ON SOLUTION CHARACTERISTICS OF COUPLING OF MULTIZONE AND CFD PROGRAMS IN BUILDING AIR DISTRIBUTION SIMULATION

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ABSTRACT

Multizone network models employ several assumptions, such as uniform pressure and quiescent air inside the zone, which may cause inaccurate results in flow calculations. This study intended to eliminate these assumptions in the zones, where these assumptions are inappropriate, by coupling a multizone network program with a CFD program. Through theoretical analysis, this paper proves that the solution of a building air distribution simulation by using the coupled program exists and is unique. Three possible coupling methods are then discussed and the best one is identified by studying their convergence and stability characteristics. A numerical test is further performed to verify the theory and it shows that the coupled program is able to effectively improve the accuracy of the results.

INTRODUCTION

Multizone network models (hereafter multizone) have been used as a research and design tool for over 20 years (Emmerich, 2001). They are widely used in such areas as air distribution analysis, smoke controls, and etc. To achieve fast computing speed, a number of assumptions must be made regarding zone parameters and airflow characteristics. For example, multizone network models typically assume each room of a building as a zone with quiescent air and neglect the airflow momentum preserved inside a zone. For a flow with strong momentum effect, these assumptions may compromise the accuracy of the results obtained.

Murakami et al. (1991) noted current multizone network models fail to account for the preservation of kinetic energy of the airflow. Gao and Chen (2003) found that multizone models produce incorrect results in a T-junction due to the neglect of preserved momentum within a zone. Our previous study (Wang and Chen, 2004) also found airflow rates as calculated by a multizone model could be quite different from those calculated by a CFD program for a zone with a highly non-uniform pressure distribution.

To avoid the multizone assumptions, thereby improving the accuracy of airflow calculations, one solution is to couple multizone program with a CFD program. Schaelin et al. (1993) proposed a method called 'method of detailed flow path values', in which the perfect mixing assumptions of multizone models were remedied by provided with detailed pressures, velocities and contaminant concentrations of flow paths from CFD. This study, however, only implemented the coupling of contaminant concentrations and did not actually perform the coupling in airflow simulations. The coupling procedure was also an external or 'manual' iteration. Clarke et. al (1995) and Negrao (1998) implemented an automatic airflow coupling inside ESP-r (Clarke, 1985). However, in their studies, different coupling methods resulted in different airflow patterns for the same airflow problem, which indicated multiple solutions of airflow coupling. Some other studies of coupling multizone network models with CFD programs are also found in the literature (Jayaraman et. al, 2004; Yuan and Serebric, 2002; Musser, 2001).

None of the previous studies, however, have conducted theoretical analysis on the solution characteristics of coupling multizone network models with CFD programs. Through theoretical analysis and numerical experiments, this paper investigates whether the coupled program can have a solution for an airflow problem and if the solution is unique. This paper also proposes three possible coupling methods and tries to identify the best one. All these efforts require the study of basic equations used in a coupled simulation.

THEORETICAL ANALYSIS

Basic equations and coupling principles

The idea of multizone-CFD coupling is to apply a multizone program to most zones of a building while applying a CFD program to the zones where the multizone assumptions are not appropriate. Figure 1 illustrates the coupling schematic for natural ventilation in a portion of a three-story building with an atrium. The atrium is so large that the homogeneous assumption is inappropriate and Zone c is thus chosen as the CFD zone while the remaining zones are modeled with the multizone program. Although the zones modeled with the multizone program are connected to Zone c by paths at their interfaces, the equations solved by the multizone and CFD programs are quite different from each other.

If Path ij connects Zone i and Zone j and F_{ij} is defined as the airflow rate through Path ij, F_{ij} is normally calculated in a multizone program by a power-law function of the pressure drop across Path ij,

$$F_{ij} = C_{ij} |\Delta P_{ij}|^{n_{ij}} = C_{ij} | P_i - P_j + P_{S,ij} + P_{W,ij} |^{n_{ij}} \quad (1)$$

Suppose Path ic connects Zone i for the multizone program and Zone c for the CFD program, and the flow rate through Path ic is F_{ic}, a mass continuity equation under steady state condition can be obtained for Zone i by the multizone program

$$\sum_j F_{ij} - F_{ic} = b_i \quad (2)$$

In the CFD program, a set of partial differential governing equations for mass, momentum, and energy conservation are solved. The equation can be written for steady state flow in a general form

$$\rho(\mathbf{V} \cdot \nabla)\phi - \Gamma_\phi \nabla^2 \phi = S_\phi \quad (3)$$

where ϕ can be 1 for mass continuity, U_j for air velocity component in the j direction (j=x, y, z), and T for temperature. With the SIMPLER algorithm (Patankar, 1980) the mass continuity equation actually becomes a pressure equation. If Path ic has n discrete grid points and we focus only on the grid point P (or cell P), the pressure equation for point P can be written in the following linear form

$$\sum a_{nb} p_{nb} - a_P p_P + f_P = b_P \quad (4)$$

A linear form can also be obtained for non-linear Eq. (2) in a multizone program

$$\sum_j C_{L,ij}(P_j - P_i) - F_{ic} = b_i' \quad (5)$$

where $b_i' = b_i - \sum_j C_{L,ij}(P_{S,ij} + P_{W,ij})$, by defining a linear flow coefficient

$$C_{L,ij} = \frac{F_{ij}}{\Delta P_{ij}} \quad (6)$$

Eqs. (4) and (5) show mathematically that, F_{ic} and f_P, are the only linkages between the multizone and CFD equations. It is thus important to know how they are calculated in both of the programs and how they are related to each other.

A CFD program calculates

$$f_P = C_{L,P}(P_{u,ic} - p_P) \quad (7)$$

where $P_{u,ic} = P_i + d_{ic}$, which is the upwind total pressure of Path ic if airflow is from Zone i to Zone c. The flow direction is determined by comparing $P_{u,ic}$ and p_P in the CFD program (Wang and Chen, 2004). In a multizone program

$$F_{ic} = C_{L,ic}(P_{u,ic} - P_{d,ic}) \quad (8)$$

where $C_{L,ic}$ is the linear flow coefficient and $P_{d,ic}$ is the average downwind total pressure for Path ic. Eq. (8) is actually the integral form of Eq. (7) and it comes

$$F_{ic} = \sum_{P=1}^{n} f_P \quad (9)$$

An assembled total matrix equation can then be obtained by applying Eqs. (4) and (5) to all the zones in Figure 1.

$$\mathbf{CP} + \mathbf{F} = \mathbf{B} \quad (10)$$

where **P** is the unknown pressure vector of zones and cells and **F** is the vector of unknown flow rates at interface paths and cells. To ensure that Eq. (10) is closed, two coupling principles must be followed.

- Eq. (9) should be used as the convergence criterion of the coupled simulation.
- The relationship of flow rate and pressure drop in Eq. (7) must be the known condition for each grid points of Path ic.

With the above two principles and Eq. (10), we can perform a theoretical study on the important parameters linking the multizone and CFD equations to investigate the numerical characteristics of the coupled simulation.

Parameter analysis

To study the numerical characteristics of the coupled simulation, we need to find the relationships of such important parameters as $P_{u,ic}$, $P_{d,ic}$ and F_{ic} for both multizone and CFD programs. The following simplifications are employed to make current theoretical analysis possible:

- Flow coefficients, $C_{L,P}$, $C_{L,ij}$, and $C_{L,ic}$, the source terms, b_i, b_i', d_{ic}, b_P, and **B**, and the coefficients a_P and a_{nb}, are constant.
- In the CFD calculation, the flow coefficients, $C_{L,P}$ and a_P, and the pressures, p_P and p_{nb}, are uniform at Path ic.
- The derivatives of Pd,ic and Fic over Pu,ic exist and are bounded.

Then, we can obtain the following relationships for a multizone program by using Eqs. (5) and (8)

$$P_{d,ic} = \frac{C_{L,ic} + C_{L,ij}}{C_{L,ic}} P_{u,ic} - \frac{C_{L,ij}P_j - C_{L,ij}d_{ic} - b_i'}{C_{L,ic}} \quad (11)$$

$$F_{ic} = -C_{L,ij}P_{u,ic} + C_{L,ij}P_j - C_{L,ij}d_{ic} - b_i' \quad (12)$$

By using Eqs. (4), (7), (8) and (9) for a CFD program we have

$$P_{d,ic} = \frac{C_{L,P}}{a_P + C_{L,P}} P_{u,ic} + \frac{\sum a_{nb}p_{nb} - b_P}{a_P + C_{L,P}} \quad (13)$$

$$F_{ic} = \frac{a_P C_{L,ic}}{a_P + C_{L,P}} P_{u,ic} - \frac{C_{L,ic}(\sum a_{nb}p_{nb} - b_P)}{a_P + C_{L,P}} \quad (14)$$

These equations reveal the mathematical relationships of $P_{u,ic}$, $P_{d,ic}$, and F_{ic}, which are exchanged between the two programs iteratively through boundary conditions. The existence and uniqueness of the solution to this iterative procedure can be investigated by studying the derivatives of these equations for a coupled simulation.

Solution existence and uniqueness

Zhai and Chen (2003) successfully coupled a building energy simulation program with a CFD program. A similar approach to Zhai's study is adopted here to prove the solution existence and uniqueness.

Applying the derivatives over $P_{u,ic}$ for both sides of Eqs. (11)-(14), we have

$$\frac{\partial P_{d,ic}}{\partial P_{u,ic}} = \begin{cases} \dfrac{C_{L,ic} + C_{L,ij}}{C_{L,ic}} - \dfrac{C_{L,ij}}{C_{L,ic}} \dfrac{\partial P_j}{\partial P_i} \text{(multizone)} \\ \dfrac{C_{L,P}}{a_P + C_{L,P}} + \dfrac{\sum a_{nb} \dfrac{\partial p_{nb}}{\partial P_{u,ic}}}{a_P + C_{L,P}} \quad \text{(CFD)} \end{cases} \quad (15)$$

$$\frac{\partial F_{ic}}{\partial P_{u,ic}} = \begin{cases} -C_{L,ij} + C_{L,ij} \dfrac{\partial P_j}{\partial P_i} \quad \text{(multizone)} \\ \dfrac{a_P C_{L,ic}}{a_P + C_{L,P}} - \dfrac{\sum a_{nb} \dfrac{\partial p_{nb}}{\partial P_{u,ic}}}{(a_P + C_{L,P})/C_{L,ic}} \text{(CFD)} \end{cases} \quad (16)$$

For a coupled simulation, normally, $0 \le \partial P_j / \partial P_i < 1$ and $\partial p_{nb} / \partial P_{u,ic} \ge 0$, then we have

$$\frac{\partial P_{d,ic}}{\partial P_{u,ic}} = \begin{cases} (1, \dfrac{C_{L,ic} + C_{L,ij}}{C_{L,ic}}] \quad \text{(multizone)} \\ [\dfrac{C_{L,P}}{a_P + C_{L,P}}, 1) \quad \text{(CFD)} \end{cases} \quad (17)$$

$$\frac{\partial F_{ic}}{\partial P_{u,ic}} = \begin{cases} [-C_{L,ij}, 0) \quad \text{(multizone)} \\ (0, \dfrac{a_P C_{L,ic}}{a_P + C_{L,P}}] \quad \text{(CFD)} \end{cases} \quad (18)$$

Eqs. (17) and (18) illustrate how $P_{d,ic}$ and F_{ic} change with $P_{u,ic}$ in multizone and CFD programs. The solution existence and uniqueness can then be studied through Eqs. (17) and (18).

The $P_{d,ic}$ - $P_{u,ic}$ relations are plotted in Figure 2. If there is a solution for the coupled multizone and CFD program, the two curves will intersect as shown in the figure. Eq. (17) shows that the derivative of $P_{d,ic}$ over $P_{u,ic}$ for multizone calculation is always greater than unity, while that of CFD is less than unity as shown in Figure 2a. Therefore, both curves can at least intersect at one point, which indicates at least one coupling solution exists.

A similar analysis can also be applied to the relations of F_{ic}-$P_{u,ic}$, which are omitted here due to limited space available in this paper. The next concern then will be whether the solution is unique or not.

The method of reduction to absurdity is used to investigate the uniqueness of the coupling solution. For the $P_{d,ic}$ - $P_{u,ic}$ relations, Figures 2b and 2c show two possible scenarios of multiple solutions. Suppose we already find a solution at Point 1 through the above analysis of solution existence, and we then assume that the $P_{d,ic}$ - $P_{u,ic}$ curves may intersect at other points. In the first scenario as indicated by Point 2 in Figure 2b, the slope of CFD curve at Point 2 is less than unity, which satisfies Eq. (17). The slope of multizone curve at Point 2, however, does not satisfy Eq. (17) so the first scenario is impossible and Point 2 cannot be a coupled solution. The second scenario shown in Figure 2c is also impossible because one specific pressure boundary condition $P_{u,ic}$ in CFD can have only one corresponding $P_{d,ic}$ for a given situation (including given numerical models and techniques). Therefore Points 2 and 3 cannot be coupled solutions and Point 1 is the only solution to multizone and CFD coupling.

The analysis here only discusses the situation, in which the airflow of Path ic is from Zone i to Zone c as in Figure 1. It is easy to apply a similar analysis to prove solution existence and uniqueness when the airflow of path ic is from Zone c to Zone i. In conclusion there is thus one and only one solution for a multizone and CFD coupling. The question now is how to obtain this unique solution.

Different coupling methods

As shown in Figure 1, when the airflow of Path ic is from Zone i to Zone c, the upwind total pressure, $P_{u,ic}$, the downwind total pressure, $P_{d,ic}$, and the airflow rate, F_{ic}, are the boundary conditions to be exchanged between the two programs. Three coupling methods are possible according to permutation and combination:

1. multizone gives $P_{u,ic}$ to CFD and CFD returns $P_{d,ic}$ to multizone;
2. multizone gives $P_{u,ic}$ to CFD and CFD returns F_{ic} to multizone;
3. multizone gives F_{ic} to CFD and CFD returns $P_{d,ic}$ to multizone.

Negrao (1995) thought that the pressure type boundary condition was applicable to the cases where the inlet momentum changes the flow locally but does not affect substantially the zone air flow pattern. The velocity type condition was appropriate to inlet openings where the momentum magnitude can significantly modify the zone air flow pattern and must be known in advance. No further explanlations were provided for his claims.

We found that the above coupling methods will result in different assembled matrix equations. When pressure and airflow rate boundary conditions are used together, such as in Methods 2 and 3, the assembled matrix equation is in the form of Eq. (10). Howerver, when only pressure boundary conditions are employed (Method 1), Eq. (10) becomes

$$\mathbf{C_1 P = B_1} \quad (19)$$

Different assembled matrix equations will not have the same numerical characteristics. The numerical performance of one matrix equation could be better than others.

Selection of the best coupling approach by the Scarborough criterion

Scarborough (1966) established a convergent criterion for a Gauss-Seidel solution for a set of linear equations. The criterion is often used to evaluate CFD equations. In this study, multizone and CFD programs provide complementary boundary conditions and the coupled program basically tries to obtain a Gauss-Seidel solution of the assembled matrix equation. Thus the Scarborough criterion could be used.

For a Gauss-Seidel solution of a linear system like Eq. (20), a sufficient convergence condition, the Scarborough criterion, is to satisfy Inequality (21):

$$a_{\phi,P}\phi_P = \sum a_{\phi,nb}\phi_{nb} + b_{\phi} \quad (20)$$

$$\frac{\sum |a_{\phi,nb}|}{|a_{\phi,P}|} \begin{cases} \leq 1 & \text{for all equations} \quad (21a) \\ < 1 & \text{for at least one equation} \quad (21b) \end{cases}$$

The Scarborough criterion concludes that Eq. (20) has a convergent solution if the matrix is 'diagonally dominant'.

In a coupled simulation, Inequality (21b) can always be satisfied so long as at least one zone connects directly to a zone with a fixed pressure in Eqs. (10) or (19). The multizone calculation itself actually requires that at least one zone be connected to a zone with a fixed pressure. Otherwise the airflow system in a multizone program will be singular and can have no single solutions (Lorenzetti, 2002). Inequality (21b) is therefore satisfied automatically in a coupled simulation.

Among the three methods, only Method 1 satisfies Inequality (21a) since it solves Eq. (19), which is a combination of Eqs. (5) and (8) and where each independent off-diagonal pressure will introduce its coefficient to that of the diagonal pressure of the matrix. Methods 2 and 3 solve the matrices in the form of Eq. (10) and **F** is an independent vector. The coefficients of **F** do not contribute to those of the diagonal pressure in the matrix. The condition of 'diagonal dominance' may not be always satisfied for Eq. (10). Method 1 therefore is the only one that satisfies the Scarborough criterion and is guaranteed to have a convergent solution.

Since the Scarborough criterion is only a sufficient condition and the other two methods may still produce a convergent solution, it may be not convincing enough to conclude that Method 1 is the best method. A stability analysis is then performed to provide an in-depth investigation of the numerical performance of the coupling methods.

Numerical stability analysis

In order to further investigate the stability of the three coupling methods, we have further examined the iterative procedure when exchanging boundary conditions between the multizone and CFD programs in a coupled simulation. Figure 3 shows that, during a coupled solving procedure, the output of one program becomes the input of the other. When both inputs and outputs stabilize (their values do not change), the solution of the coupling is considered convergent. This iterative coupling procedure can be regarded as a closed-loop system. If r is the input parameter of a multizone program from CFD and r_k is its value at the coupling iteration k, we can define the difference of r at this iteration as $\Delta r_k = |r_{k+1} - r_k|$. For example, if r_0 is the initial value of r, the initial difference of the flow rate/pressure between the multizone and CFD program $\Delta r_0 = |r_1 - r_0|$.

Figure 3 illustrates that the system equation for a multizone program is *M*, and its solution at iteration k, i_k, can be calculate as $i_k = M\{r_k\}$. Similarly, we have $r_{k+1} = C\{i_k\}$ for the CFD program.

If Δr_k can be expressed by the partial derivatives of $M\{r\}$ and $C\{i\}$, we have

$$\Delta r_k = \left|\frac{\partial M}{\partial r} \times \frac{\partial C}{\partial i}\right| \times \Delta r_{k-1} = \left|\frac{\partial M}{\partial r} \times \frac{\partial C}{\partial i}\right|^k \times \Delta r_0 \quad (22)$$

Then when k is sufficiently large, the coupled simulation will be stable and convergent only if

$$\left|\frac{\partial M}{\partial r} \times \frac{\partial C}{\partial i}\right| \leq 1 \quad (23)$$

The derivatives of $M\{r\}$ and $C\{i\}$ are shown in Eqs. (15) and (16). Table 1 compares the stability equation for the three coupling methods. The last column provides the stability criteria for a coupling solution.

The stability criterion for Method 1 is satisfied unconditionally, because $C_{L,ic}$, $C_{L,ij}$, $C_{L,P}$ and a_P are all positive and the derivatives of $M\{r\}$ and $C\{i\}$ are always less than one. Together with the convergence analysis, one can conclude that Method 1 can lead to convergent and stable solutions. In addition, it is also indicated that the greater $C_{L,ij}$ and a_P are, the faster the coupled program reaches a convergent solution.

The criteria for Methods 2 and 3 show that the two methods are conditionally stable. With Method 2, the greater $C_{L,ij}$ and the smaller $C_{L,ic}$ are, the more stable the coupling. However, Method 3 requires a smaller $C_{L,ij}$ to reach a better stability in the coupled solution.

Thus, Method 1 seems the best. This can be further proved by numerical experiment.

NUMERICAL EXPERIMENT

Numerical experiments of the stabilities for the three coupling methods was conducted by coupling

CONTAM (Walton and Dols, 2003), a multizone program, with CFD0, a three-dimensional CFD code. The CFD0 is based on the version developed by Srebric and Chen (1999) through conversion of FORTRAN to C. The conversion makes the coupling much easier because CONTAM is written in C. The numerical experiment uses a case of cross ventilation in a four-zone building model.

Sawachi et al. (2003) used a full-scale building model in a wind tunnel to measure discharge coefficients at the building openings under different wind directions. The dimension of the building model is 5.53 m (L) × 5.53 m (W) ×3.0 m (H), and it is divided into four zones of the same size as shown in Figure 4. In the coupled simulation, the lower-left zone or Zone F is chosen as the CFD zone because of the strong momentum effect there. The flow rate through Path A is 2.386 kg/s.

Figure 5 illustrates the mass flow rates of Path B during the coupling solution with the three methods. Converged solutions are achieved with the three methods for this case. All the three methods have led to the same flow rate at Path B, which supports the theory of unique solution.

Compared with Method 1, Methods 2 and 3 fluctuated during the coupling. This is a clear evidence of their conditional stabilities. Due to the nonlinearity of the problem, the linear flow coefficients, $C_{L,ij}$ and $C_{L,ic}$, can change during the iterative coupling. It is possible that the stability criteria in Table 1 may not always be satisfied.

By using CONTAM alone, one would obtain the same flow rate for Paths B and C at 1.193kg/s. However, the coupled program calculates the flow rate of 0.746kg/s for Path B and 1.640kg/s for Path C. Although the airflow rates through Paths B and C were not measured in this experiment, the experimental airflow pattern in Figure 4 shows that the air mostly flow through Path C. The results of the coupled program are therefore more reasonable. The difference is around 60% between the solutions by CONTAM alone and by the coupled program. This is because the strong momentum at Path A can be captured by the coupled program when applying CFD for Zone F. Thus this numerical experiment shows that the coupled program is able to effectively improve the accuracy of the results of the multizone program.

CONCLUSIONS

This investigation studied three methods to improve the accuracy of airflow calculations in a multizone network model by coupling it with a CFD program. The multizone and CFD programs were coupled through the airflow rates or pressure drop at the interfaces. This paper further proved that the coupled program has a solution and the solution is unique with the three coupling methods.

This investigation used the Scarborough criterion to evaluate the convergent performances and analyzed the stabilities of the three coupling methods during their iterative coupling process. Method 1, which exchanges pressure boundary conditions between multizone and CFD programs, performed the best. Finally, a numerical experiment was conducted in a four-zone building model indicating the theory to be correct.

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NOMENCLATURE

a	coefficient of an unknown variable
b	source term in a mass continuity equation
b'	source term in the linear form of mass continuity equation for a zone in a multizone program
$\mathbf{B_1}$	vector of the source terms in the assembled total matrix equation for Method 1
c	index of CFD zones
C	nonlinear flow coefficient
$\mathbf{C}$	coefficient matrix in an assembled total matrix equation
$\mathbf{C_1}$	coefficient matrix in the assembled total matrix equation for Method 1
C	system equations for a CFD program
C_L	linear flow coefficient
d	difference between the local pressure of a flow path and the pressure of the zone, to which the path connects
F	air mass flow rate
$\mathbf{F}$	vector of unknown flow rates through interface paths and cells
f	airflow rate through the face of a CFD cell, perpendicular to the flow direction
g	acceleration of gravity
i	index of the zones for a multizone program; input parameter for C
ic	index of the flow paths linking zone i and zone c

ij	index of the flow paths linking zone i and zone j
j	index of the zones for a multizone program
M	system equations for a multizone program
n	flow exponent
p	pressure at a grid point
P	pressure of a zone; index of grid points or cells
P	vector of unknown pressures of multizone zones and CFD cells
P_d	downwind total pressure of an airflow path
P_S	pressure difference due to density and elevation differences
P_u	upwind total pressure of an airflow path
P_W	pressure difference due to wind
r	input parameter for M
S	source term
V	velocity vector
Greek symbols	
ρ	air density
Δ	difference
ϕ	general variable
Γ	diffusion coefficient for ϕ
Subscripts	
i	index of the zones of a multizone program
ic	index of the flow paths linking zone i and zone c
ij	index of the flow paths linking zone i and zone j
j	index of the zones of a multizone program; coordinate direction
k	index of coupling iterations
nb	neighboring
P	index of grid points or cells

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FIGURES

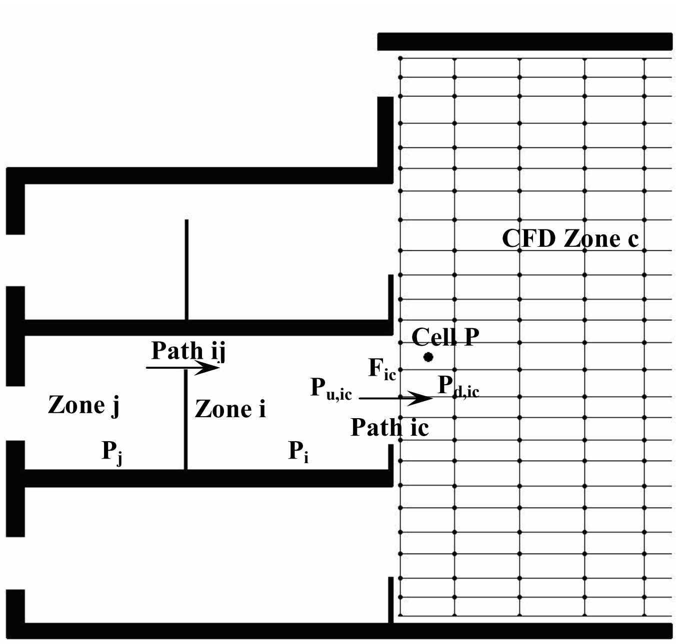
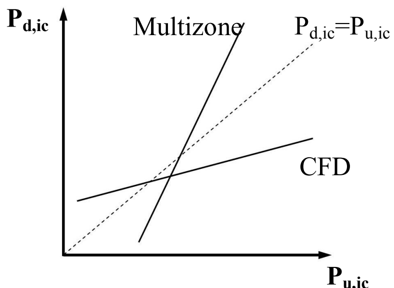
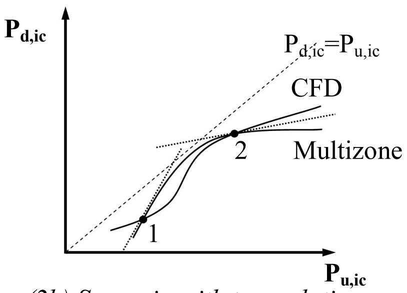


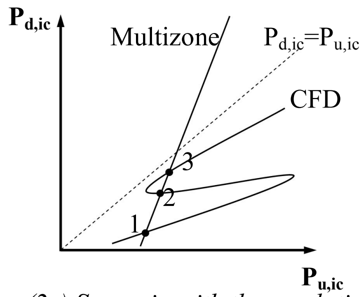
Figure 1 Coupling schematic in a portion of a three-story building with an atrium



(2a) Analysis of solution existence



(2b) Scenario with two solutions



(2c) Scenario with three solutions

Figure 2 Solution existence and uniqueness analysis of the curves of $P_{d,ic}$-$P_{u,ic}$

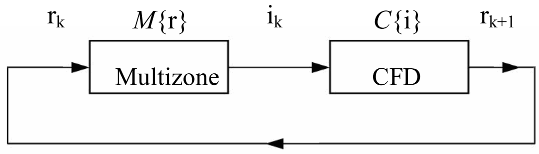


Figure 3 Schematic of the coupling procedure at the coupling iteration k

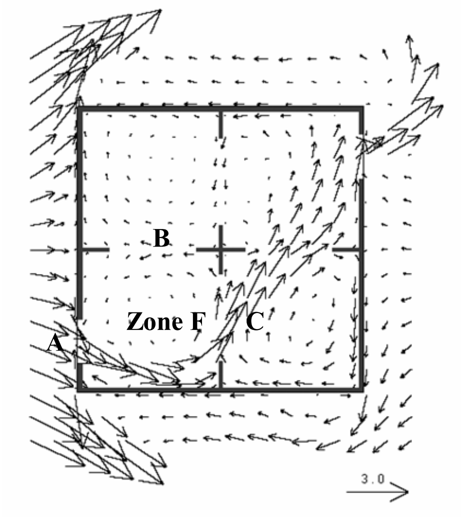


Figure 4 The experimental airflow pattern for the 4-zone building model with cross ventilation

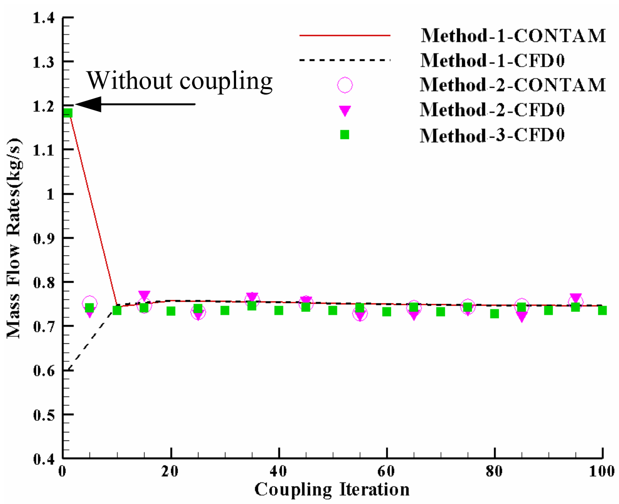


Figure 5 Airflow rate through Path B during the iteration with the three coupling methods in a 4-zone building model with cross ventilation

TABLES

Table 1
Stability conditions for the three coupling methods

	i	r	$\left\|\frac{\partial M}{\partial r}\times\frac{\partial C}{\partial i}\right\|$	STABILITY CRITERIA
Method 1	$P_{u,ic}$	$P_{d,ic}$	$[\frac{C_{L,ic}}{C_{L,ic}+C_{L,ij}}\times\frac{C_{L,P}}{a_P+C_{L,P}},1)$	unconditionally stable for all $C_{L,ic}$, $C_{L,ij}$, $C_{L,P}$, and a_P
Method 2	$P_{u,ic}$	F_{ic}	$(0,\frac{a_P C_{L,ic}}{C_{L,ij}(a_P+C_{L,P})}]$	$\frac{C_{L,ij}}{C_{L,ic}}(1+\frac{C_{L,P}}{a_P})=\begin{cases}<1, & \text{conditionally stable}\\ \geq 1, & \text{stable}\end{cases}$
Method 3	F_{ic}	$P_{d,ic}$	$(0,\frac{C_{L,ij}C_{L,P}}{a_P(C_{L,ij}+C_{L,ic})}]$	$\frac{a_P}{C_{L,P}}(1+\frac{C_{L,ic}}{C_{L,ij}})=\begin{cases}<1, & \text{conditionally stable}\\ \geq 1, & \text{stable}\end{cases}$