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A Comparison of Coupled and Decoupled Solutions for Temperature and Air Flow in a Building

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ABSTRACT

This paper concerns modeling and simulation of coupled heat and air flow in buildings. A brief overview of the current state in modeling this issue is included. Starting from a zonal mass balance approach, the paper describes a method used for the simultaneous solution of the associated nonlinear equations, and the solution coupling of the heat and mass conservation equation sets.

By means of a case study involving a case of strongly coupled heat and air flow, this paper aims to quantify the differences—in terms of accuracy and computer resources—resulting from coupled and decoupled solution methods.

The main conclusion from the case study is that the coupled solution method will be able to generate accurate results, even with simulation time steps of one hour. Reducing the time step will increase the computing resources used considerably, with a relatively small improvement in the accuracy. For equal length of time step a coupled solution method will use more computer resources than a decoupled solution.

In the case of the decoupled method it is necessary to reduce the time step, to ensure the accuracy. For the current case study, the decoupled solution method using a simulation time step of 360 s was less accurate than the coupled solution method with a time step of one hour. However the computer resources used were more than double. Based on the case study it may be concluded that the coupled solution gives the best overall results in terms of both accuracy and computer resources used.

INTRODUCTION

In buildings, and the heating, ventilating, and air-conditioning systems which service them, air flow phenomena are encountered in three principle areas:

- air flow through cracks and openings in the building structure, that is, infiltration and natural ventilation;
- the flow of air through the distribution network designed to satisfy thermal comfort and air quality demands;
- the convective air flows within interior building spaces and plant components.

Some knowledge of the magnitude of these flows is necessary for load and energy calculations, system control analysis, thermal comfort assessment and contaminant/moisture dispersal estimation. Although air flow is demonstrably an important aspect of building/plant performance assessment, the sophistication of its treatment in many modeling systems has tended to lag behind the treatment applied to the other important energy flow paths. The principal reason for this would appear to be the inherent computational difficulties and the lack of sufficient data. In recent times more emphasis has been placed on air flow simulation mostly focused on the following two approaches:

Computational fluid dynamics (CFD), in which the conservation equations for mass, momentum and thermal energy are solved for all nodal points of a two- or three-dimensional grid inside or around the object under investigation. In theory, the CFD approach is applicable to any thermo-fluid phenomenon. However, in practice, and in the building physics domain in particular, there are several problematic issues, of which the amount of necessary computing power, the nature of the flow fields and the assessment of the complex, occupant-dependent boundary conditions are the most problematic (Chen 1997). This has often led to CFD applications being restricted to steady-state cases—or very short simulation periods—which are atypical of many building performance contexts.

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The zonal method, in which a building and its plant are treated as a collection of nodes representing rooms, parts of rooms and plant components, with internodal connections representing the distributed flow paths associated with cracks, doors, ducts and the like. The assumption is made that there is a simple, nonlinear relationship between the flow through a connection and the pressure difference across it. Conservation of mass for the flows into and out of each node leads to a set of simultaneous, nonlinear equations which can be integrated over time to characterize the flow domain.

In the context of combined heat and air flow simulation in buildings, it is the zonal method which is currently most widely used. The reasons for this are threefold. First, there is a strong relationship between the nodal networks which represent the air flow regime and the corresponding networks which represent its thermal counterpart. This means that the information demands of the energy conservation formulations can be directly satisfied. Second, the technique can be readily applied to combined multizone buildings and multicomponent, multinetwork plant systems. Finally, the number of nodes involved will be considerably less than that required in a CFD approach and so the additional CPU burden is minimized. The remainder of this paper will focus on the zonal method.

CURRENT STATE IN MODELING COUPLED HEAT AND AIR FLOW

In building energy prediction it is still common practice to separate the thermal analysis from the estimation of air infiltration and ventilation. This might be a reasonable assumption for many practical problems, where the air flow is predominantly pressure driven; i.e., wind pressure, or pressures imposed by the HVAC system. However, this simplification is not valid for cases where the air flow is buoyancy driven; i.e., involving relatively strong couplings between heat and air flow. Passive cooling by increasing natural ventilation to reduce summertime overheating is a typical example.

Given the increased practical importance of such applications, there is a growing interest among building professionals and academics to establish prediction methods which are able to integrate air infiltration and ventilation estimation with building thermal simulation (see, e.g., Heidt and Nayak 1994).

Starting from the observation that it is not very effective to set up single equations describing both air and heat flow,[1] we see in practical applications two basic approaches for integrating or coupling a thermal model with a flow model: (1) the thermal model calculates temperatures based on assumed flows, after which the flow model recalculates the flows using the calculated temperatures, or (2) the flow model calculates flows based on assumed temperatures, after which the thermal model recalculates the temperatures using the calculated flows. This means that either the temperatures (case 2) or the flows (case 1) may be different in both models, and steps need to be taken in order to ensure the thermodynamic integrity of the overall solution.

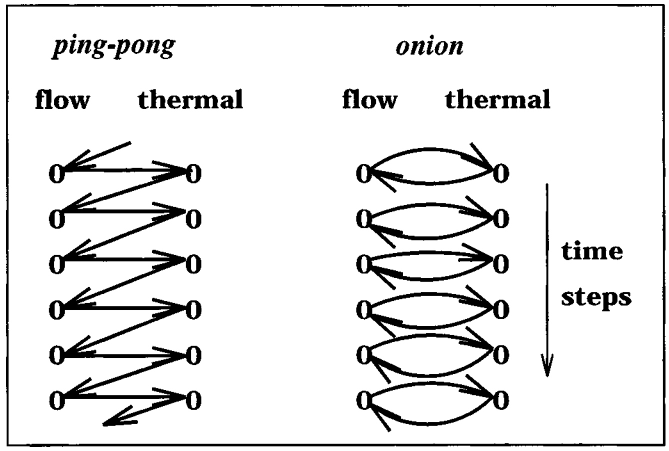

Figure 1 Schematic representation of a decoupled non-iterative (ping-pong) vs. a coupled iterative (onion) approach.

In the case where the thermal model and the flow model are actually separate programs which run in sequence, the above procedure cannot be done on a per time step basis. This is the so-called sequential coupling as described by Kendrick (1993) and quantified with case study material by Heidt and Nayak (1994).

For applications involving buoyancy driven air flow, the thermodynamic integrity of the sequential coupling should be seriously questioned. For those types of applications relatively large errors in predicted temperatures and flows may be expected when using intermodel sequential coupling.

In the case where the thermal and flow models are integrated in the same software system, the above procedure is possible for each time step and thermodynamic integrity can be guarded by: (1) a decoupled approach (''ping-pong'' approach) in which the thermal and flow models run in sequence, i.e., each model uses the results of the other model in the previous time step,[2] and (2) a coupled approach (or ''onion'' approach) in which the thermal and flow models iterate within one time step until satisfactory small error estimates are achieved. Obviously, the final results in terms of evolution of the thermodynamic integrity will depend on how fast boundary values and other external variables to the models change over time. Therefore the length of the simulation time step is also an issue which needs to be considered.

[1]Other opinions exist (see, e.g., Axley and Grot 1989); single equations describing both air and heat flow are sometimes referred to as ''full integration'' (Kendrick 1993).

[2]In Figure 1 (and in our implementation) the air flow calculations use air temperature calculated in the previous time step. Obviously the other way around is also possible.

In literature, several publications exist which relate to the modeling of coupled heat and air flow applications. Our own coupling approach has already been described earlier in detail (Clarke and Hensen 1991; Hensen 1991) and is summarized in the next section.

Kafetzopoulos and Suen (1995) describe sequential coupling of the thermal program Apache with the air flow software Swifib. The results from both programs were transferred manually from one to the other, and this process was repeated until convergence to the desired accuracy was achieved. This procedure is very laborious, and so it was attempted for short simulation periods only.

Within the context of the IEA Energy Conservation in Buildings and Community Systems research, Dorer and Weber (1997) describe a coupling which has been established between a general purpose simulation package (see, e.g., SEL 1994) and a multizone air flow model (see, e.g., Allard et al. 1990).

Andre et al. (1998) report on usage of these coupled software packages. However, according to Andre (1998), the automatic coupling between the two software packages was not yet fully functional, so the results were transferred between the two programs in a way similar to the procedure followed by Kafetzopoulos and Suen (1995).

As reported and demonstrated by Dorer and Weber (1999), the automatic coupling of the two software packages is now fully functional.

In all the above referenced works, the importance of accurate modeling of coupled heat and air flow is stressed, and in several cases demonstrated by case study material.

The current paper aims to illustrate some specifics regarding accuracy and computer resources used for both the coupled and decoupled solution methods in an integrated software.

IMPLEMENTATION

Although this paper concerns a generic issue, in order to generate quantitative results, it is necessary to become specific in terms of implementation of the solution methods.

The work described in this paper has been done with a general purpose building simulation package (Clarke 1985). For modeling transient heat flow, this software uses a numerical approach for the simultaneous solution of finite volume energy conservation equations. For modeling air flow, the system features both a mass balance network approach and a CFD approach (see, e.g., Clarke et al. 1995). The former approach is used for the studies in the current paper.

In outline, the mass balance network approach involves the following: during each simulation time step, the mass transfer problem is constrained to the steady flow (possibly bidirectional) of an incompressible fluid (currently air and water are supported) along the connections which represent the building/plant mass flow paths network when subjected to certain boundary conditions regarding (wind) pressures, temperatures and/or flows. The problem therefore reduces to the calculation of air flow through these connections with the internal nodes of the network representing certain unknown pressures. A solution is achieved by an iterative mass balance technique (generalized from the technique described by Walton 1989) in which the unknown nodal pressures are adjusted until the mass residual of each internal node satisfies some user-specified criterion.

Each node is assigned a node reference height and a temperature (corresponding to a boundary condition, building zone temperature or plant component temperature). These are then used for the calculation of buoyancy driven flows (or stack effect) which are obviously of importance in the current context. The approach for buoyancy calculations has already been described in a previous paper (Clarke and Hensen 1991).

Coupling of building heat flow and air flow models, in a mathematical/numerical sense, effectively means combining all matrix equations describing these processes. While, in principle, it is possible to combine all matrix equations into one overall ''super-matrix,'' this is not done within this software, primarily because of the advantages which accrue from problem partitioning.

The most immediate advantage is the marked reduction in matrix dimensions and degree of sparsity—indeed the program never forms two-dimensional arrays for the above matrices, but instead holds matrix topologies and topographies as sets of vectors. A second advantage is that it is possible to easily remove partitions as a function of the problem in hand when, for example, the problem incorporates building-only considerations, plant-only considerations, plant+flow, and so on. A third advantage is that different partition solvers can be used which are optimized for the equation types in question—highly nonlinear, differential and so on.

It is recognized, however, that there often are dominating thermodynamic and/or hydraulic couplings between the different partitions. If a variable in one partition (e.g., air temperature of a zone) depends on a variable of state solved within another partition (e.g., the air flow rate through that zone), it is important to ensure that both values are matched in order to preserve the thermodynamic integrity of the system.

Two methods are available[3] to deal with such problems. Figure 2 schematically shows the implementation of coupled (''onion'') and decoupled (''ping-pong'') solution approaches for air flow and energy balance calculations.

[3]For research reasons, the underlying building and plant energy simulation environment is effectively a virtual laboratory for energy modeling issues. Thus the system offers more than one method to deal with coupling heat and air flow, as well as several alternative methods for simulation time step control (including, e.g., boundary condition look ahead, simulation rewind), for evaluating convective heat transfer coefficients, for HVAC modeling HVAC approaches, etc.

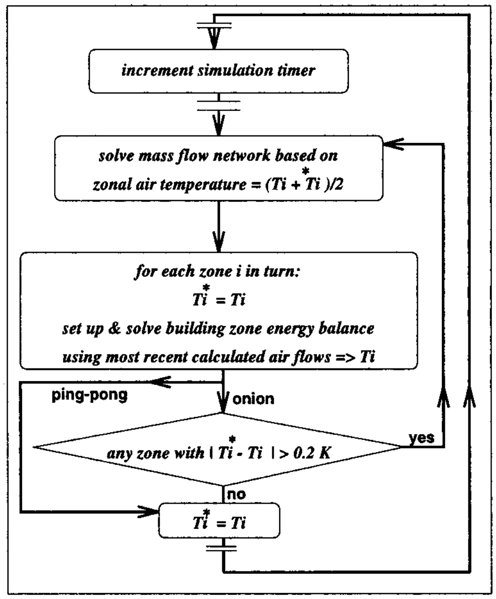

Figure 2 *Schematic flow diagram showing the implementation of a coupled ("onion") and decoupled ("ping-pong") solution method for heat and air flow.*

The flow diagram shows that in decoupled mode, within a time step, the air flows are calculated using the zonal air temperatures (T_i) of the previous time step; i.e., during the first pass through a time step, $T_i = T_i^*$ (history variable). In coupled mode, the first pass through a time step also uses the zonal air temperatures of the previous time step. However, each subsequent iteration uses $(T_i^* + T_i)/2$, which is equivalent to successive substitutions with a relaxation factor of 0.5.

CASE STUDY

Each of the various approaches for integrating heat and air flow calculations have specific consequences in terms of computing resources and accuracy. One way to demonstrate this is to compare the results for a typical case study.[4]

One of the most severe cases of coupled heat and air flow in our field involves a free running building (no mechanical heating or cooling) with air flow predominately driven by temperature differences caused by a variable load (e.g., solar load). A frequently occurring realistic example is an atrium using passive cooling; i.e., doors and windows are opened to increase natural ventilation so as to reduce summertime overheating.

Model and Simulations

The current case concerns the central hall of a four-wing building located in central Germany. This central hall is in essence a five-story atrium, of which a cross-section and plan are sketched in Figure 3. Each floor has a large central void of 144 m^2 (1550 ft^2). The floors and opaque walls are

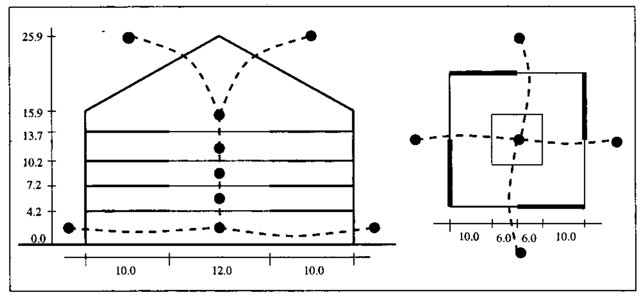

Figure 3 *Cross-section and plan of atrium with air flow network. Dimensions in m; to obtain ft, divide by 0.3048.*

concrete, while the transparent walls and the roof consist of sun-protective double glazing.

In order to increase the infiltration, there are relatively big openings at ground and roof level. The eight building envelope openings (2 m^2 or 21.5 ft^2 each) are evenly distributed and connected as indicated in the flow network. For the present study, all openings are continuously open. Apart from solar gains, there are no other heat gains. There is no control

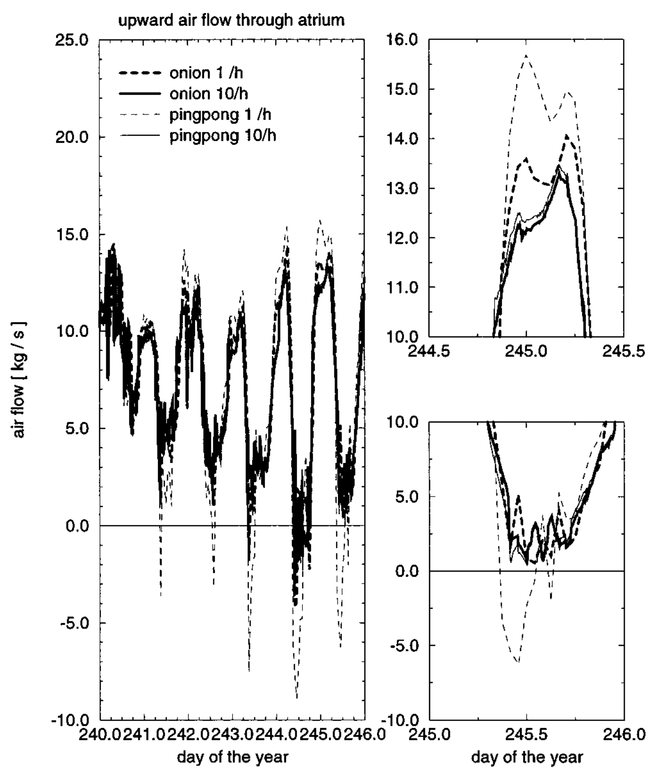

Figure 4 *Simulation results for vertical air flow through atrium starting with day 241 and ending with day 246 of a reference year. Frames on the right show selected results in more detail. Flow rate in kg/s; to obtain lb/min divide by 0.00756.*

[4]Here the case study first presented by Hensen (1995) is further elaborated.

(heating, cooling, window opening, etc.) imposed on the building.

The ambient conditions are taken from a weather test reference year for Wuerzburg, which is in the southwestern part of Germany. The simulation period (28 August until 2 September) consists of a six-day period with increasing outdoor air temperature to include a range of medium to maximum temperatures.

As indicated earlier, the software features various modes of time step control. However, in order to avoid ''interferences'' that might make it difficult to interpret certain results in the current case, it was decided not to activate time step control. Instead of time step control, two time step lengths of respectively one hour and one-tenth of an hour were used during simulation.

Results and Discussion

Figure 4 shows the simulation results for the vertical air flow through the atrium. In order to focus on the differences between the various methods, the right hand side of the figure shows two blown-up parts of the graphs. In the blow-ups, the different methods can clearly be distinguished. It can be seen that the ping-pong method with 1-hour time steps is clearly an outlier relative to the other cases. For the 6-minute time steps, the onion and ping-pong approaches give almost identical results. In general, the flows tend to be higher during the night, and become less during the day. This effect is less pronounced during the first day, which has relatively low ambient air temperatures and levels of solar radiation.

Figure 5 shows the simulation results for the air temperatures on the ground floor. The general graphs and the blow-ups show very little difference between the various approaches. This is probably due to the fact that the incoming air temperature (=ambient) is equal in all cases and because of the large thermal capacity of the ground floor.

Figure 6 shows the simulation results for the air temperatures on the top floor. Here the general graph and the blow-ups show larger differences between the various approaches. This is due to the succession of differences occurring at the lower floors and due to the fact that the top floor has a much higher solar gain (via the transparent roof) than the other floors.

It is interesting to compare Figure 6 with Figure 4, because it shows that the flow increases with the difference between zonal and ambient temperatures and not with zonal temperature itself. Obviously the temperature difference depends on the amount of air flow, while the amount of air flow depends on temperature difference. As is clearly shown

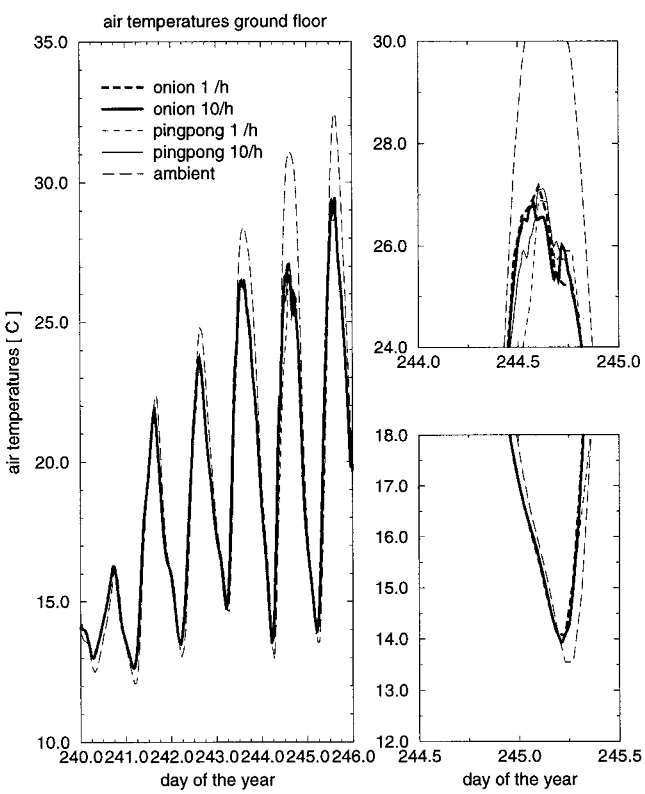

Figure 5 *Simulation results for ground floor air temperatures starting with day 241 and ending with day 246 of a reference year. Frames on the right show selected results in more detail. Temperatures in °C; to obtain °F multiply by 1.8 and add 32.*

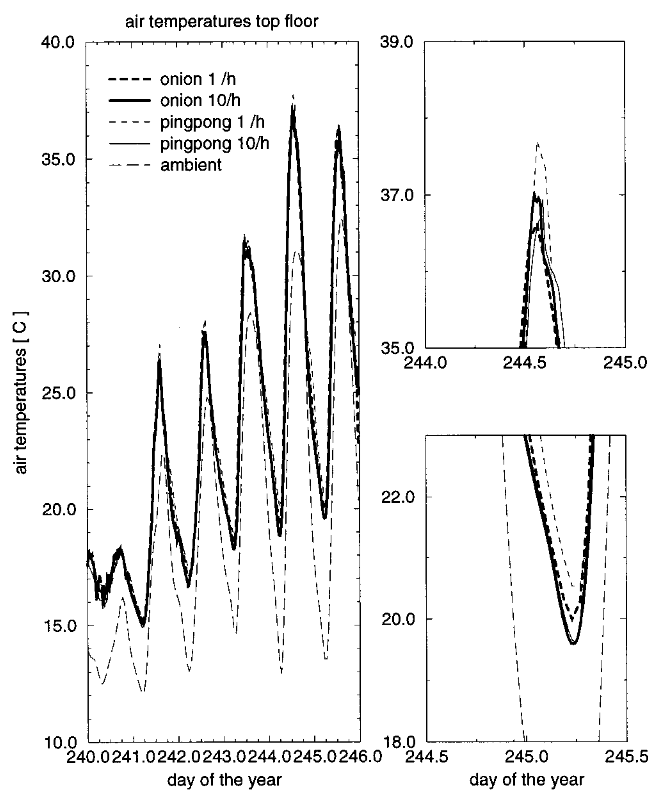

Figure 6 *Simulation results for top floor air temperatures starting with day 241 and ending with day 246 of a reference year. Frames on the right show selected results in more detail. Temperatures in °C; to obtain °F multiply by 1.8 and add 32.*

TABLE 1
Statistical Summary of Air Flow and Temperature Results for the Various Methods (On=onion, PP=ping-pong). Values in Brackets Are the Percentage Differences Relative to the On-10 case, i.e., Coupled Solution with 10 Time Steps per Hour

		On-1		On-10		PP-1		PP-10	
Vertical flow									
Max.	kg/s	14.51	(+2.3)	14.19	(0)	15.69	(+11)	13.49	(−4.9)
Min.	kg/s	−4.21	(+17)	3.60	(0)	−8.90	(+247)	−3.67	(+1.9)
Mean	kg/s	7.35	(+1.2)	7.26	(0)	7.04	(−3.0)	7.05	(−2.9)
Std. dev.	kg/s	4.37	(+18)	3.71	(0)	5.93	(+60)	3.87	(+4.3)
Range	kg/s	18.72	(+5.2)	17.79	(0)	24.58	(+38)	17.16	(−3.5)
Ground floor temperature									
Max.	°C	29.21	(−0.7)	29.42	(0)	28.87	(−1.7)	29.37	(−0.2)
Min.	°C	12.67	(+0.3)	12.63	(0)	12.66	(+0.2)	12.63	(+0.0)
Mean	°C	18.95	(+0.1)	18.93	(0)	18.64	(−1.5)	18.84	(−0.5)
>27°C	h	2	(−62)	5.3	(0)	1	(−81)	6.3	(+19)
>30°C	h	0		0		0		0	
Top floor temperature									
Max.	°C	36.63	(−1.0)	37.00	(0)	37.70	(+1.9)	36.94	(−0.2)
Min.	°C	15.24	(+1.2)	15.06	(0)	15.16	(+0.7)	14.91	(−1.0)
Mean	°C	23.19	(+1.0)	22.96	(0)	23.27	(+1.4)	22.83	(−0.6)
>27°C	h	36	(+4.0)	34.6	(0)	38	(+9.8)	34.3	(−0.9)
>30°C	h	22	(−3.9)	22.9	(0)	24	(+4.8)	23.4	(+2.2)
Iterations	–	429	(−58)	(1028)	(0)	–		–	
Relative user CPU	–	3.3	(−77)	14.2	(0)	1	(−93)	8.3	(−41)

in the graphs, it takes an integrated approach to predict the net result.

Table 1 and Table 2 show a statistical summary of the results. Included are the number of hours above certain temperature levels, since such parameters are used in certain countries to assess summer overheating. For the ground floor air temperature there are relatively big differences in hours >27°C (80.6°F) between the one per hour and the 10 per hour time step cases. This is because the maximum air temperature for that zone is close to 27°C (80.6°F) the number of hours above 27°C (80.6°F) is very sensitive.

This paper focuses on the relative comparison of methodologies to model coupled heat and air flow in a building. Although no mathematical proof is presented, it could be argued that in the current situation the results for the coupled solution method with small time steps are the most accurate. This is why for each result the percentage difference is shown relative to the results for the coupled solution with 10 time steps per hour.

Since the main interest here is the relative differences, no attempt has been made to compare the case study results by intermodel comparison, for example with a CFD approach, or to validate the outcome in an absolute sense by comparing with experimental results. A comparison with CFD results is not a feasible option because modeling of coupled building energy and air flow is still very much in its infancy (see, e.g., Negrao 1995).

Each of the decoupled building energy and air flow prediction methods have been subjected to extensive and rigorous experimental validation exercises in the past (e.g., CEC 1989). Unfortunately for the case considered, no experimental results are readily available. The generation of such results is currently considered as a suggestion for future work.

The largest discrepancies between the various coupling methods are found for case PP-1; i.e., decoupled solution with relatively large time steps. The results for the coupled solution cases and for the decoupled solution with small time steps are relatively close.

Table 1 and Table 2 also show the number of iterations needed for each case with the coupled solution approach. The amount of code involved in the iteration is only a fraction of

TABLE 2
Identical to Table 1 Except for Units. Statistical Summary of Air Flow and Temperature Results for the Various Methods (On=onion, PP=ping-pong). Values in Brackets are the Percentage Differences Relative to the On-10 Case, i.e., Coupled Solution with 10 Time Steps per Hour

		On-1		On-10		PP-1		PP-10	
Vertical flow									
Max.	lb/min	1919	(+2.3)	1877	(0)	2075	(+11)	1784	(−4.9)
Min.	lb/min	−557	(+17)	−476	(0)	−1177	(+247)	−458	(+1.9)
Mean	lb/min	972	(+1.2)	960	(0)	931	(−3.0)	933	(−2.9)
Std. dev.	lb/min	578	(+18)	491	(0)	784	(+60)	512	(+4.3)
Range	lb/min	2476	(+5.2)	2353	(0)	3251	(+38)	2270	(−3.5)
Ground floor temperature									
Max.	°F	84.58	(−0.7)	84.96	(0)	83.97	(−1.7)	84.87	(−0.2)
Min.	°F	54.81	(+0.3)	54.73	(0)	54.79	(+0.2)	54.73	(+0.0)
Mean	°F	66.11	(+0.1)	66.07	(0)	65.55	(−1.5)	65.91	(−0.5)
>80.6°F	h	2	(−62)	5.3	(0)	1	(−81)	6.3	(+19)
>86.0°F	h	0		0		0		0	
Top floor temperature									
Max.	°F	97.93	(−1.0)	98.60	(0)	99.86	(+1.9)	98.49	(−0.2)
Min.	°F	59.43	(+1.2)	59.11	(0)	59.29	(+0.7)	58.84	(−1.0)
Mean	°F	73.74	(+1.0)	73.33	(0)	73.89	(+1.4)	73.09	(−0.6)
>80.6°F	h	36	(+4.0)	34.6	(0)	38	(+9.8)	34.3	(−0.9)
>86.0°F	h	22	(−3.9)	22.9	(0)	24	(+4.8)	23.4	(+2.2)
Iterations	–	429	(−58)	1028	(0)	–		–	
Relative user CPU	–	3.3	(−77)	14.2	(0)	1	(−93)	8.3	(−41)

the code which needs to be processed for a complete time step. In terms of computer resources used, it is more relevant to compare the user CPU time[5] as shown at the bottom of Table 1 and Table 2. The results are shown relative to the PP-1 case, which was the fastest method. In absolute values, the PP-1 case, including reading user definable run parameters, took 5.1 s user CPU time on a Sun SPARC station 4. It is clear that the other cases use much more computer resources, especially the coupled solution method with small time steps.

CONCLUSIONS

The case study presented here involves a case of strongly coupled heat and air flow in buildings. Two different methods, i.e., coupled and decoupled solutions, for linking heat and air flow models have been considered using two different time step lengths.

It was found that the differences are much larger in terms of air flow than in terms of air temperatures. The temperature differences between the various methods increases with the number of stacked zones.

The main conclusion from the case study is that the coupled solution method will be able to generate accurate results, even with simulation time steps of one hour. Reducing the time step will increase the computing resources used considerably, with a relatively small improvement of the accuracy. For equal length of time step a coupled solution method will use more computer resources than a decoupled solution.

For the decoupled method, it is necessary to reduce the time step to ensure the accuracy. For the current case study, the decoupled solution method using a simulation time step of 360 s was less accurate than the coupled solution method with a time step of one hour. However, the computer resources used were more than doubled.

Based on the current case study, it may be concluded that the coupled solution gives the best overall results in terms of both accuracy and computer resources used. Although the results presented here are for an imaginary (but

[5]User CPU time is CPU time used for the actual calculations, i.e., excluding time for swapping, etc.

realistic) building, the observed trends may be expected to be more generally valid.

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