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Development and Evaluation of a Multizone Air Flow and Contaminant Transport Model within the Frame of the International Energy Agency

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ABSTRACT

A number of interzonal air flow models have been developed to calculate air flows and pollutant transport mechanisms in both single-zone and multizone buildings.

The International Energy Agency's Energy Conservation in Buildings and Community Systems program adopted a working group on multizone air flow modeling to study physical phenomena causing air flow and pollutant transport (e.g., moisture) in multizone buildings, develop numerical modules to be integrated into COMIS, and evaluate the computer code.

COMIS allows to model flows and pollutant transport from zone to zone through cracks, large vertical openings, ducts, flow controllers, kitchen hoods, and user-defined air flow components. The program allows dynamic time steps and introduces schedules for several input parameters.

This paper introduces the multizone air flow model COMIS and shows an application of the program.

Introduction

To provide good indoor air quality or to calculate space conditioning loads for energy consumption it is important to know the air flow pattern into and within a building. Correct sizing of space conditioning equipment also depends upon accurate air flow information. A number of air flow models have been developed to calculate air flow related energy losses and the resulting flow distribution in both single-zone and multizone buildings (Feustel and Dieris 1992).

The air-mass flows and their distribution in a given building are caused by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems, or a combination of these. But air flow is also influenced by the distribution of openings in the building shell and by the inner pathways. Actions by the occupants can also lead to significant differences in pressure distribution inside a building (see Figure 1).

There are two fundamental approaches in determining the air flow rate in buildings. The most straightforward method is to measure air flows (e.g., using one of the tracer gas techniques). While tracer gas measurements give a value for air flows only under prevailing leakage and weather conditions, a second technique can be used to determine values of infiltration for all leakage and weather combinations. This method uses mathematical models.

Interzonal air flow models can be divided into two main categories, single-zone models and multizone models. Single-zone models assume that the structure can be described by a single, well-mixed zone. The major application for this model type is the single-story, single-family house with no internal partitions (e.g., all internal doors are open). Unfortunately, single-zone models are often used to calculate air flows in multizone structures - which is beyond the limits of these models.

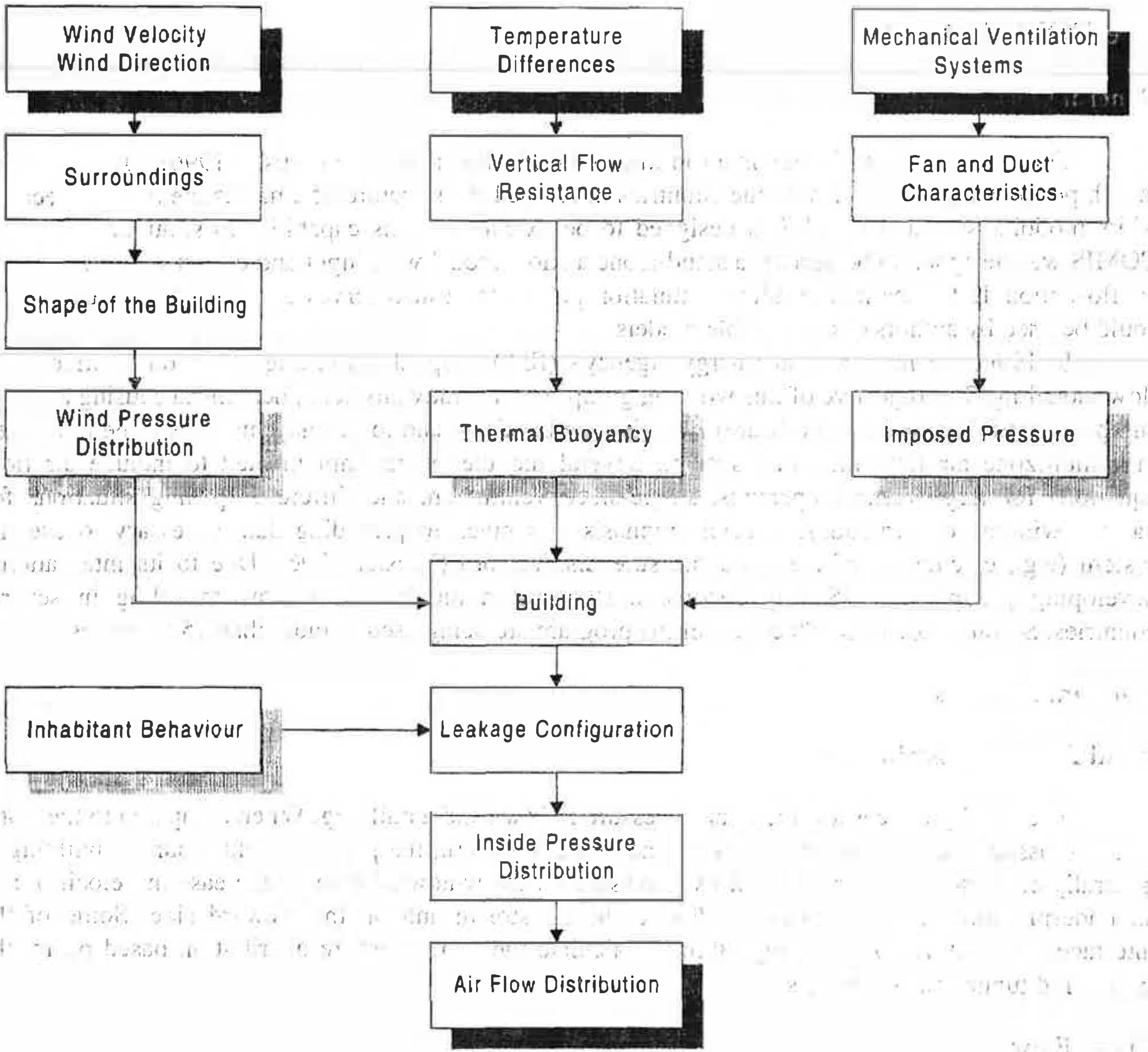

Figure 1: *Influences on the air flow distribution in buildings*

Before the advent of physical single-zone models a number of computer models were developed to calculate the air flow distribution in multizone buildings.

In terms of air-mass flow, buildings represent complicated interlacing systems of flow paths. In this grid-system the joints represent the zones of the building and the connections between the joints simulate the air flow paths. These include the flow resistances caused by open or closed doors, HVAC components as well as windows and air leakage through interior and exterior walls. The boundary conditions for the pressure can be described by grid points outside the building (outside zones). This shows that these models require extensive information about flow characteristics and pressure distributions. All of the multizone air flow models are based on the mass balance equation.

The COMIS Model

General

COMIS is a recent development in interzonal air flow modeling (Feustel 1996). Over a twelve month period ten scientists from nine countries developed the structure of a multizone model. Because of its modular structure COMIS is designed to be expanded in its capability to simulate buildings. COMIS was designed to be used as a stand-alone airflow model with input and output features or as an air flow module for thermal building simulation programs. It also serves as a module library, which could be used by authors of comparable models.

In 1990, the International Energy Agency's (IEA) adopted a working group on multizone air flow modeling. The objective of this working group[1] was to study physical phenomena causing air flow and pollutant transport (e.g., moisture) in multizone buildings and to develop modules to be integrated in a multizone air flow modeling system. Several modules were implemented to include air flow equations for large vertical openings, single-sided ventilation, and different opening situations for various window constructions. Special emphasis was given to providing data necessary to use the system (e.g., calculation of the wind pressure distribution) (Feustel 1996). Due to its international developing group[2], COMIS may become a standard in multizone air flow modeling in several countries. So far, more than 100 copies of the program are being used in more than 15 countries.

Program Features

Wind Pressure Distribution

The wind produces a velocity and pressure field around a building. When compared to the static pressure associated with an undisturbed wind-velocity pattern, the pressure field around a building is generally characterized by regions of overpressure on the windward side (a decrease in velocity), and an underpressure on the facades parallel to the air stream and on the leeward side. Some of the interfaces for COMIS provide algorithm to calculate the wind pressure distribution based on results from wind tunnel measurements.

Crack Flow

The air flow through a crack is always a mixture of laminar, turbulent and transition flow. The proportion of each flow regime depends on the shape of the crack and the pressure difference.

The power law equation is widely used to express the air flow characteristics of cracks: The numerical representation shows that the air flow depends on the pressure difference, however, this equation does not take the influence of the air properties and the air flow rate into account. Correction factors for the simple power law equation were introduced in the COMIS Fundamentals (Feustel and Raynor-Hooson 1990).

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[1] International Energy Agency's Energy Conservation in Buildings and Community Systems implementing agreement, Annex 23 "Multizone Air Flow Modeling"

[2] Annex 23 participating countries are: Belgium, Canada, France, Greece, Italy, Japan, Switzerland, The Netherlands, USA

Flow through Vertical Large Openings

The large opening model implemented in COMIS calculates the mass flow and its derivative in both flow directions. The density profiles in the neighboring zones are represented by pressure or density values at the bottom and the top of the opening and at several equidistant levels within the opening. The mass flow is calculated for each level. The total flow is obtained by summation of the flows for the whole opening.

Ducts

In COMIS the flow through a duct is modeled as a the power law function. Because the friction along the duct is different for laminar, turbulent and transitional regions, the flow coefficient and the exponent are calculated by means of iteration. Due to the nonlinear interdependency of flows in the branches of a junction, duct work with many junctions increases the number of iterations. A flow path, which resistance is dominated by pressure drops in the junction, might make the system unstable.

Fans

Fans are a source of pressure differences, lifting the pressure level between two zones. In COMIS, fans are described by the polynomial fan curve either provided by the user or approximated by COMIS from a set of volume flow/pressure data pairs. In order to avoid unstable fan performance, the flow/pressure relationship outside the rage given by data pairs is assumed to be of linear character.

Following the fan laws, the flow through the fan is calculated for deviating values of fan speed or air density. The fan speed can be changed by means of a fan schedule, which allows the change of fan speed at any time during the simulation period.

Flow Controllers

Four types of flow controllers are distinguished which, between them, represent most of the available dampers or regulators as long as the input signal comes from the pressure drop or (duct) flow. Controllers with temperatures as input must be simulated with the schedules -- not yet an ideal situation. The basic premise of the controllers is that they have an opening through which the air flows. At higher pressures a flap or valve may throttle the flow by gradually closing the opening.

Kitchen Hood

COMIS models kitchen hoods in different ways. Kitchen hoods can be either fan operated or stack operated. The hood itself can be simulated by means of a set of power law equations (i.e., by using the crack component), or by using a component which calculates the spread of pollutants into the zone. In the latter case, the spread will be calculated using the spread characteristics as a function of the exhaust flow of the hood. The spread characteristics (hood efficiency) must be provided by the user. These data are often available from kitchen hood manufacturers.

User-Defined Air Flow Components

COMIS allows to create user-defined air flow components. The characteristics of these components are provided by the user in terms of data pairs describing the flow/pressure relationship. With this feature, air flow components which are not hard-wired into the program can be described.

Time Step

COMIS works with two different time steps; one time step for the air flow calculations and another time step for the calculation of pollutant transport. As air flows are quasi-steady state phenomena, the time step used for air flow calculations is based only on "external events", which are the schedules provided by the user. Pollutant transport and the related buildup or decay of contaminant concentrations are not steady-state physical phenomena. Therefore, the time step is calculated based on the shortest time constant of all zones within a building for a particular simulation configuration (Feustel and Raynor-Hooson 1990).

Zone Layers

A zone can be divided vertically into several sub-zones (layers). Layers allow the introduction of zones with more than one gradient for zone temperature and/or zone humidity (e.g., shafts, stair cases). Layers may also be used to introduce different sources or sinks in different heights of a zone. There is no limit to the number of layers in one zone.

Schedules

A series of events for a particular parameter are described by schedules. Schedules describe the time of the event and the event itself. COMIS provides the following options for schedules: weather data (wind velocity, wind direction, air temperature, absolute humidity, and barometric pressure, window schedule (window opening fraction), fan schedule (fan speed factor), temperature schedule (zone temperature), humidity schedule (absolute humidity), sink schedule (sink factor for up to five pollutants), source schedule (source factor for up to five pollutants), multi-schedule (for up to ten parameters with a common time step.

Contaminant Transport

Besides calculating air flow between zones, COMIS also calculates the transport and distribution of up to five contaminants. Simulation of contaminant transport in a multizone building leads to the definition of mass balance equations for each pollutant considered in each zone. The main assumption is that the concentration is well mixed in a zone and is transported from zone to zone by the flow of air. COMIS allows for filter effects for all air flow components; these filters can represent a solid absorption along the path or any kind of reaction (chemical reaction, phase change, ...) due to contact of the pollutant with a solid material when flowing from one zone to another.

Output Options

COMIS provides a variety of output options. Besides the basic output option to provide air flow and pollutant transport data for each time step, there are options to record or calculate user-defined data in the form of tables. These include calculation of the air change rates for individual zones and/or the whole building, the mean age of air, the air change efficiency of the building, and the room air change index. It is also possible to have the mean values for the whole simulation period being calculated and reported.

User Interface

There were several interfaces developed for COMIS. The simplest is the FORTRAN program COMIN. This program reads and writes COMIS input files and allows the addition, change and deletion of input data. COMIN is hardware-independent, but bothersome to work with.

COMERL offers an alphanumeric user interface allowing the creation or modification of COMIS input files using a specific task-adapted editor. A data base for air flow components (e.g., cracks, windows, or HVAC components) is integrated into COMERL.

Progress in the computer hardware environment has opened new horizons, allowing the development of a graphics interface to run on both PCs and workstations. IISiBat is the Intelligent Simulation Environment (ISE) adapted for COMIS. It provides a sophisticated graphical environment allowing the user to enter information in a straightforward way. The purpose is to deal with the problem of transferring research technologies to engineering practitioners. IISiBat provides both inexperienced and advanced users with tools that enable complex systems to be calculated.

XCOMIS is another attempt to provide a user-friendly interface. Morgner (1997) also uses a GUI (graphical user interface), however, XCOMIS does not provide a graphical representation of the air flow network. This user-interface represents the input sequence of the conventional COMIS input file.

Model Evaluation

The goal of Annex 23 was to provide a reliable, practical, and user-friendly multizone air flow model. The user should be able to have confidence in the results of the simulations performed with the program. Therefore, a variety of tests were used to make sure that the program contained no numerical errors. COMIS simulation results were compared with more than fifty benchmarks for which either an analytical or a numerical solution was obtained. Two user tests were developed and performed as a joint contribution by the Air Infiltration and Ventilation Centre and researchers in Switzerland (Liddament 1996).

COMIS was also checked by means of model inter-comparison. Fourteen other simulation programs[3] were used by the five research groups involved to compare results between different simulation tools. Furthermore, nine studies were performed, using results from tracer gas tests for single-family houses, test cells, flats and small office buildings. These results were compared with results obtained by numerical simulation. Fürbringer et. al. (1996) report about the evaluation effort and the level of uncertainties in more detail.

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[3] Models compared include AIDA, AIRNET, ASCOS, BREEZE, BREVENT, CBSAIR, CONTAM93, ESP, LBL, MZAP, NORMA, PASSPORT AIR, TURBUL and VENCON.

Example Model Application

Building Description

The Margolis Apartments is a modern, 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston metropolitan area. The building was designed and built in 1973-1974 and is typical of high-rise construction from that period (see Figure 2). The building has thirteen stories and is of steel-frame construction. The individual apartments have electric-resistance heaters in each room, and double-pane windows and sliding balcony doors.

The building has a mechanical ventilation system, with kitchen and bathroom exhaust fans in each apartment vented into separate vertical shafts which have additional exhaust fans located on the roof. The supply air system for the building is provided by a fan and heating unit on the roof that connects to a vertical shaft which has supply registers in the main hallway on each of the floors. Supply air enters the apartments by a slot under the front door of each unit.

The building is exposed on all sides to the wind. Weather data from an airport located within 5 km indicate a mean annual wind speed of 6 m/s with up to 26 m/s wind speeds in winter. The prevailing winds are from the northwest in winter and from the southwest from Spring to Fall.

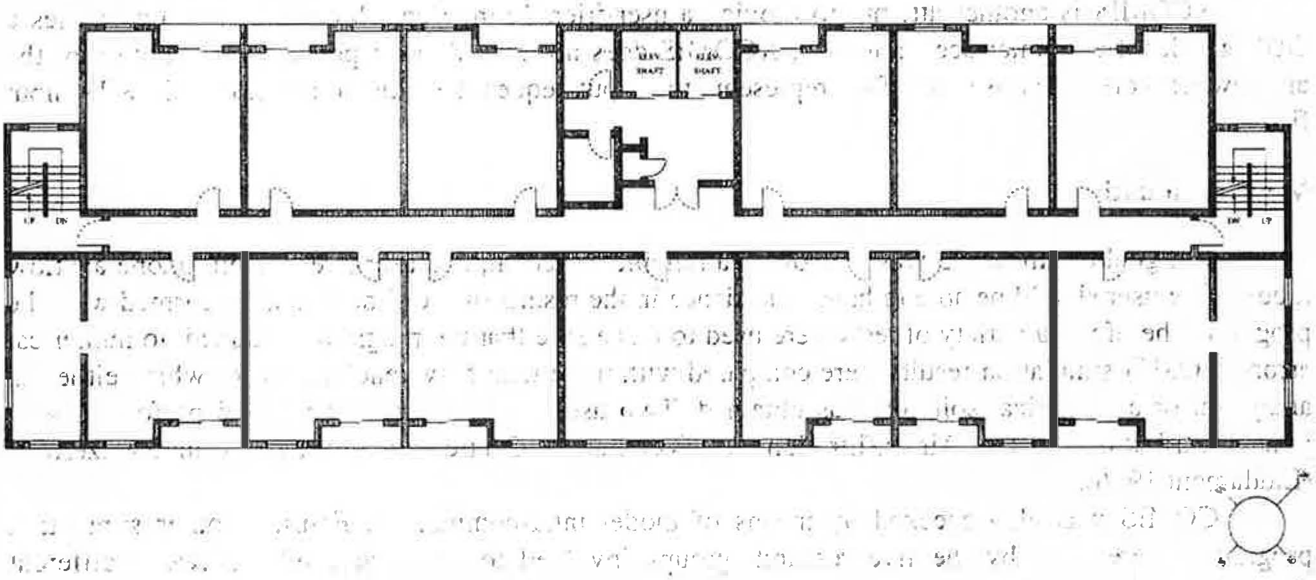

Figure 2: *Typical floorplan for stories 2 - 5*

In December, 1993, the building underwent extensive retrofits. New double-pane windows with low-e glass replaced the old windows throughout the building. A computerized energy management system was installed that allowed for tracking and controlling of the thermostats in the individual apartments. Efficient light bulbs were installed in the individual apartments and in the parking areas. A new sprinkler system was installed throughout the building. Improvements to the abandoned ventilation system were completed a year later.

Prior to the window retrofit, drafts were a major complaint expressed by the tenants. Since the retrofit, there have been--according to building management--fewer complaints about window drafts.

The northwest-facing units (weather side) continue to be the hardest units to maintain thermal comfort. Also the second floor units (above the open parking areas) continue to be a problem in cold weather.

Measurements & Analysis

The measurements and analysis we performed consist of four parts: 1) air leakage measurements of the apartments measured pre- and post-retrofit, 2) air flow measurements of the apartments pre-retrofit, 3) pressures and flows between the apartments and the circulation areas and 4) computer simulations of the air flows in the building under different weather conditions. Details of the measurement and analysis work are described by Diamond and Feustel (1995).

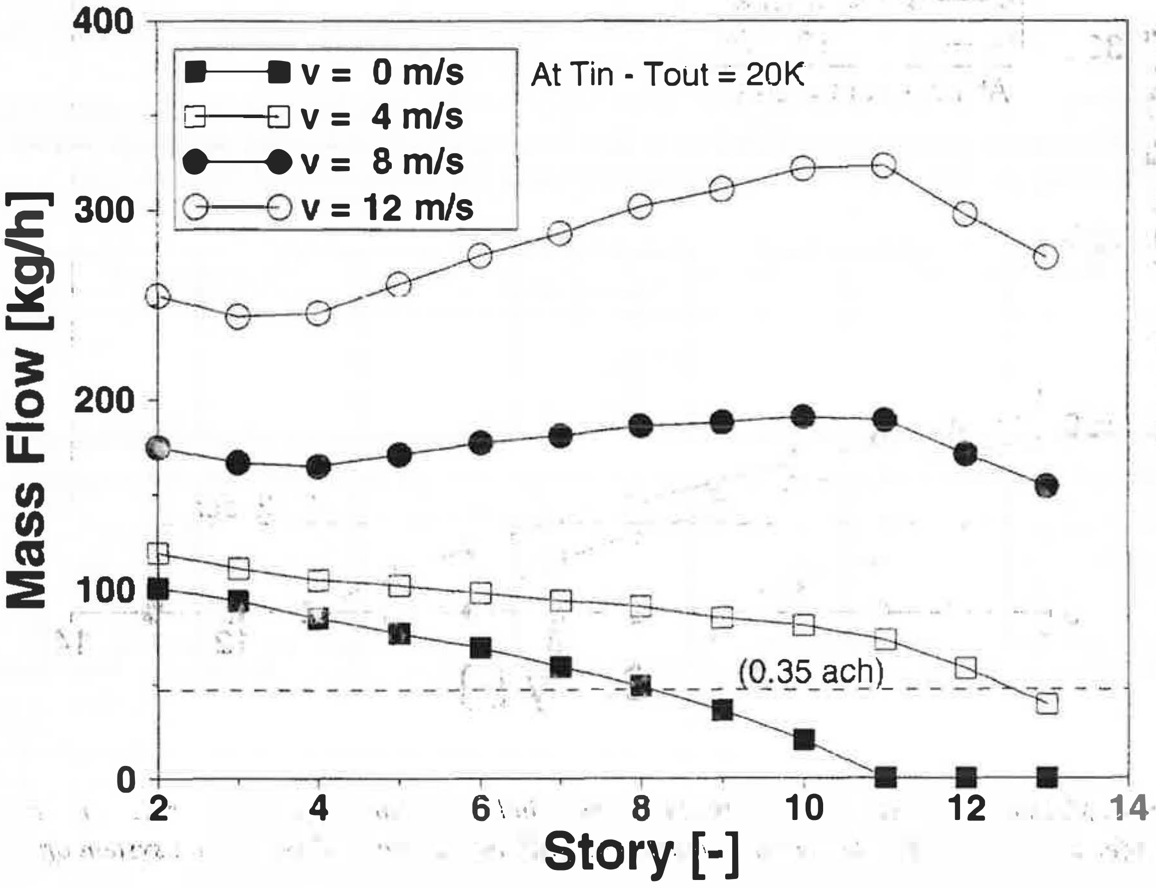

Figure 3: *Mass air flow into apartments at different wind speeds and an inside/outside temperature difference of 20 K for the* ***windward*** *apartments with the mechanical ventilation system off.*

Ventilation Simulations

Based on the measured air leakage data from the building we conducted extensive air flow modeling of the apartments. In order to limit the amount of input needed for the simulation model, each apartment was modeled as one zone, assuming the internal doors of an apartment to be open. In order to account for the stack effect and the inter-zonal flows between the floors, all 13 floors were modeled.

The results show, that with wind blowing perpendicular to the windward side and no stack effect present, air moves from the windward side facade through the corridors into the leeward side apartments. Under the previous conditions with no ventilation system present, only a small portion of the infiltration air is exhausted through the vertical shafts of the exhaust system. Dampers at the apartment level and on top of each of the shafts restrict the exhaust flow.

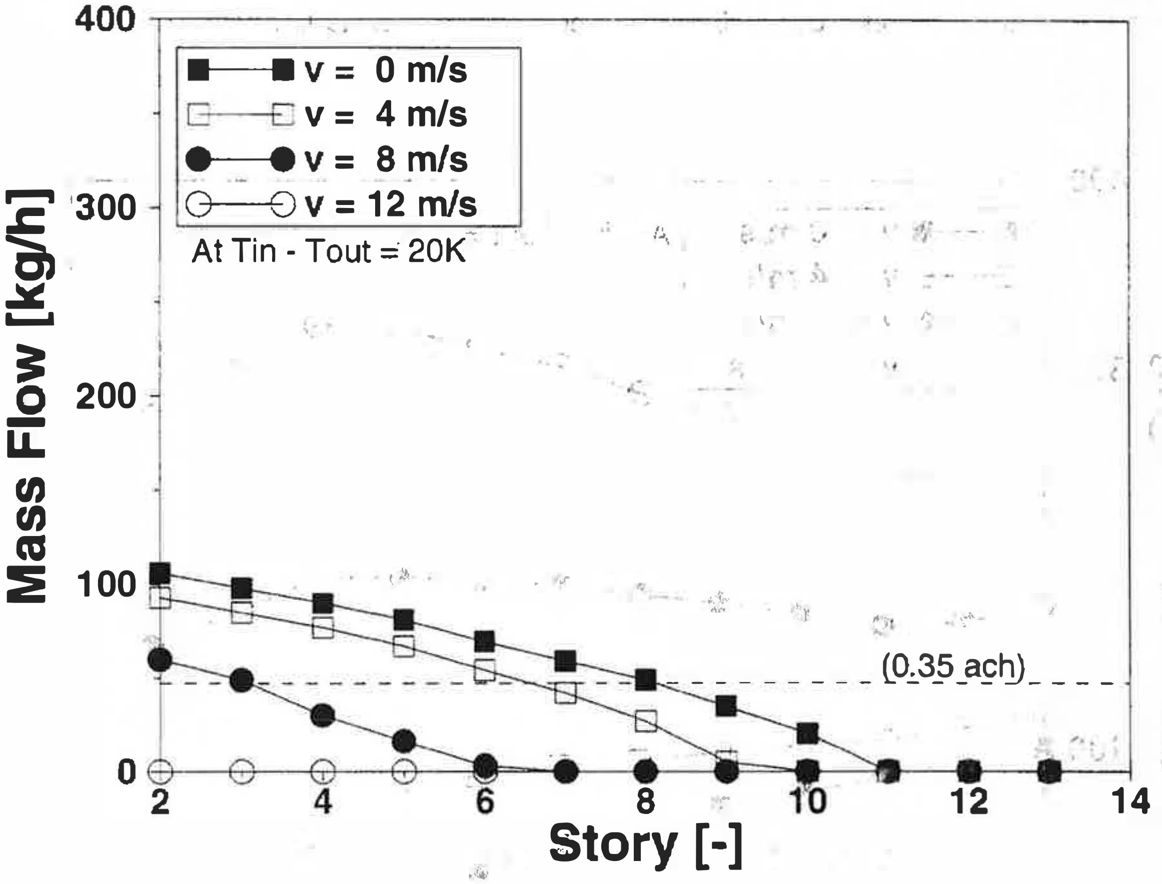

Figure 4: *Mass air flow into apartments at different wind speeds and an inside/outside temperature difference of 20 K, for the* **leeward** *apartments with the mechanical ventilation system off.*

When the building is operating without the mechanical ventilation system, the air mass flow distribution for windward side apartments on different floors follows a predictable pattern. With increasing wind speed, the distribution of infiltration becomes more pronounced, showing a minimum at the third floor and a maximum at the 11th floor.

With a larger inside/outside temperature difference of 20 K and zero wind speed, the air flow for the windward apartments decreases with height above ground from 83 m^3/h (23 l/s) on the second floor to zero at the level of the 11th floor (Figure 3). With increasing wind speed the air flow curves show a more balanced air flow distribution until the velocity driven air flows override the stack effect.

As the pressures forcing the air flow are additive, the air flows for any given wind speed are higher if stack pressure is present.

The air flows for the leeward side are shown in Figure 4. With increasing wind speed the air flow entering the apartments through the outside wall becomes smaller. The zero wind speed curve is the same for the windward side and leeward side. The top floors do not experience any infiltration. Higher wind speeds cause higher negative pressures on the facade, which lower the level for the neutral pressure. At wind speeds of 12 m/s no infiltration occurs at the apartments facing the leeward side.

Air flows into the apartments are slightly higher when the ventilation system is in operation. Figure 5 shows the air flows entering the apartments located on the windward side through the facade for different wind speeds when no stack effect is present. At low wind conditions, infiltration is almost independent of the height above ground. With higher wind speeds, we see that the infiltration flows follow the wind pressure profile.

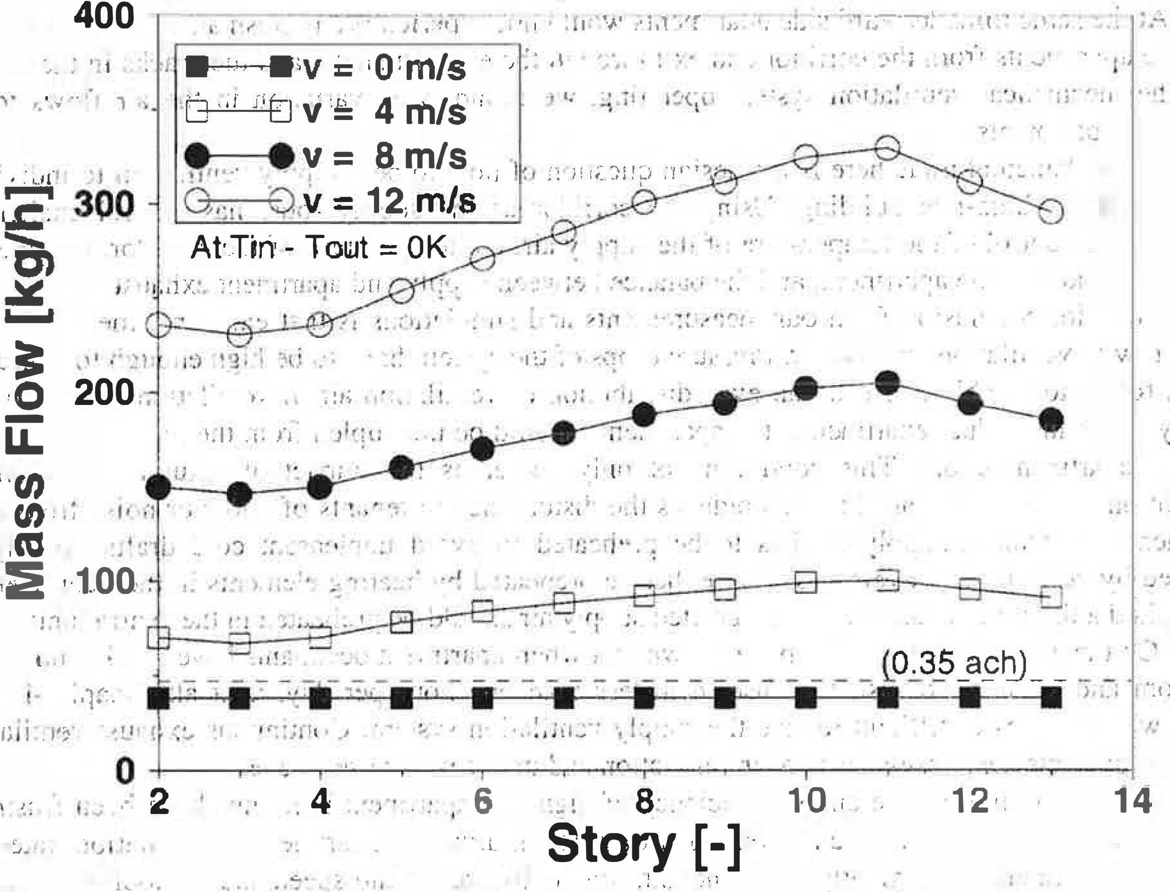

Figure 5: *Mass air flow into windward apartments at different wind speeds, with no inside/outside temperature difference and the mechanical ventilation system on.*

Conclusions for this Example

In any study of a building as complex as a high-rise apartment it is important to verify the findings using as many techniques as possible. In the case of the Margolis we have been fortunate to have different data sources: leakage measurements, pressure tests and air infiltration measurements which have all been used to evaluate the simulation results. Because comparisons between the model and spot-measurement data agree well in several areas, such as similar directions and magnitude of pressure differences across apartment doors and stairwell doors, we have greater confidence in the simulation results (Diamond and Feustel 1995).

Based on our analysis of the air flow simulations at Margolis we see that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled (pre-retrofit case), units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. Units facing the windward side were over-ventilated when the building experienced wind directions between west and north. At the same time, leeward side apartments would not experience any fresh air — air flows would enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. With the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments.

A fundamental issue here is the design question of how to best supply ventilation to individual apartments in a high-rise building. Using the corridor as the supply route has several challenges, including the control of the temperature of the supply air, the temperature of the corridor, the opening from the corridor to the apartment, and the balance between supply and apartment exhaust.

A major conclusion from our measurements and simulations is that each apartment has to be supplied with ventilation air directly. Pressure drops of the system have to be high enough to overcome natural forces to be able to ensure an even distribution of ventilation air. If ventilation air is supplied directly to the individual apartments, the apartments should be uncoupled from the rest of the building by tight apartment doors. This condition not only decreases the impact of natural forces on the distribution of ventilation air, but also reduces the disturbance to tenants of odors or noise from other apartments. In winter, supply air has to be preheated to avoid unpleasant cold drafts. Supply air provided by vents in the envelope should either be preheated by heating elements in the vent itself, or be supplied adjacent to heating sources. Ducted supply air should be preheated in the central unit.

On the exhaust side, studies have shown that when apartment occupants have local control over bathroom and kitchen exhaust, they use them less than one hour per day, if at all (Shapiro-Baruch 1993), which makes it difficult to size the supply ventilation system. Continuous exhaust ventilation, however, presents the possibility of over ventilation and unnecessary use of energy.

Efforts to improve the energy efficiency of high-rise apartment buildings have been frustrated because of the lack of knowledge on air flows for individual apartments. Ventilation rates for individual apartments vary greatly due to height, orientation, and wind speed and outdoor temperature. Any recommendations for reducing air leakage will have to take these variables into account, so that efforts to tighten the shell for energy efficiency do not create health and comfort problems for the residents

How to obtain COMIS

For updated information about COMIS and its availability, please visit the COMIS Homepage at:

http://www-epb.lbl.gov/comis

Conclusions

The multizone air flow model COMIS has been developed by an international group of building scientists. It contains modules which allow to calculate air flows through a number of different air flow components, such as cracks, open windows and doors, passive and mechanical ventilation systems. The built-in features allow to work with variable time steps, divide zones into horizontal layers, and provide schedules for fan operation, pollutant sources and sinks, zone air temperatures, and outside weather conditions.

User-friendliness and confidence in a model are the prerequisites for its use. The graphical user interfaces developed for COMIS (XCOMIS, IISiBat) are a significant step towards "user-friendliness", while the evaluation exercise provides the results needed to have confidence in the program. The international authorship and the efforts to maintain the program in the future will help to establish COMIS as a standard for air flow/pollutant transport models.

Acknowledgments

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