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Application of a New Method for Improved Multizone Model Predictions

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Abstract

Multizone models are a common tool for calculating air and contaminant exchange within rooms of a building and between building and outside. Usually a whole room is then modelled by one calculation node with the assumption of homogeneously mixed conditions within this room. In real cases, however, temperature and contaminant concentrations vary in space. The exchange to the neighbouring nodes via the flow paths is then a function of the local values of these variables. Detailed knowledge can be obtained from the solution of the transport equations for the air flow pattern within the room at the expense of higher computation cost.

This work shows the application to several examples of a new method which includes results from detailed calculations for one room of importance in a multizone model of a whole building. The examples with air in/exfiltration, ventilation and contaminant propagation show the effects on the results of the prediction of the air flow and the contaminant spread by relaxing the homogeneity assumptions.

The proposed name of the method is "Detailed flow path value method" (DFPV method) as separate local variable values are considered for each flow path from the room of importance to the neighbouring rooms instead of one average value. It is discussed in which situations the DFPV method can be expected to improve the multizone model predictions.

1. Introduction

Multizone models are computer tools for calculating air and contaminant exchange between rooms of a building and between the building and outdoors. Usually a whole room is modeled by one calculation node (a zone) under the assumption of homogeneous conditions within this room.

In real cases, however, temperature and contaminant concentrations vary in space. The exchange to the neighbouring nodes is then a function of the local values of these variables near the flow paths within each zone. These local values are very strong functions of the position of heat and contaminant sources and of the resulting air flow pattern. The air flow pattern itself is determined mainly by the heat sources and the mechanical and natural (e.g. open doors or windows) ventilation systems.

Examples where local values have a strong influence on the multizone model predictions include:

- Pollutant spread from a zone with a non-homogeneous concentration (i.e. a local source) into other rooms
- Enclosures of large horizontal (e.g. open-plan offices) or vertical (e.g. atria, staircases) dimensions
- Rooms with thermal stratification (e.g. displacement ventilation, open doors and windows) or generally complicated flows

Detailed knowledge about the air flow can be obtained from the field solution of the transport equations (Computational Fluid Dynamics, CFD). In theory, the air flow pattern for the whole building could be solved, but in practice the computational effort is too high. A method which does the CFD calculation for one room (or, generally, a small part of the building) only and allows it to feed the more adequate results somehow into the multizone formulation is a great help to improve the predictions of the whole building transport behaviour.

A link between multizone models and CFD can be also very useful the other way around, i.e. to calculate the CFD boundary conditions by the multizone program for a specific ventilation problem and for desired climatic conditions. This holds especially for cases with a combined mechanical/natural ventilation system, i.e. small mechanical exhaust systems with inlets and infiltration paths considerably influenced by stack and wind pressures.

This paper summarizes a method already presented in two previous papers [Schaelin et al. 1992, 1993] to include results from detailed single-room calculations in multizone models for a more adequate description of the real cases. We propose the name "Detailed flow path value method" (DFPV) as separate local variable values are considered for each flow path from the room of importance to the neighbouring rooms instead of one average value..

Parameter transfer between a multizone program and a detailed air flow simulation program is discussed. The advantage of the method is then demonstrated in several example cases with air infiltration and exfiltration, mechanical ventilation, large openings and contaminant propagation.

Parameter studies of simple examples illustrate the importance of considering local values and are used to derive recommendations when the DFPV method is useful to improve multizone calculations. As more and more people use today "easy-to-use" CFD codes for ventilation design, there is only little additional work to improve the multizone model predictions.

2. The linking method between a multizone model and a CFD program

2.1. Brief description of multizone models (MZ model) and CFD (Computational Fluid Dynamics) programs

In a multizone model a building is represented by a network of nodes and links (flow paths) between nodes. Usually a whole room is modeled by one calculation node (a zone) with the assumption of homogeneous conditions within this room. Different connections (flow paths) between zones are described by functional relationships between mass flow and pressure difference. Figure 1a shows a simple example of a house with two rooms with wind from the left. Figure 1b shows its network representation for the multizone modeler.

A system of algebraic equations derived from mass continuity is then set up. In the case of the presently used program COMIS [Feustel et al. 1990, 1992] the equations are solved for pressure. Mass flow is then derived from the pressure values; humidity and concentrations of contaminants are subsequently found from the calculated mass flow rates. Heat transfer is not considered by COMIS as also energy balance is not checked by COMIS, but temperature values are used as input boundary condition for the calculation of the mass flow between two nodes; even stratification profiles can be provided as input. The temperature values have to be known by experiments or calculated by a thermal building program.

In the example of Figure 1b the node values 1 and 2 are calculated by the multizone program; the other nodes serve as boundary conditions. The results are in general time-dependent in accordance to the climatic data used in the input.

In a CFD program for the calculation of a single-room air flow pattern, the room is divided into a large number of cells (typically 10'000) and for each cell transport equations for mass, momentum, energy, turbulence quantities and concentrations of contaminants are solved. Figure 1c shows schematically the detailed air flow pattern calculation for room 1. In the

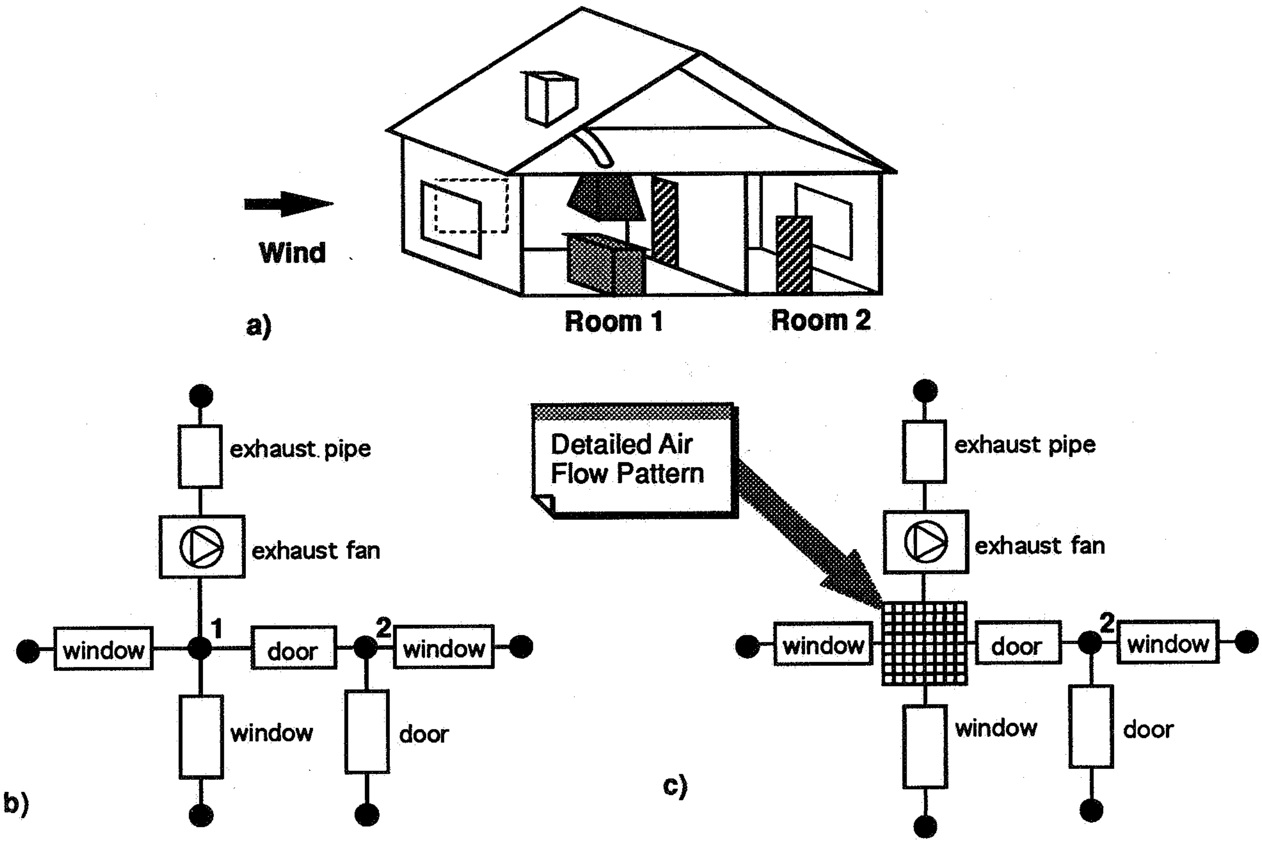

Figure 1: a) Example house with living room and kitchen combination. b) Multizone network of the whole building. c) The same network with the kitchen (Room 1) calculated by CFD.

new method all the variable values at the air flow links to room 1 (zone 1) are treated specially in the multizone program part as discussed in the next sections.

The following variables are solved for and discussed for the here presented application:

- pressure
- velocity components
- temperature
- concentrations of contaminants like humidity, CO_2, smoke ...

The turbulence variables depend on the turbulence model (the standard k-ε model was used) and are not discussed in the present paper. In the present examples the commercial code PHOENICS was used [Rosten and Spalding 1987, Chen et al. 1990]. The calculations have been performed in steady state, but could also be solved for time-varying boundary conditions. In most cases it is usually preferred to calculate stationary solutions for three or four different boundary conditions rather than the dynamical behaviour of the room air flow.

2.2. Method of detailed flow path values (DFPV method)

Figure 2 demonstrates the principle of the new method for a single-room in comparison with a purely multizone solution, discussed for concentration values of a certain contaminant.

Figure 2a shows the way the purely multizone approach goes and which concentration values are taken. We assume for this example that the external wind from the left (see Figure 1a) forces the air to enter room 1 through the two infiltration paths (two windows) and to leave room 1 through the exhaust to outside and through the exfiltration path to room 2. A certain room average value C_1 is calculated, determined by $C_{outdoor}$, internal sources of C and the air change rate (see also examples in section 3). This value C_1 is then also the same concentration value of the exhaust air and of the air which is passing to room 2.

Figure 2b shows the same situation for the new method where for room 1 detailed air flow and contaminant concentration patterns have been calculated. The air entering room 1 through the two infiltration paths is the same, but due to the concentration distribution, indicated by some contour lines in Figure 2b, the values at the exhaust, C_{exh}, and at the door to room 2, C_{door}, are different from each other and also from the room average value. These values can be extremely different depending on the air flow pattern and the position of the contaminant sources as illustrated by the examples in section 3.

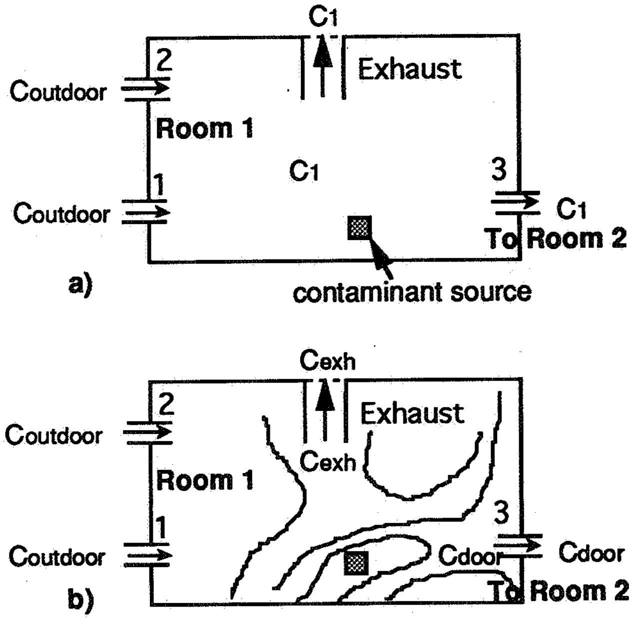

Figure 2: Schematic drawing of room 1.
a) Concentration values in multizone model.
b) Concentration values in DFPV method.

Instead of one average variable value for node 1 (C_1) different variable value (C_{exh} and C_{door}) are fed to the multizone program for each flow path connecting other nodes (exhaust and room 2 in the example above).

A suggested name of the whole method is "method of detailed flow path values" (DFPV). The following lines show which field values in the CFD program interact with the multizone program flow values across the CFD computation domain.

values in CFD program		***values in MZ program***
pressure, velocity field	↔	mass flow
local temperature field	↔	heat flow
local concentration distribution	↔	contaminant propagation

The application recipe of the method works generally as follows for the case of one room with CFD calculation as part of a whole building:

- A full-case multizone calculation is performed first (i.e. for the whole building)
- Flow path parameters are taken from this solution and transfered to the CFD program as input boundary conditions (see next section)
- The CFD code is then run for the single-room
- Variable values at the flow paths to the neighbouring rooms are transfered back to the multizone program.

In cases, where the new multizone values affect the solution values which have been transfered previously to the CFD code as input boundary conditions, the whole procedure can be repeated as many times as necessary (2 to 3 times is probably enough), i.e. the multizone results are fed back into the CFD code which is run another time, and the new results put again into the multizone program and so on. This procedure could be called an external or "manual" iteration or also "ping-pong"-technique.

2.3. Parameter transfer between MZ and CFD

Multizone programs like COMIS provide many flow paths which the user can choose for his particular needs. We discuss here only those of practical importance for the present connection to air flow calculations:

- Fans (ventilation supply, exhaust), flow controller
- Leakage flow paths with infiltration or exfiltration
- Large openings (open doors, open windows)

In the example cases the method is applied to some of these flow paths.

All the field values mentioned above can be transferred from one program to the other but will be handled differently. For each of the two programs they can be either input value (i.e. boundary condition) or output value (i.e. a result) or irrelevant, depending mainly on the flow direction and also on the flow path type. Usually the values are input to the CFD code for a flow into the calculation domain and output (results) from the CFD code for a flow out of the calculation domain. The following paragraphs give a short discussion of possible ways of interaction for the different variable types:

- Pressure: The node pressure as a result of the multizone program can be given to the CFD code, but is irrelevant in the case of a single-room calculation as discussed here. In a case where a flow path like an exhaust pipe would be included in the calculation domain it could be used, but it is generally preferred to use velocity boundary conditions rather than pressure boundary conditions for numerical reasons. However it is possible to transfer local pressure values (i.e. differences to the room mean pressure which is the same as the node value) due to temperature or air velocity differences to the multizone program allowing for higher accuracy. Example 4 shows a case with an additional pressure term due to thermal buoyancy.
- Velocities or mass flow belong to the main variables of concern here. Usually the multizone model will calculate first the whole network and therefore the resulting mass flows provide the boundary conditions for the CFD code. In some cases however (e.g. in a room with several large openings) it can also depend on the local air flow pattern and therefore be an unknown. In the case of only one outflow path, the outflow is the same as the inflow, and therefore the mass flow is already given.
- Temperature and gradients as a result of the CFD calculation can be given back to the multizone program and be used as input boundary conditions in the case of the COMIS program for a calculation with higher accuracy.
- Concentrations are the other main variables of concern. They will be input or output variable depending on the flow direction.

Table 1 shows an overview of input and output parameters for different flow paths, as seen from the CFD program. The role of the different variables depends mainly on the flow direction. The case of the large opening must be treated specially because bi-directional flow is possible and often occurs.

	Velocity	Temperature	Concentrations
Ventilation inlet	i	i	i
Ventilation outlet	i(o)	o	o
Leakage infiltration	i	i	i
Leakage exfiltration	i(o)	o	o
Large opening	i/o	i/o	i/o

Table 1: Input and output parameters for CFD program for different flow paths (i = input parameter, o = output parameter).

For the contaminant transport the new concentrations (the above-mentioned output parameters) can be fed directly into the contaminant modules of the multizone program without a second run. The Swiss version of COMIS (called COMERL) which was actually used for this application was adapted for this special type of input. With such local values, also time-dependent contaminant concentrations can be calculated under the assumption that the room air flow pattern remains unchanged.

3. Application examples of the DFPV method

The method has been demonstrated with examples which show the importance of considering non-homogeneous contaminant distributions, therefore enabling a more accurate prediction of the contaminant spread.

The first example, presented previously [Schaelin et al. 1992], shows how the air flow pattern in a room in a simple building with infiltration is calculated by a CFD program while most boundary conditions are given by the output of a multizone program. From the CFD results for a 3-dimensional calculation, temperature and concentrations at those locations where outflow occurs can be fed back to the multizone program. The contaminant transport in the whole building can be calculated with the new input values. The results obtained by the new method differ by a factor of 2 from the purely multizonal approach (see Schaelin et al. 1992 for details).

The second example, presented previously [Schaelin et al. 1993], shows the contaminant distribution in a building with 2 rooms which are connected by a crack in between and with a window each to the outdoors. For a certain wind condition, a study with varied contaminance source location in one room showed that the contaminance concentration in the second room varies by factor up to 5 for different source positions for a typical air flow pattern with three eddies in the first room (see Schaelin et al. 1993 for details).

The third (see section 3.1 below) example shows the contaminant distribution in a building with 3 rooms which are connected by cracks to outdoor and in between. A parameter study shows that the air flow pattern can change quite dramatically at moderate parameter changes. The forth example (see section 3.2 below) shows in a case where two rooms are connected by two flow paths finally the importance of taking buoyancy effects into account.

3.1. Example with 3 rooms and cracks (one connection between 2 zones)

In this example study the CFD calculation is only two-dimensional in order to save computation time, and it has been done for the whole building including the surroundings. In a real application the CFD calculation would be done only for room 1 with boundary conditions obtained from the MZ calculations.

Figure 3a shows the basic geometry of a two-storey building. Each room measures 4.2 m x 3.0 m. In room 1, which is the room of importance, there are some obstacles, a heater of 100 W below the left crack, a unit contaminant source of S = 0.01 ml/s, one connection to room 2 and another one to room 3, at separate room heights. Cases with 3 different wind conditions have been investigated for three different contaminant source locations each. The cracks are 1 cm high and 0.2 m long to the outdoors and 3 cm high and 0.2 m long between the rooms.

Figure 3b shows a part of the flow field for a wind of 1 m/s and Figure 3c some contaminant contour lines for source location 1 (Case 1.1). There is a separate smaller eddy in the lower right corner of room 1 yielding higher concentrations in that area of the room. The air

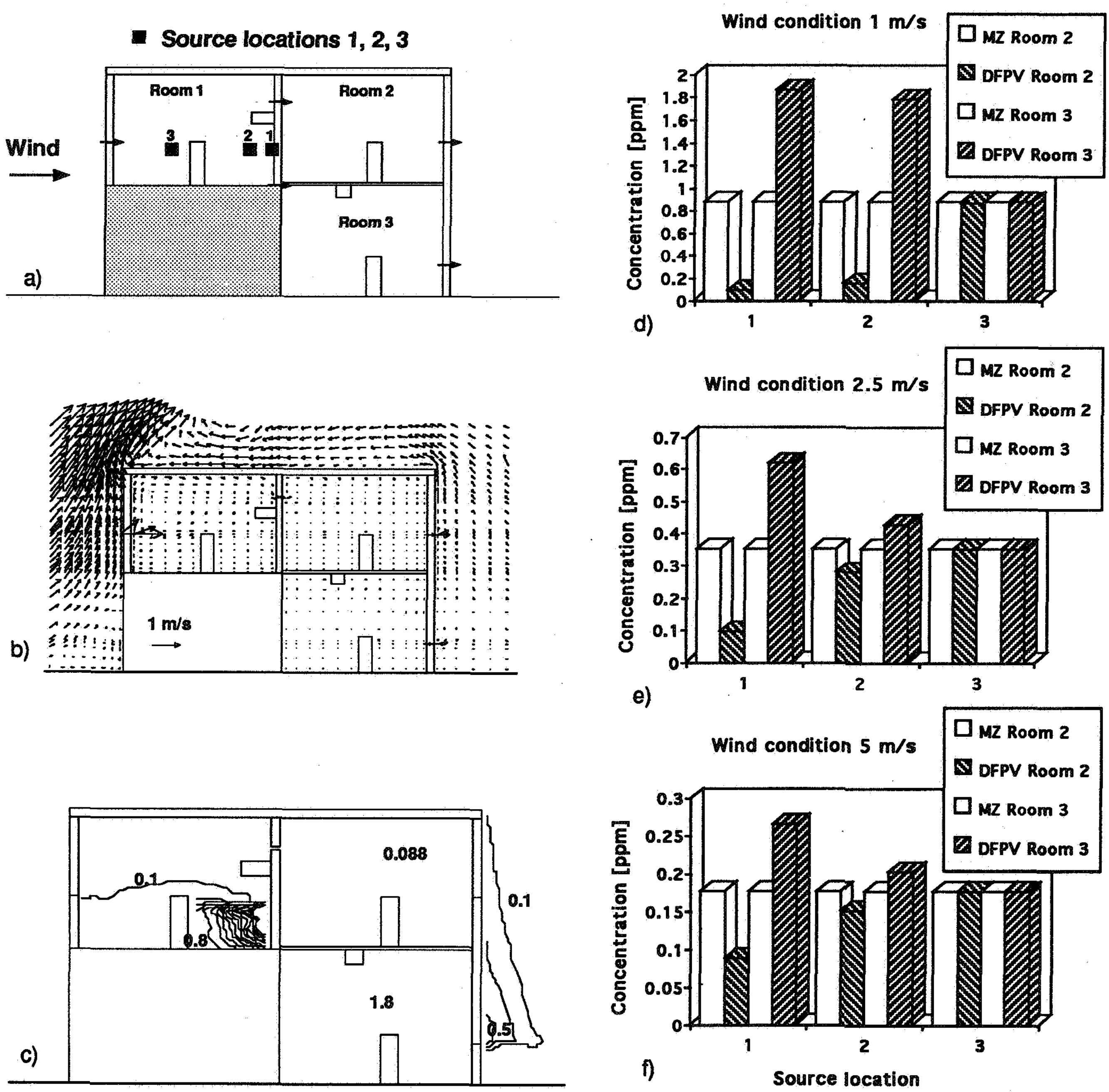

Figure 3: a) Sketch of the geometry with 3 rooms. b) Air flow field and c) contaminant contour lines for Case 1.1. d-f) Multizone and DFPV values in Room 2 and Room 3 for the 3 cases with wind velocities 1, 2.5 and 5 m/s.

velocity through the infiltration crack in to room 1 is 1.145 m/s in the Case 1.1, hence a ventilation rate of $r = 0.011\ m^3/s$ or 3.27 ach. The multizone concentration value in room 1 is is calculated in this case by $C = S/r = 0.873$ ppm in this case. The MZ concentrations in room 2 and room 3 are identical to this value because there is only one inflow path in each of these rooms.

Figures 3d-f show then graphically the CFD concentration values in room 2 and room 3 for all the subcases (these values are equivalent to the DFPV values). For source location 3 the values in the other rooms do not differ and are the same as the MZ values. However as soon as the source is located near the smaller eddy, the concentration values differ dramatically from the MZ value and are also very different from room 2 to room 3.

It is also interesting to note that for source location 2 the concentration distribution changes strongly between the wind condition 1 m/s and 2.5 m/s, i.e. the air flow pattern changes significantly between these cases. The tendency shows that at higher wind velocities the air flow pattern yield homogeneous conditions in this geometry.

3.2. Example with 2 rooms and 2 connections in between

This example is included as an illustration for buoyancy effects which are superimposed to the pure flow effects due to the wind pressure. The building geometry in this case is the same as in section 3.1, but with two rooms and one crack for each room to the outdoors and with two cracks between the two rooms at different heights. Room 2 is slightly warmer with a heat source of 100 W close to the right of the obstacle and a heat transfer of 20 W through the wall to room 1. Again the CFD calculation has been done for the whole building including the surroundings.

Figures 4a shows the air flow pattern inside the building for the case without wind and Figure 4b for a wind velocity of 0.3 m/s. In the case without wind a net flow occurs from room 2 to room 1 (to the left) due to buoyancy-caused pressure build-up of about 0.3 Pa inside room 2. Hence a net flow through the whole building to the left results.

At increased wind velocities from the left the net flow changes slowly to the right and very different flow pattern arise at such low wind velocities. Figures 4c-f show the velocities in the 4 cracks for wind velocities from 0.0 m/s to 0.3 m/s. The consideration of inhomogeneous distributions is more important at low wind velocities. The air flow distribution between the two rooms is then quite sensitive to a varied wind velocity. At higher wind velocities the buoyancy effects are dominated by wind pressure effects, and homogeneous distributions are more likely to occur.

4. In which situations is the DFPV method useful?

Multizone programs are used for the air and contaminant distribution in a whole building, i.e. a net of many rooms, based on the assumption of homogeneously mixed conditions within each room (purely MZ regime). As soon as this assumption is no longer valid, which is quite often the case (as demonstrated by the examples), one has to consider the use of CFD calculations for at least a part of the building. The mixing conditions clearly depend on the type of air flow pattern.

If the conditions are very inhomogeneous in all the rooms, a CFD calculation is needed for the whole building (possibly including the surroundings of the building). This is the purely CFD application regime.

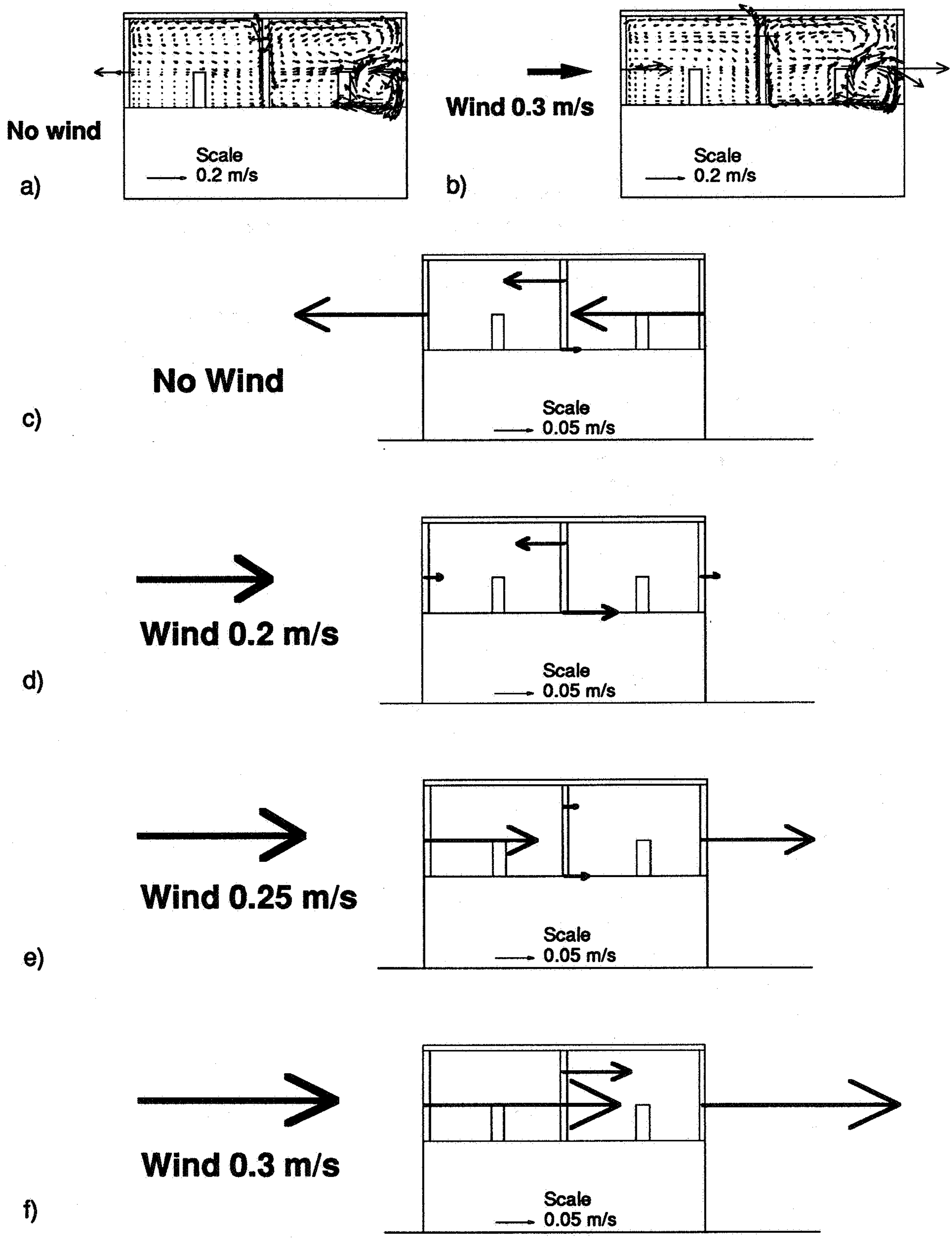

Figure 4: Case with 2 rooms and 4 cracks: a) Air flow pattern without wind. b) Air flow pattern for wind velocity 0.3 m/s. c-f) Air flow in cracks for wind velocities 0.0, 0.2, 0.25, 0.3 m/s.

If the conditions are such that in only one room (or sometimes a few rooms out of many) inhomogeneously mixed conditions are found, then a CFD calculation for this room (called "room of particular interest") is sufficient to calculate properly the air and contaminant distribution through the whole building. This is then the regime of the DFPV method. Figure 5 shows in an overview the regimes of the MZ and DFPV method.

The results of the example cases allow us to draw the rule that the contaminant distribution from the room of particular interest into other rooms is determined by:

- mainly the type of air flow pattern (namely whether homogeneously mixed or inhomogeneous conditions result) and
- secondly the positions of the contaminant source and of the flow paths into the other rooms (n the case of inhomogeneous conditions which is often found).

In most cases the contaminant is "passive", i.e. the air flow pattern itself is not affected by the presence of the contaminant (e.g. CO_2). If the contaminant is hot and/or highly concentrated, it can change the air flow pattern itself (mainly due to buoyancy effects). In summary the air flow pattern is determined by:

- Geometry
- Type, location and strength of inlets and outlets
- Position and strength of heat sources
- Position and strength of contaminants (in some cases)

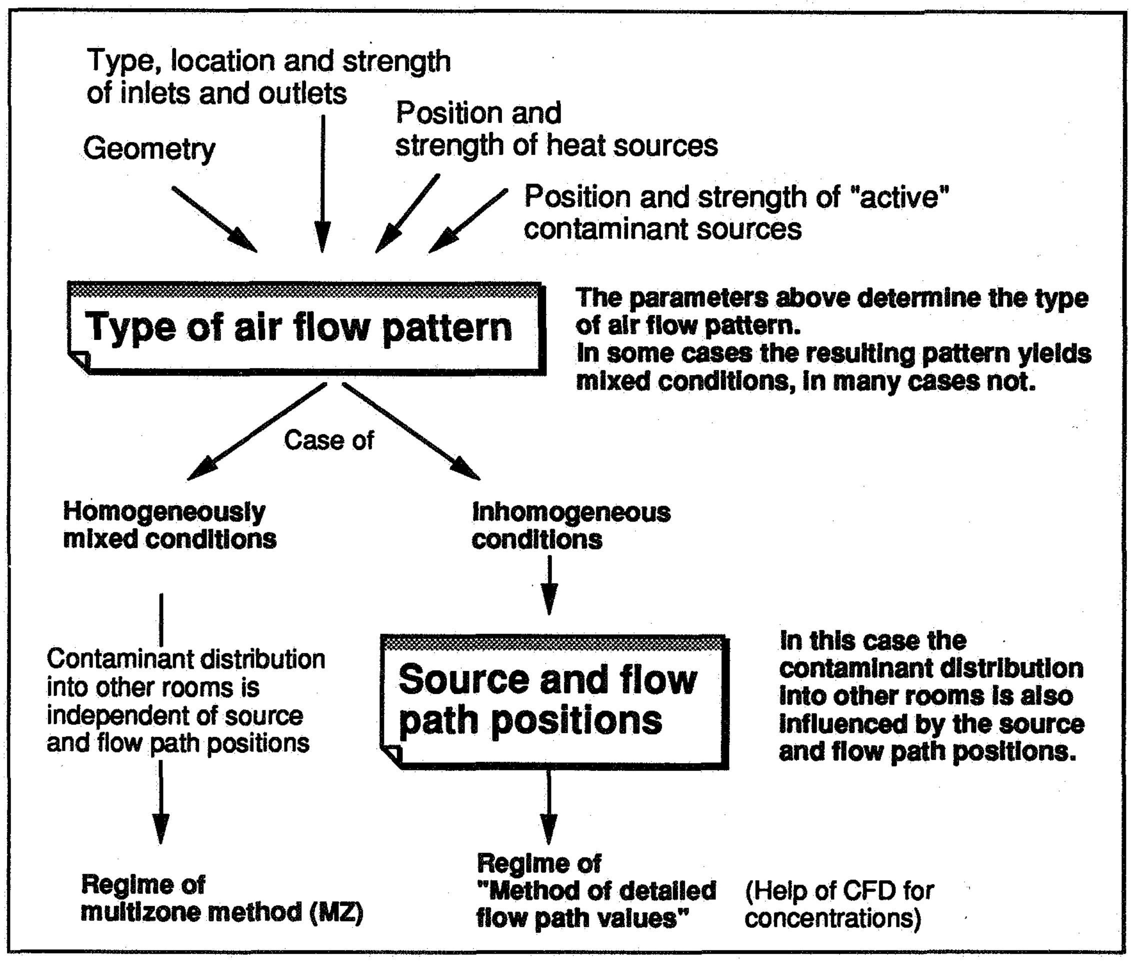

Figure 5: Application regimes of MZ and DFPV method. The DFPV regime is determined by the type of air flow pattern and by the source and flow path positions in the room of particular interest.

If the air flow pattern leads to homogeneously mixed conditions then the MZ model can give correct results, otherwise the DFPV method can be used to improve the MZ predictions. It is hardly possible to tell in advance whether mixed conditions will occur or not in a room. As an indication one could say that mixed conditions are very likely if there is only one large eddy in the whole room and if the wind pressure effects are dominant over buoyant effects. In the simple (but rare) case of piston-type flow the conditions are extremely inhomogeneous.

In many cases several eddies are interacting. That can lead to homogeneous concentration distributions depending on the source position only. The example in section 3.1 shows the strong effect of the source position on the contaminant distribution for an identical air flow pattern. In one case multizone calculation results are appropriate, in other cases not at all. Therefore the contaminant source position is the second important parameter after the air flow pattern which determines the contaminant distribution.

The case of time-dependent problems

Multizone models are often used for time-dependent calculations over a certain period of time, in the case of contaminant distributions in a building typically for a whole day. A full CFD calculation for such a case is very time-consuming and requires also enormous amounts of data storage. A combination with a multizone model can be very useful, as during the day the flow pattern changes only a few times substantially. For each of such a situation a steady-state CFD calculation can be done at very little additional work and computation time once the basic CFD case setup is done. The multizone model can then be applied with a few sets of CFD-MZ interface data and, possibly, a linear interpolation in between.

5. Conclusions

A method for linking CFD detailed air flow pattern results with multizone models has been presented. The accuracy of results of multizone simulations is limited by the assumption of homogeneously mixed conditions in each node. This condition is not fulfilled in many cases of practical importance. Therefore the accuracy can be considerably enhanced by using the presented method.

- The proposed name of the method is "method of detailed flow path values" (DFPV). Instead of the node variable value (the room average value) taken for each flow path to other nodes, a separate value from CFD calculation is provided for each flow path connecting this node with other nodes. In many cases no additional iterations (feeding back the new multizone results to the CFD code and repeating the procedure) are needed; when needed in some cases, 2-3 iterations might be sufficient.

- The method is demonstrated with simple examples which show the importance of considering non-homogeneous contaminant distributions. In the cases shown the calculated concentration values differ by up to a factor of 10 from the purely multizonal approach.

- The DFPV method should be used when in only one or a few rooms of a building inhomogeneously mixed conditions are found. A CFD calculation for these few rooms is then sufficient to calculate properly the air and contaminant distribution through the whole building. An inhomogeneous contaminant distribution depends mainly on the air flow pattern and secondly on the contaminant source location.

- The method can also be applied to more complicated or even time-dependent cases. It can be used to determine detailed transfer values of all the variables solved in the multizone program like pressure, mass flows, temperature and contaminant concentrations. The method so far is suited for applications to cases where detailed air flow knowledge in a few rooms or only one room (in the important ones) is sufficient to give a better prediction of the overall air and contamination transport. In these cases, the method promises to improve the multizone model predictions with few additional CFD computations.
- The method can also be used only for calculating appropriate boundary conditions for a CFD calculation of a room as part of a building.

Acknowledgements

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