a PC with respectively alternating and static air supply show only minor differences. They agree well with experimental investigations of the same room in both cases. The only influence of the alternating ventilation shows up to be a faster reaching the final distribution.

INTRODUCTION

In order to minimize the energy consumption of air conditioned buildings or to optimize the comfort inside rooms normally expensive experiments are necessary. Since the costs of computing power have developed a rapid decrease during the last decade, numerical simulations of air flow within rooms are a tool of accordingly increasing interest. They may support the designer in optimizing the layout and thereby reducing the costs of experiments. Experiments are still necessary to validate numerical results and will remain. But with validated algorithms predictions on air flow in rooms of standard layout can be achieved within days or hours, that closely resemble the reliability of experimental results.

Although the mathematical models for a realistic simulation of air flow in complicated three-dimensional geometries or with extreme boundary conditions still require the computational power of large mainframe systems, the same algorithms produce sufficiently realistic results for two dimensional cases or not too complicated three dimensional geometries within hours of computing time on a standard PC with common hardware configuration.

The computer program SIMULAR AIR has been ported on a PC with four MB internal memory and a standard VGA graphics display. It's usage only requires the selection of menues and the filling out of forms in order to define the geometry of the room under consideration. After the calculation is finished, the results can either be viewed in a three dimensional display of the geometry or a plane in one of the space directions may be selected for a two dimensional display.

As a sample application this report presents some computational results calculated with SIMULAR AIR. Their comparison with experimental results on the same sample room configuration shows the good quality of the simulation. The task of the calculation was to show if alternating air supply/exhaust could reduce the net energy consumption for the air conditioning of a realistic sample room. Calculations and experiments have thus been performed on the same room geometry with each, alternating and static air supply/exhaust.

SIMULATION METHOD

In order to predict the velocity and the temperature field the conservation equation for mass, momentum and energy have to be solved. Considering the influence of turbulence it is necessary to include additional equations to describe the turbulent behavior of the airflow. SIMULAR AIR employs the k,ε-turbulence model proposed by (Harlow et. al. 1968) and (Launder et. al. 1972). This set of model equations was originally designed for high-Reynolds-number flow.

In the present computer code the equations are used in conjunction with wall functions, that should describe the flow near the wall. For the dependent variables semi-empirical relationships are used, based upon the functions of the dimensionless distance normal to the wall:

$$y^+ = \frac{\rho\, w_t\, y}{\mu} \quad . \qquad (1)$$

The parameter y^+ has been used by (Schlichting 1968) and others to correlate experimental-determined flow properties near the wall. The near wall region is devided into a viscous ($y^+ < 11.63$) and an inertial ($y^+ > 11.63$) sublayer.

In the present version of SIMULAR AIR the kinetic energy k and the dissipation ε are furthermore determined from:

$$\frac{\partial}{\partial t} (\overline{\rho}\ k) + \frac{\partial}{\partial x_j} (\overline{\rho}\ \overline{u}_j\ k) = \frac{\partial}{\partial x_j} (\frac{\mu_{eff}}{\sigma_k} \frac{\partial k}{\partial x_j}) + \mu_t\ G_t -$$

$$- \frac{2}{3} \frac{\partial \overline{u_m}}{\partial x_m} (\mu_{eff} \frac{\partial \overline{u_m}}{\partial x_m} + \overline{\rho}\ k) - \overline{\rho}\ \varepsilon + G_B \qquad (2)$$

and

$$\frac{\partial}{\partial t} (\overline{\rho}\ \varepsilon) + \frac{\partial}{\partial x_j} (\overline{\rho}\ \overline{u}_j\ \varepsilon) = \frac{\partial}{\partial x_j} (\frac{\mu_{eff}}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j}) +$$

$$+ C_1 \frac{\varepsilon}{k} [(G_t + G_B)\ (1 + C_3 R_f) - \frac{2}{3} \frac{\partial \overline{u_m}}{\partial x_m} (\mu_{eff} \frac{\partial \overline{u_m}}{\partial x_m} + \overline{\rho}\ k)] -$$

$$- C_2 \frac{\overline{\rho}\ \varepsilon^2}{k} + \overline{\rho}\ \varepsilon \frac{\partial \overline{u_m}}{\partial x_m} \qquad (3)$$

with

$$R_f = - \frac{G_B}{G_t + G_B} \qquad (4)$$

$$G_B = \mu_{eff}\ \beta\ g_i \frac{\partial \overline{T}}{\partial x_i} \qquad (5)$$

$$G_t = \mu_t \frac{\partial \overline{u_i}}{\partial x_i} (\frac{\partial \overline{u_j}}{\partial x_i} + \frac{\partial \overline{u_i}}{\partial x_j}) -$$

$$- \frac{2}{3} (\overline{\rho}\ k + \mu_t \frac{\partial \overline{u_m}}{\partial x_m}) \frac{\partial \overline{u_m}}{\partial x_m} \quad . \qquad (6)$$

The effective viscosity μ_{eff} is the sum of the turbulent and the laminar viscosity, i.e.:

$$\mu_{eff} = \mu_t + \mu \qquad (7)$$

with the turbulent viscosity

$$\mu_t = C_\mu\ \overline{\rho} \frac{k^2}{\varepsilon} \quad . \qquad (8)$$

The constants are given by:

$C_1 = 1.44$, $C_2 = 1.92$, $C_3 = 0.8$, $\sigma_\varepsilon = 1.2174$,
$\sigma_k = 1.0$, $C_\mu = 0.09$

The SIMULAR AIR computer code uses a finite-volume procedure to solve the transient three-dimensional conservation equations of mass, momentum, turbulence energy, dissipation rate and air purity. For the temporal differentiation of all variables a fully implicit scheme is used. The solution procedure is a revised version of the SIMPLE algorithm with under-relaxation and overall pressure correction (Caretto et. al. 1972, Chorin 1968).

The present release of SIMULAR AIR works with temperature dependent density, viscosity and specific heat capacity. The wall heat flux is calculated as a function of the dimensionsless wall coordinate as proposed by (Reynolds 1974)

$$\dot{q}_W = - \frac{\mu\ c_p\ y^+}{\sigma_h} [\frac{1}{\kappa} \ln (E\ y^+) + P]^{-1} \frac{dT_W}{dy} \qquad (9)$$

with

$$P = 9\ (\frac{\sigma_e}{\sigma_h} - 1)\ (\frac{\sigma_e}{\sigma_h})^{-0.25} \qquad (10)$$

and

$$\dot{q}_W = - \frac{\mu\ c_p}{\sigma_e} \frac{dT_W}{dy} \qquad (11)$$

for $y^+ < 11.63$.

The constants are given by $\sigma_\varepsilon = 0.7$ and $\sigma_h = 0.9$. The turbulent velocity is defined as

$$v_t = (\ 2k\ )^{0.5} \quad . \qquad (12)$$

USAGE OF SIMULAR AIR

SIMULAR AIR uses a rectangular coordinate system for the definition of the finite volume cell mesh. All the coordinates of cell boundaries in each direction are defined by the user. Thus it is possible to define a more closely spaced grid in the most interesting regions, or in those, where steep gradients of the dependent variables are expected to develop. More complicated room geometries and obstacles in the flow domain can be defined by first enclosing the room in the smallest possible rectangular volume and then deleting cells or groups of cells at any location.

All the boundaries of obstacles or those surrounding the flow domain may be defined to be of one of three types: solid wall, symmetry plane or inlet/outlet. According to the type, boundary conditions can be set up in different ways: for a solid wall the temperature, heat flux and/or heat transfer coefficient may be given; for an inlet/outlet boundary the velocity profile, mass flow rate, temperature and pressure may be defined for as many different times as appropriate. These values at certain times are used for a linear interpolation at the simulation time steps.

For the input of data defining the geometry and boundary conditions SIMULAR AIR uses a menue and form driven user interface. If some input affects input at other locations in the input data sets for consistency reasons, the latter is updated accordingly. This makes SIMULAR AIR easy to use for non-experts as well.

machine	CPU-time sec	total time sec	factor
CONVEX 220	85	92	1
VAX 3200	606	711	7.7
PC Compaq 386 (25 MHz,Weitek)		344	3.7
PC 386 (20MHz) with SCB 860		124	1.3
PC IBM PS2/80 (Intel 80387)		757	8.2
HP Vectra RS 20 (Intel 80387)		680	7.4
Startdent 3000 (1 CPU)		52	0.56

Table 1: Comparison of computing times of SIMULAR AIR on various hardware configurations.
The benchmark simulation used: 600 cells, 10 s simulated time, 110 iterations 1 inlet, 1 outlet, free convection, different wall temperatures. The executable code had been compiled with maximum optimization on Convex, VAX and PC, without optimization on the SCB 860.

SIMULAR AIR requires an 80386 - IBM AT or compatible personal computer with at least 4 MB of memory and an 80387 - or Weitek - floating point processor. A hard disk of at least 40 MB is recommended. With 4 MB of memory SIMULAR AIR can be used for grids of about 6000 cells. Table 1 shows some benchmark results, which show, that a standard 386-PC with a Weitek coprocessor achieves comparably good results. An accelerating vector coprocessor board such as the SCB 860 can even make SIMULAR AIR on the PC nearly as fast as a CONVEX 220.

SIMULAR AIR is made up of several components, the most important of which is the main module, that performs the simulation calculation. Before the main module can be started, a preprocessing has to be performed. I.e. the information about the room geometry has to be cast into a form that enables the main module to adress any cell and all it's neighbors efficiently. Besides several modules for the conversion of datasets the third major module is the graphical output. In order to enable inspection of the results of a completed calculation on a PC with the standard DOS-memory of 640 KB only one time step of the simulated period can be viewed at a time. In the graphical output any of the distributions of the dependent variables can be viewed in any plane section by selecting the plane with a pointing device (mouse) or with cursor keys.

SAMPLE APPLICATION

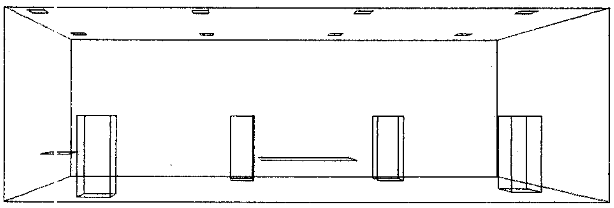
The room under consideration in the sample calculation was an office room of 10.7 m length, 4.45 m width and 3.4 m height (picture 1). Eight inlet/outlet-devices were equidistantly distributed over the ceiling. Between them there were six neon light lamps appearing as heat sources during the simulation. Two tables and four persons were arbitrarily distributed in the room. The inlet/outlet devices were configured as the one or the other in a chess-board like distribution, making up four inlets and four outlets each. In two simulation calculations the mass flow through the inlet/outlet devices was inverted every 30 s or 60 s respectively, thus interchanging the inlet/outlet configuration periodically. Another calculation was done on the same configuration but with steady mass flow (i.e. a fixed distribution of inlets/outlets).

The expectation had been, that the same mixing rate and temperature distributions could be achieved with a smaller mass flow through the inlet, if an alternating air-supply was employed, thus reducing the energy consumption. In the sample room geometry the simulation did not show the expected behaviour. Generally the final temperature and mixing rate distribution were achieved in a shorter time with the alternating supply, but after a simulated seven minutes the distributions did not any more exhibit large differences from those obtained with static supply. If on the other hand the mass flow through the inlet was reduced, an overall increase of the mean temperature resulted.

As an example the temperature distribution after five minutes simulated time is displayed for the case of alternating air-supply (picture 2). A nearly identical picture results for the static air-supply, the only difference being a somewhat smoother distribution.

The simulation calculation on the sample room took a net computing time of about 12 hours on a grid of 4000 cells. Even so, the results show a quite reliable agreement with the experimental data, being achieved with much less effort.

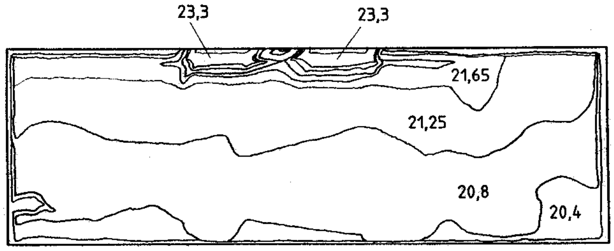
Measurements have been performed using the same room geometry. They generally reveal the same results as the simulation calculations, the main effect of the alternating air-supply being here as well, that the resulting temperature and mixing rate distributions were arrived at faster and that the energy consumption was not considerably reduced.



Picture 1: Three dimensional geometry of the sample application room with eight inlets/outlets, two tables and four persons.

NOMENCLATURE

C_1, C_2, C_3, C_μ	turbulence model constants
g	gravity
k	kinetic energy of turbulence
t	time
T	temperature
u_i	velocity in direction i
w_t	friction velocity $w_t=(\tau_w/\rho)^{0.5}$
x_i	tensor notation for space coordinates
y	coordinate normal to the wall
y_+	dimensionsless coordinate
β	gas expansion coefficient
ε	turbulence dissipation rate
μ	viscosity
μ_t	turbulent viscosity
ρ	density
σ_k, σ_ε	diffusion Prandtl numbers



Picture 2: Temperature distribution after five minutes simulated time. The values are in degree centigrade.

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