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Case Studies in Air Infiltration

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CASE STUDIES IN AIR INFILTRATION

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Case Studies in Air Infiltration

I. Background

All references to case studies in air infiltration research must ultimately go back to the group of four publications of J. B. Dick and his associates between 1949 and 1951 (Dick, 1949; Dick, 1950a; Dick, 1950b; Dick and Thomas, 1951). Dick's identification and exploration of key problems reads like a catalog of issues in air infiltration -- many of which are still unresolved. This remarkable set of papers should be read carefully by all who are seriously interested in examining air infiltration in buildings.

In the first paper of the group (Dick, 1949) the author reports detailed air change measurements in four of a group of twenty similar houses in Abbots Langley. The homes were unoccupied but operated in a manner which simulated occupation by a family of four. Different heating systems existed in the homes. The influence of the type of heating system on the infiltration rate was examined. Hydrogen was used as the tracer gas in the measurements; its concentration was monitored using a katharometer to detect changes in the thermal conductivity of the hydrogen-air mixture as the hydrogen concentration changed.

In reporting the results of this research, Dick is careful to separate the air change rates of rooms from the air change rate of entire houses. In doing this he models and experimentally measures concentrations of tracer gas due to air flow between rooms. He is therefore able to distinguish between air change in a room due to infiltration of outdoor air and air change in a room due to air movement from adjacent rooms. (We note that when central air distribution systems are used to mix the tracer gas with the air and distribute it throughout the house, this distinction ceases to be important.)

The total air change rate for the entire house is then the volume-weighted sum of the air changes due to outside air for each room.

Due to the open terrain surrounding the houses and the mild temperatures during the measurements, Dick found that the infiltration rate was adequately represented using an expression of the form:

$$INF = A + Bv$$

where INF is the infiltration rate of the entire house, A and B are constants and v is the wind speed. The variation of infiltration rate due to wind direction, humidity and outdoor temperature was explored but little dependence was found.

Surface pressures due to the wind were measured at each window location; no significant variation was found in the surface pressure measurements on any single wall. This result, it should be noted, was obtained for an exposed group of houses.

The next two papers in this series (Dick, 1950a; Dick, 1950b) are detailed descriptions of the experimental techniques of air infiltration measurements and the mechanisms driving air infiltration, respectively. Experimental results are used to support arguments but the papers deal with more techniques and processes than with results. Particularly noteworthy is the realization (supported by experimental results) that wind and temperature effects are not additive when driving infiltration. This understanding has been ignored in several computer models of infiltration; only recently have authors (Shaw and Tamura, 1977; Sinden, 1978b) again stressed the subadditive nature of these effects.

The final paper in the series (Dick and Thomas, 1951) extends the earlier work in Abbots Langley to include occupants effects on air infiltration. In addition, eight occupied homes in Bucknalls were studied. These were in a more sheltered terrain than the Abbots Langley homes; further, the Bucknalls sites all had heating and ventilation systems which were alike.

As in the earlier study at Abbots Langley the authors show that the air infiltration rate in these houses can be represented by a function of the form $INF = A + Bv$.

The effect of occupancy is to increase the total leakage area of the shell as windows and vents are opened. Measurements of air exchange rates, wind speed and number of vents open show that the effects of vent openings on infiltration rates can be represented by an expression of the form

$$INF = A + Bv + Cn + Dnv$$

where A, B, C and D are constants while n is the number of open vents.

Window and vent openings were correlated with weather conditions. Seventy per cent of the observed variance in the number of vents and windows opened could be associated with the external temperature. As the temperature fell the number of window and vent openings decreased rapidly. Since the infiltration rate increases rapidly with numbers of openings this observed relation between temperature and window openings lead to the curious but understandable result that the infiltration rate decreases in these homes as the external temperature decreases. The effect is large enough to lead to the conclusion that the heat loss due to infiltration is independent of the external air temperature! Both of these results, which are clearly not to be expected in unoccupied buildings, are evidence of the importance of understanding occupancy effects in modeling air infiltration.

The Bucknalls site, since it was more sheltered, showed examples of both temperature and wind driven infiltration. Dick and Thomas analyzed their results by separating infiltration measurements into two regimes: those for which wind driven effects predominate and those for which the stack effect, i.e. air density differences caused by different indoor and outdoor temperatures, predominate. Again occupancy effects were found to be important. Thus for n windows open they found

$$INF = (E + Fn)\ (\Delta T)^{1/2}$$

where E and F are constants, n is the number of open windows and ΔT is the indoor-outdoor temperature difference. This relationship held for measurements taken when $v^2/\Delta T$ was less than a constant which was determined empirically for each structure. When $v^2/\Delta T$ was greater than this constant they found that

$$INF = (B + Dn)v$$

where B and D are constant and the other symbols have been defined previously. The absence of a constant term which was not multiplied by $(\Delta T)^{1/2}$ or v is due to the absence of heated flues in the Bucknalls houses.

Air change rates were high in these studies. They ranged from (1.6 to 3.1) hr^{-1} in the Abbots Langley structures and (1.0 to 3.0) hr^{-1} in the Bucknalls structures. The average contribution due to occupancy of these houses was 0.95 hr^{-1} and 1.10 hr^{-1} at the two sites, respectively.

The problems identified in these papers are still not resolved. This report is testimony of that fact. Since the work of Dick and his co-workers many other studies have been done; most have measured air infiltration in single family detached buildings. One must not interpret this to mean that Dick's work is ignored. The problem rather is the generality of the results of one research group working with one group of buildings to other buildings in other countries and other climate regions. The infiltration rates measured by Dick are large by today's standards. More recent work shows that infiltration rates are lower but house to house (or structure to structure) variation is large and unpredictable. This will be discussed further in section III, below.

Recent studies in infiltration and natural ventilation have also begun to explore other building types. This work is only beginning. Current activities in these fields are reviewed in section II, below.

II. Current Activities

We shall divide current activities by building type and subdivide each of these according to the presence or absence of central forced air heating. The reason for this division is two-fold. The blower in the central forced air system can be used to mix the tracer gas and distribute it uniformly to the structure. This simplifies mixing and multi-chamber problems; however we find that complications can also occur using this procedure since the air ducts in the distribution system often leak significant amounts of air.

A. Single Family Detached Structures

1. Central Forced Air Distribution

The largest recent study reported is that of Sepsy, et. al. of Ohio State University (Sepsy, Jones, McBride, Blancett, 1978). This study will be published soon as a report of the Electric Power Research Institute (EPRI). Nine homes were monitored in the study; seven of these had central forced air heating systems. A large amount of data was obtained which related infiltration rates and weather variables; a thorough statistical analysis of these data was performed. The authors found that their results could be represented best by

$$INF = \beta_0 \, C_T \, (4\Delta P_T + \sqrt{2}\ \Delta P_v)^{1/2}$$

where $$\Delta P_T = A\, P\, h \left(\frac{1}{T_o} - \frac{1}{T_i}\right)$$

and $$\Delta P_v = \frac{B}{T_o} v^2$$

In this expression β_0 is a statistical regression coefficient (which essentially describes the construction quality of the house), A and B are constants which depend upon the system of units used, P is the absolute pressure, h is the height of the neutral zone (the horizontal plane along which indoor and outdoor air pressures are equal) for the house, C_T is the total equivalent crack length for the house, T_0 is the outside temperature, T_i is the inside temperature and v is the wind speed. This representation of the relationship between infiltration rate and weather parameters is particularly useful for it suggests that by determining a single regression coefficient, β_0, and by measuring the effective crack length of the house, the infiltration rate can be modeled through an entire heating season.

More recent work has been done and is underway at the National Research Center in Canada, the National Bureau of Standards and the Lawrence Berkeley Laboratory in the United States.

2. Non-Central Air

Non-central heating in single family detached houses is common in Europe; the major share of European studies have been made with this type of heating system. Studies examining infiltration rates in single family detached houses are currently underway in the United Kingdom, Switzerland and Sweden.

B. Low Rise Residential

The next important class of buildings are low-rise residential structures. In that category I am including row houses or townhouses as well as apartment houses three stories high or lower.

1. Central Air

A long-term study conducted by Princeton University of a large group of townhouses in New Jersey has recently been published in the journal Energy and Buildings. Air infiltration measurements in two of the centrally heated townhouses is the subject considered by Malik (1978) in his paper in this issue. Malik's work shows the effect on air infiltration of wind speed and direction, indoor-outdoor temperature difference and rate of furnace firing. One of his more interesting results is statistical evidence for a non-linear wind-temperature interaction when the wind speeds were larger than 5 $^{m}/s$. The effects had opposite signs in the two test houses. In one, the air exchange rate was enhanced when high wind speeds were coupled with large values of indoor-outdoor temperature difference, in the other the opposite was true. Sinden (1978) has argued persuasively that both effects are physically reasonable. It is inviting to speculate about the nature of the destructive interference which reduces air infiltration as the temperature decreases when one has high wind speeds. Such information could be useful for design applications.

2. Non-Central Air

Several studies are underway or are planned for this building type. The National Bureau of Standards in the U.S. is engaged in a study of air infiltration rates and air leakage rates using fan pressurization in three low-rise apartment houses in Chicago. This topic is discussed further in section III, below.

De Gids and coworkers, in the Netherlands have made a careful study of air infiltration in a third story flat located in a block of flats close to the North Sea. In this study particular attention was paid to surface pressure differences between the inside of the flat and the outside walls. The study was attempting to relate calculated air flows based upon measured surface pressure differences with measured ventilation rates. The results agreed reasonably well considering that surface pressures on walls were only measured at one point. In addition to the above, ventilation rates were correlated with the meteorological wind velocity. The correlation was very poor (the meteorological data came from a station 15 km from the test site) until the wind velocity was corrected for local surface roughness in the vicinity of the test site. After this correction was made a linear correlation was seen relating air change rates and corrected local wind velocity. This study is continuing; occupancy effects, indoor-outdoor temperature differences and humidity effects are also being investigated.

Other projects designed to measure infiltration rates in low rise apartment buildings are underway in Sweden and Switzerland. The latter work, in particular, is strongly directed at understanding occupancy effects upon ventilation rates; it will be discussed further in a later chapter in this volume.

C. High Rise Reisdential

D. Low Rise Commercial

E. High Rise Commercial

In each of these categories the number of case studies is very small. This is primarily the result of the complexity of the measurements required. This is discussed further in section III, below.

Honma (1975) developed an iterative procedure to calculate air flows between rooms in two tall blocks of flats in Sweden. His procedure allows calculation of total ventilation between rooms, of ventilation due to both supply and exhaust fans and of ventilation due to infiltration through structural cracks and cracks around doors and windows. A controlled flow tracer gas system using CO_2 is used for the measurements; measurements of changes of concentration of the tracer as a function of time allow calculation of air flows.

Kelnhofer, Hemt and Didion (1976) have reported measurements of ventilation rates in a nine-story office building using SF_6 tracer gas technique. They investigated a building in which all floors were sealed except the ground floor and the mechanical equipment room at the top of the building. A central air distribution system allowed whole building injection via the air supply system and whole-building sampling using the return air ducts. Results obtained using tracer gas correlations were compared with those obtained by measuring exhaust rates for the building. Agreement was very good. Again the existence of a central air distribution system, as in the case of measurements in single-family detached houses, permits effective use of tracer gas techniques.

A study of the air leakage properties of the central administration building of National Bureau of Standards will soon be underway. Again in this case, a central air-handling system is present in the building which will facilitate use of a tracer gas in the building.

The chart below summarizes projects completed or in progress in the areas given above.

Section II -- Summary

Building Type	Central Forced Air	Non-Central Air
Single Family Detached	Many studies completed; Additional studies in progress	Many studies completed; Additional studies in progress
Low Rise Residential	Princeton, (USA)	Hartmann (Switzerland) De Gids (Netherlands) Nevander, Adamson, (Sweden)
High Rise Residential	———	Honma (Sweden)
Low Rise, Commercial	———	———
High Rise, Commercial	Kelnhofer, et. al. (USA) NBS (USA)	

III. Problems and Needs

This section has two major thrusts: (A) Case studies must be expanded to survey building types which have not been adequately investigated. The types are shown on the chart above and include everything except single-family detached houses. (B) A major investigation, viz. the correlation of air leakage measurements using fan pressurization and air infiltration remains to be completed in single family detached homes.

Consider (A) first. The need to expand measurement of infiltration and ventilation to include larger and more complicated building styles is clear. However, many instrumentation problems must be solved before such measurements will be meaningful. The problems are not new. For example they were discussed by Dick and his co-workers in the papers referred to above. However, as measurements are extended to larger and larger buildings the problems become more severe and may require the development of entirely new instrumentation techniques.

The two most serious problems are those of adequate mixing of the tracer gas in the space under test and multi-chamber effects caused by tracer gas movement between rooms.

Mixing is assumed to be perfect when the simplest kind of concentration decay measurements are described. When a large blower is present in a closed ventilation system or heating system, mixing can be quite good. When other forms of heating systems are used, auxiliary mixing with fans or blowers is generally advisable. How should this be done? One technique is to inject the tracer gas into test space, mix it with a fan or blower, then turn off the fan to avoid disturbing the natural pressure distribution driving the infiltration. (We note that this technique can only be employed when using concentration decay, not when controlled flow injection techniques are used.) Two assumptions are implicit here. The first is the belief that once the tracer gas is mixed uniformly it will not later separate or stratify. Second is the belief that infiltrating air will mix uniformly with the tracer gas so that a uniform concentration decay will be seen. It is the author's belief that the first assumption is quite good, except perhaps when a very light tracer gas (H_2 or He) or a very heavy tracer gas (SF_6) is used. The second assumption is more dubious. The increasing noise seen on concentration signals when measuring decays with open windows is an indication of non-uniform mixing occuring when relatively large air exchange rates occur in a test space. However, beliefs and assumptions do not constitute experimental evidence. Concentrations should be sampled at many points throughout the experimental space during the course of a trial to determine if adequate mixing occurs. The effects of operating mixing fans continuously should be examined. The question of possible stratification or separation when using very light or very heavy tracer gases should be resolved.

Multi-chamber effects which complicate measurement analysis will be particularly troublesome in low rise and high rise residential buildings. In these cases the structures are divided into many small subvolumes (apartments) which are not, in normal use, connected to the other subvolumes (apartments) in the larger building volume. Measurement analysis must carefully distinguish air exchange between the apartment under test and the outside from air exchange between the test apartment and the other apartments in the structure. Honma (1975) and Sinden (1978a) have discussed this problem. Careful experimental work will be necessary to apply these ideas to understand the complicated flows present in actual buildings.

To summarize, needs can be identified by examining the lack of information associated with many of the building styles as shown in the table at the end of section II. The problems associated with the experimental techniques needed to make the measurements described are not trivial.

These problems help explain the current lack of results -- they can and should be eliminated in order to allow progress in this new area.

The other major problem is one currently associated with single family detached houses but, if solved, could have important applications to other building styles as well. Many groups currently are examining the possibility of correlating the results of air leakage measurements using fan pressurization with tracer gas infiltration measurements. If this is successful, the results will be important both for those who are interested in computer modeling of energy use in a building and also for those who are interested in establishing construction quality standards for air leakage in buildings.

The motivation for seeking the correlation arises because of the wide range of results obtained by those who attempt to relate infiltration rates to weather parameters. While the functional forms of these relationships are quite similar for measurements on different single family residence, the constants which enter the equation differ widely from house to house. The major source of this variation may be the differences in construction quality between houses which determine the leakage detail of the structure. If this hypothesis is valid an independent measurement of construction quality should reduce the variation between coefficients and allow adequate modeling of air infiltration rates to be done for a "typical" house.

How can construction quality be measured? Again one must speculate but current thinking suggests that fan pressurization measurements of air leakage may provide the best measurements for purposes of air infiltration modeling. This measurement is made by sealing a fan into the building shell and adjusting the fan speed to obtain an overpressure within the structure. Mass flow continuity then predicts that the air flow rate through the fan is equal to the air leakage rate of the structure of the working pressure difference. Fan pressurization measurements of air leakage are not analogs of air leakage due to infiltration because the pressure distributions on the building shell are quite different in the two cases. In the first, the pressure over the entire shell is quite uniform while in the second the pressures vary in a complicated manner both in space and in time over the building shell. Measurements of air leakage in two structures using the same working pressure does allow one to compare the two structures. If this comparison can also be used to predict comparative air infiltration rates for the two structures (when the air infiltration rates are normalized to the same weather conditions) then the fan pressurization measurement will be very useful, indeed. Once sufficient infiltration rate versus weather conditions for typical housing styles have been determined, a single fan pressurization measurement in a specific house, requiring inexpensive equipment and a modest amount of time, could be used to determine the coefficients in the relationship of infiltration rate versus weather parameters for that house. This information could then be used with a typical weather record for a heating season to predict the amount of air infiltration for the heating season and the energy use associated with that infiltration.

Inverting the process, knowledge of the heat load due to infiltration in houses that have a measured air leakage value should allow a standard to be written for the maximum air leakage in a house at a particular pressure when using fan pressurization.

There are many unverified assumptions associated with the statements made above. The problem is of sufficient importance that many research groups throughout the world are investigating it. This is clearly a problem of interest to all participants in the IEA. The IEA could, by helping coordinate research, play an active role in its solution.

IV. Recommended R & D Projects and Project Areas.

A. IEA Sponsorship

Participants in the 1978 Paris seminar adopted, as one of the projects appropriate for IEA sponsorship, the following: the IEA should "Examine the Possibility of a Correlation of Pressurization Air Leakage Measurements and Tracer Gas Infiltration Measurements in Single Family Residences."

This statement was later refined and written into an Annex to be considered by the IEA Executive Committee on Building and Community Systems. If approved by the Executive Committee, and if an operating agent can be found, a project lasting approximately twenty-six months would be begun. It would be oriented toward standards; the objectives put forth in the Annex are:

1. To determine if pressurization tests can be used to predict natural air leakage rates.

2. To establish a construction quality standard for air leakage.

The project shall be task shared and coordinated by the operating agent. The IEA, then, will help standardize procedures used to examine the possible correlation, aid the communication of information among the research groups examining the problem, provide a forum to allow researchers to discuss their results and aid in drafting possible standards.

Construction quality standards for new buildings have the disadvantage of only slowly affecting energy consumption. There is a need for more case studies of performance of a building before and after efforts are made to make the building shell tighter. Those who have investiments in existing housing should be able to learn how to reduce their energy consumption without having to purchase new energy-efficient housing. The experience gained in studies designed to reduce air infiltration and therefore energy consumption in existing housing, in particular the techniques used to accomplish the reduction, should become part of a catalog of construction techniques available to all countries in the IEA. This may be an appropriate task for the Data Management Center.

Finally any proposed studies of air infiltration and ventilation rates in any type of building must make a realistic assessment of the impact of occupants on the performance of that structure. In a sense, larger buildings, in which occupants have little control over the building operation are easier to study than are smaller buildings. Occupants clearly have a major impact on the air infiltration rates in houes and in any building with windows which can be opened. The need for studies of occupant behavior will be discussed further in a later chapter in this volume.

Other projects suitable for IEA sponsorship fall into other categories and will be discussed further by other authors in this volume. Clearly there are other needs but these tend to have a national focus. As instrumentation and measurement techniques improve, more studies will be made in the wide class of larger buildings about which little is currently known. Since these reflect building styles and are situated in climate types peculiar to a country or a region of a country, these are best when defined as national projects. These national projects should therefore include:

1. Low-rise residential buildings
2. High-rise residential buildings
3. High-rise office buildings
4. Larger open-plan buildings

Each of the projects assumes as prior conditions improvements in the mixing problem and a clear understanding of and an experimental technique for determining air flow between contiguous closed spaces within a building.

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