# DEVELOPMENT OF A PROCEDURE TO EVALUATE THE AIR LEAKAGE DISTRIBUTION FROM FAN PRESSURIZATION TEST – VALIDATION OF THREE AIRFLOW MODELS

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## SUMMARY

A number of airflow models have been developed to assist the designer in the design of energy efficient and healthy built environment. The models range from very simple empirical algorithms to calculate the global airflow rate to sophisticated computerized fluid-dynamic techniques solving the Navier-Stokes equations. The multi-zone approach falls between these two extreme cases. This approach assumes that the interior of the building is divided into regions of differing pressures interconnected by leakage paths. The advantage of multi-zone models, besides being able to simulate infiltration in larger buildings, is that they can be used to calculate mass flow interactions between the different zones inside buildings as well as inside and outside. This knowledge is needed for the design of heating/cooling and ventilation systems.

An essential part of the development of any computer model is its validation, and the essential information needed for validation of airflow models is the distribution of air leakage distribution. This paper first describes a methodology to distribute global air leakage of whole house and whole garage among cracks and gaps on exterior walls and roof, and report the validation of three airflow models. From the comparisons it can be seen that there are good agreement between the predictions made by the models and measured data, as well as between three models. Therefore, it can be concluded that the methodology for air leakage distribution is correct, and the performances of COMIS, CONTAM and ESP-r for predicting airflow rates in single-family house are similar.

## INTRODUCTION

A number of airflow models have been developed to assist the designer in the design of energy efficient and healthy environment building. The models range from very simple empirical algorithms to calculate the global airflow rate to sophisticated computerized fluid-dynamic techniques solving the Navier-Stokes equations. In general, the complexity of modeling can be grouped into two categories: detailed models for predicting airflow and contaminant distribution patterns in rooms – room air movement models, and simplified models for predicting the global behavior of airflow – building airflow models. Although the level of analysis is not nearly as detailed as a room air movement model, building airflow models is easy to use and it can provide an overall picture of airflow and contaminant concentration distribution pattern in the modeled building, and hence it is more frequently used.

Building airflow models can be divided into two main categories, single-zone models and multi-zone models. Single-zone models assume that a single and well-mixed zone can describe the whole building. The major application of this model type is for calculation of the air exchange rate of single-story, single-family house with no internal partitions (e.g., all internal doors are open). Multi-zone models allow the division of a building into separate zones, which may be at internal pressures and temperatures distinct from one another. Their solution can provide detailed results about the mass flow rates through all airflow paths. The advantage of multi-zone models, besides being able to simulate infiltration in larger buildings, is that they can be used to calculate mass flow interactions between the different zones inside buildings as well as inside and outside. This knowledge is needed for the design of heating/cooling and ventilation systems.

An essential part of the development of any computer model is its validation. In the case of multi-zone airflow models, errors or differences from the actual values many occur arise due to: differences between actual weather conditions and those used in the simulation; the use of simplifying assumptions in the input data; differences in the actual building thermal characteristics and those used in the model; differences in the airflow mechanisms used by the model and the actual phenomena; and finally programming or logic errors.

Haghighat and Megri (1996) conducted a comprehensive validation of two multi-zone airflow models – COMIS and CONTAM. The validation process was carried out at three different levels: inter-program comparison; validation with the experiment data from a controlled environment test; and validation with the field measurement carried out in a residential building.

The following input parameters are required to simulate the airflow distribution for a given house:

- Orientation of the building,
- Proximity of other buildings (shielding information),
- Physical dimensions of the house (including the sizes and locations of exterior doors, vent openings and windows, as well as interior doors),
- In mechanically ventilated houses, the location of all supply, return registers and vents as well as their respective airflow rate under normal conditions,
- Temperature of the various rooms in the houses; and
- Local meteorological data (wind speed and direction, and temperature)
- Magnitude and distribution of building envelope air leakage.

The magnitude of the building envelope leakage is measured with fan pressurization test. The value gives only information about the global leakage characteristics of the whole unit (i.e. whole house, whole garage, etc.). This, however, will not provide information about the distribution of cracks and gaps formed during the constructions of the building, such as the interface of window and doorframe, ceiling/wall/floor interface, penetration of pipes, etc. This information is needed for accurate prediction of airflow. It is therefore required that the global flow coefficient and exponent calculated by fan depressurisation tests be distributed among cracks and gaps. This paper first proposes a procedure for distributing the global air leakage data obtained using fan pressurization among different building envelope components, and then reports the results of comparison of the prediction made by three airflow models, ESP-r, CONTAM and COMIS, with the field measurement data.

## Airflow Models

Three multi-zone airflow models are selected for this study CONTAM, COMIS and ESP-r. They use similar fundamental including flow equations for airflow paths and algorithm for solving the equations. CONTAM (Walton 1997, Dols, et. al, 2000), COMIS (Feustel and Raynor-Hoosen 1990) and ESP-r (ESRU 1997) are well documents.

Comparison of prediction made by these models and with the field measurement was performed for two single-family houses with attached garage. This type of houses represents typical North American houses. The main difference between these houses was the heating type: house #1 was heated by electrical baseboard and house #2 was heated by a mechanical central air distribution system.

In order to simulate the airflow of two houses, the air leakage characteristics of the house, garage, and the house/garage interface were needed: they were determined by fan depressurization tests. For validation purposes, the pressure drop between the garage and the house was also measured during the test for each house.

## Measurements Methodology

The house preparation procedure followed by the air-tightness tests were according to the proposed revisions of the CGSB Standard (The Canadian General Standards Board Standard CAN/CGSB-149.10-M86, *Determination of the Air-tightness of Building Envelopes by Fan Depressurization Method*) which allow the house to be tested as “occupied”. The house preparation procedure basically does not require sealing intentional openings which would usually be left open during normal house operations. The houses were therefore prepared as they would be in winter, windows closed and latched. The “occupied’ house condition provides a more realistic evaluation of the house leakage characteristics for air infiltration simulations.

To determine the air-tightness characteristics of the house, garage and their interface, two air-tightness tests were conducted as follows: (Ruest,1997).

- **Test #1**. House only air-tightness test. For this test the house was prepared for its winter operating conditions, and the garage door was opened. This air-tightness test was done to characterize the house envelope leakage characteristics independently from the garage. With the garage door opened, the house/garage interface leaks were included in the first test values.

- **Test #2**. House air-tightness test with the house/garage interface kept at zero pressure difference. The second house test was done with the garage door closed, and while the garage was simultaneously depressurized to eliminate the flows through common surfaces between the house and garage. The garage pressures and flows were also being recorded during this test to calculate the garage air-tightness.

Results from the two air-tightness tests provided the data required for characterizing the house/garage interface. The value of flow coefficient, *K*, and the flow exponent, *n*, for the whole house envelope and the whole garage envelope were determined by regression analysis of the fan depressurization tests. The flow coefficient, K, is an indication of the size of the opening, and the flow exponent, n, is a measure of the flow type. They depend on the type of crack, material used and the quality of workmanship. In general, the flow exponent increases marginally in value with airtightness.

However, the value of *K* and *n* for the interface between the house and the garage were determined by mathematical manipulation of the two fan depressurization tests.

$$Q_{\text{int}} = K_{\text{int}} \left(\Delta P\right)^{n_{\text{int}}} = K_1 \left(\Delta P\right)^{n_1} - K_2 \left(\Delta P\right)^{n_2} \quad (1)$$

Where, the subscript of “1” is for the test #1, “2” is for the test #2, and “int” is for the interface. The air-tightness test results for two houses are showed in Table 1.

| **Building** | *House* | | ***Garage*** | | ***Interface*** | |
|---|---|---|---|---|---|---|
| | **K** [L/(s Pa$^n$)] | ***n*** | ***K*** [L/(s Pa$^n$)] | ***N*** | ***K*** [L/(s Pa$^n$)] | ***N*** |
| House-1 | 50.76 | 0.65 | 117.88 | 0.54 | 1.54 | 0.68 |
| House-2 | 19.38 | 0.82 | 18.68 | 0.65 | 2.12 | 0.82 |

**Table 1** Air Leakage Data Given by Air-Tightness Test and Calculation

Pressurizing the garage and carrying out smoke pencil test provided a further assessment of the house/garage interface air leakage. For this procedure, the garage was pressurized while the house remains under normal pressure. From inside the house, smoke pencils were used to locate the air leaks from the garage to the house. The leakage location observations from this procedure provide some indication of the airflow path distribution on this interface.

The meteorological data was collected for each house for the day that test was carried out, and the pressure differences between the house and garage as well as the air temperature of garage and house were monitored.

## Air Leakage Distribution

The fan depressurization tests provided only the information about the global air leakage characteristics of the whole unit (i.e. whole house, whole garage, etc.). This however, did not provide information about the distribution of cracks and gaps formed during the constructions of the building, such as the interface of window and doorframe, ceiling/wall/floor interface, penetration of pipes, etc. This information was needed to run the simulation programs. It was, therefore, required that the global flow coefficient and exponent calculated by fan depressurization tests be distributed among cracks and gaps.

In this study, efforts and judgments were made to evaluate the distribution of the air leakage paths around the building envelope by using some reliable data in the literature for every component.

Technical Note AIVC 44 (Orme et al 1994) developed a database to provide numerical guidance on typical leakage values for use in design and simulation when no other sources of data are available. These data are based on measurements published in over 80 technical publications and on measurements provided directly by many research organizations and groups.

One of the main criteria of data on leakage values selection from literature was that it must match the construction material and condition of the tested building such as the construction materials (concrete, timber or steel), the type of windows and doors (weather-striped, unweather-striped), penetrations (location of the installations, etc.), wall junctions, etc. In general, the median value of flow coefficients was used except when a major airflow path was observed during the smoke test. In this case, the upper quartile value given in the literature was considered.

If no value for a component (i.e. type of window) was found in the literature, a *K* value was calculated by considering the airflow path as an orifice and estimating the leakage area. It was assumed the discharge coefficient $C_d$ is equal to 0.61 (Orme et al 1994).

$$Q = C_d A \sqrt{\frac{2}{\rho} \Delta P} = C_d A \sqrt{\frac{2}{\rho}} \Delta P^{0.5} \qquad (2)$$

$$K = C_d A \sqrt{\frac{2}{\rho}} \qquad (3)$$

Where $Q$ (m$^3$/s) is volume flow rate, $A$ is the opening area (m$^2$), $\rho$ (kg/m$^3$) is the air density, $\Delta P$ (Pa) is pressure difference.

Recent studies have shown that most of the flow exponents for airflow paths (leakage openings) at the material interfaces or joints are within ± 0.12 of their mean value. Therefore, it is assumed that for a given unit (i.e. a house) the flow exponents for all airflow paths on the exterior walls are identical. It was assumed that the airflow paths of the investigated buildings had similar characteristics as those given in the AIVC 44, but not necessarily the same value (only the flow exponent for every component is equal to that given in literature). The total envelope leakage airflow under a specific pressure differential (e.g. 50 Pa) could be calculated by adding leakage airflow for all components (literature value) at the same pressure differential. Equation 4 expresses the relationship between this total value and the leakage airflow determined by air-tightness test for the whole envelope.

$$\frac{\sum K_{i,lit}(\Delta P)^{n_{i,lit}}}{K_{test}(\Delta P)^{n_{test}}} = \frac{K_{i,lit}}{K_i} \qquad (4)$$

Convert this equation, the flow coefficient for each airflow path, *i*, is calculated by:

$$K_i = K_{i,lit} \times \left[K_{test}\ (\Delta P)^{n_{test}}\right] / \sum K_{i,lit} (\Delta P)^{n_{i,lit}} \qquad (5)$$

Where, $K_{i,lit}$ and $n_{i,lit}$ is the value of the flow coefficient and exponent for component *i* from the literature AIVC 44; and the $K_{test}$ and $n_{test}$ is the global flow coefficient and exponent of the whole unit (house, garage or their interface) measured by air-tightness test (Table 1). It was also assumed that the house envelope is insulated with an air barrier and the flow coefficients of exterior walls and ceiling were distributed proportionally to the exterior walls and ceiling area of each room.

Since the airflow characterization of interior components was not available in the literature, the airflow path distribution in the interface of house and garage was based on the observation made during the test. Smoke pencil was used to observe the airflow path.

## Assumptions and Parameters for Simulation

The important emphasis of this study was to ensure that identical input data is used in three models – COMIS, CONTAM and ESP-r, and then to check how they respond.

The garage air temperature was treated as constant during the simulation period, using the garage mean temperature during test period. The temperature inside the house was assumed to be uniform. The fireplaces and exhaust fans in kitchens and bathrooms were not in use during the measurements and the dampers were closed.

The house #2 had a mechanical ventilation system and the supply and return airflow rates to each zone were measured, and then used as input for the simulation. But due to inaccessibility or other reasons, it was not possible to measure the supply or return airflow in certain zones. In this case, the values were obtained by performing a simple mass balance for the zone, floor or whole house with an assumption that there was no leakage on the air distribution system in order to take into account the duct distribution leakages.

Two parameters have pronounced impact in the determination of wind induced surface pressure, that is, the wind velocity at the building height and the value of pressure coefficient. The induced surface pressure varies with the square of the wind velocity therefore; the accurate estimation of site wind velocity from the meteorological data is needed. CONTAM uses a power law wind velocity profile to calculate the wind velocity at the building height (Walton 1996).

Although the wind-induced pressure varies linearly with the pressure coefficient, it has an important impact on the final outcome of the simulation. Pressure coefficient depends on the wind angle, and the degree of surrounding shielding and spatial separation of nearby obstructions (Wiren 1985).

In this study, the urban area wind velocity profile was used to calculate the wind velocity at building height. The pressure coefficient used here was from the literature, Technical Note AIVC44, for a low-rise building, surrounded on all sides by obstructions equal to the height of the building  (Orme et al 1994).

## Models Configuration and Simulation

There are many factors that may influence the results predicted by multi-zone models. The limitations of the models themselves, due to physical approximations, are what should be found and compared in this study. On the other hand, lack of clarity or misunderstanding of the constructions of buildings and the misusing of simulation program can also give rise to incorrect results. This type of problem is easier to rectify, once it has been identified. Because of this, model configuration – building up an airflow network according to the real building, before simulation is very important.

COMIS and ESP-r are all based on text input to set up network models for building airflow. In ESP-r, the number of airflow components is limited to be less than 50, and the number of connections (airflow paths) is limited to be less than 99. In COMIS and CONTAM, there is no limitation on the number of airflow components.

These two buildings had a large number of airflow paths, and in order to handle the limitation of ESP-r, some approximations had to be made to reduce the number of airflow components (for example, to approximate two very close flow coefficient values to be one value) and remove some connections (airflow paths) with relatively very small values. So, the set of input data of ESP-r was not completely the same as in COMIS and CONTAM, but the difference is very small.

# COMPARISON AND ANALYSIS

The comparisons between the predictions of COMIS, CONTAM and ESP-r and the measured pressure differences across house/garage interface for two houses are showed in Figures 1 and 2. In general, there are good agreements between the predicted and measured values: the predicted results by three models are very close.

From the comparison between predictions and measurements, it can be seen that three simulation models often over-estimated the pressure differences for two buildings. But even the biggest difference between the prediction and measurement is not out of the range of $\pm 25\%$. This is acceptable and reasonable because the drive of natural ventilation is unsteady and is treated by average data, e.g. the wind pressure coefficients. The other reasons may be due to errors in measured data and parameters used for the building description.

From the comparison between the predictions of three simulation models, the results indicate that the sequence (from maximum to minimum) of prediction values during the measurement period for two buildings is same – COMIS, ESP-r, CONTAM. The differences of predicted values between ESP-r and CONTAM are smaller than that between COMIS and two others. This is due to the different approach used to convert wind velocity from meteorological station to building height. In CONTAM and ESP-r, a wind speed reduction factor (or wind speed modifier, which accounts for the difference between reported velocity and wind speed at building height) was input directly to keep the sets of input data identical. But in COMIS, such an option is not available and the program uses the given wind speed at the meteorological site and calculates the speed at 60m high (or higher if meteorological station or the building is in rough terrain and wind speed profile exponent, $\alpha$, is greater than 0.34. In this condition, COMIS program calculates the height of boundary layer). This speed at 60 m (or higher) is assumed to be equal to the wind speed at the same height above the building. Along the profile near the building the velocity at the building reference height is calculated (Feustel and Smith, 1997). Therefore, it is impossible in COMIS to get the same wind velocity at building height as that in CONTAM and ESP-r. This caused different input wind pressures and consequently resulted in different performance of three models predictions.


**Figure 1** Measured and Predicted Differential Pressure across Garage-House Interface of House #1

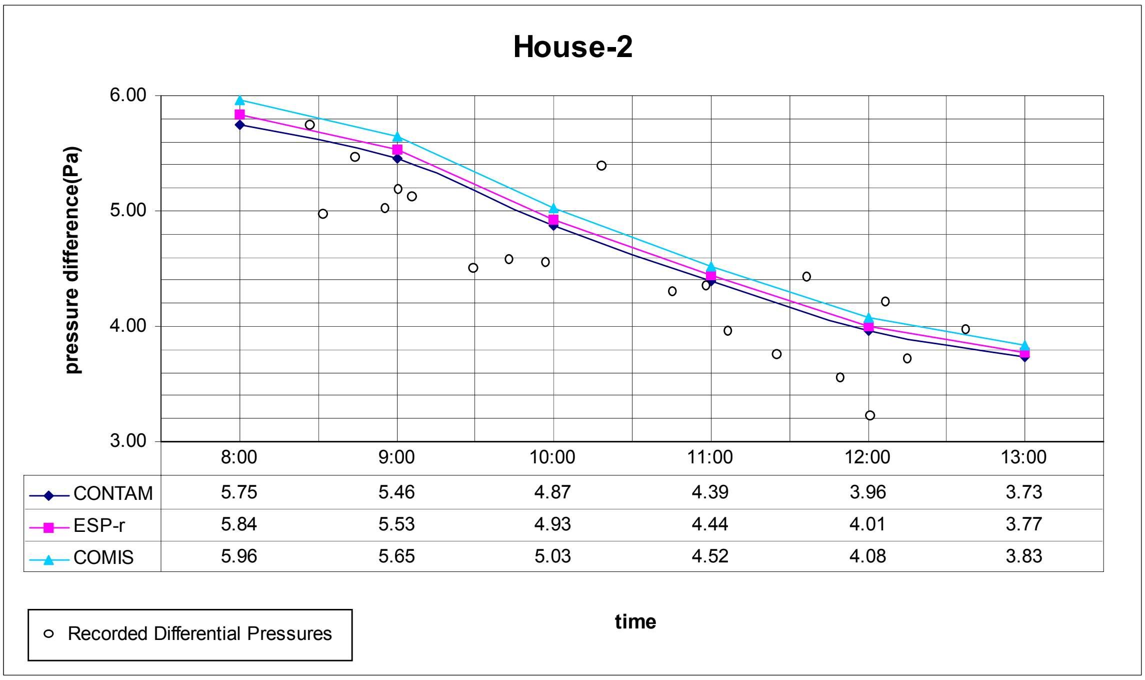


**Figure 2** Measured and Predicted Differential Pressure across Garage-House Interface of House #2

These results also show that the approximation made in the ESP-r simulation, reducing the number of airflow elements, did not significantly impact the predictions. This means that the small difference of airflow network description did not induce significant discrepancy in the outputs: one can conclude that locating and sizing the airflow components with relative bigger values (for example the observed house air leakage paths) should be pay more attentions than the general background leakage, because these elements influence the simulation results very much.

## CONCLUSIONS

In general, similar principles are used in the development of three multi-zone airflow models; COMIS, CONTAM and ESP-r, to describe various airflow/pressure relationships including the definitions for driving forces (wind pressure, thermal buoyancy and the mechanical ventilation systems) and airflow elements. Similar algorithms are also used to solve the non-linear equations.

The validation process was carried out at three different levels: inter-program comparison; validation with experimental data which was collected in a controlled environment; and finally, validation with field measurement data. The experimental data collected in the controlled environment include both summer and winter condition.

The results of validation with the data collected in the controlled environment show that there are significant differences between predicted and measured airflow rates from one zone to another, and even for the total airflow rates in each zone. However, there is good agreement between the predictions made by COMIS, CONTAM and ESP-r.

In the second validation, a method was developed first to distribute the global air leakage characteristics of whole house and whole garage among cracks and gaps on exterior walls and roof. From the comparisons it can be seen that there are good agreement between the predictions made by the models and measured data, as well as between three models. Therefore, it can be concluded that the methodology for air leakage distribution is correct, and the performances of COMIS, CONTAM and ESP-r for predicting airflow rates in single-family house are similar.

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