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EXPERIMENTAL AND NUMERICAL STUDY OF LOCAL MEAN AGE OF AIR

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ABSTRACT

This paper presents the results from the experimental and numerical study of a room with mixing ventilation, focused on the local mean age of air (LMA). The measurements were performed using the tracer gas concentration decay method. The numerical predictions were obtained from the computational fluid dynamics (CFD) module of the latest version of the ESP-r software.

In order to address the requirement for a proper choice of the number of control volumes in CFD, the analysis is made by comparing the results from two consequently finer numerical grids. Some guidelines for practising engineers are given concerning the number of numerical grid points and their distribution, reasonable for buildings energy simulations. The guidelines are based on common CFD rules supported by examples from the presented computations.

Both the fine and the coarse grid computations gave results, which were very close to the measurements. An important issue of the present study is that the coarse grid computations are reasonably close to the measured values, which allows the computation of LMA to be made on relatively coarse numerical grids - sometimes (as in the present study) as low as approximately 1000 grid points.

INTRODUCTION

When carrying out CFD calculations conflated with building energy simulation, the CPU-time for obtaining the results from iterations becomes very important. It is a known fact that the CPU time increases with $\sim N^2$, where N is the number of numerical grid points. On the other hand decreasing the number of grid points means decreasing the accuracy of the results. Therefore a proper choice of the number of grid points should be balanced with respect to these two contradictory requirements. Most often this is not a trivial task: the choice depends on a number of factors like the geometry complexity, the size and the number of ventilation openings as well as on the available computer hardware.

The present investigation aims to answer the question about the appropriate choice of numerical grids with respect to the needs of integrated building simulations. For this task computations of the local mean age of air on both the coarse and the fine numerical grids were made. The results were compared both to each other and to the measurements made by the authors in a laboratory room with mixing ventilation. This makes possible to draw the conclusions and establish the guidelines for practising engineers when quick and reasonably accurate results are required for the local mean age of air in ventilated rooms.

Generally, accuracy of CFD computations is determined by a complex interaction of the grid density with various other factors between which are the accuracy of discretization of the convective terms, the limitations of turbulence models and the uncertainties in the specification of boundary conditions. These factors are beyond the scope of the paper and therefore are only addressed briefly in the corresponding chapters specifying properly the conditions for the present study.

LABORATORY EXPERIMENTS

The LMA measurements were performed in a test room 4.2 m long, 3.6 m wide and 3 m high with isothermal mixing ventilation (Figure 1). The supply air opening 0.3 m × 0.2 m was placed symmetrically on the west wall having the bottom edge 2.05 m above the floor. A special lemniscate-shaped inlet nozzle was designed in order to obtain inlet velocity profiles as uniform as possible. The outlet position was on the ceiling, close to the east wall (opposite to the air supply).

The test room was placed in a bigger air-conditioned enclosure providing required external conditions for the experiments, i.e. the same air temperature as in the test room and its inlet opening. The average inlet velocity (over the inlet section) was 1.68 m/s with fluctuations in the inlet centre ±0.03 m/s, yielding the ventilation rate of 8 ach (approx. 363 m^3/hr). The temperature of the supplied air was 23±0.3 °C.

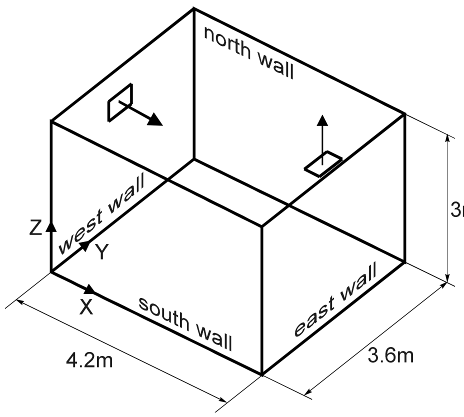

Figure 1: Schematic drawing of the test room

The concentration decay method was used to determine the local mean age of air using SF_6 as the tracer gas. At first a uniform tracer-gas distribution in the test room was reached, then the tracer-gas marking was cut off and the decay of the tracer-gas concentration due to the fresh (non-marked) ventilating air was measured. The local mean age of air (LMA) was calculated as the area under the concentration vs. time curve. The INNOVA AirTech Instruments multi-gas monitor type 1302 and sampler/dozer type 1303 were used for the concentration measurements. Tracer-gas dosing and monitoring were controlled via personal computer and the INNOVA 7620 software. The same software was used also for the evaluation of the local mean age of air.

The concentration decay curves were measured individually at 23 positions. Some of the points were measured more then once showing a reasonable repeatability (max. deviation 6.5%). Most of the measurements were done in the middle longitudinal vertical plane. Several locations in the corners and near the walls were also investigated.

NUMERICAL COMPUTATION OF THE FLOW FIELD AND THE LOCAL MEAN AGE OF AIR

In the present study a new version of the CFD model incorporated in the ESP-r integrated simulation software has been used. The CFD module is aimed to extend the possibilities for integrated building simulation in terms of detailed indoor air flow modelling (Beausoleil-Morisson *et al* 2001). However, in order to keep the program simple for users from a wide range of background (also with limited or no experience in CFD), some restrictions apply. Between these restrictions, which are also valid for the present investigation, is that a user specifies only airflow rate (and optionally velocity direction) in the inlet. Then the program calculates the inflow boundary conditions by setting equally distributed velocity and turbulence characteristics in all control volumes of the inlet. The turbulent kinetic energy k is calculated assuming the turbulence intensity 14% and the kinetic energy dissipation rate is calculated from $\varepsilon = k^{1.5}/(0.005\times A^{0.5})$, where A is the inlet area. Another restriction is that the number of control volumes in each spatial direction should be kept less or equal to 32.

For the discretization of partial differential equations on structured staggered numerical grids the CFD module uses the finite volume numerical method based on the first-order power-law scheme for the convective terms. The model includes equations for three velocity components and for the pressure correction segregated by the SIMPLEC algorithm. A standard version of the k-ε turbulence model is used together with the wall functions approach for the boundary conditions on rigid walls. As described below, the local mean age of air (LMA) is calculated using a separate partial differential equation.

LMA is one of the most important parameters when the removal of contaminants from a room or the ventilation efficiency in a closed space is considered. At an arbitrary point P of the room LMA is defined as the average time needed for air to reach the point P since it entered the room, e.g. Liddament (1993).

The calculation of the local mean age value θ is made by means of solving an additional partial differential equation. For numerical purposes the equation is derived from the concentration equation (called also 'passive scalar' equation, as it does not interact with the velocity field) with the assumption that the production of contaminants throughout the room is uniform (see Sandberg and Sjöberg 1983, Davidson and Olsson 1987). The final form of this equation used also for obtaining the present results is:

$$\begin{aligned}&\frac{\partial}{\partial x}\left[\rho u\,\theta-\left(\frac{\mu}{\sigma_l}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial\theta}{\partial x}\right]\\&+\frac{\partial}{\partial y}\left[\rho v\,\theta-\left(\frac{\mu}{\sigma_l}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial\theta}{\partial y}\right]\\&+\frac{\partial}{\partial z}\left[\rho w\,\theta-\left(\frac{\mu}{\sigma_l}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial\theta}{\partial z}\right]=1\end{aligned}\qquad(1)$$

Here u, v and w are the velocity components, ρ is the density of air, μ and μ_t are the physical and turbulent viscosities, σ_l and σ_t are the laminar and turbulent Schmidt numbers.

Equation (1) uses the results from the velocity distribution as well as the distribution of turbulent viscosity throughout the room. As the distribution of θ does not affect the velocity field and the turbulent viscosity distribution in the room, the calculation of θ

is made after the iterations according to the SIMPLEC algorithm are completed. Thus the calculation of LMA takes usually much less CPU-time, than the converged solution of air velocity vectors in the room.

The values of LMA can be reduced by an increased flow rate of air through the room. However, when different arrangements of the ventilation openings with different flow rates trough them should be compared between each other, it is useful to introduce a form for the results which will not depend on the flow rate of air. Therefore the dimensionless form of this parameter is introduced, indicating how efficiently different room airflow structures remove contaminants regardless of the particular flow rate trough the room:

$$\overline{\theta} = \frac{\theta}{V/Q} \qquad (2)$$

Here V is the volume of air in the room and Q is the volumetric flow rate through the room. This form of presentation was found to be convenient in a number of previous investigations of the authors (Denev *et al* 1997 and Stankov *et al* 1992) and hence it is used in all consequent figures.

RESULTS AND DISCUSSION

Two numerical grids – a coarse and a fine one have been used to compare the accuracy of the results. In both cases the airflow was simulated as three-dimensional. The coarse numerical grid consists of 11×9×11=1089 points (control volumes) which is reasonable for integrated building performance simulations. A grid which is three times finer in each direction, consisting of 30×27×30=24300 points (control volumes) was used for the comparison.

On the SGI O2 workstation with R5000SC/180 MHz CPU and 192 MB memory (which is similar to an average PC purchased in the last one or two years) the CPU-time per iteration was 0.5 s on the coarse grid while it was approx. 15 s on the fine grid. One should take into account that the fine grid requires much more iterations to achieve convergence – 180 iterations were necessary for the coarse grid, while with the fine grid it took 1240 iterations to reach the same convergence criteria (the sum of residuals for each calculated variable less than 10^{-4}).

The Figures 2a, 2b and 2c give an overall view of the flow patterns in the room showing vector plots for the coarse grid in the middle plane (y = 1.8 m), at the east wall (x = 4.1 m) and the south wall (y = 0.2 m). From the vector plots it is clear that the ventilation is of a mixing type, which in the case of perfect mixing would result in the room average LMA value of 1.0.

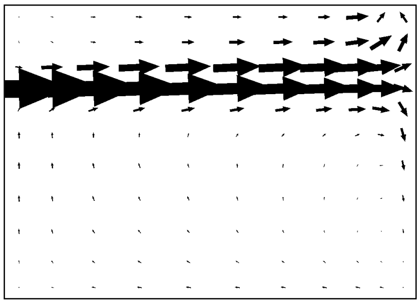

Figure 2a: Vector plot in the middle plane

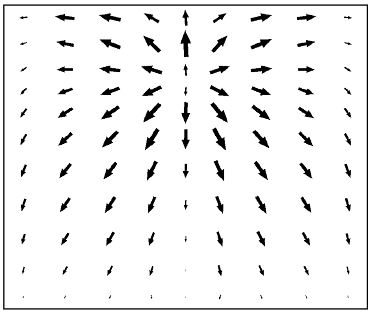

Figure 2b: Vector plot near the east wall

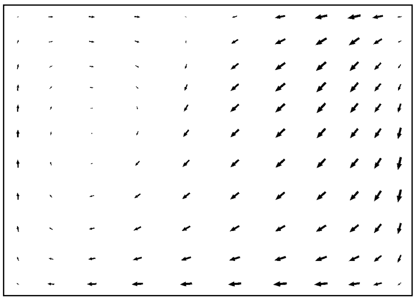

Figure 2c: Vector plot near the south wall

Any short-circuits and stagnant areas in the room (as these happened in our case) would increase the average LMA to a value greater than 1.0 (see e.g. Grieve 1991 or Roos 1999). The coarse grid computations resulted in the room average LMA of 1.171 while the fine grid computations resulted in the value of 1.126.

The higher predicted values for LMA in the case of the coarse numerical grid can be observed also from the comparison of Figs. 3a and 3b, which present the middle plane of the room (all values are made dimensionless using eq. (2); the dimensionless value 1.0 in the figures corresponds to 538 seconds).

As it can be seen in the figures, the LMA distribution follows the airflow patterns in the room increasing gradually from the inlet along the jet and reaching the highest values in recirculation zones with stagnant air. The mixing ventilation exhibits LMA values between 1.1 and 1.2 (Fig. 3b, fine grid) almost everywhere at the height of 1.1 m, which is representative for the breathing zone of a sitting person.

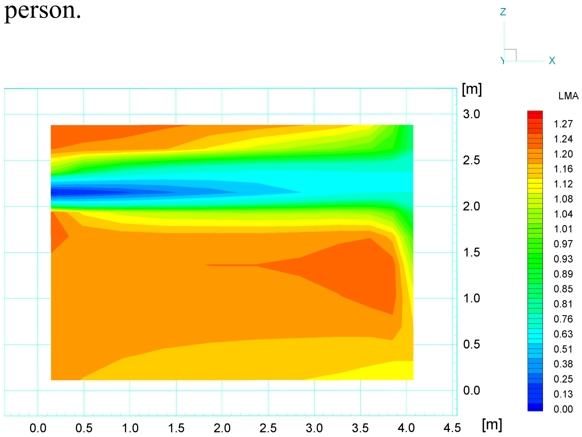

Figure 3a: Contours of LMA – coarse grid

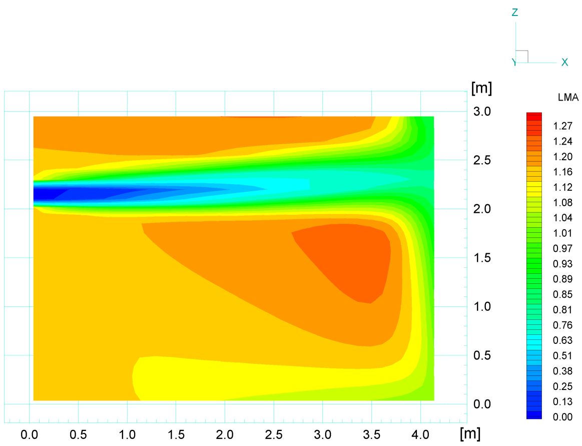

Figure 3b: Contours of LMA – fine grid

The differences between the two grids do not exceed 0.1 in numerical values for almost all regions below and above the jet. One exception is the difference of 0.2 in LMA observed in the inflow jet. This is due to the numerical diffusion in the coarse grid, which causes the jet to be more widely "spread". Some other exceptions are observed at the location where the main jet impinges the opposite wall (at x = 4.2 m) of the room and changes its direction. This region is featured by a strong curvature of the flow streamlines. Therefore, as a guideline, in regions of larger gradients of all flow parameters (like e.g. close to the inlet openings) and in regions where the streamlines are highly curved and not following the lines of the numerical grid, more grid points are required.

The comparison of the results from the two numerical grids with the laboratory experimental data along several vertical lines is presented in Figs. 4a, 4b and 4c. Since the numerical points were not coinciding with the locations of measured points, the lines in the figures are obtained after bilinear interpolation. The x-coordinates were chosen from the measurements and they cover regularly the middle plane of the room.

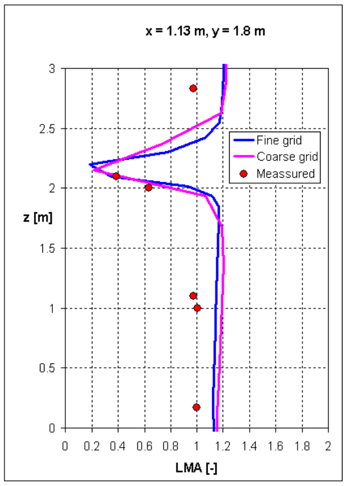

Figure 4a: Comparison between simulations and measurements

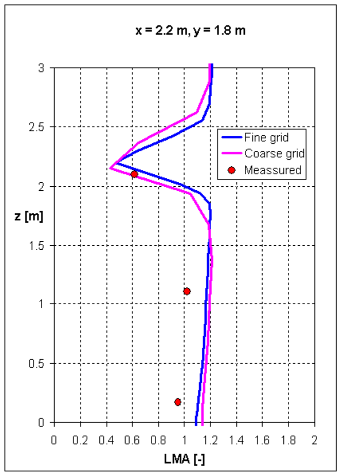

Figure 4b: Comparison between simulations and measurements

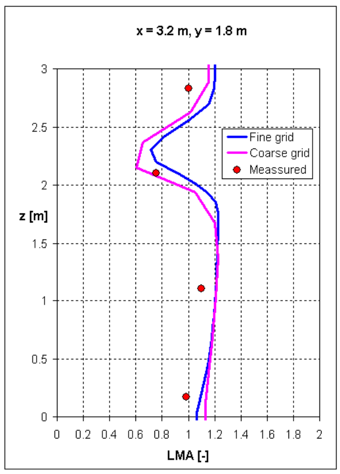

Figure 4c: Comparison between simulations and measurements

The difference between experimental and numerical values of LMA is between 10% and 20%, which we do not see as a large or unusual discrepancy, considering a number of similar results reported in the field of indoor airflow measurements and simulations (see e.g. Lemaire 1993 or Heiselberg 1997). At the same time the values obtained from the coarse grid are very close to those from the fine grid and therefore we may conclude that even the results on the coarse grid are good enough for practical engineering purposes.

Both the fine and the coarse grid data are slightly higher than the measured ones. This is similar to the results reported by Roos (1999) regarding the comparison between experimental and numerical data. As a whole, the agreement between laboratory experiments and numerical data in the present paper is better than that of Roos (1999) and of Davidson and Olsson (1987). The latter authors report discrepancies up to 25% for a grid of 2000 cells for a mixing ventilation case. The reason for better agreement in the present work is most likely in the fact that the present study is isothermal, unlike above cited investigations. It is known that for room flows with presence of large buoyancy forces effects like relaminarization due to stratification arise which deteriorates the assumption of isotropic turbulence on which the k-ε model is based (Davidson 1990 and Heiselberg 1996).

Major sources of discrepancies in the present work are in the first order scheme for convective terms and the restrictions of the used turbulence model to predict such a complex, highly three-dimensional flow with separation, reattachment, and re-circulation for which inconsistencies in predicting one region affect adversely the whole physical space (Heiselberg 1996). Another source is the need for interpolation of the numerical results in the measured locations as well as the rather integral specification of the boundary conditions, not allowing the presentation of boundary layer characteristics or exact specification of the turbulent quantities. And finally, though with a decreased value, the numerical diffusion is still present also in the second grid and forms still a source of discrepancies.

Some comments about the spread of the measured data: the measurements in some points were repeated several times in order to see their deviation as it is shown in Table 1. As it can be seen, the relative error between the different measurements is within 6.5%. The average values obtained from the individual sets of measurements (wherever available) are used in the graphs (Figures 4 a, b, c).

Several points were also measured outside of the middle plane - see Table 2. Generally, the results in the Table 2 show once again that the coarse grid computations are close enough (in terms of practical needs) both to those from the fine grid and to the measured data.

CONCLUSIONS

The present study shows the comparison of data from laboratory measurements with two sets of numerical results – one on a coarse numerical grid and one on a three times finer grid. The comparison is made for the local mean age of air parameter and the main results could be summarised as follows:

1. Both the fine-grid and the coarse-grid numerical results are found to be close to each other as well as to the experimental data. As expected, the fine grid data were found to be closer to the experimental values. However, even the coarse grid values are in a very good agreement with the experiments, which is accurate enough for practical engineering needs;
2. The values predicted on the coarse grid are higher than the fine grid values. The relative error for the mean value of the local mean age in the room for the coarse grid is 4%;
3. Differences between the coarse and the fine grid values are on average below 0.1 (dimensionless) in the occupied zone. This is slightly higher than the accuracy of measurements (which have an relative error up to 6.5% between repeated data series) and hence is quite accurate for solving practical engineering problems;
4. Even results on the coarse grid, containing 1089 numerical points proved to be sufficiently accurate for the presented problem (mixing ventilation, one air supply and one air extract opening, isothermal conditions). This is quite promising for integrated building simulations, i.e. it allows the CPU-time for such simulations to be kept in reasonable bounds;
5. Both the fine and the coarse grid data are slightly higher than the measured experimental values. This is similar to the results from comparison of other authors (Roos 1999);
6. The agreement between experimental and numerical data is better that the one reported by other authors (e.g. Davidson and Olsson 1987). The most likely reason is that the present investigation is for isothermal conditions.

x [m]	y [m]	z [m]	Location	Comments	LMA [s]	Average LMA [s]	Maximum relative deviation
4.10	1.80	3.00	outlet	---	573, 512, 550, 515	538	6.5%
2.20	1.80	2.10	along the jet	locations of low LMA	310, 326	318	2.5%
3.20	1.80	2.10			412, 379, 380	390	5.6%
2.20	1.80	1.10	height of a sitting person's head	locations of higher LMA than along the jet	523, 534	529	1.1%
3.20	1.80	1.10			578, 553	566	2.3%

Table 1: Laboratory test results in the middle plane – repeatability of the measurements

x [m]	y [m]	z [m]	Location	Comments	LMA [-] measured	LMA [-] coarse grid	LMA [-] fine grid
4.01	0.92	2.10	east wall	right to the impinging jet	0.94	1.05	1.02
4.01	2.68	2.10		left to the impinging jet	0.94	1.05	1.02
0.20	0.20	2.83	west wall corners	locations with high LMA	1.08	1.26	1.18
0.20	3.40	2.83			1.01	1.26	1.18
2.20	0.20	1.70	south and north walls	test of symmetry	0.97	1.14	1.10
2.20	3.40	1.70			0.93	1.14	1.10

Table 2: Comparison between the measured and calculated data outside of the middle plane

ACKNOWLEDGEMENTS

This work was made with the financial support from the European Commission (INCO Copernicus project ERB IC15 CT989 0511) and the Czech Ministry of Education (project MSM 210000011). The authors are indebted to the International Centre for Indoor Environment and Energy in Denmark, which provided the instruments for our laboratory experiments.

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