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MULTIZONE MODELING AND AIR LEAKAGE ANALYSIS

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Abstract

Research on ventilation and infiltration has proliferated steadily over the last several years. *Air leakage analysis* and *multicell modeling techniques* have emerged as two of the most interesting topics in current infiltration-related basic research. At the annual meeting of the *American Society of Heating, Refrigeration, and Air-conditioning Engineers* (ASHRAE) held in Honolulu, Hawaii in June of 1985, over two dozen papers related to infiltration and ventilation research were presented, the largest single group of which dealt with infiltration studies in multi-cellular structures. In this report we review twelve significant papers concerned with multizone infiltration and air leakage presented at the ASHRAE conference. Other infiltration-related papers are mentioned, and abstracts for the twelve symposium papers plus seven technical papers are presented.

Keywords. Modeling Air Leakage, Multicell Infiltration, Ventilation, Multizone Air-flow, Review

INTRODUCTION

Throughout the last ten years, research on infiltration in buildings has become quite intense.[1-3] In 1985 the American Society for Testing and Materials (ASTM) developed a standard test procedure for measuring infiltration by tracer dilution.[4] Since 1980 the *Air Infiltration Centre* (AIC) has held five conferences and published their proceedings.[5-9] This research effort has advanced understanding of the physical processes that drive infiltration and, in the process, raised many more research topics.

Of the numerous symposia and technical papers presented by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) on the topic of infiltration, it is the three symposia devoted to the topic at its annual meeting that will be discussed here: *Air Leakage Analysis Techniques* (HI-85-3);[10-13] *Multicell Infiltration Studies — Part 1* (HI-85-35);[14-17] *Multicell Infiltration Studies — Part 2* (HI-85-40).[18-21] (The full papers will be printed in the archival publication of ASHRAE, ASHRAE *Transactions*, Vol. 91 (II), 1985.)

MULTICELL INFILTRATION STUDIES

A whole range of computer programs has been developed for calculating a buildings energy consumption due to infiltration. Those that treat the true complexity of air-flows caused by internal flow resistances require extensive information about flow characteristics and pressure distributions. For this reason, simplified models have been developed to simulate infiltration of single-cell structures such as single-family houses. A high percentage of existing buildings, however, have floor plans that characterize them more accurately as multicellular structures, which cannot be treated by single-cell models.

The highlights of eight papers dealing with multicell infiltration studies presented at the 1985 annual ASHRAE meeting are summarized below. (The full abstract for each paper is reproduced in the appendix.)

"Modeling Parameters for Boundary Layer Wind-Tunnel Studies of Natural Ventilation" presented by **Richard Aynsley of Papua New Guinea University of Technology:** The primary purpose of this paper was to describe the modeling parameters for *Boundary-Layer Wind-Tunnel* (BLWT) modeling to ensure reliable data from tests. The author identifies four main purposes for BLWTs: 1) to gather data on local mean hourly wind speeds and directions at a site relative to long-term wind data from a nearby meteorological recording site; 2) to determine the influence of nearby obstructions, topographic features, or vegetation on local wind speeds; 3) to determine the influence of architectural features such as extended eaves, sun-screen devices, etc. on the surface pressure distribution around a building; and 4) to determine the influence of the size and location of a building's openings on its indoor air-flow pattern and pressure distribution. The author reports that there are three BLWT-specific modeling parameters: 1) the vertical profile of mean longitudinal velocity; 2) the vertical profile of turbulence intensity; and 3)

the power spectral density of the air-flow. He also determines and describes the six most important modeling considerations for using BLWTs in conjunction with buildings: 1) wind-tunnel blockage; 2) length scale; 3) ability to reproduce small architectural details; 4) modeling surrounding environment; 5) influences of Reynold's number influences; and 6) measurement time scale. The author notes that direct modeling of infiltration in a BLWT is not practical because of Reynold's number considerations, but the pressure coefficients measured in the BLWT can be used in various models to estimate it. The author admonishes the reader not to overlook these effects — especially the more subtle ones — when making a BLWT study.

"Estimating Comfort Cooling from Natural Wind inside Buildings Using Boundary Layer Wind Tunnels" presented by **Richard Aynsley:** In this paper, Aynsley describes two methods for using *Boundary-Layer Wind-Tunnel* (BLWT) data to estimate air-flow through buildings and use it to determine thermal comfort conditions for occupants. Two distinct methods are presented: the pressure difference/discharge coefficient method and the wind speed coefficient method. The former method relates the flow through an orifice to the dynamic pressure across it; since the method is only defined at the orifice, it must be combined if there are orifices in series. The latter method is more direct because it has the potential for defining the entire velocity field within the structure; but, because of wind speed coefficients require more detailed data collection, pressure coefficients are more widely compiled and published. The author believes that the primary advantage of the discharge equation approach is that estimates of air-flow can be calculated in design buildings without recourse to specific BLWT tests; the disadvantage is that local mean velocities can be estimated only near openings. Aynsley concludes that the use of mean wind speed coefficients is a potentially superior option, but that they will not be generally used until a larger database of measurements is created.

"Multizone Infiltration Measurements Using a Passive Perfluorocarbon Tracer Method" presented by **Russell Dietz of Brookhaven National Laboratory, USA:** This paper purports to be a validation of the *Brookhaven National Laboratory* (BNL) *Perfluorocarbon Tracer* (PFT) technique. In this technique one or more PFTs are continuously released from a passive emitter and the PFT contained in the room air is passively adsorbed using a diffusion tube sampler. Ignoring start-up effects, the result of this technique is to give a measurement of the *average inverse infiltration** over the sampling period. Although there is no validation *per se* in the paper, several datasets are generated using the PFT system in multizone buildings. The author describes the PFT methodology, applies it to several multizone buildings, and discusses some modeling concepts for larger buildings. The advantages of the technique appear to be its low cost and ease of installation; the disadvantages appear to be the limited number of tracers, the length of time required to obtain a measurement, and the lack of service centers to do the chemical analysis. The last half of the paper contains field data from a variety of applications where the BNL/PFT system was employed. The data is worthy of a closer look for those considering using a PFT-type system.

* Average inverse infiltration is the quantity of interest for indoor air quality; average infiltration is the quantity of interest for energy considerations. The two quantities can be simply related if the (geometric) standard deviation of either distribution is known.

"Errors Resulting from the Use of Single-Zone Ventilation Models for Multizone Buildings: Implications for Energy Conservation and Indoor Air Quality Studies" presented by **Russell Dietz:** The reason for the recent interest in multizone models is that the assumptions made by the simpler single-zone models are, in many situations, violated. Dietz looks at these assumptions and illustrates the errors that can result when single-zone methods are used but its assumptions are violated. A typical ranch-style house serves as an example of the errors so induced in tracer-decay measurements. The overall single-zone results evidently were better when the volume of the basement (i.e. the second zone) was included; however, in general, all single-zone models reportedly over-predicted the infiltration rate by at least 10%. When the authors calculated the amount of energy required to heat the infiltrating air, they found that if the entire structure was treated as a single zone the errors were less than 15% over a range of outdoor temperatures, but that if the basement volume was excluded the errors were over 35%. The authors concluded that an accurate measurement of air-exchange rate, combined with a single-zone model and (inappropriately) applied to a multizone dwelling, can give only a reasonable first approximation for energy conservation and indoor air quality calculations.

"MOVECOMP: A Static Multicell-Airflow Model" presented by **Magnus Herrlin of the Royal Institute of Technology, Stockholm, Sweden:** MOVECOMP is a multizone air-flow model developed for the Swedish Council for Building Research to study the following: 1) air movements in a building caused by wind, stack, and HVAC effects; 2) air movement effects on energy and power demands in different parts of the building; and 3) the distribution of pollutants within the building. Recognizing that there already exist many computer models capable of accomplishing these needs, after completing a survey of the open literature the author concludes that none of them are public domain programs and the ones available are still in development. MOVECOMP is constructed along the classic lines of such programs — a network of interconnected pressure/flow nodes solved iteratively from mass-balance considerations. The bulk of the paper is devoted to subtleties of the program and will be of interest to experts in such modeling techniques. A companion program, FLOWCOMP, used for designing mechanical ventilation systems, is also mentioned.

"An Automatic Multitracer Gas Method for Following Interzonal Air Movement" presented by **Josephine Prior of the Polytechnic of Central London, United Kingdom:** The paper presents a new technique for measuring multizone air movement using multiple tracer gas. The *Perfluorocarbon Tracer* (PFT) technique is similar in most ways to to the Brookhaven (BNL) technique described above with the notable exception of BNL's patented emission system. The paper is structured into three parts: the general description of the apparatus and method; an illustration of the development of a discrete time matrix analysis of both single-zone and multizone data; and a report of multizone experiments which have already been carried out by the authors. Because the injection system is automated, the approach has the advantage of versatility, but at a higher cost than the BNL technique. A sophisticated eigenvalue technique for reduction of the decay data is presented and demonstrated on measured data. It would have been interesting to see a comparison of the errors associated with the reduction of multizone tracer-decay data and those associated with the reduction of analogous continuous injection data (e.g. the BNL method).

"Documenting Air Movements and Infiltration in Multicell Buildings using Various Tracer Gas Techniques" presented by **David Harrje of Princeton University, Princeton, USA:** This paper summarizes the tracer gas techniques currently in use for determining infiltration in multizone buildings. The techniques are grouped into three categories: tracer gas dilution (i.e. decay techniques); constant injection of tracer gas; and constant concentration of tracer gas. One or more tracer gas can be used with any of these methods. The authors describe each technique and, in some detail, its own single-gas, multizone, constant-concentration technique including the control and analysis segments. Also discussed is the calibration of tracer-gas and related equipment, including the relationship of the measurement technique to the calibration requirements. The authors conclude that multiple gas are not always required in multizone measurement system provided that a) a constant concentration technique is used and b) information about interzone flows is not needed. The technique is intended for determining the outside infiltration rates from as many as ten building zones. The authors recommend that the constant injection technique be used for multiple tracer-gas applications, but state that the tracer-decay technique *can* be used for two-zone applications.

"Evaluation of a Simple Technique for Measuring Infiltration Rates in Large and Multicelled Buildings Using a Single Tracer Gas" presented by **Richard Walker of the Building Research Establishment, Garston, Watford, United Kingdom:** The purpose of the paper is to describe a simple, single-gas tracer technique for characterizing large or multicelled buildings. Determining the ventilation rates in such buildings involves such problems as local variations in infiltration, imperfect internal mixing, and difficulties associated with injection and distribution. According to the authors, these problems could be eliminated if an acceptable single-gas technique could be found. The report is based on the fact that if a building is seeded with a tracer and allowed to come to steady state, the concentration of gas in each zone in the building may be quite different but all will decay at the same rate. The authors claim that it is this global decay rate that characterizes the infiltration performance of the building. They then proceed to derive a matrix decay/eigenvalue method of analyzing the tracer data. They tested their technique on two buildings: a mechanically-ventilated, multicelled office building and a large, naturally-ventilated, single-zone building. Their most interesting conclusion is that the dominant decay rate can be measured by partially seeding the building with tracer gas (i.e. seeding any sub-section of the building), thus allowing measurements to be made on a large building with very modest equipment (e.g. bag sampling technology). Although the applicability of the dominant decay rate concept is debatable, the authors have presented an efficient and simple method of measuring it.

Discussion

This double symposium, presenting results from researchers all over the world, supplied a significant amount of information for potential multicellular users. The most common thread among the papers in the sessions was the discussion of tracer gas methods. Several different types of tracer techniques were discussed, including single-zone and multizone, active and passive, as well as decay and constant concentration. In addition to *true* multicell techniques, some of the papers discussed *limited* techniques that could have advantages in specific circumstances; included in this category are two-zone decay techniques, single-gas techniques, and local seeding techniques. Several of the papers alluded to the advantages (necessities) and disadvantages (limitations) of the various techniques, but valid conclusions await more field data and comparative trials.

Two issues that have become topical of late were discussed by Richard Aynsley: the use of boundary-layer wind tunnels in infiltration modeling and the estimation of natural ventilation-induced cooling for summer comfort. The two associated papers were instructive in the art of wind-tunnel modeling and its relationship to ventilation.

Many of the papers discussed, presented, or referred to multizone analysis models that are currently under evaluation or testing. Notable for its public availability was the MOVECOMP program developed in Sweden.

These two sessions clearly indicate the international flavor of the research effort in multicell infiltration; eight papers from four countries were presented. Each research group had slightly different priorities (e.g. simplified testing procedures, error analysis methods, modeling capability, etc.), which led to differing research agenda. When viewed as a whole, these diverse efforts span most of the research topic. There is, however, still a lack of information exchange in the field; research groups are at times repeating experiments because the results of other's efforts (e.g. multicell model development) are not distributed sufficiently.

AIR LEAKAGE ANALYSIS TECHNIQUES

As the heat-load and indoor air quality aspects of infiltration become of increasing concern, the need to measure the air tightness of residential buildings becomes increasingly important. Various techniques are used to measure air tightness; most of them involve calculating of an effective leakage area, which can be used as a quantitative measure of air tightness. The most common technique for measuring a building's air tightness involves fan pressurization, but few practitioners understand the issues related to calibration accuracy and analysis techniques. This symposium contained four papers addressing some of the accuracy issues of conventional fan systems and introduced some less conventional techniques for analyzing air leakage in buildings. The paragraphs below summarize the highlights of these papers. (The full abstract for each one can be found in the appendix.)

"Fan Pressurization of Buildings: Standards, Calibration and Field Experience" presented by **Ken Gadsby of Princeton University, Princeton, USA:** This paper is a good review of current practices for measuring air leakage. It discusses the fan pressurization test method, ASTM Standard E779, as well as currently available pressurization equipment. It emphasizes the importance of appropriate calibration procedures and it presents field experiences that point out both the potential applications and the cautions necessary when using fan pressurization. Although current practice is limited to single-family detached structures, recently emphasis has been put on the problems associated with attached dwellings as, for example, in military housing. Multiple zones are currently being pressurized using multiple pressurization devices. The authors compare various techniques in use for calibrating pressurization devices and give special emphasis to low-

flow situations. The paper concludes with applications of pressurization results and a discussion of consensus standards in progress.

"Accuracy in Pressurization Data Analysis" presented by **Richard Grot of the National Bureau of Standards:** This paper zeros in on the issue of the accuracy and precision of pressurization results using current equipment. The authors point out the importance of measurement accuracy in the formulation of air-tightness standards. There are two types of internal errors: air-flow rate errors and differential pressure errors. Additionally, there are errors caused by external conditions at the time of the test, such as the building's configuration or the weather, wind being noted as the most significant. The authors have found that magnetic linkage gauges are often significantly out of adjustment and require frequent, individual calibration. Although some studies of *RPM*-type equipment have demonstrated an accuracy of 4%, the authors defer general statements about accuracy to the ASTM task group (E6.41.05) investigating this issue. The authors also discuss the statistical methods used to analyze pressurization data, and they compare the most widely used methods. The paper closes with some specific examples of errors in real data and offers specific recommendations for reducing them. The trade-off between accuracy and precision when extrapolating data is also discussed.

"AC Pressurization: A Technique for Measuring Leakage Area in Residential Buildings" presented by **Mark Modera of Lawrence Berkeley Laboratory, Berkeley, USA:** The previous two papers discuss the conventional air leakage measurement technique using fan pressurization. This paper presents a qualitatively different measurement technique, AC pressurization. In this system, air is alternately pulled in and pushed out of the building envelope by a sinusoidally driven piston mounted in the fabric of the building. This volume drive and the attendant oscillating pressure are detected synchronously and used to calculate the effective leakage area in real time. The device has only been used only by the research group that invented↓ it, but there appear to be many advantages to the device: because it operates at low pressures, the issue of extrapolation discussed in earlier papers is not significant; because it operates at low flow rates, the problem of high air exchange in inclement weather is not relevant; because it operates in real time, the user receives immediate feedback as to the amount of air leakage and the amount of change in air leakage caused by on-site retrofits; and because it uses synchronous detection to exclude all but a small range of frequencies, most sources of random error are rejected. The paper contains both laboratory and field results using this device. Preliminary results indicate that AC pressurization can be used as a delicate probe of the physics of leakage. One limitation reported is that the device is "blind" to very large leaks, such as those associated with flues or undampered fireplaces. The authors conclude by indicating research areas they intend to pursue to further test their new technique.

"Determination of the Effective Leakage Areas of Houses by Multilinear Regression Analysis of the Energy Consumption Data" presented by **Gren Yuill of Yuill and Associates, Winnipeg, Manitoba, Canada:** The concept behind this paper is that for certain applications (e.g. the administration of energy audit programs) it may be desirable to have a cheap, but less precise method of estimating effective leakage area — a method

↓ Patent Pending

that would not require the use of instrumentation but, instead, would rely on utility-bill information. Utilities would then be able to determine prime candidates for envelope-sealing type measures without an on-site inspection. The regression model presented uses weather data and consumption data to fit a steady-state model to the energy consumed. The regression constants produced are interpreted as the conductances, the interior and solar gain utilization factors, and the effective leakage area. The approach was used on two (relatively tight) houses built since 1977, both of which were oil-fired, two-story buildings without basements. Although the method holds promise, the results of this albeit limited study are disappointing. The estimated leakage areas do not agree with the results obtained with fan pressurization. The author sees three possible interpretations: 1) that regression cannot be used to determine leakage area; 2) that the current regression model technique is insufficiently robust; and 3) that the data was contaminated. (The data was not collected by the author.) The author ends by suggesting that a larger, better controlled study be instigated to determine whether the approach is practical.

Discussion

The four papers of this symposium represent an excellent cross-section of ongoing studies of air-leakage detection. The paper by Harrje et al. is a snapshot of experiences of *blower door* users and serves as a good introduction to the topic. Persily and Grot, on the other hand, have already begun to explore the limitations on both accuracy and precision of standard fan pressurization techniques.

As a technology matures, such fine tuning is critical. The last two papers present novel methods--each quite different--that represent the leading edge of research in the field — but are quite different. Modera describes a ***high-tech*** method for real-time determination of leakage area, a method that could solve some of the well-known limitations of blower-door technology but at the cost of increased complexity. Yuill on the other hand attempts to use utility-bill information to ***back out*** leakage information without the need for on-site measurements. If these techniques prove viable, they could become important components of future energy conservation technology.

OTHER PAPERS

In addition to the symposia discussed above were other papers (not reviewed by the author) that may be of interest to the reader. Two technical sessions (seventh and eighth) contained seven papers relevant to measuring air leakage: #2922,[22] *Ventilation Measurements in Large Office Buildings;* #2923,[23] *Air Exchange Rate Measurements of the National Archives Building;* #2924,,[24] *A Correlation for Estimating Wind Ventilation;* #2925,[25] *Interrelations Among Different Ventilation Parameters and Indoor Pollutants;* #2926,[26] *Thermal Effect on Pressure Distribution in High-Rise Buildings: Experiment and Analysis;* #2927,[27] *Effect of an Exterior Air Infiltration Barrier on Moisture Condensation and Accumulation withing Insulated Frame Wall Cavities;* #2928,[28] *Air Leakage Flow Correlations for Varying House Construction.* The appendix contains the abstracts of these technical papers as well as the papers from the aforementioned symposia.

Several other symposia dealt with topics related to infiltration and ventilation: HI-85-20, *Design of Ventilation Systems for Hazardous Gas Processes;* HI-85-22, *Instrumentation and Measurement Methods for Performance Evaluation of Buildings;* HI-85-34, *Air Flow around Buildings and Exhaust Re-entry Problems;* and HI-85-39, *Measurement and Control of Radon and its Daughter Products.* Additionally, the reader is encouraged to investigate Vol. 91 (II), 1985, of *ASHRAE Trans.* for several isolated technical papers of some interest.

CONCLUSIONS

The 1985 annual meeting of the American Society of Heating Refrigeration and Air-conditioning Engineers presented an extraordinary amount of archival literature dealing with the topic of infiltration and ventilation. Although the symposia concentrated on the areas of multizone modeling and air leakage analysis techniques, spread throughout the proceedings were high quality research papers. Anyone interested in keeping up with research in this field should consult the ASHRAE's *Transactions* for the texts of the various papers.

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APPENDIX: *SELECTED ABSTRACTS*

This appendix contains author-prepared abstracts of selected papers referred to in the body of this report. All papers are to be published in *ASHRAE Trans.*, Vol. 91 (II), 1985.

HI-85-3, *Air Leakage Analysis Techniques*

1) **Fan Pressurization of Buildings: Standards, Calibration and Field Experience**

by David Harrje and Ken Gadsby

The fan pressurization method has been widely used by groups working with building retrofits and with new construction to evaluate the air tightness of building envelopes. To ensure uniformity in the testing method ASTM Standard E779-81 was developed. This standard is reviewed with commentary on practical aspects of its application. Calibration of these fan systems, often referred to as blower doors, will also be discussed, pointing out where calibration difficulties have arisen and the implications on field inspections. Use of fan pressurization together with infrared scanning is one of the best methods to pin-point air leakage sites in building envelopes. The application of such methods in a variety of buildings will be discussed in order to demonstrate the utility of the methods in the evaluation of building tightness, including seasonal variations; effectiveness of envelope sealing; and the location of problem areas in the building envelope.

2) **Accuracy in Pressurization Data Analysis**

by Andrew Persily and Richard Grot

There are several different ratings of building airtightness used to report the results of fan pressurization tests. These are generally based on air-flow rates at specific reference pressures predicted by curve fits to the test data. The statistical analysis of the data used to obtain these curves allows estimates of the predictive errors associated with these calculated airtightness ratings. The accuracy of the various ratings of building airtightness are important issues in airtightness standards enforcement and the evaluation of retrofit effectiveness. In this paper we discuss the uncertainties associated with pressurization test results due to measurement errors, fan calibration, and test conditions, but concentrate primarily on the errors in the airtightness ratings calculated using standard statistical techniques. Using data from many pressurization tests, we calculate several common airtightness ratings and determine the predictive errors associated with each. This discussion is based on a dataset of pressurization test results in about seventy houses of different sizes, construction and airtightness, along with detailed measurements made on a single house. The implications of the results are discussed in relation to the reporting of pressurization test results, their use in models to predict natural infiltration rates and airtightness standards.

3) **AC Pressurization: A technique for Measuring Leakage Area in Residential Buildings**

by Mark Modera and Max Sherman

Currently, fan pressurization (often performed using a "Blower Door") is the predominant technique for measuring the airtightness of residential buildings. This technique has several known deficiencies from both a theoretical and practical perspective: 1) it exerts pressures on the envelope which are significantly higher than those experienced under natural conditions; 2) it requires extrapolation outside of the measurement range in order to calculate the effective leakage area; 3) because pressurization or depressurization require separate tests, and extrapolation must be performed for both sets of results, it cannot give real- time results; 4) the physical process of installing a blower door is cumbersome and time consuming; 5) the large volumes of air displaced by the fan may cause inconveniences such as fireplace ashes on the floor, indoor temperature changes, etc; and 6) the accuracy of the test can be severely degraded by wind effects. In this report we present a new air-leakage measurement technique called AC Pressurization. This technique is designed to overcome most of the short-comings of fan pressurization (sometimes known as DC pressurization) and to quantify air tightness more accurately and conveniently. The physical apparatus and analysis technique, as well as the laboratory measurements which led to the specifications of the final field device are described. Finally, field measurements of leakage area using AC pressurization are compared with fan pressurization measurements.

4) **Determination of the Effective Leakage Areas of Houses by Multilinear Regression Analysis of the Energy Consumption Data**

by Gren Yuill

The steady state heat loss of a house can be expressed as the sum of the above grade conduction loss, the below grade conduction loss, and the infiltration loss, minus the solar gain. Each of these terms is the product of a weather related variable and a coefficient which describes a physical characteristic of the house.

If the infiltration driving force is properly defined, the infiltration coefficient is the equivalent leakage area. Thus a multilinear regression analysis of the total energy consumption of the house (including internal gains) against the four weather parameters will yield values of the four coefficients, including the equivalent leakage area.

This technique has been applied to two houses. The equivalent leakage areas determined correlate well enough with those measured by a blower door, to indicate that the method has promise.

1) **Modeling Parameters for Boundary Layer Wind-Tunnel Studies of Natural Ventilation**

by Richard Aynsley

Reliable surface pressure and indoor wind speed data from model buildings in boundary layer wind tunnels can only be expected if appropriate modeling parameters are carefully considered. Modeling parameters to consider when planning boundary layer wind tunnel studies of indoor air-flow and external surface pressures due to wind are identified and criteria for assessment are suggested.

2) **Estimating Comfort Cooling from Natural Wind Inside Buildings Using Boundary Layer Wind Tunnels**

by Richard Aynsley

Two techniques for estimating natural wind air-flow through buildings for comfort cooling utilizing data derived from boundary layer wind studies are presented. The modeling parameters necessary for reliable data from the boundary layer wind tunnel studies of indoor air-flow are identified.

3) **Multizone Infiltration Measurements Using A Passive Perfluorocarbon Tracer Method**

by Russell Dietz, Robert Goodrich, and Ted D'Ottavio

A miniature passive perfluorocarbon tracer system was successfully applied to the determination of air infiltration and exfiltration rates from each zone of a multizoned structure as well as the air exchange rates between zones in homes, multiple unit condominiums, naturally ventilated apartment buildings, and large commercial buildings with multiple air handling systems. Use of the multizone technique in indoor air quality assessments and air handling system stratification studies appears to be quite feasible with the availability of this measurement system.

4) **Errors Resulting from the Use of Single-Zone Ventilation Models on Multizone Buildings: Implications for Energy Conservation and Indoor Air Quality Studies**

by Ted D'Ottavio and Russell Dietz

Errors resulting from treating a house as an enclosure surrounding a single, well-mixed volume of air are explored in detail for a ranch house with a basement. A fairly typical ventilation pattern is assumed and three quantities, the air exchange rate, the indoor pollutant concentration from a given emission, and the energy required to heat infiltrating air, are calculated and compared using both the one and two zone models for this house. In general, the errors were around 10-20% if the basement was included in the one zone models and 30-40% if the basement was neglected. Other factors that affect the magnitude of these errors include the length of a pollutant release, the outdoor temperature and the air exchange rate measurement protocol as well as the particular ventilation characteristics of the house.

HI-85-40, *Multicell Infiltration Studies — Part 2.*

1) **MOVECOMP: A Static Multicell-Airflow Model**

by Magnus Herrlin

This paper deals with a new computer program, MOVECOMP, which calculates the in- and exfiltration and the air-flows between the rooms of a multicell building. The calculations are made due to wind- and thermal forces and the characteristics of the leakage openings.

MOVECOMP is intended to be incorporated in a more complex model, AIRCOMP. This latter model will be used also to calculate the air-flows in a ventilation system.

MOVECOMP was developed to be "user friendly"; input data are limited and output data are very flexible. The user chooses which output he wants from a menu. The building is described with a system of pressure nodes, connected to each other through flow - pressure difference functions. A modified Newton-Raphson method was chosen to solve the nonlinear system of equations. AIRCOMP was started to be developed because no complex model was found to be available.

2) **An Automatic Multitracer Gas Method for Following Interzonal Air Movement**

by Josephine Prior, John Littler, and Christopher Martin

A new method for measuring interzonal air movement, using up to four different tracer gases simultaneously has been developed at the Polytechnic of Central London, and tested in a solar air heated experimental house in Peterborough UK. This paper describes the method and its application in an investigation of the transfer of air between a passively heated conservatory and the main living space of the house.

Four perfluorocarbon tracer gases are injected, and samples of tracer gas in air are collected automatically using the principle of gas adsorption on a solid adsorbent. Samples of room air are taken simultaneously at up to five points in space and up to ten points in time, leading to a profile of gas concentration with time for each gas at each sampling position.

The tracers are retrieved from the adsorbent by thermal desorption, and are separated and analyzed using a gas chromatograph. The injection system, sampling system, tracer retrieval, quantitative analysis and data collection are all controlled by a microcomputer. Air flow rates are calculated using a new matrix method of analysis.

3) **Documenting Air Movements and Infiltration in Multicell Buildings using Various Tracer Gas Techniques**

by David Harrje, Gautum Dutt, D.L. Bohac, and Ken Gadsby.

Tracer gas techniques for measuring air-flows in buildings fall into three categories -- dilution, constant injection, and constant concentration. Dilution of a single tracer works well in buildings with a single zone and also in some two zone buildings. Multiple tracer gas measurements, necessary to characterize flows among more zones, are best conducted using the constant injection approach. The constant concentration method uses single tracer gas to determine the air-flow rates from the outside into each of as many as ten building zones.

The paper outlines the different tracer techniques for making air flow measurements in multi-cell buildings and describes the operation of a constant concentration system. This system measures tracer gas concentration in different zones and injects accordingly to maintain a constant concentration in each zone. The system was tested in a single zone structure and successfully applied to a small three-zone house. Sensitivity analyses and calibration procedures described in this paper define the capabilities and limitations of this technique. Although this method does not fully characterize all inter-zone air-flows in the building it can be useful in analyzing the energy balance of multi-zone buildings. Additionally, these measurements can be used to evaluate the dilution of indoor air pollutants and the ventilation efficiency of buildings.

4) **Evaluation of a Simple Technique for Measuring Infiltration Rates in Large and Multicelled Buildings using a Single Tracer Gas**

by Richard Walker, M.D.A.E.S. Perera, O.D. Oglesby and M.B. Hathaway.

Large, multicelled and naturally ventilated buildings pose many inherent problems for the measurement of overall infiltration rates using tracer gases. Considering a single tracer gas decay technique, the most obvious problems are:

1. local variations in infiltration,

2. imperfect internal mixing of the air, and

3. practical difficulties in distributing (i.e. seeding) the tracer gas and subsequently obtaining air samples.

A previous paper proposed a relatively simple technique which avoids these problems. By considering a multicell model, it showed that it was sufficient to seed part of a building with a single tracer gas in order to measure the overall infiltration rate to a good approximation.

Technical Papers

#2922 **Ventilation Measurements in Large Office Buildings**

by Andrew Persily and Richard Grot

Ventilation rates were measured in nine office buildings using an automated tracer gas measurement system. The buildings range in size from a two-story federal building with a floor area of about 2000 m^2 to a 26-story office building with a floor area of 64,000 m^2. The ventilation rates were measured for about one hundred hours in each building over a range of weather conditions. The measured ventilation rates are discussed in relation to the outside air intake strategy in each building. The ventilation rates are also compared to design rates in the buildings and ventilation rates in ASHRAE standard 62-81. Some of the buildings are at times operated at lower ventilation rates than recommended in Standard 62-81.

#2923 **Air Exchange Rate Measurements of the National Archives Building**

by Samuel Silberstein and Richard Grot

To aid in improving the performance of the heating, ventilating, and air-conditioning system of the National Archives Building so that it can better protect paper-based records of the United States, the National Bureau of Standards (NBS) measured air exchange rates under various combinations of temperature and wind speed. The average air exchange rate under normal operation of the HVAC system was 0.9 h^{-1} for an average temperature difference of 11.3°C and an average wind speed of 2.7 m/s. This rate is approximately twice those for new General Services Administration (GSA) office buildings. No clear dependence of air exchange rate on temperature differences up to 17°C or wind speeds up to 5 m/s was found.

#2924 **A Correlation for Estimating Wind Ventilation**

by C.K. Krishnakumar, Stephen Fields, Robert Henninger
Clyde Schafer, Donald A. Bettge

Wind tunnel tests were carried out using models of fallout shelters to determine correlations between shelter ventilation rate, area and distribution of wall openings, wind speed and its direction relative to the orientation of the shelter. Models of bermed shelters with five different opening configurations were used in these tests. A simple correlation was formulated between the shelter ventilation rate, the total area of windward openings, the ratio of leeward to windward opening areas and the velocity of the approach wind. Results were compared with those projected from available correlations for general type buildings.

#2925

Interrelations Among Different Ventilation Parameters and Indoor Pollutants

by Elia Sterling and Theodore Sterling

Measures of a number of ventilation parameters and of a number of pollutants from 21 locations furnished data for evaluating interrelations among commonly used descriptors of ventilation as well as their relation to frequently measured indoor gaseous and particulate pollutants (including carbon dioxide, carbon monoxide, particulates, and hydrocarbons). The analysis of the data is presented in three sections: (1) The intercomparison between different ventilation measures, (2) The relationship between ventilation and pollutant concentrations across buildings, (3) The relation of pollutants to ventilation measures in specific buildings.

#2926

Thermal Effect on Pressure Distribution in High-Rise Buildings: Experiment and Analysis

by Yung Lee and Kyu Lee

A study has been made, both experimentally and analytically, on the characteristics of thermal performance of high-rise buildings using an idealized model building with a number of openings at various locations and temperature distributions. The building was assumed to have no internal partitions. The effect of the factors affecting on the location of the neutral pressure level (NPL) was of particular interest of the present study.

#2927

Effect of an Exterior Air Infiltration Barrier on Moisture Condensation and Accumulation within Insulated Frame Wall Cavities

by Heinz Treschel and J. Robert Ebbets

Increased air tightness of buildings has been promoted for energy savings. One method for achieving greater air tightness is the installation of an air infiltration barrier on the exterior of building sheathing. Although most barrier materials promoted for this application have a high water vapor permeance, it has been a concern that such installations could lead to moisture problems. To evaluate the potential for such problems, a series of laboratory tests were conducted. The results indicate that the air infiltration barrier installed between the sheathing and the siding causes a more even moisture distribution by decreasing the accumulation of condensation in building materials in areas of high moisture content and by increasing it in areas of low moisture content. It was also observed that the highest moisture content in the sheathing occurred under moderately cold conditions, while the highest moisture accumulation in the fiberglass occurred under more severely cold conditions.

#2928 **Air Leakage Flow Correlations for Varying House Construction**

by David Wilson, Darwin Kiel, and Max Sherman

Fan pressurization techniques are being employed by an increasingly large number of contractors and auditors to determine the leakage characteristics of structures. In this study, a large data base of flow exponents and flow coefficients are compiled to determine the degree of correlation that exists between flow parameters. The resulting empirical relationships are then used to determine the feasibility of predicting these flow parameters directly from a single pressure difference test.

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