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AN APPROACH TO THE DESIGN OF NATURAL AND HYBRID VENTILATION SYSTEMS FOR COOLING BUILDINGS

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ABSTRACT

This paper presents an approach to the design of natural and hybrid ventilation systems that accounts for specific climatic and operational conditions and is organized to serve the building designer at each distinct phase of design – predesign analysis, preliminary design, design development, and design performance evaluation. The approach makes use of: a) a *climate suitability analysis* method, presented in a companion paper, that establishes design ventilation rates needed for preliminary design calculations; b) the *loop equation design method* to estimate preliminary sizes of system components and control and operational strategies; and c) detailed *multizone coupled thermal-airflow analysis,* using CONTAM97R, for design development and, ultimately, system performance evaluation. A representative application, limitations of the approach, and research needed to support the approach will be briefly outlined.

INDEX TERMS

Natural Ventilation, Hybrid Ventilation, Design Method, CONTAM, Climate Suitability

INTRODUCTION

Recent innovative European natural and hybrid ventilation systems for cooling buildings appear to offer significant advantages when compared to conventional mechanical alternatives. Primary energy consumption and associated global emissions may be reduced, occupant health and preferences may be better served, and firsts costs associated with mechanical cooling and complex air distribution systems may be significantly reduced. Yet, in spite of the documented successes of these systems, no systematic design method has been put forward for their design.

As outlined in the abstract above, this paper presents such a systematic method – a method based on fundamental principles that, therefore, is applicable to the task of the design of natural and hybrid ventilation systems of arbitrary configuration for specific climatic and operational conditions. A detailed presentation and application of this approach is presented in a recent US National Institute of Standards and Technology (NIST) report (Axley, 2001) – this paper has been abstracted from this more complete report.

METHODS & THEIR APPLICATION

The design of natural and hybrid ventilation systems logically involves the selection and specification of system components and building form (*system configuration*) for anticipated environmental conditions (*design conditions)* given a clear definition of ventilation objectives and associated performance criteria (*design requirements*). The often-overloaded word *design* must also be understood to be the process used to achieve these ends.

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Technical systems are invariably configured by selecting and specifying the system's:
1. *General Configuration* – The selection of the general configuration of the ventilation system and, importantly, building form that will serve it.
2. *System Topology* – The selection of type and connectivity of system components needed.
3. *Component Sizes* – The selection of component sizes and related details to achieve specific natural ventilation objective(s) for anticipated environmental conditions.
4. *Control and Operational Strategies* – The selection of control and operational strategies to achieve specific natural ventilation objective(s) for anticipated environmental conditions.

In North America, the design process – and, importantly, the exchange of design products for design fees – is commonly organized into five distinct phases:
1. *Predesign Programming and Analysis* – The definition of the building design program or brief that establishes *design requirements* and analytical investigations (e.g., climate and site analyses) needed to define *design conditions*.
2. *Conceptual or Preliminary Design* – The development of the general configuration and topology of the building system – often done with little quantitative analysis using intuition, precedents, general guidelines, and rules of thumb.
3. *Design Development* – The development of system component sizes and details and system control and operational strategies.
4. *Design Performance Evaluation* – Quantitative evaluation of the technical performance of the proposed system relative to the *design requirements* for given *design conditions*.
5. *Construction and Commissioning of the Proposed System.*

Consequently, a systematic and complete design method must provide empirical, analytic or algorithmic techniques to achieve the appropriate configuration objective at each distinct phase of design. Three techniques – *climate suitability analysis*, *the loop equation design method,* and *multizone coupled airflow-thermal analysis* – when applied in the order given, can largely achieve these ends.

Climate Suitability

The *climate suitability analysis* technique was developed to evaluate the potential of a given location for direct ventilative cooling and complimentary nighttime ventilative cooling (i.e., of a building's thermal mass). As such, it is a useful predesign analytical technique. It also establishes preliminary estimates of design ventilation rates needed for preliminary design calculations (i.e., given knowledge of the likely internal gains in a building and local climatic conditions). Specifically, with it a designer may estimate the ventilation rate needed to offset internal gains when direct ventilation can be effective and the internal gains that may be offset by nighttime ventilation when direct ventilation will not work. Importantly, the method may be applied to ventilative cooling achieved by natural, mechanical, or combined means.

This technique is based on a general single-zone thermal model of a building configured and operated to make optimal use of direct and/or nighttime ventilative cooling. With this model in hand, an algorithm was defined to process hourly annual weather data, using well-established thermal comfort criteria, to complete the evaluation. A summary of this approach is presented in a companion paper included in these proceedings.

Here, consideration will be limited to a brief review of the results obtained by applying this technique to climatic data for Los Angeles, CA – Table 1. From these results, we may tentatively conclude, for example, direct ventilative cooling may be expected to be effective for 98% of the year for an optimally designed commercial building that has an expected internal gain rate of 20 W/m^2. To be effective, however, a direct ventilation rate of 3.0 ± 2.1 air changes per hour (ACH) will have to be provided. In addition, for those few days of the year when direct ventilative cooling is not effective, night cooling may be used. The climate suitability analysis indicates that comfort can be achieve for 93% of these overheated days (i.e., 27 days in this case) by night cooling where a night cooling ventilation rate of 1 ACH can offset 5.9 ± 2.3 W/m^2 of daytime internal gain. Thus, to offset a daytime internal gain of 20 W/m^2 the nighttime ventilation system would have to be designed for a ventilation rate of approximately (20 W/m^2 ÷ 5.9 W/m^2-ACH) = 3.4 ACH.

Table 1 Climate suitability results for Los Angeles.

	Direct Cooling				Night Cooling[1]
	10 W/m^2	20 W/m^2	40 W/m^2	80 W/m^2	
Los Angeles, CA – CALOSANW.WY2 data					*Hot-Arid-Coastal*
Vent. Rate or Cooling Potential	1.5 ±1.0 ACH	3.0 ±2.1 ACH	5.9 ±4.2 ACH	11.8 ±8.4 ACH	5.9 ±2.3 W/m^2-ACH
% Effective[2]	95%	98%	98%	98%	93% (27 days)

[1] Night cooling for subsequent days when direct cooling is not effective.

[2] For direct cooling % = hours effective ÷ 8760 hours; for night cooling % = days effective ÷ days needed.

As a predesign analytical aide, then, these results indicate cooling by natural ventilation in Los Angeles is a very suitable strategy. Furthermore, for the relatively low internal gain rate considered (i.e., 20 W/m^2), the likely ventilation rates needed for both direct ventilative cooling and night cooling are not particularly great – i.e., 3.0 ± 2.1 ACH for the former and on the order of 3.4 ACH for the latter. These preliminary estimates may then be used to compute estimates of ventilation system components sizes – here, using the *loop equation design method* – after the building designer selects an appropriate system configuration and topology (e.g., using examples of other building precedents or general design guidelines (Irving and Uys 1997; Martin and Fitzsimmons, 2000))

Loop Equation Design Method

Design development tools are used to size ventilation system components (e.g., the free area of a ventilation opening) given the general configuration and topology of the building ventilation system, the *design requirements*, and the *design conditions*. A number of manual and simple computational tools achieve this objective but only partially. Most are based on simplistic single-zone models of building systems that, most often, ignore the relatively complex problem of coupled thermal/airflow behavior, some are limited to specific climates, and few account for internal resistances to ventilation airflows. One approach, the *inverse solution* method presented by Irving (Irving and Uys, 1997) has, however, been generalized to create the *loop equation design method* (Axley 1999; Axley 2000; Axley,2001) that provides the means to size internal as well as envelope components of multi-zone ventilation systems of arbitrary configuration and complexity for specific climatic conditions.

The *loop equation design method* is based on the same theory currently used in general-purpose multi-zone airflow analysis programs like CONTAM and COMIS (Dols, Walton et al. 2000; Haas, 2000). The approach taken is both fundamental and simple – equations are written for the changes of pressure that must occur along each ventilation *loop* of a building ventilation system following a ventilation flow path from inlet to exhaust and back to the inlet again. The sum of these pressure changes around any loop must necessarily equal zero. The resulting loop equations define combinations of system component sizes that will provide desired ventilation flow rates given specific environmental *design conditions*. Therefore, these equations may be used directly to size ventilation system components. Furthermore, as the loop equations generally do not define a unique design solution, specific nontechnical design constraints (e.g., selecting component details from commercially available units) may be specified and operational strategies (e.g., for with-wind and without-wind conditions) formulated when applying the *loop equation design method*.

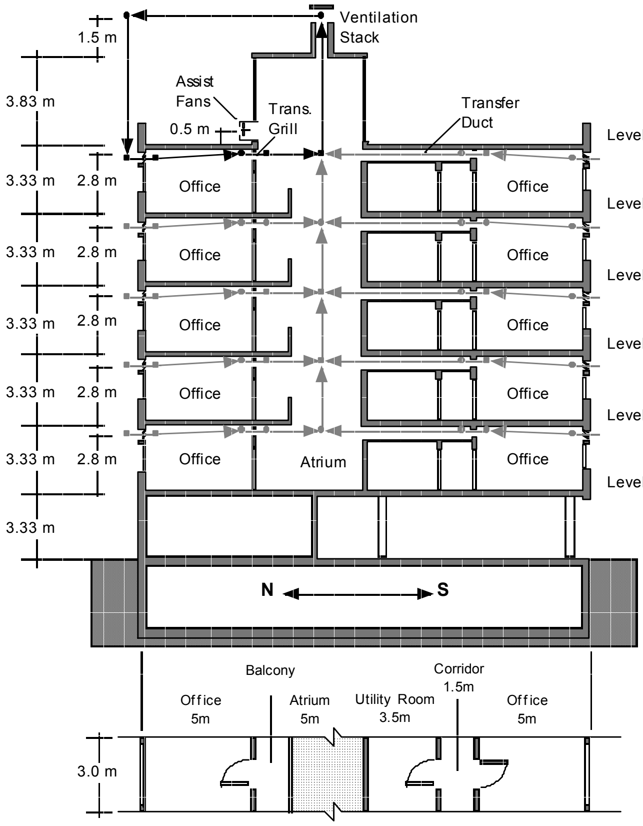

Figure 1 Plan and section of the Enschede Tax Office building. Solid dots and linking arrows indicate, diagrammatically, pressure nodes and airflow paths of all ventilation loops.

Details and representative applications of the *loop equation design method* are presented in the references cited above. This method was used to adapt the design of an innovative naturally ventilated building build in the Netherlands – the Enschede Tax Office – to climatic conditions of Los Angeles, CA (Axley, 2001). A representative section and partial plan of this building is illustrated in Figure 1 showing diagrammatic representations of each of ten ventilation flow loops. In this case, the *loop equation design method* was used to size the atria stack terminal opening to insure that self-regulating inlet vents maintained authority over ventilation flow rates for both low, air-quality control, ventilation flow rates (100 m^3/h per office) and higher, night-cooling, ventilation flow rates (200 m^3/h per office) – a relatively challenging design task, given the current state-of-the-art.

Multizone Coupled Airflow-Thermal Analysis

With preliminary sizes of system components estimated and operational strategies defined, the designer can proceed to design performance evaluation – the phase of design development used to estimate global measures of system performance and to fine-tune system characteristics. For natural and hybrid ventilation systems, performance evaluation must not only account for the coupled thermal/airflow interactions that characterize natural driving forces but must do so dynamically over long-term simulation time periods. As few computational tools are available to do this, the building design community has had little experience in this important area of system performance evaluation.

The research program CONTAM97R, presently under development, is a general purpose multizone analysis code that offers, in principle, these capabilities (Walton, 1998). In addition, this program has been designed to enable modeling of system control and non-trace air contaminant dispersal – useful for evaporative cooling schemes. Unfortunately, in its present state CONTAM97R is difficult to use, as it lacks a complete user interface, and is not fully operational. Furthermore, as coupled thermal/airflow analysis is numerically demanding, convergence and other exotic numerical problems add to the difficulty of using CONTAM97R.

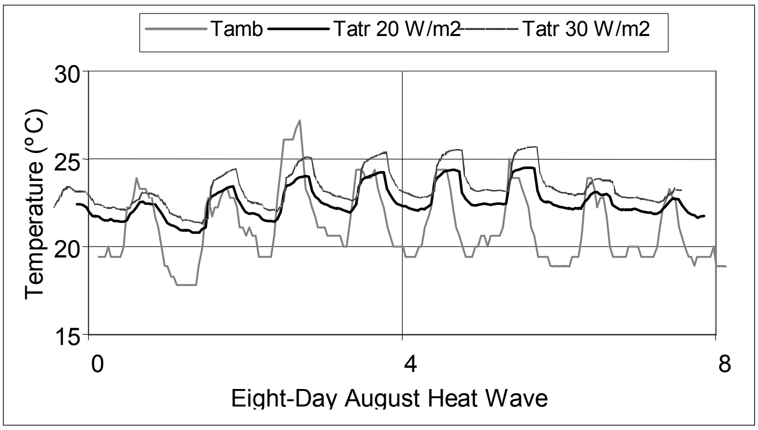

Figure 2 Detailed atrium temperature response for the Enschede Tax Office building to Los Angeles' summer conditions operated in a natural night cooling mode. Results plotted for two assumed combined solar and internal gains – 20 W/m^2 and 30 W/m^2.

Again, as a complete discussion of *multizone coupled airflow-thermal analysis* is well beyond the scope of this short paper, the presentation here will be limited to a discussion of the type of results that may be produced using this type of analysis. CONTAM97R was applied to the task of design performance evaluation of the (climate-adapted) Enschede Tax Office shown in Figure 1 to an overheated period representative of Los Angeles' summer conditions. Figure 2 illustrates one representative indoor temperature time history – that of the central atrium – for a key eight-day period. Time histories of both temperatures and ventilation system airflow rates were also computed for each of the ten offices shown in Figure 1.

Clearly, such computed indoor temperature time histories may be used to evaluate the thermal comfort performance of a natural or hybrid ventilation system – e.g., the results shown indicate the reasonable upper comfort limit of 26 °C was not exceeded during this period. This particular plot is, however, deceiving. Thermal comfort performance evaluation demands the review of computed indoor temperature responses in all occupied spaces of the building and a systematic and quantitative evaluation of all comfort exceedance events. This will entail the review of vast amounts of data that will demand the definition of new criteria of performance evaluation. An *overheated degree hour* procedure has been proposed by the authors (Axley 2001) that accounts for comfort adaptation thought to be important in naturally ventilated buildings but without further investigation the value of this approach has yet to be determined.

CONCLUSION AND IMPLICATIONS

The design of natural and hybrid ventilation systems for cooling buildings is inherently different from the design of more conventional mechanical systems directed to the same purpose. Clearly, a part of this difference is related to the need to account for the natural driving forces provided by wind and buoyancy effects that these systems seek to take advantage of. Less obviously, this difference also relates to system performance evaluation – familiar energy metrics like peak energy demand and annual energy consumption for mechanical cooling must now give way to new metrics for thermal comfort and, importantly, the degree to which it may be exceeded in natural and hybrid ventilation systems.

The techniques briefly reviewed here – *climate suitability analysis*, *the loop-equation design method*, and *multizone coupled thermal-airflow analysis* – address the former need but, being relatively new analytical techniques, have not yet been subjected to thorough evaluation and development. Of these, *multizone coupled thermal-airflow analysis* is both the most advanced yet most unreliable analytical technique. It is a technique that has emerged out of the convergence of advanced methods of building thermal, airflow, and contaminant dispersal analysis yet is currently available in relatively crude computational implementations that fall well-short of theoretical capabilities and are plagued by numerical problems (e.g., problems of convergence, stability, stiffness, and solution uniqueness). Both fundamental and applied research efforts must be direct to correct these problems if these computational tools are to become reliable. Given the central importance of *multizone coupled thermal-airflow analysis* to the design of natural and hybrid ventilation systems, this needed research must be given the highest priority.

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