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# DEVELOPMENT AND VALIDATION OF A SIMPLIFIED MULTIZONE INFILTRATION MODEL

Helmut E. Feustel
Indoor Environment Program
Energy Performance of Buildings Group
Lawrence Berkeley Laboratory
Berkeley, CA 94720, U.S.A.

Jean-Louis Scartezzini
Groupe de Recherche en Energie Solaire
Ecole Polytechnique Federale de Lausanne
CH-1015 Lausanne, Switzerland

## 1. Introduction

Infiltration is the random flow of air through openings in the building envelope due to wind pressure fields around the building and the thermal buoyancy caused by temperature differences between the inside and outside of the building. Multizone infiltration models have been developed to simulate the air mass flow pattern for given weather conditions [1].

The amount of air flow through a building for given weather conditions is determined by the air permeability of the envelopes for the different zones as well as permeability distribution. The permeability of a building's envelope is dependent upon the number of cracks, windows, doors, and gaps between building components. In addition to these observable visual leaks, there is also background leakage caused by porosity of building materials with resultant cracks in these materials. The value of air flow through the structure can be measured by the fan pressurization technique (DC) [2] or the AC pressurization technique [3].

Since straightforward infiltration models, which treat the true complexity of air flows in multizone buildings, require extensive information about flow characteristics and pressure distribution, simplified models are being developed [4]. In order to validate the model developed at the Lawrence Berkeley Laboratory (LBL), we have used tracer gas measurement systems [5,6] and developed a method to measure the leakage areas of a zone [7], both to the outside and the other zones in buildings. Wind tunnel measurements and leakage area measurements have been made to determine the boundary conditions.

## 2. Simplified Model

The physical fundamentals of the pressure distribution and the air flow pattern are described elsewhere [8]. In order to simplify the calculation procedure, certain measures have been taken. We defined a set of lumped parameters to describe the permeability distribution of the building, used a single exponent for the calculation of air flows, calculated the wind and stack driven air flows separately, and used superposition to combine the air flows.

### 2.1 Resultant Permeability

The effective air permeability for a building is most often a combination of air permeabilities arranged in series and/or parallel. Parallel permeabilities can be easily added, but for a series arrangement permeability must be calculated in the following manner:

$$Q = D_{res}\left\{(p_1 - p_2) + (p_2 - p_3) + \cdots + (p_{k-1} - p_k)\right\}^n = D_1\,(p_1 - p_2)^n = \cdots \tag{1}$$

$$D_{res} = \left\{D_1{}^{-1/n} + D_2{}^{-1/n} + \cdots + D_{k-1}{}^{-1/n}\right\}^{-n} \tag{2}$$

The use of these equations assumes that all permeabilities have the same flow characteristics and they have the same exponent, $n$.

### 2.2 Lumped Parameters

To describe the air flow distribution inside a building we introduce three lumped parameters, which reflect the different permeability distributions of the building's envelope and flow resistances inside the building. We use the envelope permeability ratio *epr* to describe the horizontal air flow through a structure:

$$epr(\phi) = \frac{D_{lee,envelope}}{D_{total,envelope}} \tag{3}$$

As the value of the resultant permeability in a series arrangement is governed by its smallest permeability, the infiltration rate for a given permeability of the envelope reaches its maximum at $epr = 0.5$ (typical row house). The wind-driven infiltration under steady state conditions will be zero if all air permeability is located on either side (see Fig. 1).

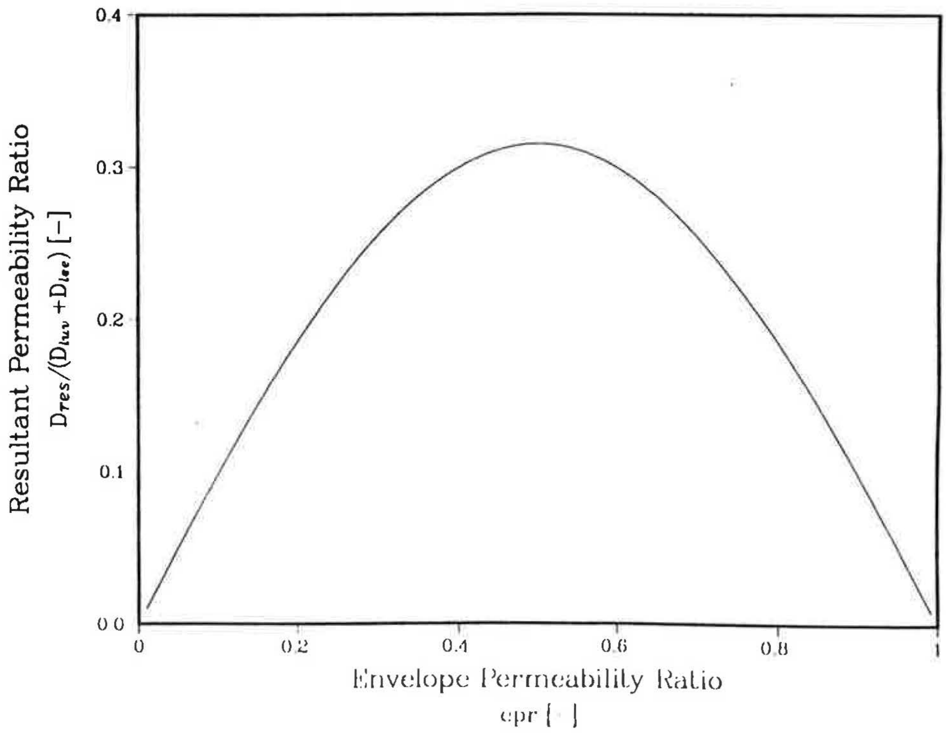


**Fig. 1:** Resultant Permeability Ratio versus Envelope Permeability Ratio

Based on a parameter given by the German standard on heat loss calculation for buildings [8], we introduce the ratio of the permeabilities from one floor to another, and the overall permeability of the building envelope:

$$vpr = \frac{D_{shaft}}{D_{total,envelope} + D_{shaft}} \tag{4}$$

Two extremes exist with regard to thermal pressure distribution: — *story-type buildings* with no permeability between floors ($vpr = 0$), and *shaft-type buildings* with no air-flow resistance between the different stories ($vpr = 1$). The vertical permeability ratio for real homes lies between these theoretical limits.

To describe the air-flow distribution for the different zones at the story level, the resultant permeability ratio *rpr* has been established [4]. Resultant permeabilities are defined as the combination of all flow paths (parallel or series arrangement) from this zone to either the windward side or the leeward side of the building. This lumped parameter has been defined as the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone. It was determined that air flows from zones with low *rpr*-values to those with high *rpr*-values. Therefore, the resultant permeability ratio contains all information about the direct flow paths from the zone to the outside as well as the flow paths not directly leading outside the building.

$$rpr(\phi) = \frac{D_{res,zone,lee}}{D_{res,zone,total}} \tag{5}$$

Determining the resultant permeabilities is far more complicated than determining the permeabilities used for the other two ratios. The majority of permeabilities have to be shared by different flow paths. Calculating the resulting permeability ratio for the internal flows may make an iteration procedure necessary.

### 2.3 Superimposition of Flows

Air flows caused by separate mechanisms (i.e., wind and thermal buoyancy) are not additive because the flow rates are not linearly proportional to the pressure differences. In order to superimpose the flows, pressures must be added. The superimposed volume rate can generally be calculated by:

$$Q_{tot} = D\ (\Delta p_{tot})^n \tag{6}$$

$$Q_{tot} \approx D\ (\Delta p_{wind} + \Delta p_{stack})^n = (Q_{wind}{}^{1/n} + Q_{stack}{}^{1/n})^n \tag{7}$$

### 2.4 Driving Forces

#### 2.4.1 Air Flow Due to Wind

For air flow perpendicular to the surface, the pressure difference responsible for the wind-driven air flow can be calculated by:

$$\Delta p_{wind,windward}(z) = p_{dyn}(z)\ \bar{c}_{wind}(z) - \Delta p_{in}(z) \tag{8}$$

The internal pressure $p_{in}$ is a function of the permeability distribution of the building's envelope and of the internal flow resistances. It can be derived from the continuity equation for each story. For buildings with no permeability between different stories (story-type buildings), this set of equations can be solved independently for each story. The volume rate driven by wind action only can be calculated by:

$$Q_{wind}(z) = D_{wind}(z) \, [\Delta p_{wind,windward}(z)]^n \tag{9}$$

In order to avoid calculating the pressure distribution inside the building, a method for determining the air flow path through each of the stories utilizing the story-type building as a base case can be utilized. The air flow compensation of the different stories due to given vertical air permeability, and downdraft of air flow caused by different wind speeds at different heights above ground, can be managed by using the equations given in Reference 4.

To determine the air flow path through a building for a given wind direction, the floor plan is examined for all possible paths from the windward side to the leeward side of the building. By knowing that air flows from zones with low *rpr*-values to those with high *rpr*-values, the flow direction can be determined.

### 2.4.2 Air Flow due to Temperature Differences

The difference in thermal pressure for a given temperature difference under calm conditions is a linear function of the distance of the height above ground from the neutral pressure level ($z_n$). The volume rate driven by thermal buoyancy alone is:

$$Q_{stack}(z) = sign(\Delta p_{stack}) \, D_{res}(z) \, \left| \Delta p_{stack}(z) \right|^n \tag{10}$$

$$\Delta p_{stack} = g \, (\rho_{in} - \rho_{out}) \, (z - z_n) \tag{11}$$

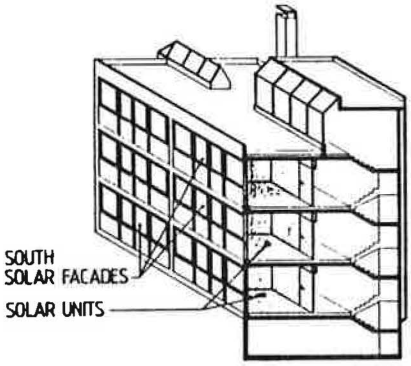
$D_{res}(z)$ is the resultant permeability calculated for the arrangement of permeabilities in a series, or parallel to the place where the stack pressure occurs (elevator shaft, stair well, etc.), and the outside. For an apartment building, these permeabilities can consist of elevator doors, doors to individual apartments, interior apartment doors, and openings to facades. In addition to the pressure gradient in shafts and vertical ducts, there is the same buoyancy effect at each individual story of the building. Because of the limited height of the story and the relatively small distances of the different openings from the local $z_n$ of the story, these pressure differences may be negligible when compared to those forced by wind and the chimney effect of internal shafts.

## 3. Validation Work

Validation work for the simplified infiltration model will be done using the heavily instrumented LESO building as a base. Measurements of physical properties of the building and weather data as well as wind tunnel tests have been performed to obtain the necessary data.

### 3.1 Description of the Building

The experimental test facility has been operating since 1981 on the EPFL Campus near Lausanne. It is a mid-sized administrative building with its main facade facing south. Fig. 2 provides a view of the building as it appears at the south facade. The main physical characteristics of the facility regarding infiltration are also given in this figure. Nine heavily-instrumented zones make up the south half of the building. Each zone is equipped with a different passive or hybrid solar facade, dependent upon its own air infiltration characteristics. A staircase occupies the other half of the building. The ventilation is provided for the most part by natural ventilation. Only a few of the solar units are equipped with mechanical ventilation systems [9].



| | |
|---|---|
| Overall building | |
| Volume | 2165 $m^3$ |
| Air infiltration rate (at 50 Pa) | 3.2 $h^{-1}$ |
| Solar units | |
| Volumes | 86 - 189 $m^3$ |
| Air infiltration rates | 0.16 - 0.5 $h^{-1}$ |

**Fig. 2:** Main Characteristics and View of the LESO Test Facility

### 3.2 On-Site Measurements

In order to compare the results of the simplified infiltration model with real building measurements, multizone tracer gas measurements were performed by applying the constant concentration method with a single tracer gas to 10 zones of the building. Samples for each zone were taken and analyzed utilizing an infrared gas analyzer.

By using different gas concentration strategies, instantaneous values of outdoor to room and interzonal flows have been measured. The measurements were performed for periods of one or two weeks.

The permeability distribution of the building is determined by performing multizone pressurization tests. Attempts to measure these permeabilities with a single blower door by applying new strategies have failed [10]. Consequently, two blower doors have been used to determine the unknown permeabilities of the building components.

Monitoring the weather conditions was done simultaneously with the tracer gas experiments. This monitoring is part of the instrumentation of the overall building containing over 450 channels. A list of quantities correlated to the air infiltration problem measured on the building is given in Fig. 3.

On-site weather data was used to calculate the wind pressure field around the building as input parameters for the simplified model.

### 3.3 Wind Tunnel Measurements

Measurements of surface pressure coefficients on scale models have been performed in a boundary layer wind tunnel of the University of California to be able to calculate the wind pressure distribution around the building. This is an important input parameter for any infiltration model. The knowledge of the wind pressure distribution is especially necessary in order to compare the infiltration calculated by the model to that measured by tracer gas measurements. Forty-four pressure probes have been installed in the vertical surfaces of the LESO model (see Fig. 4). The surface pressure has been measured by using a single pressure transducer, which is connected with one of the pressure probes via

| Measured quantity | Number of probes |
|---|---|
| Solar radiation | 9 |
| Outdoor air temperature | 1 |
| Wind speed and direction | 2 |
| Diff. pressure on south facades | 6 |
| Indoor air temperature | 38 |

**Fig. 3:** List of the Monitored Quantities

a multiple valve. The building arrangement including the vicinity of LESO has been placed on a turntable to allow the measurement of surface pressure coefficients for different wind directions (see Fig. 5). Therefore, for each 15 degree change of the wind direction, the multiple valve is scanned through the whole cicle of pressure probes, including the pitot tube used to determine the pressure at the location of the LESO weather station. Fig. 6 shows the pressure coefficients for the south facade for different wind directions.

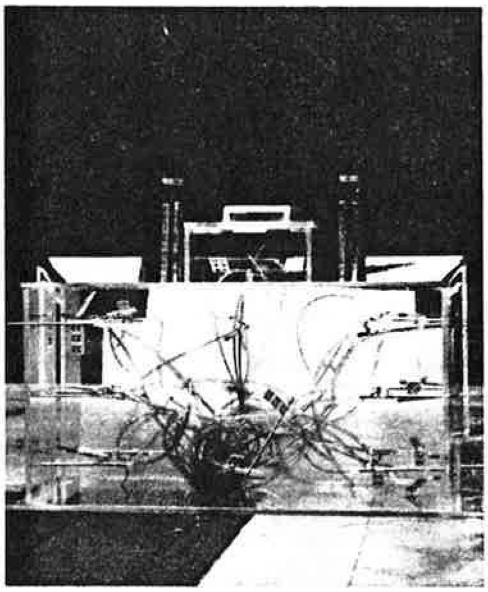


**Fig. 4:** Scale Model of LESO

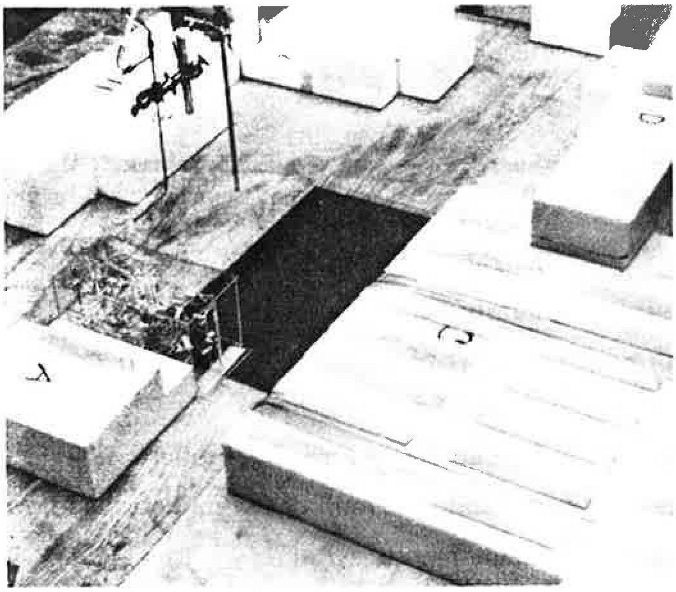


**Fig. 5:** LESO and its Surroundings

### 4. Conclusions

Comparisons between results from detailed models and the new developed simplified model showed the usefulness of the introduced lumped parameters. Furthermore, the superimposition of flows has been proven by these comparisons. In order to treat the complexity of air flow in multizone buildings with the simplified model, an iteration procedure may be necessary. The measurement effort described here was necessary to be able to validate the model with on-site measurements and to produce the necessary input parameters for the model.

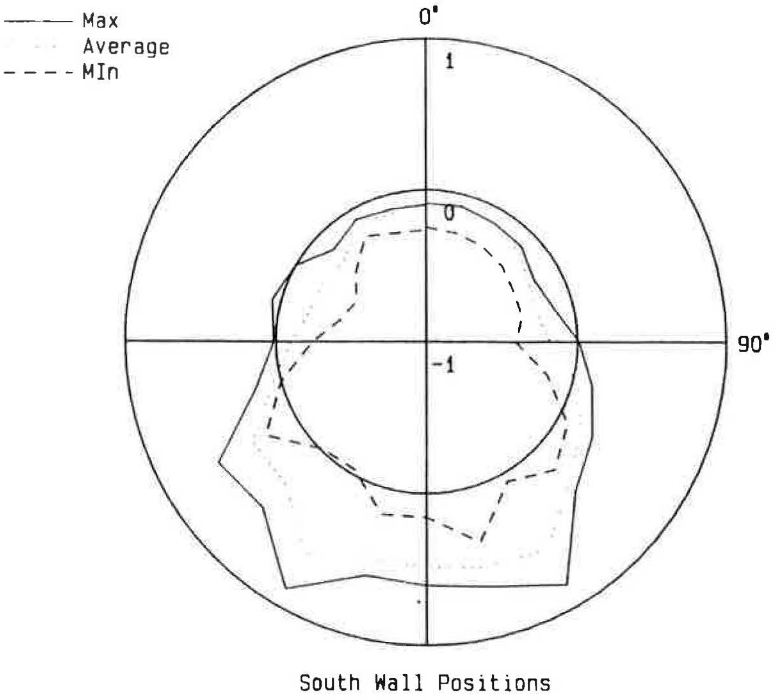


**Fig. 6:** Pressure Coefficient for the South Facade for different Wind Directions

## 5. Table of Symbols

| | |
|---|---|
| $\bar{c}$ | average pressure coefficient [-] |
| $g$ | acceleration of gravity $[m/s^2]$ |
| $h$ | height of the building [m] |
| $j$ | number of considered story [-] |
| $k$ | number of stories [-] |
| $m$ | air mass flow [kg/h] |
| $n$ | exponent of the pressure difference [-] |
| $p_{dyn}$ | dynamic pressure of the undisturbed flow [Pa] |
| $p_{in}$ | inside pressure [Pa] |
| $p_{out}$ | outside pressure [Pa] |
| $\Delta p_{stack}$ | pressure difference due to stack [Pa] |
| $\Delta p_{wind}$ | pressure difference due to wind [Pa] |
| $t_{in}; t_{out}$ | temperature inside; outside [ ° C] |
| $v$ | wind velocity [m/s] |
| $x,y,z$ | coordinates [m] |
| $z_n$ | neutral pressure level [m] |
| $D$ | air permeability of the building component $[m^3/h\ Pa^n]$ |
| $D_{res}$ | resultant permeability $[m^3/h\ Pa^n]$ |
| $Q$ | air flow through a building component $[m^3/h]$ |

| | |
|---|---|
| $\rho_{out}$ | density of the outside air $[kg/m^3]$ |
| $\rho_{in}$ | density of the inside air $[kg/m^3]$ |
| $\phi$ | wind direction [°] |

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