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Modeling the Performance of a Naturally Ventilated Commercial Building with a Multizone Coupled Thermal/Airflow Simulation Tool

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ABSTRACT

Natural ventilation systems have long been employed in European residences to control indoor air quality and provide thermal comfort. Increasingly, European building designers have turned to natural ventilation to control air quality and cool commercial and institutional buildings as well, hoping to take advantage of the potential of natural ventilation systems to conserve energy associated with mechanical cooling and fan operation. Encouraged by the early successes of the past decade, European building designers have advanced natural ventilation technology, introduced promising hybrid ventilation technologies that combine mechanical and natural means, and developed analytical tools for the design of these systems. These systems may be adapted to the North American context, but much work will need to be done to realize the full potential natural ventilation may offer to North America. The needed work includes modeling studies that may require advanced simulation tools to adequately model the complex coupled thermal and airflow dynamics.

A modeling study of a representative naturally ventilated building recently constructed in The Netherlands is presented. A multizone coupled thermal/airflow simulation tool CONTAM97R is used to investigate the performance of this building in two challenging North American climates. Comparisons of measured and predicted performance of this building in its native climate were performed as a validation exercise and to calibrate the building models used for subsequent analytical studies. Initially, two models of a five-story segment of this building were formulated—a single-zone model with detailed representations of ventilation inlets and exhausts and a highly detailed 31-zone model accounting for all purpose-provided and infiltration flow paths.

After the calibration studies, a moderately detailed 11-zone model was then used to demonstrate the application of macroscopic coupled thermal/airflow performance evaluation to the design development of night ventilation cooling systems for the Enschede Tax Office placed in a hot, arid North American location—Los Angeles, California. Following a trial-and-error procedure using an overheated degree-hour performance metric, component sizes were adjusted to achieve the night cooling objective.

This modeling effort demonstrated that a macroscopic tool such as CONTAM97R provides essential spatial and temporal details that can guide system design relating to both whole-building and inter-room air distribution and thermal performance. In some cases, greater intra-room detail may be required. In these cases, performance evaluation would reasonably proceed to detailed computational fluid dynamic studies of individual rooms.

INTRODUCTION

This paper describes a modeling study of a representative naturally ventilated commercial building that takes a fundamental approach using the simulation program CONTAM97R. The modeling effort is part of a larger study (Axley 2001) exploring the application of natural ventilation for commercial buildings in the U.S. The modeling study consists of a *calibration study* (to validate the application through the comparison of measured and predicted results) and a *night cooling design development study* (to provide an example of the use of detailed performance evaluation in the design development of a night cooling system for Los Angeles, Calif., and to evaluate the feasibility of night cooling by natural means in this climate).

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These computational modeling studies were performed using an unreleased version of the CONTAM family of programs—CONTAM97R (Walton 1997, 1998; Dols et al. 2000). This multizone dynamic analysis program supports modeling of coupled thermal/airflow interactions and ventilation control logic—both central to the behavior of natural ventilation systems. CONTAM97R may be used, in principle, to evaluate key performance characteristics, including annual and peak energy demands, indoor air temperature extremes, and time histories, and statistical analyses of whole building outdoor air change rates achieved, indoor air pollution levels, air distribution evaluated in terms of time histories, and statistical analyses of zone-evaluated age of air and indoor moisture levels.

A state-of-the-art low-energy office building—the Tax Office of Enschede, Netherlands (Perera 1998)—was used as the basis for the modeling studies. This five-story, 4,300 m^2 building, even though European, is similar in plan and organization to many mid-sized U.S. commercial buildings. It utilizes a natural ventilation system based on operable windows, self-regulating trickle ventilators, and a central slot atrium with passive stacks and mechanical-assist fans. As constructed, the natural ventilation system may be operated in a direct or indirect (i.e., nighttime cooling) mode.

DESCRIPTION OF BUILDING MODELS

The plan of the Enschede Tax Office is organized around an elongated east-west slot atrium (Figure 1). Offices and meeting rooms are distributed along the southern and northern sides of the building along corridors that, on the north, separate the offices from the atrium and, on the south, separate the offices from a row of utility spaces that flank the atrium volume—a stairway, file rooms, toilets, and storage rooms.

In one section, five levels of offices are placed above ground level parking on the south side of the building and above utility rooms on the north (Figure 2). The basic natural ventilation strategy is clearly revealed in this section. Driven by the combined effects of buoyancy forces and wind, air enters individual offices through self-regulating inlet vents, mixes within the offices, and flows out of the offices, on the north side, through transfer grilles and, on the south side, over the corridor and utility spaces through purpose-provided transfer ducts to the central atrium. This air then flows up through the atrium space to ventilation stacks and out. In the event that the natural driving forces are insufficient, assist fans are provided that exhaust air from the atrium space on the north side roof level.

Slot atria schemes, such as the Enschede Tax Office, are one of a number of common schemes used in office buildings in both Europe and North America. They offer obvious daylighting and ventilating advantages. From a technical point of view, slot atria schemes may reasonably be modeled by limiting consideration to a representative segment of the building as the influence of airflows through the narrow end walls may be expected to be slight, especially for more elongated plans. Here, a representative segment of the building equal to one office bay in width (Figure 1) and passing through the full height of the building was chosen for the basis of all modeling studies (i.e., with the section shown in Figure 2).

Initially, two models of this representative building segment were created:

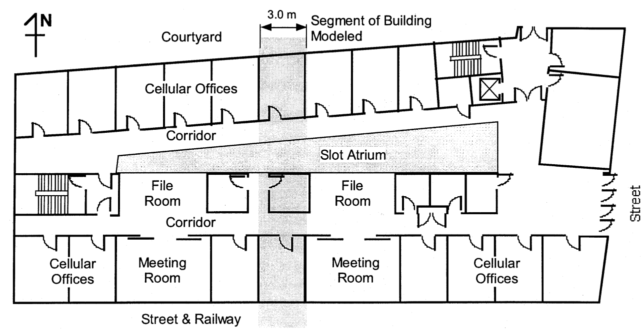

Figure 1 *Plan of the Enschede Tax Office showing the section of the building modeled.*

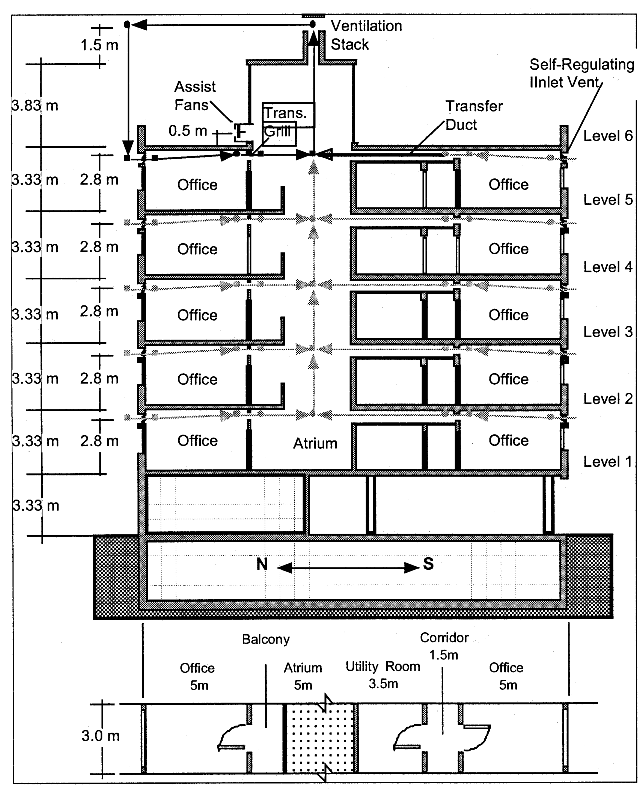

Figure 2 *Plan and section of the detailed multizone model of a representative segment of the Enschede Tax Office building. Solid dots and linking arrow indicate, diagrammatically, pressure nodes and airflow paths that will be used in subsequent loop analysis to size components for specific climatic conditions.*

TABLE 1
Spatial Variation of Wind Pressure Coefficients

	Wind Pressure Coefficients C_P			
	C_p (0°)	C_p (90°)	C_p (180°)	C_p (270°)
Stack Terminal	-0.60	-0.60	-0.60	-0.60
Level 6	0.70	-0.58	-0.36	-0.58
Level 5	0.70	-0.58	-0.36	-0.58
Level 4	0.72	-0.55	-0.35	-0.55
Level 3	0.58	-0.48	-0.34	-0.48
Level 2	0.41	-0.38	-0.29	-0.38
Level 1	0.44	-0.17	-0.28	-0.17

1. *Simplified Single-Zone Model:* a simplified single-zone model of the building in which only ventilation system components were modeled (i.e., self-regulating inlet vents, stack exhausts, and stack assist fans were modeled). In this case, the interior of the building was treated as a single lumped zone. The simplified model used to study the natural ventilation system alternatives is similar to *simplified envelope models* commonly used for preliminary analysis of natural ventilation systems that ignore internal resistances to airflow.
2. *Detailed Multizone Model:* a multizone model of the building in which all important flow paths through the envelope and within the interior of the section were modeled in detail. Thus, in addition to the flow paths considered in the simplified single-zone model, transfer grilles and duct components of the natural ventilation system and wall, window, and door leakage are included for each of 21 zones corresponding to the ten offices, ten corridors/halls, five utility rooms, and five levels of the central atrium shown in Figure 2.

The relevant geometry used for both models is shown in Figures 1 and 2. Floor-to-floor heights were assumed to be 3.33 m with an effective floor-to-ceiling height of 3.0 m based on published information (BRE 1999). Self-regulating inlet vents in the Enschede Tax Office were located close to the ceiling to take advantage of the *coanda* effect during cold outdoor conditions—here their location was assumed centered 2.8 m above the floor level in all offices. Finally, the actual dimensions of the monitor at the top of the atrium, the ventilation stack height, and the location of the assist fans were estimated from photographs of the Enschede Tax Office (BRE 1999).

Wind Pressures

Wind pressures p_w acting on envelope openings of the building were modeled in the usual manner using the kinetic energy per volume of the reference approach wind velocity modified by empirically determined wind pressure coefficients C_p.

$$p_w = C_p \frac{1}{2} \rho U_{ref}^2 \tag{1}$$

where ρ (kg/m^3) is the air density of the approach wind and U_{ref} (m/s) is the reference wind velocity taken at the height of the building. Utilizing the capabilities of the program CONTAM to account for terrain and elevation effects (Walton 1997; Dols et al. 2000), reference wind velocities were modeled for an assumed urban location using airport wind speed data for all model studies except the calibration studies. The calibration studies discussed below used actual wind speeds measured at the site of the Enschede Tax Office for the reference wind velocity.

The variation of C_p with wind direction ϕ was modeled using the Walker/Wilson model (1994). The spatial variation of these wind pressure coefficients over the height of the building were based on published wind pressure coefficient data for a five-story building of simple rectangular geometry (Orme et al. 1998). The variation of C_p with direction and height is summarized in Table 1.

Due to the central importance of the ventilation stack in natural ventilation system design, it is important to select stacks that (a) are relatively insensitive to wind direction and (b) provide relatively large suction pressures (i.e., to maintain control *authority* over the natural ventilation airflow rates and direction). Stacks terminating above nearby roofs and having a more-or-less axisymmetric configuration tend to provide wind direction insensitivity. Wind pressure coefficients between –0.5 to –0.7 or even greater may be realized with properly configured and detailed stack terminal devices (Welsh 1995a, 1995b; Parkins 1994; de Gids and den Ouden 1974; Holmes and McGowan 1997; Gage 1999). As indicated in Table 1, the stack wind pressure coefficient was assumed to be –0.60 for all modeling studies.

Natural Ventilation System

Natural ventilation systems involve both the physical assembly of ventilation system components and the logical control of these components to achieve one or more ventilation objectives. From a modeling point of view, five component types are used in the natural ventilation system of the Enschede Tax Office: (1) self-regulating inlet vents, (2) the ventilation stack, (3) the assist fan, (4) transfer grilles used to link the north offices to the atrium, and (5) transfer ducts used to link the south offices to the atrium.

The self-regulating inlet vents and the ventilation stack were included in the simplified single-zone model, while all five components were included in the detailed multizone model of the Enschede Tax Office.

In addition, control strategies were formulated for winter and summer conditions that were modeled as discussed below.

Self-Regulating Inlet Vents and Design

Self-regulating inlet vents (Knoll and Kornaat 1991; Wouters and Vandaele 1990; Cavannal et al. 1999; Schultz 1993) provide relatively constant airflow rates over the range of air pressure differences likely to be encountered. Consequently, they provide the means to achieve controlled design airflow rates for the stochastically varying natural driven conditions that must be expected in the field. However, they cannot sustain design airflow rates when wind and buoyancy forces drop to negligible values.

The self-regulating inlet vents used in the Enschede Tax Office were designed to provide a constant flow rate of 50 m^3/h for driving pressure differences between 1 Pa and 25 Pa at their lowest setting and 100 m^3/h at their highest setting. Two of these vents, each approximately 0.3 m wide and 0.1 m high, were installed at near-ceiling locations in each of the offices. Consequently, by setting both of these vents at the lowest ventilating position, an airflow rate of 100 m^3/h could be achieved—this rate was the design airflow rate specified for air quality control in the Enschede Tax Office. By setting both vents to the highest setting, an airflow rate of 200 m^3/h could be achieved (i.e., when driving forces were sufficient)—this rate was the design airflow rate specified for night cooling ventilation in the tax office.

The following power-law component relation using an unusually low exponent of $n = 0.1$ was used to model one of the two vents placed in the offices set at its lowest setting.

$$\dot{V} = 38.84\Delta p^{0.10}(\mathrm{m}^3/\mathrm{h}) \tag{2}$$

where $\dot{V}$ (m^3/h) is the volumetric airflow rate through the component and Δp (Pa) is the pressure difference across the component. Relative to the power law model, using an exponent of $n = 0.5$ that is commonly used to model simple openings in building envelopes, the relation chosen to model the self-regulating inlet vents (Equation 2) provides a fairly constant airflow rate over a range of pressure differences likely to be encountered in practice (i.e., from 0 Pa to 25 Pa).

During winter operation, then, when the design airflow rate of 100 m^3/h is the ventilation objective, the component relation defined by Equation 2 is scaled by 2.0 for modeling the combined use of both vents at their lowest setting. Similarly, for night cooling operation, Equation 2 is scaled by 4.0.

Ventilation Stack

Unfortunately, the pressure-flow characteristics of the stack used in the Enschede Tax Office building are not available. Consequently, the performance of the stack had to be modeled based on a reasonable design strategy that the self-regulating inlet vents maintain authority over the natural ventilation airflow rates, as they were intended to be the controlling flow component. To ensure that these vents do, indeed, limit flow, one may examine pressure drops around each of ten airflow *loops* passing through each office, to the atria, up the stack, and back again to the inlet vents. Of these ten loops, the loop passing through the upper office, shown as a linked series of black arrows and nodes in Figure 2, provides the critical case, as pressure differences in this loop due to buoyancy will be smallest in comparison to all other loops.

Design loop equations may be directly formulated once mathematical models are selected for each of the flow components in a ventilation loop (Axley 1999, 2000). Design loop equations for the winter air quality control mode and the summer night cooling mode may be applied to the simplified model of the building with the inverse of Equation 2 for the inlet vent pressure loss, a simple orifice model for the stack terminal pressure losses (note that 1 stack serves 10 inlets), and stack and wind driving forces to yield (see Axley 2001 for details).

AQ Control Mode:

$$\left(\frac{0.0278}{0.02158}\right)^{10} + \frac{1.2\ \mathrm{kg/m^3}(0.278)^2}{2(0.6)^2A_{stack}^2} = 12.5 + \frac{0.129}{A_{stack}^2} = \Delta p_s + \Delta p_w \tag{3a}$$

Night Cool Mode:

$$\left(\frac{0.0556}{0.04316}\right)^{10} + \frac{1.2\ \mathrm{kg/m^3}(0.556)^2}{2(0.6)^2A_{stack}^2} = 12.5 + \frac{0.515}{A_{stack}^2} = \Delta p_s + \Delta p_w \tag{3b}$$

where A_{stack} is the opening free area of the stack terminal device.

If the loss in the stack terminal device is to be small relative to that of the inlet vent (i.e., so the inlet vent maintains control authority), then we must demand the second terms of Equations 3a and 3b be small relative to the first terms. If we set the relative difference to a tenfold difference, we obtain:

AQ Control Mode:

$$A_{stack} \geq \sqrt{0.129/1.25} = 0.32\ \mathrm{m}^2 \tag{4a}$$

Night Cool Mode:

$$A_{stack} \geq \sqrt{0.515/1.25} = 0.64\ \mathrm{m}^2 \tag{4b}$$

Based on these limiting arguments for sizing the stack terminal device, the stack terminal will be modeled as an orifice with a free opening area of 0.50 m^2 (with ρ at room air temperature and discharge coefficient C_d of 0.6) as

$$\dot{V}_{stack} = (3600)C_dA_{stack}\sqrt{\frac{2\Delta p}{\rho}} \approx 1390\sqrt{\Delta p}[=]\ \mathrm{m}^3/\mathrm{h}\ . \tag{5}$$

(Subsequent calibration studies, discussed below, were used to refine this estimate. As a result, the stack terminal free area was increased to 1.0 m^2 to maintain the inlet vent authority over ventilation flow rates.)

Assist Fans

A single assist fan was included in the building model. The fan was modeled as a CONTAM variable flow fan with a fan performance curve represented by a cubic polynomial adjusted to provide the maximum design ventilation flow rate at a low-pressure difference (i.e., 200 m^3/h for each of the ten offices in the model).

Natural Ventilation Control

Building occupants in the Enschede Tax Office were given direct control of their environmental conditions although automatic control of lighting and external shading was provided that occupants could choose to override. A graphic chart was placed at each workstation that provided instructions for ventilation, heating, lighting, and internal and external shade operation. These instructions were organized for winter and summer conditions with distinct instructions given for operations during and outside of office hours. The objectives of the control were to maximize the use of daylight, control solar gains during the overheated periods of the year, provide at least the minimum ventilation rate for air quality control during occupied hours (occupants were encouraged to increase this during overheated periods when outdoor air temperatures were low enough to provide direct cooling), limit natural ventilation outside of office hours during winter conditions, and provide the maximum ventilation rate outside of office hours during heat waves to effect night cooling.

For night ventilation during summer hot periods, building occupants were instructed to set the self-regulating inlet vents to the maximum setting "2" (i.e., intended to provide 200 m^3/h for each office) at the end of the workday. At other times, they were to set the inlet vents to the minimal airflow setting "1" (i.e., intended to provide 100 m^3/h for each office). With the workday assumed to be from 8:00 a.m. to 5:00 p.m. during weekdays, this night ventilation control strategy was modeled using a simple schedule of a setting of 1 during work hours and 2 at all other times. To introduce a more realistic operating schedule (and to avoid abrupt changes in operating conditions that are difficult to capture numerically), changes in the self-regulating ventilation settings were assumed to occur over a 15-minute time interval.

Ideally, night ventilation should be controlled in response to thermal conditions (i.e., specifically when outdoor air temperatures fall below indoor air temperatures and moisture content is not excessive) rather than by a time-of-day schedule. Consequently, one should expect the control strategy used in the Enschede Tax Office to be less than optimal—results of the calibration studies presented below indicate this was the case.

Detailed Multizone Model Assumptions

In addition to the modeling assumptions above that were common to both the simplified model and the detailed multizone model, additional flow paths and flow resistances were included in the multizone model with leakage data published by NIST (Persily and Ivy 2001).

Envelope Leakage: Envelope leakage through both windows and walls was modeled using an effective leakage area of 1.0 cm^2/m^2 of window or wall surface area for *tight* construction and 10.0 cm^2/m^2 for *loose* construction (reference pressure of 4 Pa and flow exponent of 0.65).

Interior Walls: Interior walls were modeled using an effective leakage area of 1.0 cm^2/m^2.

Doors: Doors between offices and corridors were assumed closed and not undercut and were modeled with a leakage area of 100 cm^2 per door. Doors to the utility rooms were assumed closed and undercut and were modeled with a leakage area of 250 cm^2 per door. Doors linking the southern corridor with the atrium were assumed opened and modeled using the orifice element model with opening area equal to 0.9 m × 2.1 m and a discharge coefficient of 0.6.

Transfer ducts between the southern offices and atrium and transfer grilles between the northern offices and atrium were both modeled with 150 mm (6 in.) round ducts using the CONTAM Darcey-Colebrook duct modeling element. The transfer duct was modeled as a 5 m long duct and the transfer grille as a 150 mm long duct. The resistances of both were small relative to other flow resistances along the natural ventilation flow paths and, thus, had little impact on the flow rates (i.e., they were amply sized for their intended purpose).

Finally, stack exhaust airflow was modeled using the variable flow fan model described above with an off-flow resistance defined by the orifice equation with a free area of 1 m^2. This modeling tactic allowed the control of fan-assisted stack ventilation to be modeled. For those studies utilizing fan-assisted stack ventilation for night ventilation, the assist fan was activated outside of occupied hours when the following two conditions were satisfied:

- the slot atrium temperature exceeded outdoor air temperature ($T_{atr} > T_{out}$) and
- the slot atrium temperature was greater than 24°C ($T_{atr} >$ 24°C).

Thermal Characteristics

CONTAM97R (Walton 1998) may be used to model the interaction of the natural (and mechanical) airflow and thermal systems of multizone building models—that is to say, it provides coupled thermal/airflow analysis. Presently, it provides thermal components to model dynamic one-dimensional conductive heat transfer components (i.e., accounting for both conductivity and heat capacity in multilayer construction assemblies), to model wall assemblies, dynamic one-dimensional thermal storage heat transfer components (i.e., accounting for both conductivity and heat capacity in multilayer construction assemblies with an adiabatic boundary), to model internal thermal mass, advective heat transfer due to the interzonal airflow, and to model internal gains due to occupants and equipment, solar gains, and space conditioning.

Advective heat transfer is automatically modeled using the airflows computed for the airflow system modeling. CONTM97R does not directly account for radiative transfer through glazed portions of the building envelope and does not yet correctly account for air spaces in glazed or opaque wall constructions.

Conductive heat transfer, internal thermal mass, and heat gain components were used to model the physical components of the Enschede Tax Office's thermal system and the scheduling capabilities of CONTAM97R were used to model the control of heat gains internal to building zones. Some, but not all, details of building construction were available so a number of relatively minor assumptions had to be made to build a model of the building. Details of these modeling assumptions are enumerated below. Thermal properties were taken from the *1997 ASHRAE Handbook—Fundamentals* (ASHRAE 1997a).

Envelope Resistances

Opaque roof and wall surfaces were modeled by a multilayer construction consisting of 25 mm of brick tile, 20 mm of plywood, 150 mm of fiberglass insulation, and 13 mm of gypsum wallboard. As noted above, solar absorption to outer surfaces of these constructions was not directly modeled; thus, heat transfer was limited to conductive and surface convective transfer due to temperature differences between zones and between zones and the outdoor air temperature. For the 3.0 m section of the building modeled, the total opaque envelope surface area modeled was 155.4 m^2 to 60 m^2 of roof area, 55 m^2 of wall surface, and 40.5 m^2 of an exposed floor area above a ground level parking area.

Glazed wall surfaces included higher *daylight windows* and lower *view windows* that, together, provided 4.5 m^2 of glazed area per office or 45% of the nominal exterior wall area of each office. These windows were assumed double-glazed with relatively efficient low-e glazing. As stated above, the internal air space of this double-glazed system could not be directly modeled. Instead, these windows were modeled as a multilayer construction of 3 mm of glass, 10 mm fiberglass insulation, and 3 mm of glass with both inside and outside surfaces of the double-glazed system modeled with longwave emissivities of 0.20. As noted above, solar gain through these windows was not directly modeled.

Finally, windows that flanked the north and south sides of the atrium extension were also modeled using the same double-glazed construction. For the assumed 3.83 m height of this extension, an area of glazing of 11.49 m^2 on each side of the extension was accounted for.

Internal Thermal Mass

The Enschede Tax Office was constructed to allow the massive floor construction used to be exposed on both upper and lower surfaces to room air. The effect of this "high" thermal mass was modeled using 150 mm of concrete (i.e., with an assumed adiabatic inner surface) for both floor and ceiling surfaces. Given the geometry (Figure 2), the total internal mass surface area was estimated to be 516 m^2. Night ventilation strategies depend critically on the amount of thermal mass present and its participation in the dynamic thermal response of the building that depends on the exposed surface area of the thermal mass, its thermal characteristics, and the dynamic character of the thermal excitation. For the spans involved in the tax office, an effective participating thickness of concrete of 15 cm is reasonable. The estimated surface area was based on the assumption of a flat ceiling surface—perhaps a conservative assumption given that concrete joist or waffle slab systems commonly used for this type of construction would result in larger ceiling surface areas.

Internal and Solar Gains

Natural ventilation cooling strategies must be complemented by effective and comprehensive control of solar and internal gains. In the Enschede Tax Office, this was achieved with a relatively high-resistance envelope construction to control solar gains admitted by conduction, automatic control of external shades to control solar gain admitted by radiative transmission, and automatic control of artificial lighting coupled with optimally designed daylighting systems to offset heat gains due to electrical lighting. Combined internal gains for lighting, equipment, and occupants during summer operation of the building were reported to be 27.5 W/m^2 net office floor area (BRE 1999).

Estimates of internal gains due to equipment in offices vary considerably from 4 W/m^2 to 20 W/m^2 with intensive computational facilities approaching 30 W/m^2 (see, for example, ASHRAE [1997], chapter 28, Komor [1997], or Wilkins and Hosni [2000]). State-of-the-art lighting systems may be expected to add another 5 to 10 W/m^2 (see, for example, Skaret et al. [1997]). Thus, combined with an occupant load of 8 W/m^2, internal gains in offices may be expected to range from 17 W/m^2 to 38 W/m^2 for typical uses.

Ideally, in an optimally designed low-energy building, solar gains during the summer period should be limited to just that necessary to provide sufficient daylighting. If this ideal is achieved, the combined solar and internal gain during sunny periods should fall below that of the internal gains alone required during overcast conditions. In any event, in a properly designed low-energy building, the solar gains may, arguably, fall within the uncertainty of the internal gains due to occupants, equipment, and artificial lighting alone. Thus, rather than modeling solar gains directly, simulations were completed for a range of assumed combined internal and solar gains of 20.0 W/m^2, 27.5 W/m^2, and 35.0 W/m^2 for office areas and 5.0 W/m^2 (i.e., for lighting loads alone) for corridor, atrium, and utility room areas —during occupied hours. These areas were estimated to total 150 m^2 for offices and 108 m^2 for the other areas for the 3.0 m section of the building modeled. Averaged over the floor area of the building model, these modeling assumptions correspond to combined internal loads of 13.7 W/m^2, 18.1 W/m^2, and 22.4 W/m^2 of gross floor area, respectively. Internal and solar gains were assumed to be negligible during nighttime hours and were assumed to be maintained at 5.0 W/m^2 during daytime hours on weekends.

MODELING STUDIES INVESTIGATED

Two general types of modeling studies were considered:

1. *Calibration Studies*—The Enschede Tax Office building has been the subject of detailed field measurements (Perera 1998). Consequently, its measured performance was used

TABLE 2
Climate Suitability Results for Los Angeles, Calif., Based on WYEC2 Data (ASHRAE 1997a)

	Direct Cooling at Various Internal Gains				Night Cooling*
	10 W/m†	20 W/m†	40 W/m†	80 W/m†	
Vent. rate or cooling potential	1.5 ±1.0 h^{-1}	3.0 ±2.1 h^{-1}	5.9 ±4.2 h^{-1}	11.8 ±8.4 h^{-1}	5.9 ±2.3 W/m^2- h^{-1}
% effective†	95%	98%	98%	98%	93% (27 days)

* Night cooling for subsequent days when direct cooling is not effective.
† For direct cooling % = hours effective ÷ 8760 hours; for night cooling % = days effective ÷ days needed.

to calibrate both the simplified single-zone and the detailed multizone models to quantify the reliability and accuracy of the simulation model and thereby characterize the uncertainty of computed results.

2. *Night Cooling Design Development Study*—The performance of a night ventilated version of the detailed multizone model of the Enschede Tax Office placed in a representative hot-arid U.S. climate (Los Angeles, Calif.) was investigated to illustrate the use of detailed performance evaluation to refine a preliminary natural ventilation system proposal. (Additional design development studies may be found in Axley [2001].)

Calibration Studies Data

Both winter and summer field measurements (Perera 1998) are available that were used for calibration studies. (Note: the authors did not make these measurements.) They include the following.

- March 1997—the ventilation rate was measured for selected offices for the following conditions:
  - indoor air temperatures: 20°C to 21°C—for analysis, T_{in} was assumed to be 20.5°C,
  - outdoor air temperature: 9°C to 12°C—for analysis, T_{out} was assumed to be 10.5°C,
  - wind speed: 2 to 3 m/s—for analysis, wind speed was assumed to be 2.5 m/s, and
  - wind direction: from the north.
- June, 1997—the ventilation rate was measured for selected offices for the following conditions:
  - indoor air temperatures: 21°C to 23°C—for analysis, T_{in} was assumed to be 22°C,
  - outdoor air temperature: 16°C,
  - wind speed: 3 to 4 m/s—for analysis, wind speed was assumed to be 3.5 m/s, and
  - wind direction: from the southwest.
- August, 1997—indoor air temperatures were measured for selected offices and the atrium for a four-day period for the following conditions:
  - internal gains in offices during occupancy (i.e., two people per office) of approximately 8 W/m^2 for occupants and 19.5 W/m^2 for office equipment and lighting combined and
  - measured outdoor air temperatures varying diurnally from a minimum of 17°C to a maximum of 31°C over the four-day period.

Unfortunately, wind speed and direction were not reported for the August period. Consequently, calibration analyses were based on a four-day heat wave extracted from the WYEC2 weather record for Boston (ASHRAE 1997b) that has a similar, but slightly more extreme, outdoor temperature time history.

Night Cooling Design Development Study

Los Angeles, Calif., was selected for the design development study. Although its climate may be considered hot-arid, Los Angeles' climate is moderated by its coastal location. Examination of the summer wind speed data reveals that the average summer wind speed for Los Angeles is 3.9 m/s and that very low wind speeds (i.e., < 2 m/s) seldom occur. On this basis, a nominal *design wind speed* for Los Angeles would be 4 m/s.

Table 2 presents results of a climate suitability analysis for Los Angles (Axley 2001). These results provide estimates of the potential effectiveness of natural ventilation to cool an office building at various thermal load levels in Los Angeles. For example, ventilative cooling may be expected to be effective 95% of the time for a building with an internal load of 10 W/m^2 with a required airflow of 1.5±1.0 h^{-1}. Additionally, night cooling will be required for 27 days in Los Angeles and will be effective 93% of those days. To offset a daytime internal gain of 27.5 W/m^2— the internal gain that is used in subsequent modeling design exercises—a nighttime ventilation rate of 4.7 h^{-1}, on average, and up to 7.6 h^{-1} may be required.

MODELING RESULTS

Calibration Studies Results

Computed results for both the simplified single-zone and the detailed multizone Enschede Building model are presented in this section. As expected, the simplified single-zone model predicted general aspects of the building response that were in good agreement with that predicted by the detailed model.

March 1997 and June 1997 Results: Simplified Single-Zone Building Model

Computed ventilation rates based on the simplified single-zone model for the winter (March 1997) and summer (June 1997) calibration data sets are presented in Table 3 along with the computed pressure differences at each of the ten inlet vents.

Given the inherent uncertainty in wind speed, wind direction, and wind pressure coefficients characterizing the impact of these winds on the building, the computed ventilation flow rates compare reasonably well to the reported measured results. For the winter conditions, the computed rates at the third and fifth levels are within 18% of the measured values. At the first level, greater differences are observed, but the measured ventilation rates were reported to be excessively high (i.e., relative to the winter design objective of 100 m^3/h) due to unintended air leakage—air leakage not accounted for in the model. As computed, the winter ventilation rates fall within 10% of the winter design objective, with slightly greater ventilation rates on the windward (north) side of the building and for the lower offices where buoyancy pressures play a greater role.

Computed summer ventilation rates are within 27% of the measured values with the significant exception of the fifth level north office where the computed ventilation direction was opposite of that measured. For the given southwest wind and the relatively small difference between indoor and outdoor temperatures, wind suction pressures acting on this office were able to overcome buoyancy pressures to produce a net outward rather than inward airflow. This is a characteristic problem for upper rooms on the leeward side of naturally ventilated buildings (Axley 2000). All other airflows approached but fell short of the summer design objective of 200 m^3/h—providing an average of 150 m^3/h (i.e., the stack exhaust rate divided by the number of offices, ten). An examination of the pressure differences computed for each of the inlet ventilation devices and the stack suggests an explanation.

For winter operation, the computed pressure drop across the stack terminal (0.48 Pa) proved to be an order of magnitude smaller than pressure drops computed for all inlet vents, which ranged from 2.95 to 10.29 Pa. Thus, the inlet vents acted to limit and, thus, control ventilation airflow rates as intended. For summer operation, this design objective was not realized as the computed pressure drop across the stack terminal (1.16 Pa) proved to be smaller but of the same order of magnitude as the pressure drops across the inlet vents. Consequently, ventilation flow rates were not limited and, thus, not clearly controlled by the inlet vents. To achieve better control, the free area of the stack terminal would have to be increased.

Before considering such a modification to the stack terminal, it is useful to note another subtlety of the computed results. Computed inlet vent pressure differences proved to be relatively small for both the summer and winter conditions, all falling below 10.29 Pa. Examining the form of the self-regulating inlet flow model, Equation 2 reveals that below about 3 Pa (i.e., below the knee of the flow model curve), self-regulation is not realized. This behavior is inevitable and is observed for real self-regulating ventilating devices (i.e., as driving pressures approach zero, ventilation rates necessarily must drop).

TABLE 3
Comparison of Computed and Measured Ventilation Rates for the Simplified Single-Zone Model

	Winter Conditions (T_{out} = 10.5°C; V_H = 2.5 m/s; ϕ = N; T_{in} = 20.5°C)				Summer Conditions (T_{out} = 16°C; V_H = 3.5 m/s; ϕ = SW; T_{in} = 22°C)			
	Computed Q(m^3/h) {ΔP (Pa)}		Measured* Q (m^3/h)		Computed Q (m^3/h) {ΔP (Pa)}		Measured* Q (m^3/h)	
Level	**North**	**South**	**North**	**South**	**North**	**South**	**North**	**South**
Stack	971 (0.48)		---		1500 (1.16)		---	
5	95 {5.33}	90 {2.95}	97	110	-90 {-0.004}	176 {2.98}	93	146
4	98 {6.78}	93 {4.37}	---	---	157 {0.91}	181 {3.89}	---	---
3	99 {7.87}	96 {5.80}	96	90	167 {1.78}	183 {4.38}	101	192
2	100 {8.89}	98 {7.31}	---	---	175 {2.82}	185 {4.77}	---	---
1	102 {10.29}	100 {8.74}	126	160	180 {3.65}	189 {5.94}	133	209

* Measured data reported by the European NatVent® Project (BRE 1999).

TABLE 4
Comparison of Ventilation Rates for an Increased Stack Terminal Free Area of 1.0 m²

	Winter Conditions (T_{out} = 10.5°C; V_H = 2.5 m/s; φ = N; T_{in} = 20.5°C)				Summer Conditions (T_{out} = 16°C; V_H = 3.5 m/s; φ = SW; T_{in} = 22°C)			
	Computed Q(m³/h) {Δ*P* (Pa)}		Measured* *Q* (m³/h)		Computed *Q* (m³/h) {Δ*P* (Pa)}		Measured* *Q* (m³/h)	
Level	**North**	**South**	**North**	**South**	**North**	**South**	**North**	**South**
Stack	977 (0.12)		---		1863 (0.45)		---	
5	96 {5.69}	91 {3.31}	97	110	172 {2.34}	187 {5.32}	93	146
4	98 {7.14}	94 {4.73}	---	---	178 {3.25}	190 {6.24}	---	---
3	99 {8.23}	97 {6.16}	96	90	182 {4.13}	190 {6.72}	101	192
2	101 {9.25}	99 {7.67}	---	---	186 {5.17}	192 {7.12}	---	---
1	102 {10.65}	100 {9.10}	126	160	189 {6.00}	195 {8.29}	133	209

* Measured data reported by the European NatVent® Project (BRE 1999).

Based on the observations discussed above, all results were recomputed using an increased free area of the stack terminal from 0.5 m² to 1.0 m². The results in Table 4 clearly reveal improved control of the ventilation flow rates (i.e., all ventilation flow rates now more closely approach the design ventilation flow rates). As expected, the impact of the increased stack free area was slight, but beneficial, for the winter conditions but significant for the summer—importantly, the problematic flow reversal at the upper floor leeward office has been mitigated. The computed results show higher ventilation flow rates for the windward (i.e., due to higher wind pressures) and lower offices (i.e., due to greater buoyancy pressures) as is to be expected. Curiously, the winter measured data do not reveal these effects even though these trends are more pronounced in the measured summer data than in the computed.

This single adjustment to the stack terminal area appeared to be sufficient to calibrate the simplified single-zone model to achieve computed results that approximated measured results within the inherent uncertainty of airflow modeling. All subsequent analyses were then based on a stack terminal free area of 1.0 m² and all other parameters as established above.

March 1997 and June 1997 Results: Detailed Multizone Building Model

Computed ventilation rates based on the detailed multizone model for the winter (March 1997) and summer (June 1997) calibration data sets are compared to measured results in Table 5. In contrast to the results reported above for the simplified model, however, ventilation flow rates into each office are now the sum of contributions from the self-regulating inlet vent and leakage through the windows and walls. Data are presented for both assumed tight envelope construction, with leakage areas of 1.0 cm²/m², and loose envelope construction, with leakage areas of 10.0 cm²/m².

Comparing these results with those presented earlier, multizone inlet vent airflow rates are seen to be very close but consistently smaller than those results obtained with the single-zone model. The impact of the additional internal flow resistances is, thus, slight. This is as it should be if the natural ventilation system is designed properly. The infiltration contribution through windows and walls, while relatively small, proved to be significant at 1% to 18% for tight construction and overwhelming at 9% to 164% for loose construction.

The lesson here is quite clear. One may not expect to realize effective natural ventilation control unless the envelope construction is relatively tight. The credo “build tight and ventilate right” applies equally well to effective mechanical and natural ventilation system design.

The comparison with measured results is again within any reasonable measure of expected uncertainty in prediction for the computed results and in measurement for the measured results. However, the ventilation flow rate for the tight construction assumption, on average, fell below the summer design objective—178 m³/h instead of 200 m³/h for the summer condition. By increasing the maximum setting of the self-regulating inlet vent 25% for summer conditions, the ventilation flow rate for the tight construction assumption increased, on average, to 214 m³/h with the upper floors underventilated by as much as 17% and the lower floors overventilated by as much as 18%. Accepting these variations as practically inevitable, this increase for summer ventilation appeared to be sufficient to calibrate the multizone model to achieve the design objective. Therefore, a 25% increase in the effective opening area of the self-regulating vents for the maximum ventilation setting was applied in all subsequent analyses.

TABLE 5
Comparison of Ventilation Rates for the Detailed Multizone Models with Tight Envelopes
(Results are presented separately for each ventilation contribution as: inlet vent + window + wall. Additional results for loose envelope are included in brackets{ }.)

	Winter Conditions (T_{out} = 10.5°C; V_H = 2.5 m/s; ϕ = N; T_{in} = 20.5°C)				Summer Conditions (T_{out} = 16°C; V_H = 3.5 m/s; ϕ = SW; T_{in} = 22°C)			
	Computed Q(m³/h) (values for loose envelope)		Measured* Q (m³/h)		Computed Q (m³/h) (values for loose envelope)		Measured* Q (m³/h)	
Level	**North**	**South**	**North**	**South**	**North**	**South**	**North**	**South**
Stack	1100 (2151)		---		1778 (2156)		---	
5	95+5+6 {94+47+57}	87+3+4 {83+21+25}	97	110	143+1+1 {133+5+7}	168+2+3 {165+18+22}	93	146
4	97+6+7 {96+55+68}	91+4+5 {88+30+37}	---	---	162+2+2 {159+17+21}	174+3+4 {166+23+29}	---	---
3	99+6+8 {98+62+75}	95+5+6 {91+38+47}	96	90	170+3+3 {168+26+31}	176+3+4 {169+26+32}	101	192
2	100+7+9 {99+67+82}	97+6+7 {94+46+57}	---	---	177+4+4 {176+34+42}	178+4+5 {171+28+34}	---	---
1	102+8+10 {101+75+91}	99+7+8 {96+53+65}	126	160	183+4+5 {181+42+51}	183+4+5 {176+34+42}	133	209

* Measured data reported by the European NatVent® Project (BRE 1999).

August 1997 Results: Simplified Single-Zone Building Model

The March and June 1997 calibration data were reported for relatively steady environmental conditions and could, therefore, be modeled using the standard versions of the CONTAM program (Walton 1997; Dols et al. 2000). However, the August 1997 calibration data of measured indoor air temperature time histories were collected for transient environmental conditions that cannot be directly modeled using the standard versions of CONTAM. Consequently, the research version—CONTAM97R (Walton 1998)—which models the coupled interactions between airflow and thermal exchanges, was employed. For the simplified coupled thermal/airflow model, the combined thermal conductance of walls, windows, roofs, and floors of the building envelope was lumped in two thermal conductance components placed on the north and south walls, respectively. Internal thermal mass and combined internal and solar heat gains were each modeled with single components placed within the single zone of the building.

Measured indoor air temperatures for the August 1997 four-day heat wave are compared to outdoor air temperatures in Figure 3, and computed results based on the simplified single-zone model of the tax office for a similar four-day outdoor air temperature record taken from the WYEC2 Boston weather data set (ASHRAE 1997b) are plotted in Figure 4.

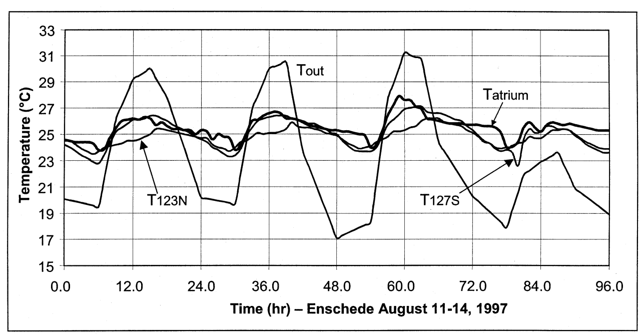

Figure 3 *Measured indoor and outdoor temperatures for the August 1997 four-day heat wave (from BRE [1999]). Atrium temperatures,* T_{atrium}*, and first floor room temperatures on the north and south sides of the building,* T_{123N} *and* T_{127S}*, are compared to outdoor air temperatures,* T_{out}*.*

Both the modeled and measured indoor air temperature swings are attenuated by the high thermal mass available, although the measured attenuation is approximately 40% while that of the computed results is on the order of 50%, suggesting thermal mass was slightly underestimated in the model. In both cases, the impact of heat gains during office hours is revealed by the rapid rise in indoor air temperatures

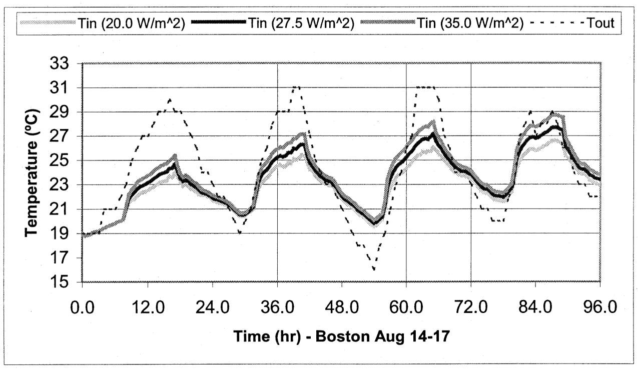

Figure 4 *Computed indoor and outdoor temperatures using the single-zone model for a four-day heat wave taken from the WYEC2 Boston weather data set MABOSTNT (ASHRAE 1997b) for office heat gains of 20.0 W/m^2, 27.5 W/m^2, and 35.0 W/m^2.*

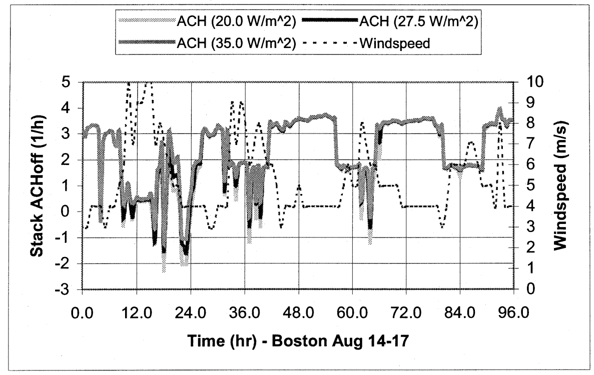

Figure 5 *Computed stack airflow rates, expressed in terms of office air volumes exchanged per hour (ACHoff), using the single-zone model for a four-day heat wave taken from the WYEC2 Boston weather data set for office heat gains of 20.0 W/m^2, 27.5 W/m^2, and 35.0 W/m^2.*

during these periods with, in the computed results, higher heat gains resulting in proportionately greater indoor air temperature increases. Conversely, the impact of night cooling is revealed by a subtle but evident decrease in slope of the temperature time histories that occurs as outdoor air temperatures fall below indoor values.

Peak indoor air temperatures in the computed results occur at the end of the workday as internal gains drop to negligible values. Similar peaks are observed for the offices in the measured data but not for the atrium. Given the ventilation control strategy used (i.e., occupants were to set the inlet vents at their maximum setting at the end of the work day) night ventilation was initiated long before outdoor air temperatures fell below indoor air temperatures in both measured and computed results. Consequently, the full benefit of night ventilation may have been compromised. Finally, for these very similar outdoor air temperature records, indoor air temperatures climbed gradually over the four-day period, staying marginally within an extended comfort zone of 28ºC. Yet on the fourth day, indoor temperatures climbed to exceed or equal outdoor air temperatures for the measured case and the high internal gain case—a problem that could be mitigated with a more optimal night cooling schedule, increased thermal mass, and/or better control of heat gains.

Overall, the modeled and measured results appear to be very similar. The model allows, however, more detailed analysis of system behavior. Figure 5 compares wind speeds to the natural ventilation airflow rate passing through the atrium stack, expressed in terms of office air volumes exchanged per hour (ACHoff). Somewhat surprisingly, effective control of night ventilation rates is achieved only on the third and fourth days of the heat wave, although at approximately 3.5 ACHoff, this control falls below the 4 ACHoff control objective. Night ventilation control for the first and second days and daytime ventilation control for all but the fourth day appear to be poor, although the daytime control objective of 2 ACHoff is erratically reached on the second, third, and fourth days. Indeed, stack airflow reverses several times during the four-day period flowing down the stack into the building. Comparing this plot to the plot of indoor and outdoor temperatures presented in Figure 4, it is seen that periods of poor control correspond to periods when outdoor temperatures exceed indoor and better control is achieved when indoor temperatures exceed outdoor.

Apparently, when stack pressures oppose wind-driven pressures, poor flow control, and reverse flow at times, is observed. This is to be expected if the net driving pressure falls below the minimal pressure difference needed by the self-regulating inlet vents to maintain effective control (i.e., approximately 3 Pa for the self-regulating vent model used) or indeed becomes negative.

To investigate this problematic flow behavior further, natural ventilation airflow rates for the first, third, and fifth level offices on the north side of the building are plotted in Figure 6. On close examination, it may be seen that during the problematic first and second days of the heat wave, air flows at times into the lower offices and out of the upper fifth floor office, at times out of all offices, and at other times into the fifth floor office and out of the lower offices as the subtle balances between stack and wind-driven pressure differences shift. Thus, the erratic behavior is more complex than suggested by the stack flow behavior alone, yet, in all cases, buoyancy pressures acting in opposition to wind pressure differences is at play.

The erratic ventilation behavior observed during this four-day heat wave represents a general problem that needs to be addressed if night cooling of thermal mass is to become a successful method. Assist fans may well serve to mitigate this problem without incurring a significant additional energy expense; if they can be activated when net driving pressures become inadequate. As the net driving pressures result from

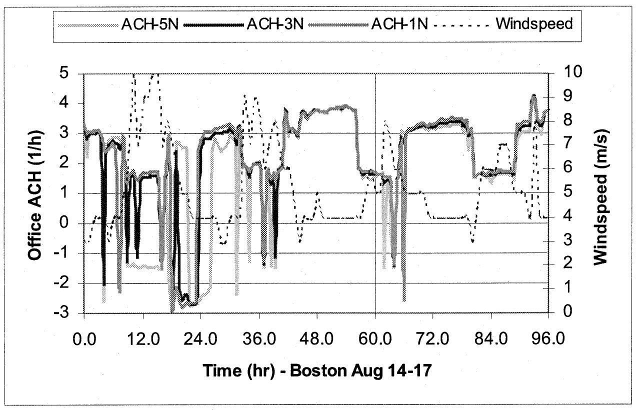

Figure 6 *Computed office airflow exchange rates for offices on the first, third, and fifth levels, north side of the modeled tax office using the single-zone model for a four-day heat wave taken from the WYEC2 Boston weather data set for office heat gains of 27.5 W/m^2.*

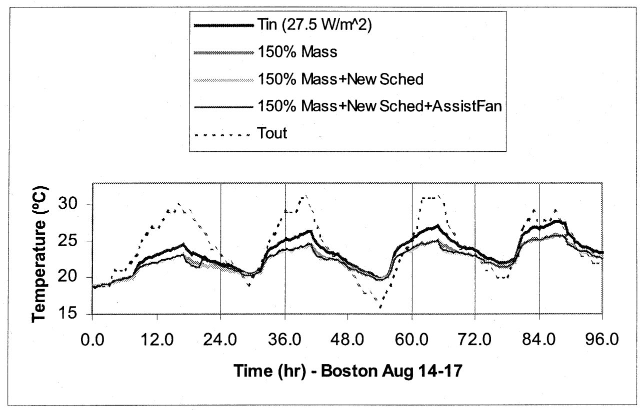

Figure 7 *Computed indoor and outdoor temperatures for a four-day heat wave taken from the WYEC2 Boston weather data set using the single-zone model for office heat gains of 27.5 W/m^2 for the original and three additional system strategies.*

the combination of stack and wind-driven pressures, inadequacy may result from

- *small driving pressures:* combinations of low wind conditions and small positive inside-to-outside temperature differences or
- *opposing driving pressures:* combinations of moderate to low wind conditions and negative inside-to-outside temperature differences.

Assist fans were installed in the Enschede Tax Office but they were controlled to be activated only when wind speeds fell below 2 m/s—a condition that never occurred for the Boston weather record. In effect, these fans were controlled for the first possibility above, while they should have ideally been controlled for both.

This erratic flow behavior also proved to lead to convergence problems in computational analysis. Quite reasonably, quasi-stable physical flow conditions lead to quasi-stable numerical solutions. Consequently, the accuracy of computed flows during such erratic behavior should be held suspect. The multizone model, by adding additional flow resistances within the building, will further shift the subtle pressure differences that drive flows under these minimal driving pressure conditions and, thus, may well produce results different from those obtained with the single-zone model. In either case, the analyst must be alert to erratic behavior and, when observed numerically, treat analytical results with cautious suspicion.

As a final exercise in this particular calibration study, three additional analyses were completed:

- *150% Thermal Mass:* The thermal mass included in the single-zone model was increased 50% and the indoor air temperature response was recomputed for the nominal heat gain in the offices of 27.5 W/m^2.
- *150% Thermal Mass + New Night Vent Schedule:* As above, plus the night ventilation schedule was modified so that the higher ventilation setting would be set two hours after the end of the work day.
- *150% Thermal Mass + New Night Vent Schedule + Assist Fan:* As above, plus an assist fan was operated at night to better maintain ventilation close to the 4.0 ACHoff objective.

The results of these additional analyses are presented in Figure 7. In this case, the impact of additional thermal mass is greatest and significant. Indeed, the 50% increase in thermal mass appears to create a response that better simulates the attenuation observed in reality (i.e., in Figure 3). Consequently, this increased thermal mass was employed in all additional studies. Practically a 50% increase in thermal mass may be realized by either increased surface area provided by, for example, cored slabs or waffle slabs or by thermally more effective surface materials such as masonry tiles.

The improved night ventilation schedule provided some slight benefit, but the difference was not significant. The assist fans produced essentially the same response that was achieved with natural ventilation alone, although, during the first day, the assist fans actually compromised the response. The assist fans were operating on the same schedule as the inlet vents; consequently, they acted to increase indoor air temperatures during a period when outdoor air temperatures exceeded those indoors. We may conclude, for this case, that (a) the response of the thermal mass was rapid enough that premature night ventilation had little effect on the performance of the system, and (b) the natural ventilation system alone provided ventilation rates sufficiently close to the design ventilation rates to achieve the cooling objective without the need of assist fans. (A fourth study investigated the impact of using an assist fan to drive the ventilation rate at 8 ACHoff rather than 4 ACHoff, but, again, the impact on daytime temperatures was marginal.)

August 1997 Results: Detailed Multizone Building Model

The detailed multizone coupled thermal/airflow model developed with CONTAM97R (as described above) was required to simulate the interactions between airflow and thermal exchanges that governed the response of the building to the four-day August heat wave. Computed temperature results based on this detailed multizone model of the tax office for the WYEC2 Boston weather data set are compared to the results obtained using the simplified single-zone model in Figures 8 and 9. These results were computed for assumed combined solar and internal gains in offices of 27.5 W/m^2, internal gains of 5 W/m^2 in corridors, utility rooms, and atrium corresponding to the minimal lighting needed in these areas, and the 50% increase in thermal mass established as a calibration correction above. The atrium temperature responses at three different levels (Figure 8) are practically identical to each other and the results obtained with the simplified single-zone model. The relatively small upward perturbations from the average response illustrated in the upper level of the atrium, T_{mz5At}, result from short-term reverse stack flows that will be considered below.

In contrast, the office temperature responses at three different levels (Figure 9) are similar to each other but are generally greater than the simplified single-zone model temperature response. This is because heat gains in the office zones were modeled at 27.5 W/m^2 and in other zones of the building at 5 W/m^2 in the detailed multizone model, while an area-weighted average was used in the simplified single-zone model. This is the advantage of the multizone model—it provides details of system response that cannot be provided by the simplified single-zone model. Again, the perturbations seen and the few instances where computed office temperatures are similar to that predicted by the single-zone model are related to reverse-flow episodes.

On the whole, then, the computed multizone temperature time histories not only compare favorably to the measured response for the similar heat wave event in Enschede (Figure 3) and the single-zone response, their variation from these response time histories is physically consistent. That is to say, these results suggest that the multizone model may well predict the response details needed to comprehensively evaluate the performance of a proposed natural ventilation system in relatively complex office buildings.

The computation of these responses was plagued, however, by numerical convergence problems—far more than those experienced with the simplified single-zone building model. The thermal system, with its significant thermal mass, tends to attenuate evidence of physical flow instabilities, and, thus, numerical difficulties, but some of the perturbations seen in the computed temperature time histories were apparently associated with these instabilities. Airflow systems, on the other hand, physically tend to respond very rapidly to changes in excitation. As a result, individual office air change rates

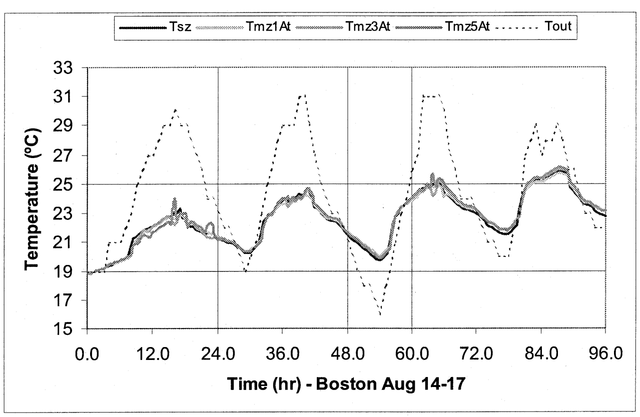

Figure 8 *Computed atrium and outdoor temperatures for a four-day heat wave taken from the WYEC2 Boston weather data set using the multizone model for office heat gains of 27.5 W/m^2. (Single-zone temperature: T_{sz}, multizone level 1 atrium temperature: T_{mz1At}; multizone level 3 atrium temperature: T_{mz3At}; and multizone level 5 atrium temperature: T_{mz5At}.*

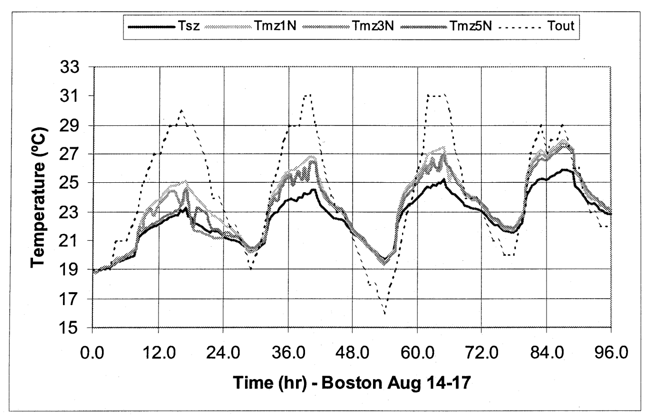

Figure 9 *Computed office and outdoor temperatures for a four-day heat wave taken from the WYEC2 Boston weather data set using the multizone model for office heat gains of 27.5 W/m^2. (Single-zone temperature: T_{sz}, multizone level 1 north office temperature: T_{mz1N}; multizone level 3 north office temperature: T_{mz3N}; and multizone level 5 north office temperature: T_{mz5N}.)*

from the multizone model were less stable than the air change rates from the single-zone modeling results (Figure 5).

These responses, and the corresponding temperature responses of Figures 8 and 9, were computed by manipulating numerical integration parameters by a trial-and-error procedure until convergence violations were minimized. Still, 11 of the 576 simulation time steps used to compute these responses failed to converge, putting the accuracy of the computed results, at least in the time periods close to these convergence failures, into question. As noted above, there was a clear association between opposing stack and wind pressures (that naturally lead to physical instabilities in the flow) with these numerical problems. Thus, the distinct reverse-flow perturbations shown in Figure 9 most often correspond to the very times when numerical convergence was not achieved. The accuracy of these perturbations must be therefore considered suspect.

A more general comment about convergence is in order. CONTAM97R does not analyze the complete dynamic coupled thermal/airflow problem. Convergence within a time step simply assures the flow solution and thermal solution are physically consistent. Violation of convergence at any time step places the flow solution into question but may not have a lasting impact on the thermal solution since subsequent building thermal system response is not, typically, sensitive to current conditions. Consequently, isolated or limited convergence failures may be expected to be significant only at that time and soon thereafter. However, to reduce concerns about convergence failures, an alternative model was developed that proved more reliable.

Summary of Calibration Modifications

A multizone model that proved to be less sensitive to convergence problems was developed by combining the interior zones of the atrium, utility room, corridor, and hall of the model discussed above, for all levels, into a single combined zone. This created an 11-zone model of sufficient detail to capture individual office response time histories, yet one where the number of flow components was greatly reduced in number. Importantly, from a numerical point of view, the remaining flow components did not vary as widely in the resistances they offered to flow compared to the components of the more detailed model.

When applied to the four-day August heat wave calibration case, this multizone model produced temperature and airflow time histories very similar to those reported in Figures 8 and 9. There were only three convergence violations in 576 simulation time steps. The single combined internal zone temperature time history and those of the offices bracketed the single-zone response results, as expected.

This modified multizone model was used for subsequent modeling studies. In addition to its simplified topology, it includes the modifications identified during the calibration exercises discussed above:

- the stack terminal device opening was set to 1 m^2,
- the self-regulating inlet vents were set to provide a maximum setting equal to 2.5 times the minimum setting to realize approximately 2 ACH at the lower setting and 4 ACH at the higher setting, and
- thermal mass was modeled using 150 mm concrete construction with an exposed surface area equal to the 150% of the nominal combined surface area of ceilings and floors.

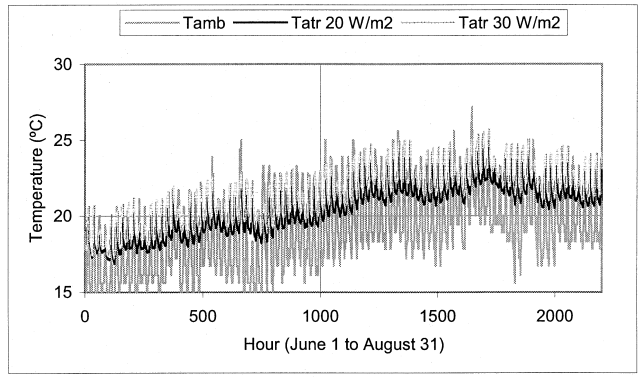

Figure 10 *Atrium temperature response for the Enschede Tax Office building to Los Angeles' summer conditions operated in a natural night cooling mode. Results plotted for two assumed combined solar and internal gains—20 W/m² and 30 W/m²—compared to ambient conditions.*

Night Cooling Design Development Study Results

To explore the application of detailed performance evaluation to the design development of natural ventilation systems, the detailed multizone model of the Enschede Tax Office was configured to operate in a night cooling mode and subjected to the three-month (i.e., June 1 to August 31) weather records for Los Angeles discussed above. Ideally, outdoor air inlet vents should have been controlled to simulate the actual occupant control strategy used in the Enschede Tax Office, but this proved difficult to model given CONTAM97R's limitations. Consequently, the inlet vent operation for all offices was controlled to a fixed schedule to be set at the minimum airflow rate (i.e., 100 m^3/h per office) during office hours and the maximum design airflow rate (i.e., 200 m^3/h per office) after office hours. For Los Angeles weather, daytime ventilation rates often could have been higher to make more optimal use of direct ventilative cooling.

The office building performed well as designed in the Los Angeles climate. Figure 10 shows the dynamic response results for the slot atrium temperature. Even for the relatively high combined solar and internal gain rate of 30 W/m^2, atrium temperatures seldom exceeded 25°C. Consequently, the evaluation of an overheating degree-hours (ODH) performance criteria (defined as the integrated sum of the temperature exceedances relative to a comfort criteria for the cooling season by Equation 3.3 of Axley 2001) for all assumed combined gain rates yielded zero results. Thus, in this case, the building as designed would be considered a success and further design development performance evaluation would not be needed.

Nevertheless, it is instructive to look at the details of the system response to better appreciate the behavior of the building as a system. Figure 11 isolates the stack airflow rate response for the hottest period of this record. The natural ventilation system with the self-regulating inlet vents is seen to provide reasonably good control of ventilation rates as desired, although there is some variation about the objective ventilation rates. A couple of reverse-flow events are observed when indoor air temperatures fall below outdoor air temperatures that appear to have had a relatively minor impact on system response. Importantly, indoor air temperatures appear to have a minor impact on stack airflow rates, indicating this airflow is driven primarily by wind.

As for distribution of ventilation airflows and its impact on individual office thermal response, Figure 12 shows temperatures for offices at the first, third, and fifth levels of the south side of the building. For these offices, ventilation rates fell below design objectives, with the upper levels being most underventilated, indicating buoyancy forces are at play. Nevertheless, office temperatures are relatively uniform but consistently higher than the atrium temperature on the warmer days. This last observation is to be expected since combined gains in the offices is greater than the atrium during office hours and both areas have the benefit of thermal mass.

From these results, it is clear that coupled thermal/airflow analysis can provide detailed dynamic response results that can be used to evaluate both general system performance and detailed air distribution and temperature response—both essential to system performance evaluation. Not readily evident but clear at the time of constructing these models and reviewing response results is the fact that direct ventilative cooling will inevitably engage the thermal mass of the building—an advantage when outdoor air temperatures fall below those indoors and a disadvantage otherwise. Thus, from a dynamic analysis point of view, the distinction between night cooling and direct ventilative cooling is artificial. Indeed, to optimize cooling system performance, inlet vents should be controlled using "night-cooling" strategies (as discussed in Chapter 3 of Axley 2001) throughout the day during warm periods.

CONCLUSION

The coupled thermal/airflow simulation tool CONTAM97R was applied to the analysis of a reasonably well-documented naturally ventilated office building in The Netherlands. Comparisons of measured and predicted performance of this building in its native climate were presented as a validation exercise of CONTAM97R and to calibrate the building models used for subsequent analytical studies. Three models of a five-story segment of this building were created—a single-zone model with detailed representations of ventilation inlets and exhausts, a highly detailed 31-zone model accounting for all purpose-provided and infiltration flow paths, and a moderately detailed 11-zone model falling between these two extremes.

The 11-zone model was then used to demonstrate the application of macroscopic coupled thermal/airflow performance evaluation, in general, and CONTAM97R, specifically,

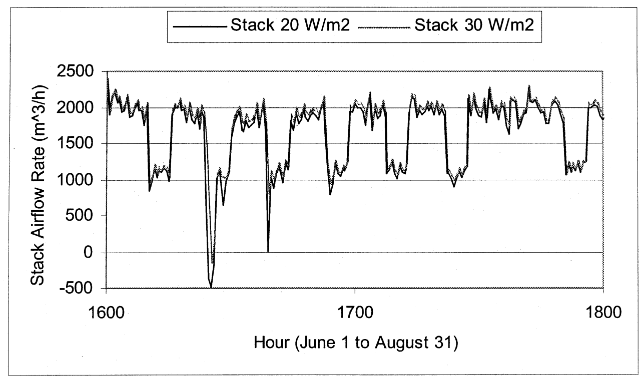

Figure 11 *Detailed stack airflow rate response for the Enschede Tax Office building to Los Angeles' summer conditions operated in a natural night cooling mode. Results plotted for two assumed combined solar and internal gains—20 W/m^2 and 30 W/m^2.*

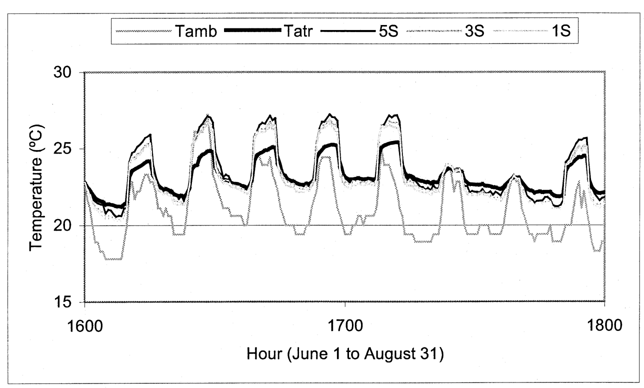

Figure 12 *Detailed office temperature responses for the Enschede Tax Office building to Los Angeles' summer conditions operated in a natural night cooling mode. Results plotted for assumed combined solar and internal gain of 27.5 W/m^2 for south offices at levels 1, 3, and 5, atrium, and ambient.*

to the design development of night ventilation cooling systems for the building placed in a hot-arid North American location. Following a trial-and-error procedure using the overheated degree hour ODH performance metric, component sizes were adjusted to achieve the night cooling objective.

This modeling effort demonstrated that macroscopic tools, such as that provided by CONTAM97R, provide essential spatial and temporal details that can guide design refinement relating to both whole-building and inter-room air distribution and thermal performance. In some cases, greater intra-room detail may be required and a performance evaluation could proceed to computational fluid dynamic studies of individual rooms.

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