Thermal and CFD Modelling vs. Wind Tunnel in Natural Ventilation Studies

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A major case study of a high rise, city-centre office building in continental Europe was undertaken in a true commercial environment. Three dimensional thermal and Computational Fluid Dynamics (CFD) modelling was carried out for major spaces in parallel with wind tunnel tests and results compared. Three different methods were used to assess the ventilation rate in the wind tunnel tests: surface pressure coefficients, tracer gas and direct velocity measurements. The objective was to obtain boundary conditions for interconnected 3-storey gardens and 9-storey atria in order to calibrate and fine-tune mathematical models. External air flow was also modelled in a CFD simulated wind tunnel. For these simulations only a very limited surroundings were entered. This was considered as insufficient for reliable generation of boundary conditions so only qualitative comparisons with wind tunnel smoke tests were made. Results from wind tunnel test showed inconsistencies and scatter well beyond expectations. This was attributed to choice of probes and their positioning. These causes were particularly obvious after the initial CFD results. The paper concentrates on comparison of physical testing methods with mathematical models and exposes some of the practical and theoretical limitations of both techniques.

1. Introduction

A 'drive' towards 'green buildings' is now an evident trend in the European commercial building design. Both architects and engineers try to answer the challenge of designing comfortable and efficient buildings the best way they can with currently available tools.

The question is: as designs become ever more imaginative and buildings and their requirements ever more complex, can the design tools available to the industry cope with sophistication required and still follow the pace of a typical building design project?

In the course of our normal project work, we have undertaken a major study on the feasibility of natural ventilation for a major high rise, quality office development in continental Europe.

At our disposal we had two Dynamic Thermal Modelling (DTM) programs (one finite-difference and one response factor), a 3D Computational Fluid Dynamics (CFD) program, commercial wind tunnel, tight commercial budgets and deadlines.

The adopted methodology is outlined in Figure 1.

The highest uncertainty was attributed to the wind-driven ventilation. The idea was to improve the accuracy and reliability of modelling by calibrating and fine-tuning the zonal and CFD models using wind tunnel test data.

2. Building Description

The building with its immediate surroundings is shown in Figure 2. The site is situated in the city centre with several buildings of similar height (150 - 200m) within 500m radius, affecting wind behaviour around the building.

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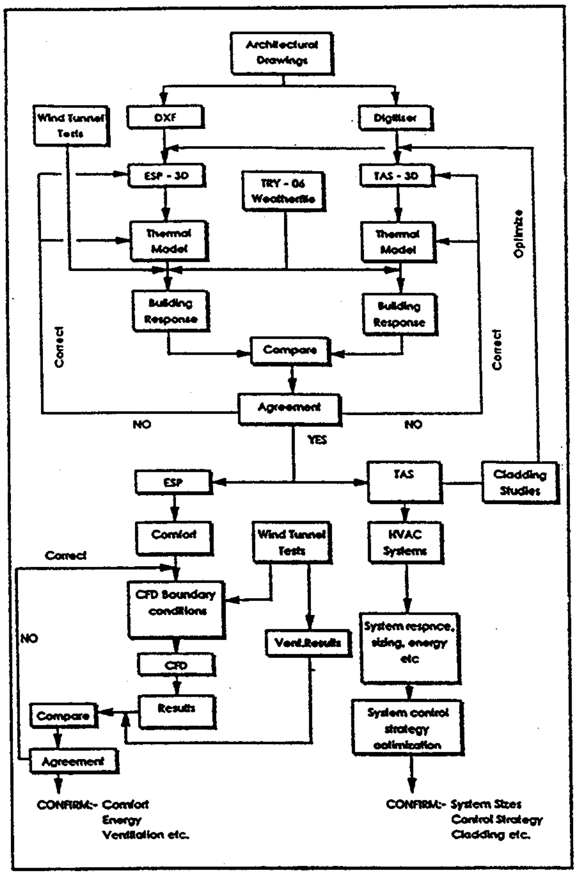

Figure 1. Methodology

The tower consists of a six-storey lower part, 4 nine-storey 'villages', each consisting of 3 three-storey 'sky gardens' linked with central triangular atrium; and a five-storey top part. Atria are separated horizontally every 9-storeys at village boundaries to limit the stack effect and fire spread. Gardens, external perimeter and atria offices have openable windows.

Offices at the perimeter are predominantly cellular. There is a central zone with meeting rooms and fire escape routes.

The building was not specifically designed for natural ventilation due to various site and functionality constraints. The floor 'wing' is over 16m deep, with raised floors and light overall construction. The ceilings are partially exposed, but partitions are light. The facade is glass-dominant (about 65%) with opaque part, fixed glazed part with ventilated blind in a cavity (extract air window) and openable glazed part with external shading.

All offices have either outward or sky garden views and access to fresh air and daylight.

3. The Scope of Study

The building was considered to be far from 'prima facie' case for natural ventilation: city-centre site, deep and partitioned floor plan, light construction, etc. Because of this we had to embark on a study with a detailed analysis of a number of important parameters in order to assess the feasibility of natural ventilation. Key parameters are:

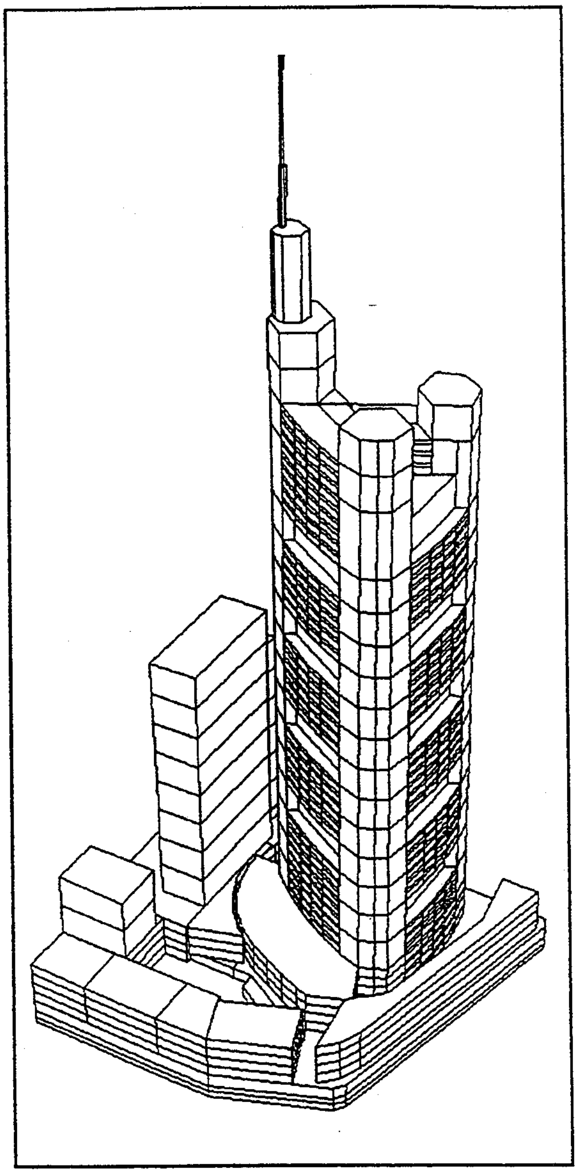

Figure 2. Perspective view of the 3D computer thermal model

- Site Microclimate with local wind conditions, ambient temperatures, precipitation, solar radiation, etc. Frequency analyses of weather data were conducted after corrections were made to meteorological office data
- Building Height and Orientation
- Cladding System and Type of Openings
- Type of Ventilation and Partitioning
- Internal Heat Gains
- Comfort Criteria
- Building Thermal Mass and Night Time Free Cooling
- Heating/Ventilation/Air-Conditioning (HVAC) Systems and Controls

- Capital and Running Costs
- Various Unquantifiable and 'Political' Factors

Since this is a high rise building (over 200m), ventilation and infiltration are largely wind-driven, especially for the upper parts of the building. Specific sheltering is significant for the lower 20 storeys from south-west; this also happens to be a prevailing wind direction.

Although all of the above mentioned factors were taken into account in the feasibility assessment, it was the wind behaviour and the way it affects building ventilation that was seen as particularly critical.

4. Physical or Mathematical Modelling

Wind tunnel tests for high-rise buildings are normally carried out for structural reasons and usually include force-balance tests and cladding pressure tests. Sometimes 'environmental' tests are conducted which normally deal with winds at pedestrian level. These are normally done rather crudely with low resolution and typical scales of 1:300 - 1:500. In this case, structural tests were done on a 1:400 scale solid model covering the radius of 480m around the site. For ventilation tests we needed a better resolution, hollow model and the same radius of surroundings included, so we ended up with a 1:200 scale hollow model in a 4.8m wide wind tunnel. Only one 9-storey module was instrumented and moved up the building in 4 different positions: A, B, C and D (see Figure 3).

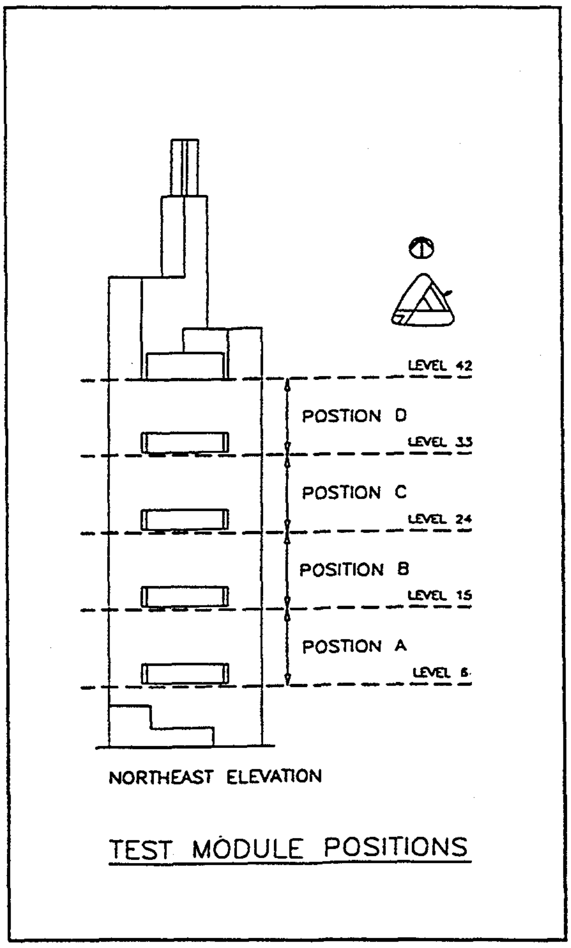

Figure 3. Elevation with Instrumented Module Positions

4.1 Offices

The resolution of the model was insufficient to include the office openings; 400mm high openings full scale convert into 2mm on the model, entering the crack flow region - it is in fact an orifice flow at full scale. So, small openings could not be modelled physically and were therefore covered in CFD modelling. Solid wind pressure coefficients were used, since the indications are that openings with area below 25% of the facade do not significantly affect wind pressure coefficients (see, for example D. R. Ernest et al., 1991 and S. Marakami et al., 1991).

In order to limit the pressure differences across the floor plate and prevent the draught through open doors, we introduced a pressure equalisation path through a raised floor plenum. However, due to a significant flow resistance (small cross section) of the introduced path, overall ventilation was calculated as only one third of the equivalent unobstructed cross flow ventilation. A cross section with CFD simulation is shown in Figure 4.

The boundary conditions were calculated using dynamic thermal modelling software and zonal ventilation model for 3 different conditions (2 summer and 1 winter). The Figure 4 shows summer 'normal' conditions (wind 0.9m/s, perpendicular to the facade, ambient temperature 21.2°C).

The type of ventilation is somewhere between a single-sided and cross ventilation. The effectiveness of this configuration could only be assessed through a limited number of CFD runs. Indications are, however, that the concept has a valuable contribution to the enhancement of natural ventilation, reduction in pressure differences accross the floor plate whilst retaining good acoustic separation at marginal cost.

We found DTM/CFD approach invaluable in evaluating the ventilation effectiveness, flow rates and comfort implications of this particular design.

4.2 Gardens

The openings in garden walls were big enough to be simulated on a model (about 3500mm full scale, 17.5mm on a model). This size would still maintain the characteristics of an orifice flow.

Reynolds number similarity was impossible to achieve, so we opted for internal flow independence threshold

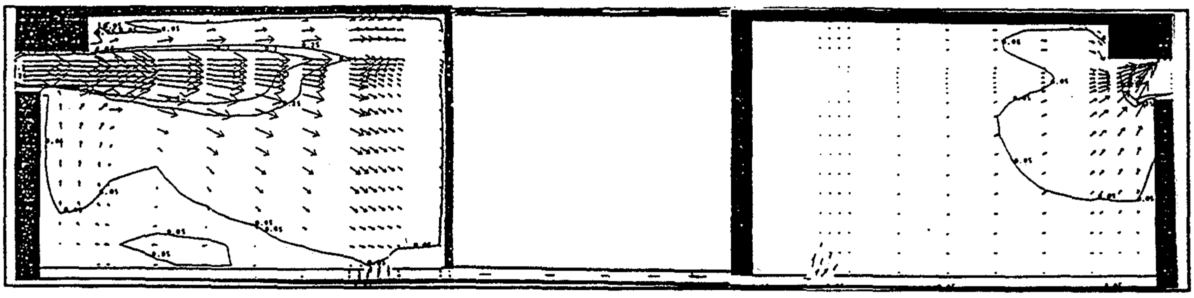

Figure 4. Velocity vectors in the office cross-section

of:

$$Re = V_{ref} H/\nu > 2 \times 10^4$$

Where: Re = internal Reynolds number
V_{ref} = reference wind speed at full model height (m/s)
H = model height (m)
ν = kinematic viscosity of air (m^2/s)

We used 1.5m/s wind speed referenced at 366m full scale height which gives Re-value close to 100,000.

Attempts were made at an early stage to consider using CFD model to generate pressure coefficients. However, when a complexity of the surroundings and sheer number of buildings to be entered into a 3D model were considered, this idea had to be abandoned. Computer hardware at our disposal would not be able to cope with the required model size. Finite-volume CFD on a mid-range workstation can currently run about 1,000,000 volumes at acceptable speeds. For the external model of this size (1000m x 1000m x 500m), we would need about 1,000,000,000 volumes - 1,000 times the current maximum. Both the size and speed would be unacceptable.

Later on, during the qualitative comparisons, it was found that k-ε turbulence model will not (even in time-domain), address transient phenomena like 'buffeting'. However, for a majority of purposes, mean pressure coefficients would suffice and they can be predicted (in simpler cases) by k-ε CFD with reasonable accuracy.

Wind tunnel tests were finally carried out for four configurations (Figure 5).

- Windows closed
- Windows 25% open
- Windows 50% open
- Windows 100% open

Scale for all ventilation tests was 1:200. Similarity with 1:400 tests was achieved by using larger wind tunnel (2.4 vs 4.8m width). Tests on 1:400 model were conducted for 36 wind directions (at 10° increments) and used for calibration of 1:200 model, where only 4 directions were tested, selected for design reasons: 60°, 150°, 240° and 300°.

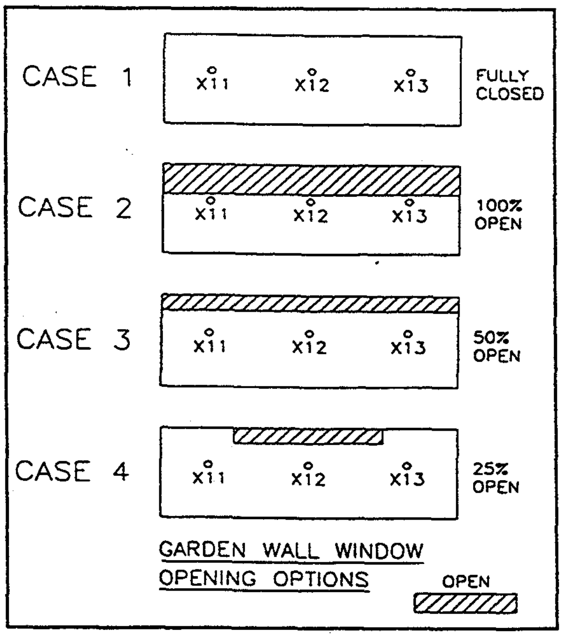

Figure 5. Window opening configurations

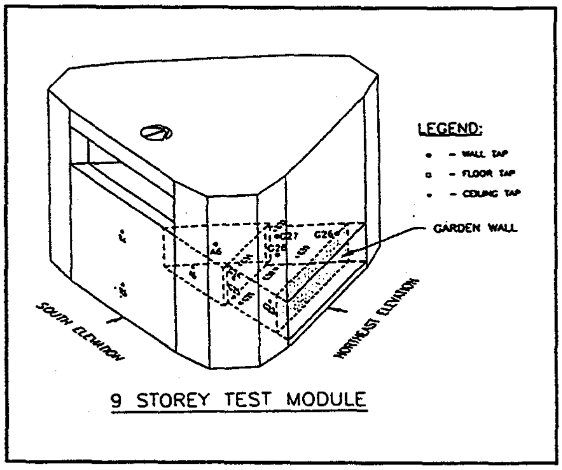

Figure 6. Tap locations - NE elevation

No attempts were made to model buoyancy effects in the wind tunnel, mainly due to similarity problems. Three different methods were used to measure internal ventilation of gardens and atrium:

- Internal ventilation rates using Tracer Gas decay method (TG);
- Velocity vector measurement at opening using vertically oriented hot wire-Measured Velocities method (MV);
- Pressure coefficients using pressure taps (CP).

Locations of pressure taps are shown in Figure 6.

The whole programme was completed for 4 vertical positions - A, B, C, D (Figure 3)

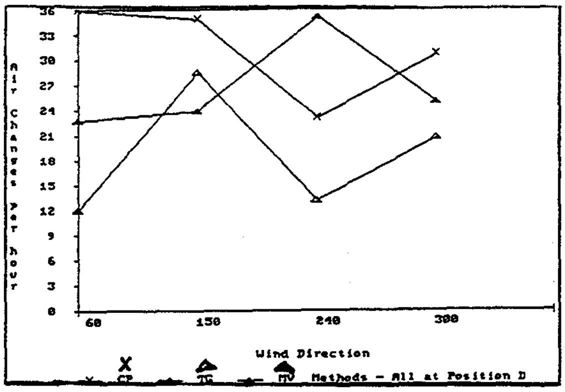

Figure 7. Comparison of the 3 methods looking at the variation of air change rates against wind direction for position 'D' only

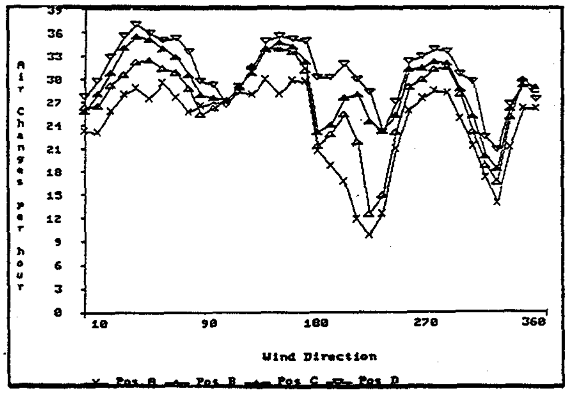

Figure 8. The variation of air change rates against wind direction using external pressure coefficients

It was hoped that these methods would improve reliability and put the 'error bounds' around subsequent CFD results.

5. Results

Selected results are shown in Figures 7, 8, and 9.

The results using the three described methods (CP, TG, MV) for the least sensitive position 'D' at the top of the building show large discrepancies, both in qualitative and quantitative terms (Figure 7).

The garden air change rate for all positions (A-D) using pressure coefficients is shown in Figure 8.

The design has proven to be exceptionally efficient in terms of ventilation and achieved air change rates are very high for 50% opening as well (1 sixth of the garden facade). (Figure 9).

The Air Change rates of 9-storey Garden/Atrium is cyclic with respect to the wind direction. It appears to be cycling between 0-120°, and repeating the cycle between 120-240° and 240-360°. This pattern is shown in Figure 6. This is completely true only for position 'D' (where the effect of surrounding buildings is minimum), whereas for other positions (A-C), this effect is obscured by the surrounding buildings.

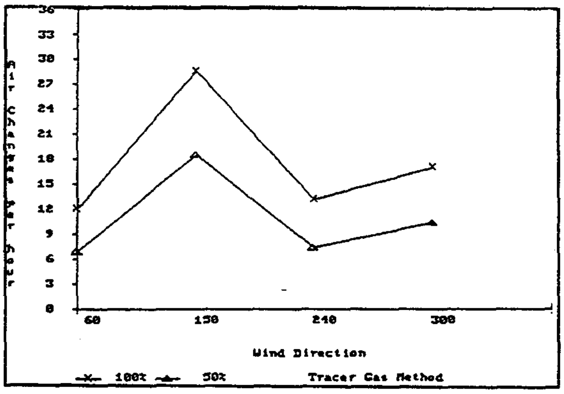

Figure 9. Comparison of air change rates for windows 50% and 100% open using tracer gas

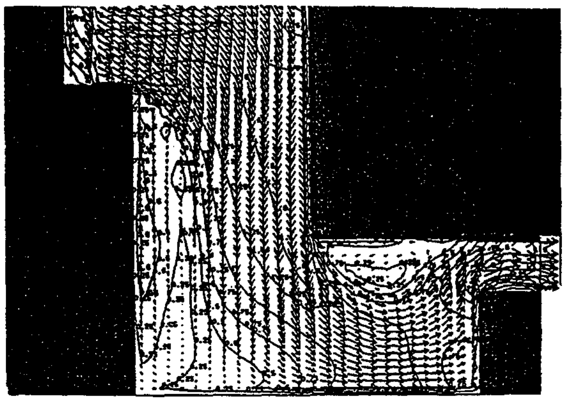

Figure 10. Velocity vectors in a vertical cross-section of the north-east garden

Measured Air Change rates at 60° wind using Tracer Gas method is lower than expected (see Figure 7). This would tend to underestimate the bulk air exchange rate; only one of the receptors was located in free flow area. Therefore averaging air exchange rate over all 8 receptors would underestimate the bulk air exchange rate. The CFD calculations show high recirculation zone in the gardens below the windows where infiltration occurs, and this could be the reason for the low measured value at 60° wind direction, see Figure 10.

The difference between inflow and outflow rates varies from 6% to 26% of airflow through the gardens/atrium; using measured Mean Velocities at gardens opening. This was considered to be due to lack of directional characteristics of hot wire anemometer.

The measured air change rates using Tracer Gas method at other angles of 150°, 240° and 300° are close to pressure coefficient method (see Figure 7). They are still lower however.

The discrepancies in Air Change rates between these three methods for varying wind speed show a clearly visible tendency for Measured Mean Velocities method to over estimate for some directions. The Tracer Gas method underestimates Air Change rates.

There are also discrepancies in the Air Change rates with windows 50% open. These discrepancies between the methods are clearly visible. Reducing the size of the opening by 50% does not reduce the air change rates by 50% but by less, (about 40%). This is due to flow 'distortion' near large openings that cannot be picked up by solid pressure coefficients.

The method that offered the best agreement with the CFD model is the Pressure Coefficient method. Therefore measured pressure coefficients at garden openings were used to generate the boundary conditions and calibrate the CFD model.

6. Conclusions

During the study, several pitfalls and serious limitations of both physical and mathematical technique were exposed.

Some of the favourite designers concepts are being challenged, e.g. relevance of the bulk air change rate in large spaces with significant recirculation zones. Local air age would be much more indicative.

Many of the problems arose out of need to make quick commercial decisions - the choice of instrumentation and a limited number of repeated corrected tests in a wind tunnel.

Wind tunnel tests are of limited value for ventilation studies. Small scale tests are difficult to commission due to model leakage, poor resolution, interference of the instrumentation with actual measurements, fast air change rates, difficult probe positioning, etc.

Modelling of combined wind/buoyancy effects on the small scale wind tunnel models is not normally commercialy attempted due to theoretical (scaling, similarity) and practical complexities involved.

Tests at larger scale might have the problem with tunnel blockage.

They are however invaluable for qualitative observations, rough assessments and confirmation of a 'settled' design parameters. Wind tunnel is still irreplacable for generation of external pressure coefficients in complex cases. Particular attention has to be given to large openings in building structure.

DTM/CFD combination is very promising in terms of flexibility, analytical potential and resolution. However, external air flow for large building in complex surroundings will need much more powerful computers than available in design offices of today; also more sophisticated turbulence model is needed to deal with transient turbulence effects.

DTM/CFD modelling remains an indispensable tool in designing buildings for natural ventilation, developing and evaluating the solutions.

The generation of accurate boundary conditions can be considered as the critical and least validated factor in the performance assessment process where much more effort is needed, notably in the area of the CFD field-to-boundary interaction.

Acknowledgements

In the preparation of this paper, data from two commercial reports were used: JRP Report 5733/SS/AJF on Environmental Modelling and RWDI Report 92-213T-3 on wind tunnel testing. The software used included ESP+ (dynamic thermal modelling), ARIA (3D computational fluid dynamics) and TAS (dynamic thermal modelling-response factor).

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