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# MODELLING COUPLED HEAT AND AIR FLOW: PING-PONG VS ONIONS

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## SYNOPSIS

By means of a case study involving a severe case of coupled heat and air flow in buildings, this paper aims to quantify the differences resulting from different methods (ping-pong and onion approach) for linking heat and air flow models.
The main conclusion is that when used improperly, the onion method will have implications in terms of computing resources, but - more seriously - the ping-pong method may generate substantial errors.


## 1 INTRODUCTION

In building energy prediction it is still common practice to separate the thermal analysis from the estimation of air infiltration and ventilation. Although this might be a reasonable assumption for many practical problems, this simplification is not valid for cases involving relatively strong couplings between heat and fluid 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 in practice and academia to establish prediction methods which are able to integrate air infiltration estimation and building thermal simulation (see eg Heidt and Nayak 1994).

There are various approaches for integrating heat and air flow calculations, each having specific consequences in terms of computing resources and accuracy. One way to actually quantify this, is to use a simulation environment which supports these various approaches, and to compare the results of the approaches for a typical case study. This topic is elaborated in the current paper, after a brief outline of the background and implementation details.

## 2 BACKGROUND

Starting from the observation that it is not very effective to set up single equations describing both fluid and heat flow*, 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 fixed flows, after which the flow model recalculates the flows using the calculated temperatures, or
2) the flow model calculates flows based on fixed temperatures, after which the thermal model recalculates the temperatures using the calculated flows.
This means that either the temperatures (case 2) or the flows (1) are different in both models, and something needs to be done in order to ensure the thermodynamic integrity of the overall solution.

In case the thermal model and the flow model are actually separate programs which run in sequence, the above procedure can not even 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 many applications, the thermodynamic integrity of this type of coupling should be seriously questioned and will undoubtedly generate relative large errors in predicted temperatures and flows.

* other opions exist (see eg Axley and Grot 1989)

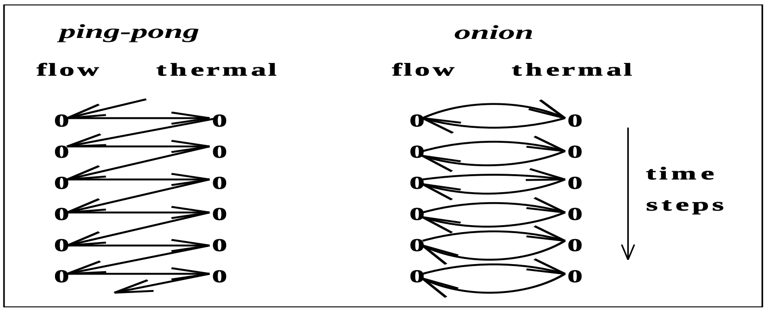

Figure 1 Schematic representation of ping-pong vs onion approach

In case the thermal and flow model are integrated, the above procedure is possible for each time step and thermodynamic integrity can be guarded by:

1 the "ping-pong" method in which the thermal and flow model run in sequence (ie each uses the results of the other model in the previous time step)#, and

2 the "onion" method in which the thermal and flow model 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 length of the simulation time step is also an issue which needs to be considered.

The above has some bearing on computational fluid dynamics approaches as well. However, the current paper focusses on combining a nodal network flow method with a comprehensive thermal model.

## 3 IMPLEMENTATION

Although, the above is a quite generic problem, in order to generate quantitative results, it is necessary to become specific in terms of implementation of the methods.

In earlier publications a full account has been given of the internal workings of the ESP-r building and plant simulation environment both with respect to energy simulation in general (Clarke 1985) and with respect to simultaneous heat and mass flow simulation (Hensen 1991).

ESP-r features both a mass balance network approach and a CFD approach. The latter approach is described in a separate paper (Clarke et al. 1995). The former approach is used for the studies in the current paper.

An outline of the mass balance network approach could be: during each simulation time step, the mass transfer problem is constrained to the steady flow (possibly bi-directional) 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 fluid flow through these connections with the internal nodes of the network representing certain unknown pressures. A solution is achieved by an iterative

# in Figure 1 (and in our implementation) the air flow calculations use air temperatures calculated in the previous time step. Obviously the other way around is also possible.

mass balance technique 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 - and building moisture flow and plant heat flow and plant fluid flow(s) and lighting and electric power and ....- models in a mathematical/ numerical sense, effectively means combining all matrix equations describing these processes. (Referred to as 'full integration' by Kendrick (1993).)
While in principle it is possible to combine all matrix equations into one overall 'super-matrix', this is not done within ESP-r, 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 ESP-r 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; for example when the problem incorporates building only considerations, plant only considerations, plant + flow, and so on. A third advantage is that, potentially, different partition solvers can be used which are well adapted for the equation types in question - highly non-linear, differential and so on.

It is recognised however that there are often dominating thermodynamic and/ or hydraulic couplings between the different partitions. If a variable in one partition (say air temperature of a zone) depends on a variable of state solved within an partition (say 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.

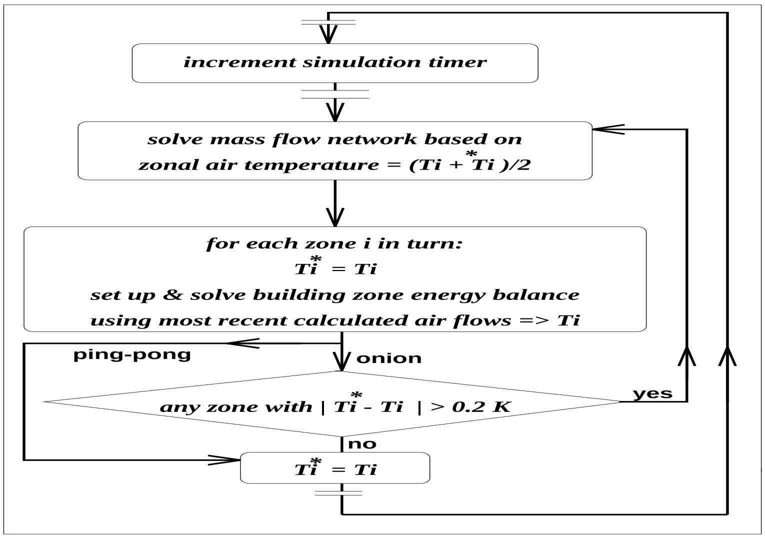


Figure 2 Schematic flow diagram showing the implementation of resp. pinp-pong and onion coupling of air flow and energy balance calculations

As explained in more detail elsewhere (Clarke et al. 1995), the ESP-r building and plant energy simulation environment is a virtual laboratory for energy modelling issues. For research reasons, ESP-r features various ways of coupling heat and air flow. Figure 2 schematically shows the implementation of respectively pinp-pong and onion approaches to coupling of air flow and energy balance calculations.

The flow diagram shows that in ping-pong mode, within a time step, the air flows are calculated using the zonal air temperatures ($T_i$) of the previous time step; during the first pass through a time step, $T_i$ equals $T^{*}{}_i$ (history variable). In onion 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 basically means successive substitutions with a 0.5 relaxation factor.
Not shown in the diagram is that during the simulation start-up period, the onion method reverts to the ping-pong approach to avoid unnecessary iterations.

In line with ESP-r's virtual laboratory philosophy, the system also supports various modes of time step control, for example: boundary condition look ahead (monitors user specified control variable(s) and reduces time-step value if rate of change greater than user specified value), time-step reduction by iteration (reduces time-step value until diference in control variable for current time-step and previous time-step is within user specified limit), user specified time-step value, iteration without time-step reduction (this is the onion method in essence), simulation rewind (rewind simulation clock to user specified start period if user specified control variable is outside user specified limit).

## 3 CASE STUDY

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 (eg solar load). A frequently occuring practical example is an atrium using passive cooling by increasing natural ventilation to reduce summertime overheating.
Although it would be interesting to consider other cases, this is not possible here due to space constraints.

### 3.1 Model & Simulations

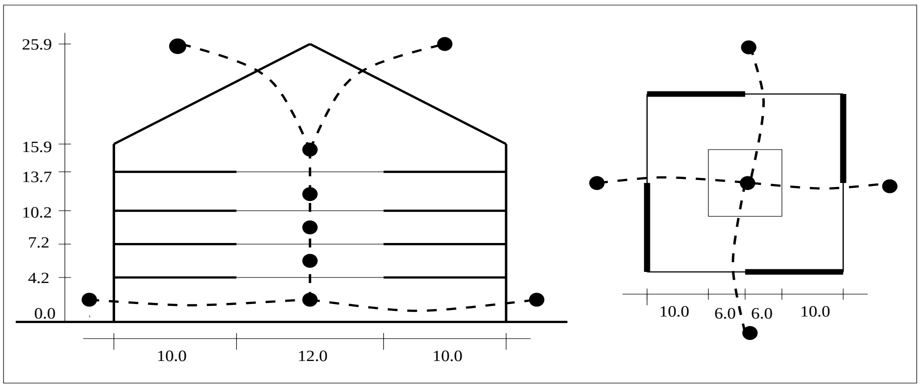


Figure 3 Cross-section and plan of atrium with air flow network

The current case concerns the central hall of a 4-wing building located in central Germany. This central hall is in essence a 5 storey atrium, of which a cross-section and plan are sketched in Figure 3. Each floor has a large central void of 144 $m^2$. The floors and opaque walls are from 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 8 building envelope openings (2 $m^2$ each) are evenly distributed and connected as indicated in the flow network. For the present study, all openings are continuously opened. Apart from solar gains, there are no other heat gains.
There is no control (heating, cooling, window opening, etc.) imposed on the building.

The ambient conditions are taken from a climatic test reference year for Wüerzburg, Germany. The simulation period (28 August until 2 September) consists of a 6 day period with increasing outdoor air temperature to include a range of medium to maximum temperatures.

As indicated above, ESP-r features various modes of time step control. However, in order to avoid 'interferences' which might make it difficult to interpret certain results in the current case, it was decided not to activate time step control other than to achieve the onion type of coupling. Instead of time step control, two time step lengths of respectively one hour and one tenth of an hour were used during simulation.

## 3.2 Results & Discussion

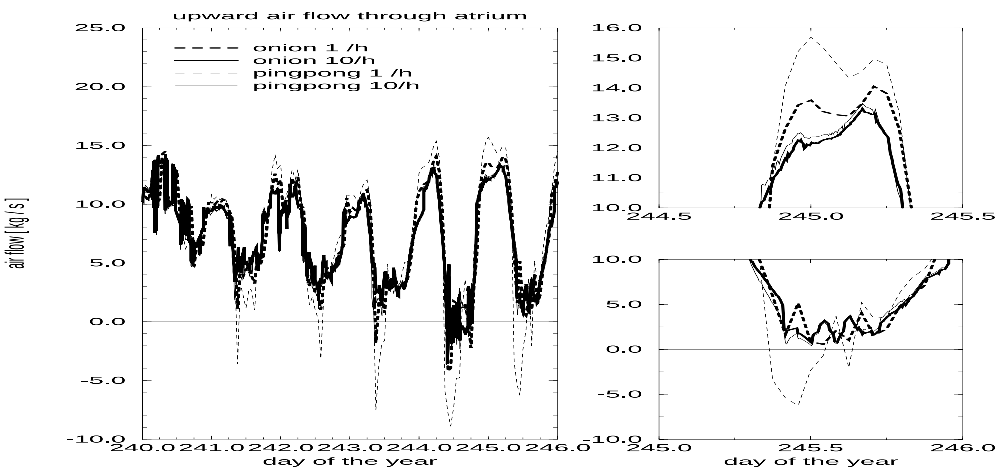


Figure 4 Simulation results for vertical air flow through atrium

Figure 4 shows the simulation results for the vertical air flow through the atrium. The right hand side of the figure shows two blown up parts of the graphs, in order to focus on the differences between the various methods. In the blow-ups, the different methods can clearly be distinguished, and 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 pinp-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.

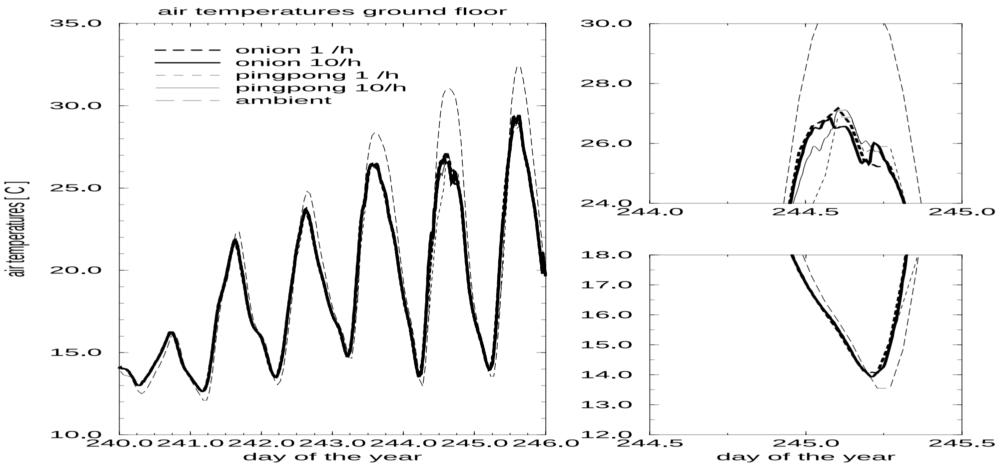


Figure 5 Simulation results for ground floor air temperatures

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 the incoming air temperature (= ambient) is equal in all cases, and because of the large thermal capacity of the ground floor.

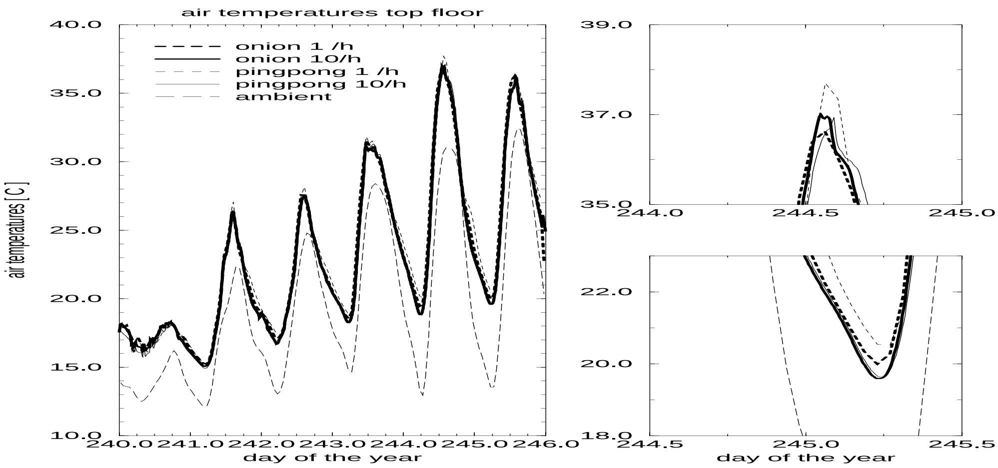


Figure 6 Simulation results for top floor air temperatures

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 occuring 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 difference between zonal and ambient temperatue and not with zonal temperature itself. Obviously the temperature difference depends on the amount of air flow, and the amount of air flow depends on temperature difference. As clearly shown in the graphs, it takes an integrated approach to predict the net result.

Table 1 holds a statistical summary of the results. Included are 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 relative big differences in hours > 27°C between the once 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 (hours > 27°C becomes very

Table 1 Statistical summary of air flow and temperature results for the various methods (On = onion, PP = ping-pong)

| | | On-1 | On-10 | PP-1 | PP-10 |
|---|---|---|---|---|---|
| **vertical flow** | | | | | |
| max | $kg/s$ | 14.51 | 14.19 | 15.69 | 13.49 |
| min | $kg/s$ | -4.21 | -3.60 | -8.90 | -3.67 |
| mean | $kg/s$ | 7.35 | 7.26 | 7.04 | 7.05 |
| std.dev. | $kg/s$ | 4.37 | 3.71 | 5.93 | 3.87 |
| range | $kg/s$ | 18.72 | 17.79 | 24.58 | 17.16 |
| **ground temperature** | | | | | |
| max | $°C$ | 29.21 | 29.42 | 28.87 | 29.37 |
| min | $°C$ | 12.67 | 12.63 | 12.66 | 12.63 |
| mean | $°C$ | 18.95 | 18.93 | 18.64 | 18.84 |
| hours > 27 $°C$ | $h$ | 2 | 5.3 | 1 | 6.3 |
| hours > 30 $°C$ | $h$ | 0 | 0 | 0 | 0 |
| **top floor temperature** | | | | | |
| max | $°C$ | 36.63 | 37.00 | 37.70 | 36.94 |
| min | $°C$ | 15.24 | 15.06 | 15.16 | 14.91 |
| mean | $°C$ | 23.19 | 22.96 | 23.27 | 22.83 |
| hours > 27 $°C$ | $h$ | 36 | 34.6 | 38 | 34.3 |
| hours > 30 $°C$ | $h$ | 22 | 22.9 | 24 | 23.4 |
| iterations | $-$ | 429 | 1028 | - | - |

sensitive),
In general, the ping-pong once per hour case is a bit of an outlier in terms of the air flow and the maximum top floor temperature. The other results are relatively close.

On its last line, Table 1 shows the number of iterations needed by the onion approach. Obviously this has computing resource implications. Since the amount of code involved in the iteration is much smaller than the code which needs to be processed for a time step, the number of iterations can not be compared directly to the number of ping-pong time steps. In the the current case, the onion once per hour needed approximately the same total amount of processing time than the ping-pong 10 per hour case.

# 4 CONCLUSIONS

The case study presented here, involves a severe case of coupled heat and air flow in buildings. Two different methods (ping-pong and onion method) of linking heat and air flow models have been considered using two different time step lengths.

It was found that the differences in air flow are larger than the differences in air temperatures. The temperature differences between the various methods grow with the number of stacked zones.
The results indicate that when properly used, each method will give satisfactory results. In this context the term "properly" is mainly related to the time step issue. When used improperly in terms of time step, the onion method will have implications in terms of computing resources, but - more seriously - the ping-pong method may generate substantial errors.
Which method to choose depends on the required accuracy. In general it is advisable to be careful with the ping-pong approach in combination with long time steps for problems with strongly coupled heat and air flow.

Although the coupled heat and air flow results are for an imaginary (but realistic) building the observed trends are expected to be valid for many cases. The actual consequences for a particular building configuration will be the result of many complicated interactions with opposite effects. This makes it extremely difficult - if not impossible - to create simplified design-aids for this purpose. Detailed building performance evaluation can be achieved through an integral building & systems simulation approach.

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