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Natural Ventilation via Courtyards: Theory & Measurements

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SUMMARY

Existing regulations concerning the design and construction of residential buildings which are naturally ventilated via courtyards and lightwells have origins in daylighting rather than in aerodynamics. The design of narrow, high-sided courtyards which achieve healthy conditions for occupants has long been a problem and a subject of various guidance and research, although many doubts and gaps in knowledge still remained. The work described below resolves these problems, and the coherent theory developed may lead to clearer guidance on the design of courtyards for natural ventilation.

A fresh approach was adopted using computational fluid dynamics (CFD) software as an integrated technique in combination with measurements at both model and full scale. The adequacy of infiltration and ventilation rates in rooms opening onto the courtyard was also assessed. The salient results were used to develop a coherent descriptive model which explains the apparent discrepancies in earlier work and enabled revised design guidelines to be presented.

1. INTRODUCTION

Existing regulations[1,2] concerning the design and construction of residential buildings which are naturally ventilated via courtyards and lightwells have origins in daylighting rather than in aerodynamics. Their design to achieve healthy conditions for occupants has long been a problem and a subject of various guidance and research. Current guidance limits the height to width ratio of such courts, which effectively precludes narrow, high-sided courtyards as proposed elsewhere (eg Japan) for residential developments. By default, existing knowledge could be used as the basis of proposed new guidance on non-domestic buildings. Previous research left many doubts and gaps in knowledge which, if resolved, could lead to clearer guidance on the design of courtyards for natural ventilation. This is consistent with the increasing emphasis on natural ventilation as the primary design option, reflecting current concerns over indoor air quality, energy use and environmental issues.

This report addresses these needs by reviewing the salient findings of past research and identifying key issues. Work is then described in which computational fluid dynamics (CFD) software was used (in association with the University of Sheffield) as part of an integrated approach in combination with measurements at both model and full scale. The adequacy of infiltration and ventilation rates in rooms opening onto the courtyard was also assessed using a multizone prediction model. The salient results were used to develop a coherent descriptive model, which explains the apparent discrepancies in earlier work, and to present revised design guidelines. The CFD approach is described in more detail in a related paper[3] (Part II).

2. HISTORIC BASIS OF CURRENT REGULATIONS

Local and national building regulations and Acts [1,2,4] from the 19th and 20th centuries contain requirements about the location of windows and/or ventilators which open onto external air spaces (eg courtyards and lightwells) closed on three or four sides. The origins of the restrictions on ventilation to a partly enclosed external air space strongly suggest that an emphasis on daylighting played a part. The essential core of the Regulations in the UK can be summarised, for a closed court, as stipulating that the height of the wall above an opening shall be less than twice (or, in Scotland three times) the distance to the facing wall. The aerodynamical basis of this restriction is not clear.

3. KEY ISSUES AND CURRENT KNOWLEDGE

There are two key issues concerned with any revision to guidelines on ventilation of buildings arranged around courtyards or lightwells:

- adequacy of courtyard ventilation, including contaminant dispersal;
- adequacy of ventilation in rooms opening onto the courtyard

The wind environment in the court itself may also be an important design consideration, but is outside the scope of this paper. The relevant findings of past studies are summarised below.

3.1 Full and model scale studies of courtyard ventilation

The court should be well ventilated to provide a reservoir of 'fresh' outside air to habitable rooms with ventilation openings in the court. In addition, contaminants released into the court should adequately disperse to avoid possible re-ingestion at ventilation openings.

A literature survey of wind tunnel studies (5 - 14) revealed some instances of conditions where stable vortices may occur. In this case it may be that air remains trapped within the court, with only poor exchange with the free airstream above. In some cases a stable circulation has been observed to be confined to the upper portion of deep courts, leaving a zone of stagnant air below. These studies left some doubt as to whether air flowing above the courtyard effectively exchanged with air within it or, instead, 'skimmed over'.

There are very few published studies at full scale[6,10,14,15], and these mostly record air speeds and turbulence in the courtyard. Cockroft and Robertson[6] used a tracer gas technique to measure air change rates of between 13 and 40 ach; unfortunately, experimental details and meteorological conditions were not given. Murakami[9] used smoke dispersal to measure air change rates and proposed a relationship between air change rate and wind speed.

3.2 Ventilation within the building

It is possible that the presence of the court (compared to a completely open area) may adversely affect wind-induced ventilation within rooms, particularly those which have openings in the courtyard. Two relevant past studies[6,15] concerned with hospital buildings predicted that ventilation rates would be less than 3 air changes per hour for as much as 50% of the winter period. However, minimum ventilation rates lower than 3 ach are recommended for health and safety of occupants office buildings and dwellings. Even so, the second study also predicted ventilation rates of less than 0.5 ach for significant periods of time. Recent measurements of leakage in office buildings [16] suggest that leakage may have been underestimated by as much as 50% in the above studies. To address these unresolved problems, the predicted ventilation performance of a building with lightwell is assessed below.

4. CFD MODELLING OF COURTYARD VENTILATION

Whilst previous research represents significant progress, clearly many doubts and gaps in knowledge still remained to be resolved to enable a consistent and general understanding of the problem to be developed. In general, field measurements provide data such as air flow and ventilation rate only at a particular location and time. Tests at model scale using a wind tunnel enable air flow in a range of situations and conditions to be considered, but do not provide sufficient information alone, and may not truly represent the flow regime at full scale.

A fresh approach was therefore adopted using computational fluid dynamics (CFD) software, which is now capable of simulating and predicting air flow over a wide range of situations with sufficient resolution in three dimensions, due to advances in computer memory and speed. The CFD studies described below can be divided into three parts,

(a) studies of the mechanism of ventilation of courtyards
(b) parametric study of key features of flow, building and surroundings which may impact on courtyard ventilation
(c) model study of a real eight-storey building with lightwell

4.1 Mechanism of Ventilation of Courtyards

Details of the CFD modelling used to study the mechanism by which air flows through a courtyard are described in a linked paper [3]. The main findings of this study are that there are two distinct air flow patterns involved in the exchange of air within deep plan courtyards. One pattern comprises a circulation at the top of the court ('top vortex'), with stagnant air below, and in the other a vortex occupies the full width and depth of the courtyard ('full vortex'). A full vortex was shown to be created when the separated flow at the top upwind edge of the building re-attaches upstream or in the vicinity of the court opening at roof level.

Time-dependant solutions for contaminant removal were also used to trace flow paths through the court and, together with the concept of 'mean age of air', to calculate local ventilation rates. These showed that a top vortex would not provide an efficient air exchange throughout the court. A full vortex, on the other hand, was found to bring outside air deep into the court and give an efficient air exchange over nearly the whole of the space.

4.2 Parametric Studies of Courtyard Ventilation

Using CFD, a parametric study was carried out to assess the possible influence of various factors (parameters) on reattachment at or near the courtyard as a criterion for achieving a full vortex. The basic calculation configuration consisted of a simple rectangular building 16 m x 16 m x 24 m high with a lightwell. An urban velocity profile[17] was defined upstream with a velocity of 5 m/s at the top of the domain (at twice the building height) and, initially, with no surrounding buildings or other local effects. Upwards of 20,000 nodes were used. By varying each in turn, the following key parameters and their effects were identified:

- Building width - there is a tendency to form a top vortex as building width is increased (Figure 1). This is because flow over the top of the wider buildings is greater, increasing the separation at the upwind edge of the roof.

- Building height - the taller the building the greater the tendency to form a top vortex (Figure 2), caused by a greater vertical component of velocity and consequent greater separation at the upwind edge of the roof.

- Courtyard location - a full vortex is more likely as the distance of the courtyard from the upwind face[17] increases.

- height of surrounding buildings - surrounding buildings of similar height assist formation of full vortex (Figure 3). This would appear to explain why a top vortex has frequently been observed in wind tunnel tests using isolated buildings, but not in full scale tests, particularly those in towns and cities.

- wind direction - a full vortex is more likely when the wind is not blowing normal to the facade.

Also varied but found to make no significant impact were absolute height of building and surroundings (varied together), terrain and wind profile (ie changing the inlet profile from an urban to a city profile) and wind velocity.

These results constitute a consistent and coherent model which explains the apparent discrepancies observed in earlier work. As such, they provide the basis for design guidance, although the detailed results should be interpreted only qualitatively, since many indeterminate factors could influence the air flow in a real situation.

4.3 Eight-storey lightwell

The above predictions were tested further, with a view to subsequent full scale measurements, by carrying out calculations of air flow over a real eight-storey building which incorporated two lightwells to its full height (Figure 4). Investigations focused on the smaller of the two lightwells measuring approximately 16 m x 7 m x 27 m deep. Simulations were carried out initially for only the half of the building including this lightwell, although insignificant differences were found when these were repeated for the full building (but ignoring the larger lightwell to keep within computer memory limits).

A full vortex was predicted for conditions were the wind was blowing broadly parallel to the long side of the lightwell, without considering local shelter. When the wind speed was set to zero below roof level, to simulate the local shelter of surrounding tall buildings, the predicted depth of vortex was slightly increased. As expected, a top vortex was predicted when the air flow was parallel to the short side of the lightwell, but a full vortex was predicted when shelter was included (Figure 5).

Two further cases were simulated for the full building with shelter, for comparison with field measurements at full scale. In both cases a full vortex was predicted, and the air change rate was crudely estimated by summing all inflow and outflow for all grid cells across the opening in the lightwell at roof level, and then halving to give an estimate of the total in- or outflow. 43 ach was calculated for a wind of approximately 2.0 m/s from the south, and 35 ach for a similar windspeed from 30 north of west. Figure 6 shows the latter case, which used 148,000 nodes. These two results are broadly consistent with full scale field measurements described below.

5. MEASUREMENTS AT FULL AND MODEL SCALE

Guided by the features of the air flow predicted above, and to test their validity, a series of measurements were carried out in the eight-storey building both in the field at full scale and in a wind tunnel at model scale.

5.1 Field Measurements in an eight-storey lightwell

Tracer gas and smoke tests were carried out to assess the air movement and ventilation rate in the smaller of two lightwells in the real eight-storey building in its city-centre site. The lightwell was temporarily covered at roof level with a tarpaulin and the enclosed space was filled with tracer gas. Air samples were taken at two locations, one at second-storey height and the other at sixth-storey height, and initial conditions were arranged to give approximately equal tracer concentrations at these points. The tarpaulin was then quickly removed and the falling concentration of tracer, recorded as it was diluted by incoming fresh air, was used to calculate the ventilation rate.

These were elaborate and labour intensive tests and consequently only two have been carried out. In the first test the wind speed observed at roof level was between 2 and 3 m/s, blowing from approximately northwest. The measured ventilation rate at both locations was approximately 50 air changes per hour, and tracer concentrations remained reasonably well-mixed. For the second test the average wind speed recorded at roof level was approximately 3.3 m/s, blowing from approximately south-southwest. An air change rate of approximately 45 ach was calculated. Within broad limits of accuracy, these results compare quite well with CFD predictions of 43 and 35 ach, respectively.

Each of the above two tests were immediately followed by tests using smoke released at various points to visualise air movement in the courtyard. In both cases, we observed smoke descending at the downwind face of the court, traversing the base, then rising up on the upwind face. These results are consistent with the ventilation tests in indicating that there was an adequate flow of fresh air deep into the courtyard.

5.2 Measurements at model scale

A boundary layer wind tunnel at BRE was used to carry out a series of smoke visualisation tests using a 1/200 scale model of the eight-storey building (Figure 1) using an urban wind profile. With air flowing parallel to its long side at roof level, smoke was introduced into the small lightwell and, as expected, a full vortex was clearly observed. Consistent with this, when the smoke release was stopped (using a slow wind speed of approximately 1.3 m/s) smoke was observed to clear initially from the downwind side and subsequently away over the full depth.

However, when the wind was blowing parallel to the short side of the court, smoke was observed to remain circulating in the upper portion. This was contrary to expectations from the CFD modelling where sheltering was included. CFD was therefore used to simulate the airflow over the building at the model scale. A top vortex was predicted, as observed in the wind tunnel, but contrary to the predictions for the full scale. However, the vortex progressively extended over the full court depth as the simulated wind speed was increased by more than a factor of four. This result would appear to suggest that the Reynolds number may be too low at model scale, specifically where air speeds may be much lower than in the free airstream, eg in the lightwell.

6. PREDICTED VENTILATION PERFORMANCE WITHIN BUILDING

The adequacy of ventilation within rooms with openings into the courtyard was identified (above) as a key issue. This raised some concerns that ventilation may be inadequate for significant periods of time in courtyard buildings. We have therefore used a commercially available multizone ventilation prediction procedure (BREEZE) to assess the wintertime ventilation performance of an eight-storey office building based on the design described above.

Infiltration flow through the fabric is calculated in the model using the empirical power-law relationship,

$$Q = k \,.\, (\Delta P)^n \qquad (2)$$

were k is a constant coefficient, ΔP is the inside-outside pressure difference due to wind and temperature differences and the exponent n was taken[16] as 0.6.

It was assumed that trickle ventilators were installed at window-head height, with an open area of 400 mm^2 per 10 m^2 of floor area [18]. Air flow through these vents was represented as flow through a sharp-edged circular orifice of the same open area and a discharge coefficient of 0.62. Ventilation requirements were calculated on the basis of an estimated design occupancy of 80 people per storey, a recommended rate of 8 litres/sec per person and a minimum of 5 litres/sec per person. This gave 0.57 and 0.35 ach respectively. This would reduce to 0.43 and 0.26 ach in a domestic building of the same size, based on typical occupancy of 1 person 20 m^2 of floor area.

6.1. Building in urban terrain

Surface pressure data were obtained[19] for a generalised rectangular building 30 m tall with a single courtyard, set in an urban terrain (or on the edge of a city). Local effects of possible surrounding tall buildings were not included in these measurements. Typical background air leakage of 10 m^3/hr per m^2 of permeable envelope area was assumed, based on recent data[16] for office buildings.

The whole building air change rates were calculated for a wind speed of 4 m/s for each of twelve wind directions at 30 degree intervals, with typical design air temperatures[20] of 7°C outside and 20°C inside. Internal doors were assumed to be open. Due to the symmetry of the building from which the pressure data were derived, air change rates varied very little with wind direction, with a minimum of 0.49 ach for winds blowing from the north and a maximum of 0.54 ach for winds blowing from the west.

The results from these two wind directions were then taken to define the extremes of an envelope containing all other possible air change rates. For these two wind directions the whole building air change rates were then calculated for the range of wind speeds and outside air temperatures expected to occur during the hours between 9.00 am and 6 pm in the winter months September to March inclusive. These results were then combined with a weather data set for an urban site (Garston) consisting of hours of co-occurrence of intervals of wind speeds with outside air temperatures, for an average winter period as above. Results for all possible wind directions were assumed to be represented by either the 'maximum' or the 'minimum' condition and a cumulative frequency of occurrence of small intervals of air change rate was constructed.

The predicted mean (50% value) was approximately 0.46 ach, with a very narrow spread (approximately 0.5 ach) between the two extreme assumptions. The minimum requirements of 0.34 ach (office) and 0.26 ach (domestic) were easily met, and in fact exceeded more than 90% of the time.

Effects of reduced air leakage, closed internal doors and zonal air change rates

The effect of assuming a very tight envelope (half typical leakage)[16] was considered. The mean (50% of time) ventilation rate was determined to be 0.35 ach, and greater than 0.26 ach for 90% of time.

The effect of closing all internal doors was represented by typical leakage through joints given by[21] Q (l/s)=1.3(ΔP)$^{0.6}$ per metre crack length of total 5.6 m each door. This had the effect of reducing the whole building air change rate by approximately 40% (calculated at a wind speed of 4 m/s). This is an extreme condition, and it may be more appropriate to assume half of all doors are open in practice.

Air change in selected zones with doors closed were calculated and found to be lowest in areas between the two lightwells. This is consistent with the expectation that wind pressure differences across these areas should be lowest. Nevertheless, they were broadly similar to whole building air change rate.

6.2. Effect of shelter by tall buildings

Surface pressures were measured on the surface of the 1/200 scale replica of the eight-storey building located amongst other tall buildings of similar height, set within an urban terrain. Although not fully representative of the actual surrounding city terrain of the real site, ventilation rates predicted using these data could be directly compared with predictions (above) using data collected with the same terrain but with no shelter.

The procedure for predicting whole building air change rates was repeated as above. For 4 m/s wind speed, air change rates varied by less than 2% from a mean of 0.45 ach. These are only approximately 13% less than the corresponding results predicted for the generalised building with no shelter.

It is noted, however, that this work highlights a general issue concerning the common practice of using pressure data which take no account of possible local shelter effects. However, when local shelter is included, there may be the difficulty of significant Reynolds number effects where air speeds are low between the tall buildings, as discussed above. This could cause errors in measurements of surface pressures on the sides of the building. However, this issue is a subject for further research in itself.

7. PROPOSED BASIS FOR REVISED DESIGN GUIDANCE ON COURTYARD DESIGN

It has been shown (above) that adequate ventilation can achieved within the building, which addresses one of the two key issues raised earlier. The other concerned the requirement for adequate ventilation of the courtyard. In the light of the coherent theory of flow into the courtyard developed above, the salient facts can now be drawn together to formulate a basis for a revised design guideline.

If we take a criterion that wind driven ventilation in the courtyard should be adequate down to 1 m/s, then it can be concluded from Murakami's work[10] at model scale, and in the light of full scale measurements described above, that we might expect 10 ach as a conservative estimate. In the small lightwell in the eight-storey building considered, this is equivalent to 300 m^3/h per m^2 of courtyard area, or an effective purging velocity component of 0.08 m/s. The ratio of this velocity to the stated wind speed of 1 m/s is 0.08, which is less than 0.15 measured by Murakami, thus reinforcing the belief that we have taken a conservative estimate of the flow in the court.

Assuming an occupancy density of one person per 20 m^2 of dwelling floor area, then the ventilation requirement (based on 8 litres/sec per person) is 300 m^3/h per 200 m^2 of floor area. We calculated above that this flow rate will be supplied by 1 m^2 of courtyard area.
If we also allow for the additional burden of diluting kitchen extract flow rates, rated at approximately 30 litres/sec (per dwelling). Assuming three people per dwelling, and that only half of all extracts operate at any one time (ie a diversity factor of 50%), this amounts to an additional

ventilation requirement of 5 litres/sec per person. This increases the requirement (ie courtyard area) by a factor of about 3/2. We may further conservatively allow for a ventilation efficiency factor of approximately 1/3 for poor dispersion of contaminants, eg emitted from kitchen extracts, flues etc, which increases the requirement by a factor of 3. Taking both requirements together for diluting contaminants efficiently suggests a final figure of 50 m^2 floor area per m^2 of court area.

8. CONCLUSIONS

Existing regulations concerning the design and construction of buildings which are naturally ventilated via courtyards and lightwells have origins in daylighting rather than in aerodynamics, and currently effectively preclude narrow, high-sided designs. Previous research left many doubts and gaps in knowledge which, if resolved, may lead to revised guidance so that courtyards can become an option for natural ventilation. Work was therefore carried out to re-assess these restrictions, using CFD as part of an integrated approach in combination with measurements at both model and full scale. The results revealed the mechanism and key design parameters governing air flow into a deep courtyard, so forming a coherent descriptive model which explained the apparent discrepancies in earlier work.

This model showed that effective air exchange in a courtyard does not depend simply on the ratio of its height to its width, as typically addressed by regulations, but rather on the surrounding buildings, the shape and orientation of the courtyard building and the position of the open courtyard relative to the upwind edge of the roof. To summarise, effective ventilation can be expected in the following cases:

- a court building sheltered by other buildings (of similar height) nearby, such as in towns or cities,
- an exposed court building (ie in open country, seaside or the edge of urban areas), except for the infrequent case of winds normal to one face
- a building with a shallow court (courtyard height/width ratio less than about 1.5) an exposed location, for all wind conditions,

and the following minimum area should be maintained :

- horizontal courtyard area, open to the sky, of 1 m^2 per 50 m^2 of habitable floor area of surrounding building.

In addition, the ventilation performance within the building was assessed using a multizone prediction model. This indicated that minimum ventilation requirements can be met in the case of an eight-storey design with typical envelope air leakage and trickle ventilators. However, important questions were raised concerning the effect of (a) local shelter, (b) closing of internal doors. These are considered to be general problems which should be addressed in future work.

In practice, for residential developments, planning authorities would not allow the relatively high density of building which could follow from the above guidance. Nevertheless, it can be said that ventilation in itself imposes no practical restraint on courtyard design and, as a result, the regulation has been removed from the proposed revisions to the Building Regulations for England and Wales (Part F).

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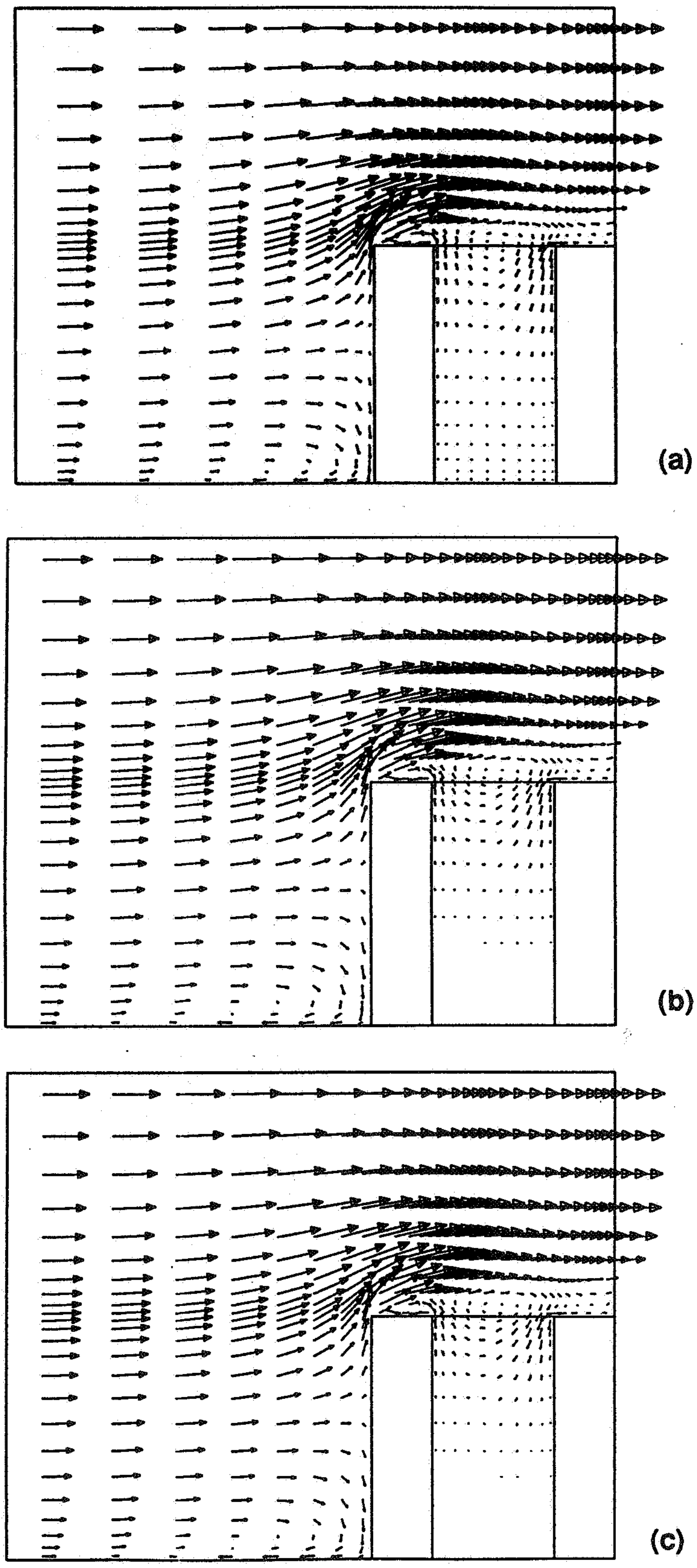


Figure 1. Building width perpendicular to flow increased by factors (a) 1.0 (b) 1.5 (c) 2.0

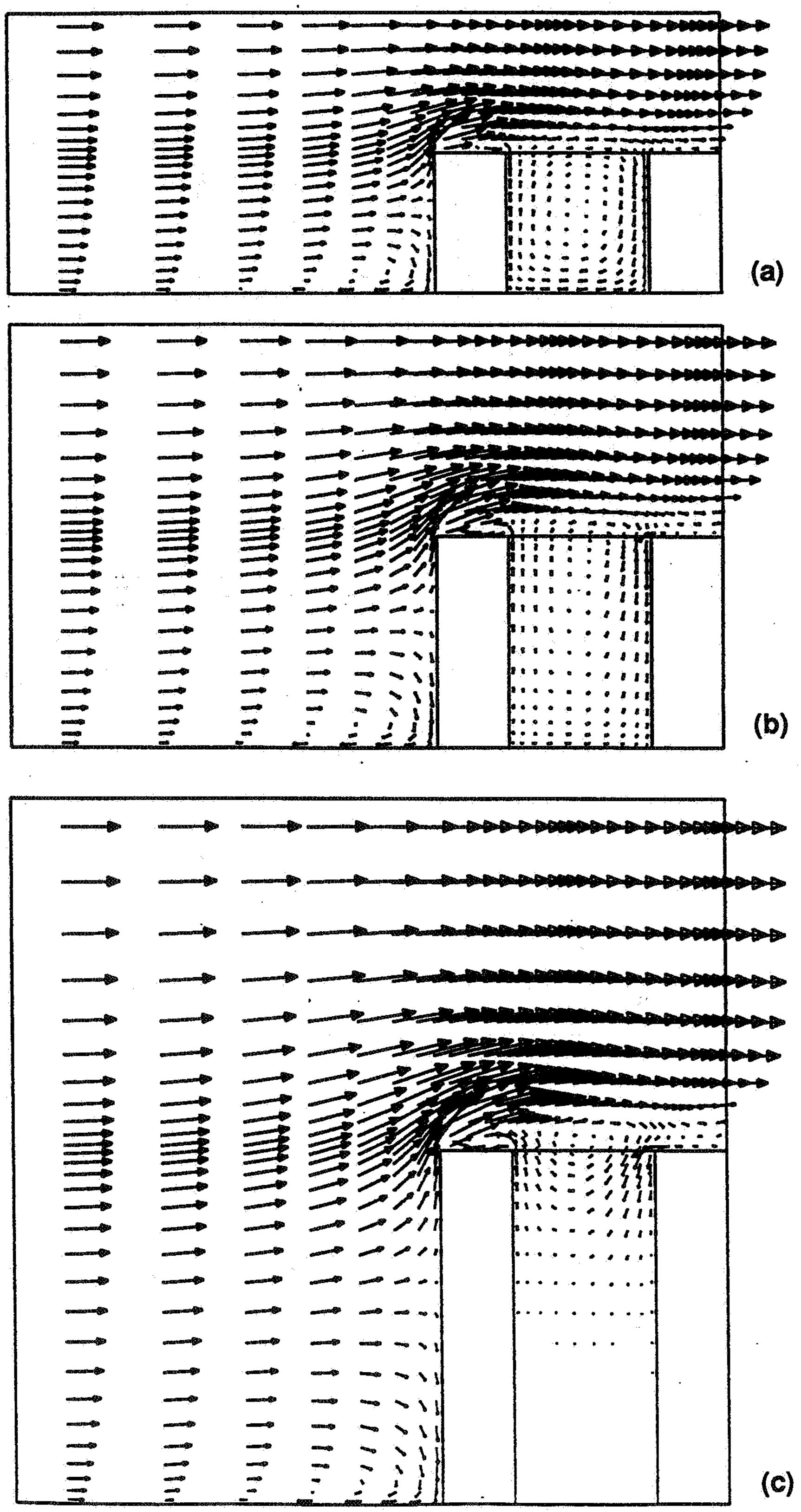
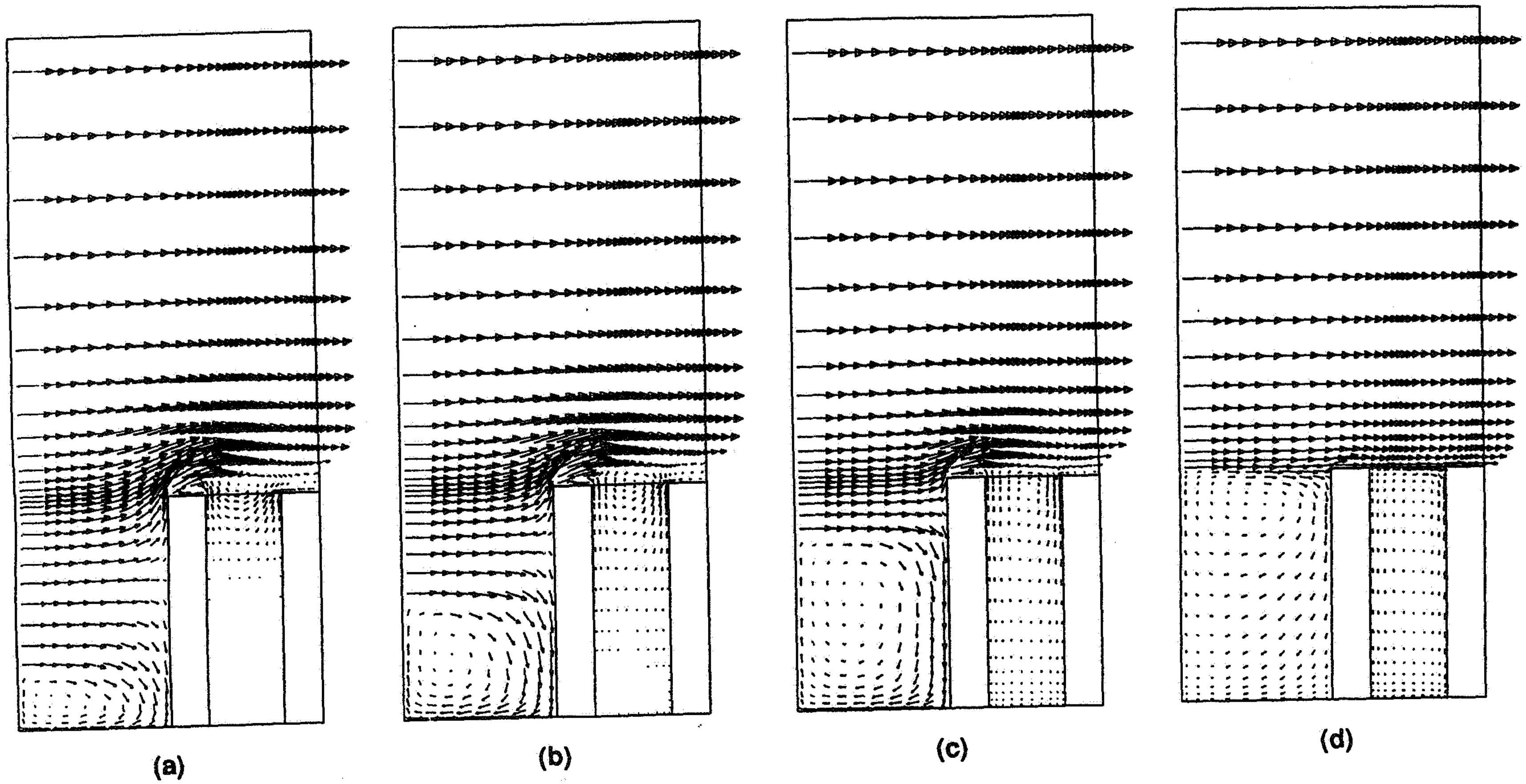


Figure 2. Building height increased by factors of (a) 1.0 (b) 1.5 (c) 2.5



(a) (b) (c) (d)

Figure 3. Velocity reduced below roof level to simulate effect of surrounding buildings (upwind) of heights; (a) 1/4 x building height (b) 1/2 (c) 3/4 (d) equal heights

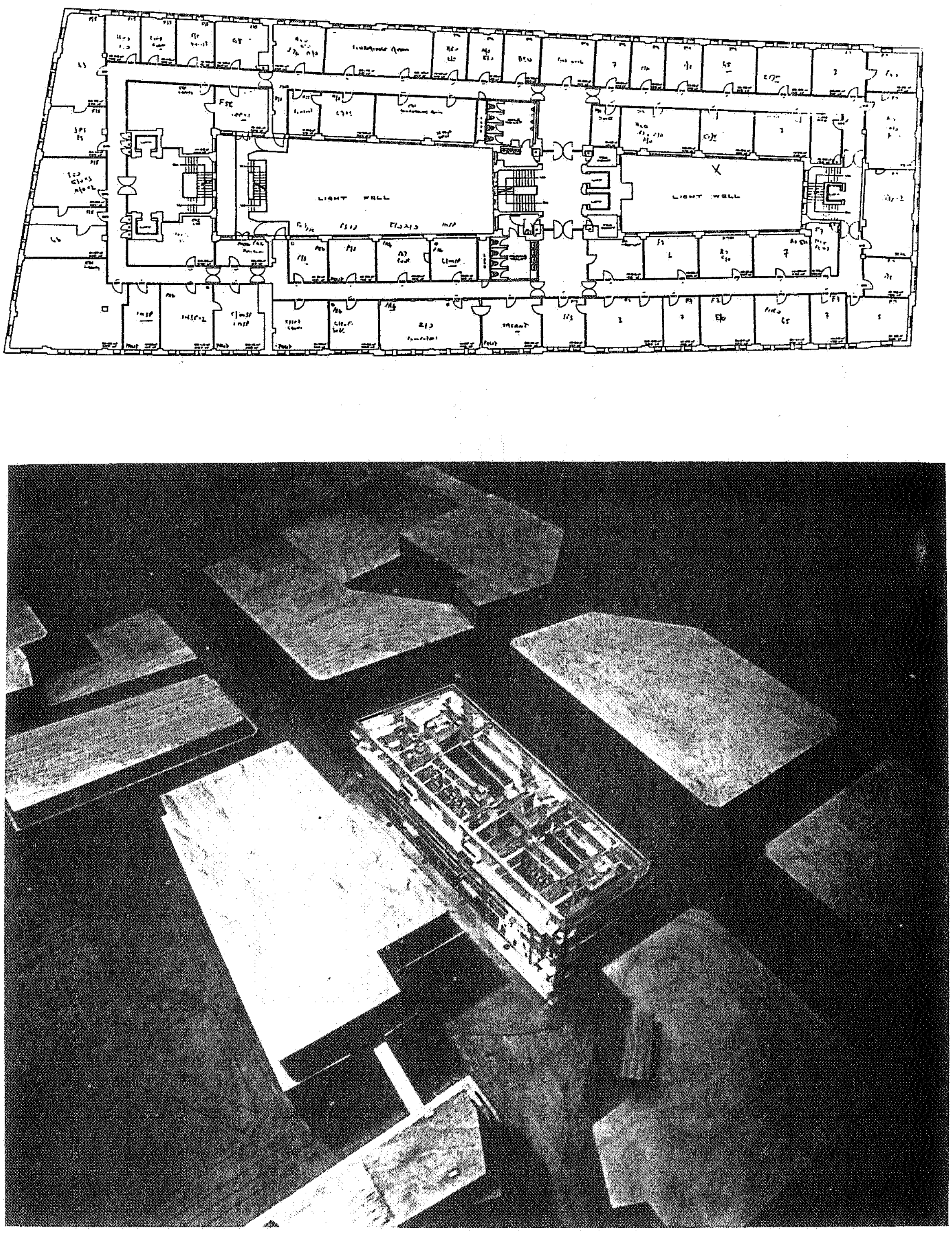


Figure 4. Eight-storey building; (above) floor plan, and (below) 1/200 scale model, shown mounted on turntable with surrounding buildings

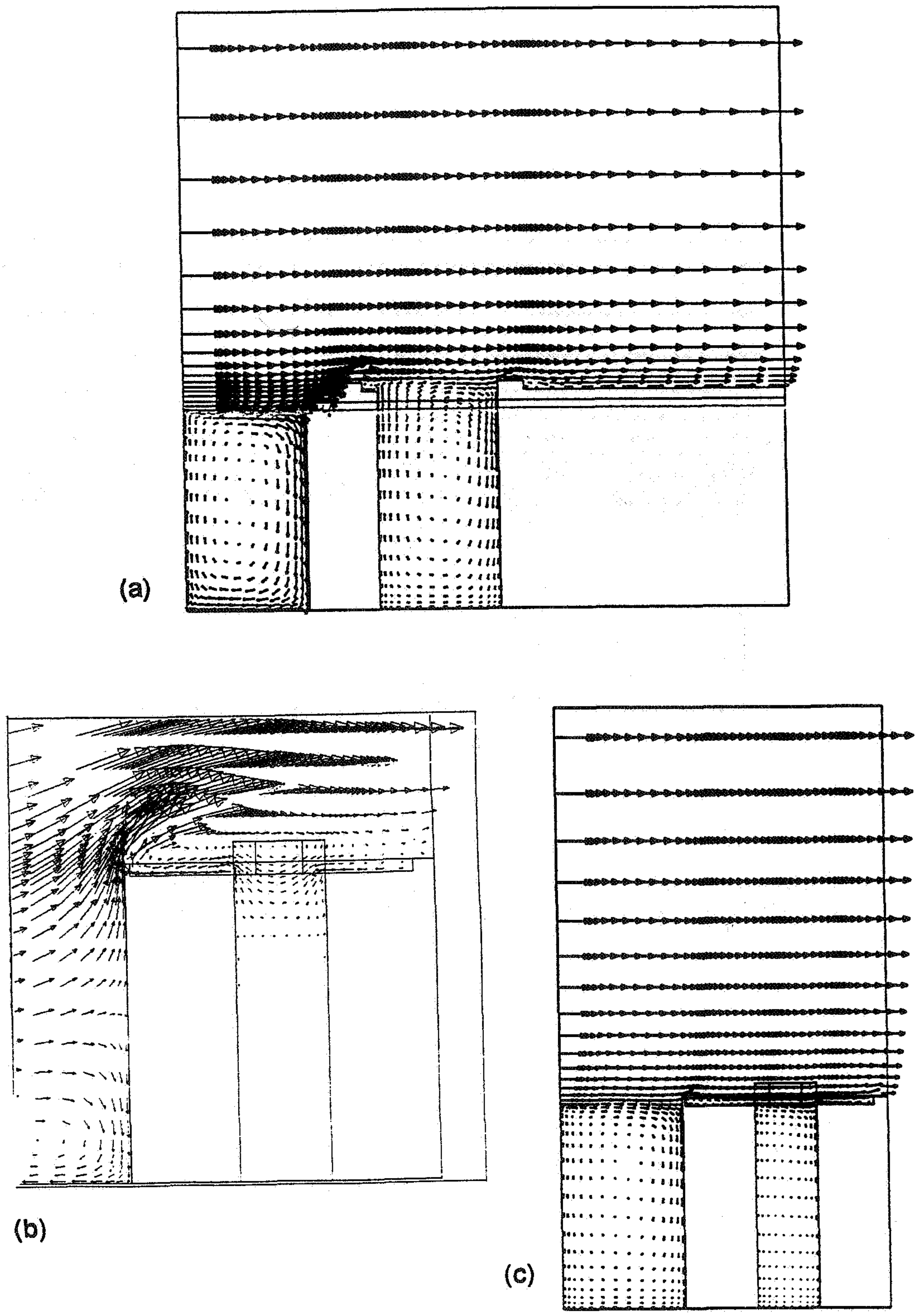


Figure 5. Airflow over eight-storey building; (a) full vortex with south winds, (b) top vortex for west winds (re-attachment too far downstream of narrow dimension of opening), (c) as (b) but full vortex due to simulated shelter effect of local tall buildings.

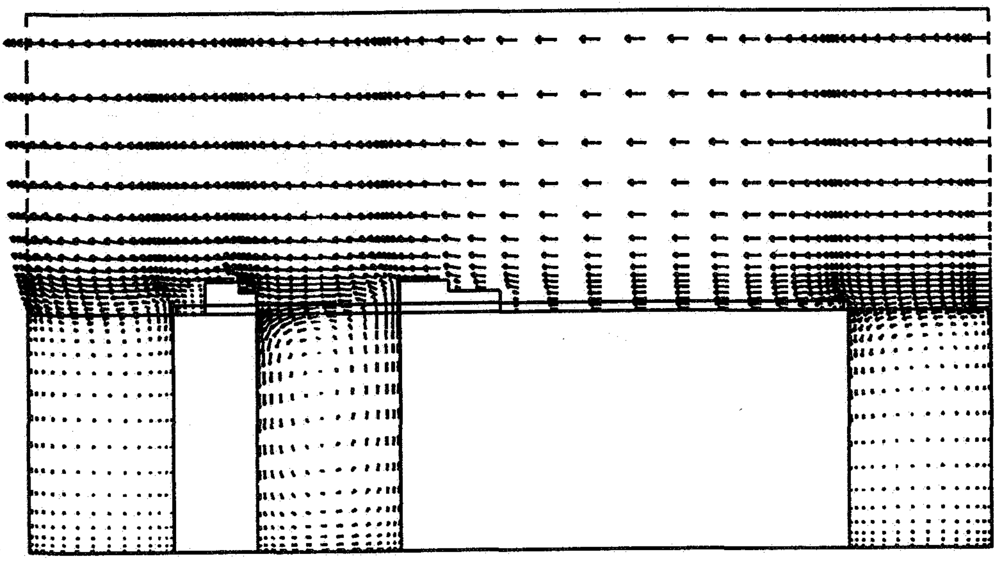


Figure 6. Eight-storey building modelled in full, for winds 30° north of west with shelter effect included; full vortex and air change rate compared with field measurements