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ABSTRACT

The paper presents a brief review of existing smoke control models. The review includes each model's concepts, numerical technique, capabilities, limitations and assumptions. Potential applications of the models are also discussed.

RÉSUMÉ

Cet article présente un aperçu des modèles de limitation des fumées existants. L'auteur indique, pour chaque modèle, le concept de base, la technique numérique employée, les capacités, les limitations et les hypothèses. Il examine aussi les applications possibles de ces modèles.

A review of smoke control models

A look at the capabilities, limitations and assumptions of existing smoke control models

By M. Nady A. Said, Ph.D., P.Eng.

SINCE THE early 1970's it has become evident that the design of tall buildings should include techniques for the control of smoke under fire conditions to increase the life safety of the building occupants. Several analytical models have been developed for the design and development of various techniques for smoke control in tall buildings. These models encompass a wide variety of modeling capabilities and techniques.

The objective of this article is to bring together a brief review of the key features of existing smoke control models so that users can identify the model best suited to their applications. References 6-25 describe the models in detail. This article also briefly discusses potential applications of the models; for detailed discussion, see Reference 5. No attempt is made here to assess the features or the performance of each model.

The specific topic of this article is smoke (from a fire) and air movement models that predict the average values of the flow characteristics (such as flows, pressure, temperature) throughout a building. It is noted that there are more detailed models that predict the local values of the flow characteristics in a building compartment (e.g., 1); such models are not addressed in this article. The compartment fire models (also known as zone models) that predict the spread of fire, smoke and toxic gases in a building (e.g., 2, 3) are also out of the scope of this article. Reference 4 presents a review of zone models.

Smoke control models have been used primarily as a research tool to advance the understanding of the dynamics of air and smoke movement in multi-story buildings, and enhance the technical basis for the development and design of smoke control techniques. In addition, smoke control models have potential applications in the design of systems and fire safety education.

As a design tool, computer modeling will facilitate, speed up and improve the systems design. The model also can be integrated with a CAD system. The designer may use modeling to assess the expected performance of the system while it is in the design stage. This will help identify and rectify potential design problems before the design is implemented. The analytical model, by facilitating trial of several design options, could help the designer make the best design choice for a building. Modeling also can be used to assess the smoke hazard (extent and severity) in a building for various fire scenarios. This knowledge can be utilized in the system design, for identifying the optimum locations for smoke and heat detectors, and the preparation of evacuation plans.

Smoke control models can play a significant role in the greatly needed fire safety education. The graphical representation of resulting data may provide a smoke migration simulator which maps out the dynamics of smoke movement in buildings, and demonstrates the factors affecting it. This is an effective teaching and training aid for the fire service, building officials and the public. It may be used to demonstrate to individuals the significance of smoke and fire safety regulations, and the extreme danger to life resulting from failure to comply with the regulations. Designers also can use the graphics capability of the model to demonstrate the design to clients.

Smoke control models

Smoke control models employ mass balance equations, flow equations, and may include additional equations for smoke concentration and temperature. Fire is usually described in terms of its temperature and smoke production characteristics as a function of time. Typical input data of network models are meteorological data (air temperature and wind speed), building characteristics (height, leakage areas, conditions of openings), ventilation air supply, fire characteristics and indoor air temperatures.

Major contributors to the analytical modeling of smoke movement in multistory buildings are: The Institute for Research in Construction, National Research Council of Canada (IRC/Canada);

Center for Fire Research, National Bureau of Standards, USA (NBS/USA); Building Research Establishment, U.K. (BRE/UK); The Building Research Institute, Japan (BRI/Japan); Oscar Faber & Partners, Consulting Engineers, U.K. (Oscar Faber/UK); and The Institute of Applied Physics TNO-TH, The Netherlands (TNO/Netherlands). In the following, the models are reviewed briefly in a chronological order. These models are assessed in more detail in Reference 5.

Table 1 lists the capabilities and the key features of the models reviewed. In general, all models assume that smoke follows the normal aerial currents in the building. Also, they all assume that smoke is completely mixed with the air and that the mixing process occurs immediately.

The concept of the physical model is basically the same for most models. The building is divided into compartments (nodes), each at a uniform pressure and temperature. These compartments are connected to each other through the leakage openings (flow paths) and vertical shafts. The generalized orifice flow equation is employed to relate the mass flow rate to the pressure difference across a given flow path. The pressure is initially assumed in all compartments. Then pressures are adjusted progressively by an iterative technique until the mass rate balances (with a specified tolerance) are obtained at all compartments.

BRI/Japan model

Wakamatsu developed a steady-state model (6,7) and a transient model (8) for smoke movement in compartmented buildings. These are considered to be among the pioneer models for smoke control.

The steady-state model predicts steady-state airflows and pressures, and only smoke concentration is predicted as a function of time. It calculates the steady-state temperature of smoke in the corridor of the fire floor only, which is assumed to be a linear function of the distance from the fire compartment opening. The temperature everywhere else in the building is assumed to remain constant during a fire. The model also calculates the safe egress time in the event of a fire. It accounts for the ventilation air supply but assumes it to be constant.

An electric circuit analogue is used to simulate the flow resistance of openings and motive forces such as wind pressure and stack effect. The characteristics of the fire are specified by the user in terms of the temperature and smoke density profiles in the fire compartment.

The model first calculates the steady-state airflows throughout the building. Then, smoke concentration, relative to the concentration in the fire compartment, and the safe egress time are calculated using the calculated airflow data.

The model was validated against data from full scale fire tests (21-24). Predicted pressures were within 25 percent of measured data for the stairshaft pressurization system, but there was a considerable difference between predicted and measured airflows (21). Wakamatsu attributed that to unknown air leakages.

The main improvement of the transient model (8) over the steady-state model is the inclusion of the dynamic effect. The transient model predicts the airflows, pressures, smoke concentration and temperature as a function of time for every compartment in the building. In addition to the mass balance equation and flow equation, two partial differential equations (PDE) are used to predict the smoke concentration and temperature. The burning rate during the initial stage of a fire and smoke concentration in the fire compartment are supplied by the user. The convergence of the numerical scheme is conditional upon satisfying the time step constraints.

TABLE 1
Comparison of Smoke Control Models' Capabilities

Parameters / Model	BRI/Japan Steady-state (7)	BRI/Japan Transient (8)	BRE/U.K. (10)	IRC/Canada (14)	Oscar Faber/UK (16)	NBS/USA (20)	TNO/ Netherlands (18)
Predicted data:							
airflows & pressures	yes	yes	yes	yes	yes	yes	yes
smoke concentration	yes	yes	yes	yes	yes	no	yes
air temperature	yes[a]	yes	yes[a]	no, SU	yes	no, SU	yes
Dynamic simulation	no[b]	yes	no[b]	no[b]	yes	no	yes
Compartmented buildings	yes	yes	yes	no	yes	yes	yes
Fire characteristics	SU	SU	SU&BI	SU	SU	no	SU, BI
Main driving forces:							
stack effect	yes	yes	yes	yes	yes	yes	yes
wind pressure	yes	yes	yes	yes (SU)	yes	yes	yes
thermal expansion	no	no	no	yes	yes	no	yes
HVAC air supply	yes[c]	yes[c]	yes[c]	yes[c]	yes -	yes[c]	yes
Friction pressure loss in shafts	no	no	no	yes	no	yes	no
Variable mixing	no	no	no	no	no	no	no[e]
Numerical scheme convergence	unconditional	conditional	unconditional	unconditional	unconditional	unconditional	conditional
Validated by exptl. data	yes	yes	no	no	no[d]	yes	no

a: predicts air temperature in the corridor on the fire floor only
b: only smoke concentraton is calculated as a function of time
BI: built-into the model
c: air supply is assumed to remain constant
d: predicted smoke spread was compared to known smoke spread following a fire incident
e: accounts for it in a separate program, will be included in this model in future
SU: supplied by the user

Smoke control models

BRE/UK model

The features of the BRE/UK model (developed by Evers and Waterhouse; 9,10) are very similar to the BRI/Japan's steady-state model with few differences. The BRE/UK model is capable of operating in either of two modes, deterministic or stochastic. In the stochastic mode, the variables are sampled at random from specified statistical distributions. The principal stochastic parameters of the model are the location and severity of the fire, the ambient wind and temperature conditions, and the number of doors and windows left open. In the deterministic mode, the user specifies values for all the stochastic variables.

The convergence criterion is expressed in terms of the absolute values, typically 0.004 kg/s (0.53 lb/min) for the mass balance calculations, and 4.788 N/m^2 (6.94×10^{-4}PSI) for the pressure predictions. The major assumptions included in the model are:

- Each compartment of the building, except the fire compartment, is considered to be at a uniform pressure.
- The flow and temperature are in steady state throughout the fire (including the fire compartment).
- Leakage flows through floor and wall construction cracks are assumed to be negligible in comparison with other effects.
- Smoke diffuses instantaneously in all compartments except the corridor outside the fire room and vertical shafts.
- The layer of smoke in the corridor on the fire floor is at a constant depth throughout the length of the corridor, and this depth increases uniformly.
- The initial expansion of gases and any mass production by the fire are neglected.
- If the windows in the fire compartment break, they are assumed to break immediately at flashover. Also, the time it takes for the fire door to burn down is assumed to be greater than the evacuation time of the building.

The model was tested with general observations of smoke movement during fires and cold smoke tests in certain buildings. Appleton (9) reported that the model "appears" to agree with these observations.

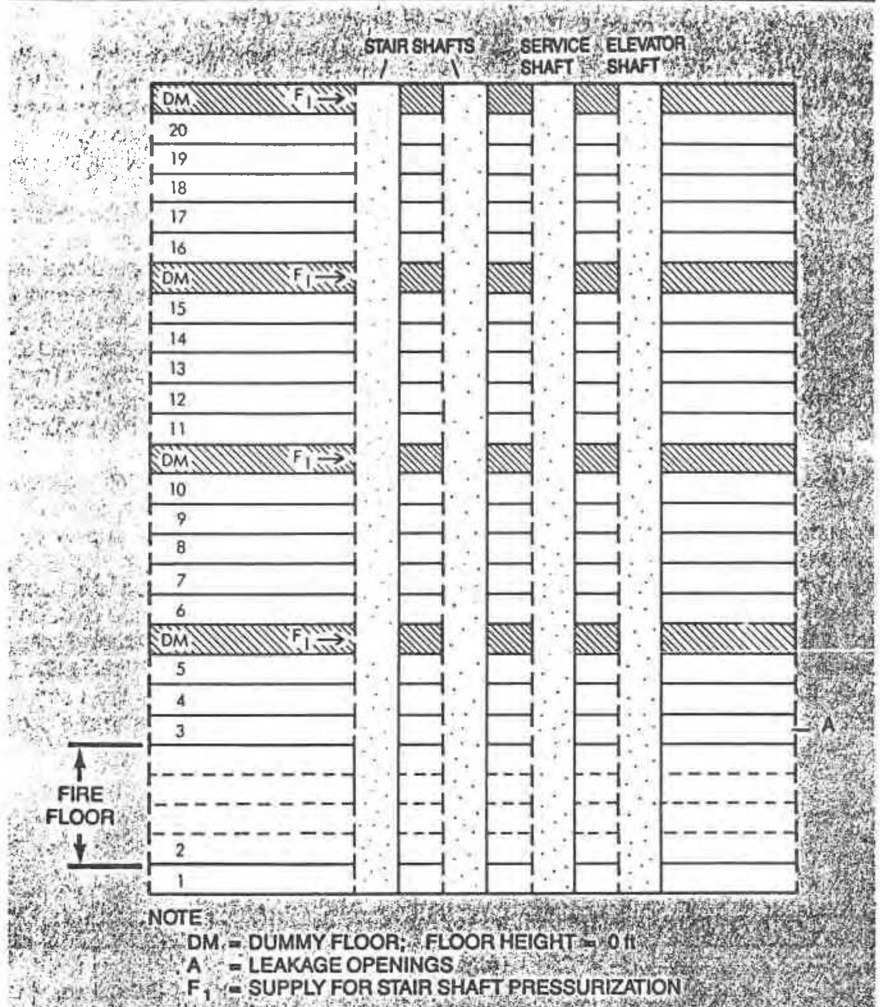

Figure 1—Example of a 20-story building with a multiple injection stair shaft pressurization system

IRC/Canada model

IRC/Canada developed their first model for air movement in multi-story buildings in 1973 (11). Since then, this model has gone through several developments (12-14). The final version (1979) is discussed here.

The IRC model predicts steady-state airflows and pressures, and only smoke concentration is predicted as a function of time. The model is applicable only to buildings with an open floor plan with no provision for vestibules. It accounts for friction losses in vertical shafts, operation of stair and elevator doors during the course of the simulation, broken window effect, and operation of air handling systems. The supply and exhaust rates of the latter, however, are assumed to be constant.

The building is represented by a series of vertically stacked compartments interconnected by vertical shafts (see *Figure 1*). Pressures, flows and leakage openings are assumed to be at the mid-height of each level. The fire compartment is subdivided into four levels to obtain the vertical distribution of leakage openings. A dummy floor with zero height is used to provide air supply or exhaust into a particular location of a vertical shaft. The enclosure of the dummy floor is assumed to be airtight except for a large opening communicating to the stair shaft. Flow in stairwells is simulated by temperature-time and smoke concentration-time profiles, which are specified by the user. The model does not predict indoor air temperature, but it can be specified by the user. Also, pressures due to wind are specified by the user.

The IRC model consists of two main subroutines, one for airflow calculations and the other for smoke concentration calculations. First, for a given building and weather conditions, the steady-state air movement throughout the building is calcuated by the airflow subroutine. Then, smoke concentrations are calculated using the calculated airflow data. The convergence criterion is satisfied when the percentage change of flow rates from current iteration to the previous one is 5 percent or less.

Oscar Faber/UK

Oscar Faber & Partners developed their first model, Shannon (15), in 1975. It was then further developed by Irving (16,17) in 1979. Shannon's model is no longer available, thus only Irving's model is discussed here.

Irving's model is comprehensive, dynamic, and takes into account all the main driving forces that govern smoke movement in a multi-story building. It accounts for buoyancy and expansion forces due to a fire, pressure forces due to wind, stack effect, and mechanical ventilation system.

The Oscar Faber model predicts both steady-state and transient airflows, pressure, smoke and heat movement as a fire develops in a compartmented building. It accounts for variable ventilation air supply, which is simulated by a quadratic polynomial through the fan's flow-pressure characteristics profile. The characteristics of the fire, supplied by user, are prescribed in terms of a temperature-time profile and a pollutant (smoke) production rate. The spread of smoke and heat is determined by performing mass and energy balances for each compartment in the network.

The model includes four levels of complexity, which allows the user to choose the accuracy level of the simulation and hence the computing cost. These four levels of analysis are:

1) A steady-state level, in which flows and pressures are assumed to remain constant. Irving noted that this form of analysis may be used to predict smoke movements in the case of a fully developed fire, if conditions can be regarded as steady.

2) A pseudo-steady-state level, in which room static pressure is assumed to remain constant, while stack effect is allowed to vary. In this level of analysis, the course of a fire is subdivided into a series of pseudo-steady-states. Irving indicated that this method tends to overestimate the smoke spread, which in terms of a safety analysis is an error in the right direction.

3) A variable pressure - variable stack in which both the pressure and stack are recalculated at every time step.

4) A full dynamic simulation where the thermal expansion of the hot gases is accounted for, in addition to the effects of stack, wind and mechanical ventilation.

The first level of the fire analysis is common to all levels of simulation, and involves the setting up of the steady-state infiltration into the building. A separate program is used for that stage. The output, steady-state pressures and flows, is stored in a file for access by the smoke movement program.

Irving noted that modeling the dynamics of the air movement during the course of the fire predicts a greater spread, and more rapid buildup of smoke than does the steady-state method. He also compared the computation cost of the four levels of analysis. Compared to the computation cost of the first level, the fourth level cost is about 15 times higher, the third level cost is about five times higher, while the second level cost is only about 1.2 times higher.

The model was tested with general observations of known smoke spread following a fire incident in a large hospital complex (17). Irving indicated that the model predicted a general flow of smoke similar to the staining observations seen in the real fire.

TNO/Netherlands model

The Institute of Applied Physics, The Netherlands, developed a dynamic model (18) for smoke movement in compartmented buildings. The model predicts the transient airflows, pressures, temperatures and smoke concentrations. It accounts for the changes in openings (cracks, windows, etc.) as the fire progresses by continuously changing the flow coefficient in the flow equation with changes in temperature. As may be seen from *Table 1*, the model accounts for all the major driving forces.

The ventilation air supply and exhaust rates are either assumed to remain constant or the ventilation network is simulated by a room-orifice network. The fire characteristics are either supplied by the user (in terms of the temperature-time and smoke production-time profiles) or calculated by the model using a global function which calculates the burning rate in terms of the oxygen supply and the remaining fire fuel mass.

The spread of heat and smoke is determined by performing heat and mass balances for each compartment. The pressure is calculated by a differential equation which includes the sum of the mass flows through the openings and from mechanical ventilation and the gaseous products produced by the fire. The convergence is conditional upon satisfying the time step constraints. There is no indication in the literature that the model has been validated with experimental data.

NBS/USA model

The NBS/USA model was originally developed (19) as a research tool to analyze pressurized stairwells and pressurized elevator shafts, and to evaluate factors affecting the performance of these systems. The model has been included in the ASHRAE Manual (20) for the design of smoke control systems for buildings. The model version published in the ASHRAE manual is discussed here.

The NBS model calculates steady-state airflows and pressures (no smoke calculations) throughout a building in which a smoke control system is operating. The model is applicable to compartmented buildings and to zoned smoke control systems where the fire zone is exhausted and other zones are pressurized. It accounts for the air supplied by the air handling systems, but assumes it to be constant. The wind pressure profiles are either calculated by the model or supplied by the user.

A building is simulated by a network of nodes each at a specific uniform pressure and temperature. The stairwells and shafts are modeled by a vertical series of spaces, one for each floor. Doors and windows are treated as leakage openings and may be specified as either opened or closed at the start of the program.

The convergence is achieved when the absolute value of the sum of all the mass flows into a compartment is less than a specified value, typically 0.2 kg/sec (26.67 lb/min).

The model has been checked against data from tests on a pressurized stairwell. Klote and Bodard (25) indicated that predicted pressure differences were in "good agreement" with test data for which the wind effects were minor; but in situations where wind is a significant factor, the program was not capable of performing a satisfactory simulation. This could be due to the lack of proper data for the calculation of wind pressure profiles. Further research is needed in this area.

Summary and discussion

It is understood that some of the models reviewed are still evolving and that existing limitations or inadequacies may be removed in the future. Of all the models reviewed, the most readily accessible is the NBS/USA model; a complete listing of the computer coding and sample simulations are published in an ASHRAE publication (20). It is also available on a mini-diskette (from the Society of Fire Protection Engineers) and runs on a personal computer.

The most extensive model(s) appear to be the Oscar Faber/UK model and the TNO/Netherlands model. These models appear to fully describe the dynamics of smoke movement in multi-story buildings. They take into account all the main driving forces that govern smoke movement, which include the effect of the heat released from a fire in terms of the buoyancy and thermal expansion of hot gases. Ignoring such an effect will underpredict the spread of smoke within the building. The Oscar Faber model has the feature of offering four levels of analysis complexity. This allows the user to choose the level of accuracy best suited to the application under consideration.

As may be seen from *Table 1*, the IRC/Canada model and the NBS/USA model are the only models that consider the friction losses in vertical shafts. This parameter is particularly significant in analyzing smoke control systems (e.g., pressurized stairshaft system) which involve injection of a substantial quantity of air.

For some design applications, a steady-state air (only) movement model may be sufficient. However, to analyze the systems performance and assess the smoke hazards in buildings, it is preferable to have a dynamic smoke movement model which is capable of predicting the smoke concentration, temperature, pressure and airflows as a function of time for every compartment in the building.

Before any of the existing models can be used extensively, the accuracy of predictions and the range of validity need to be established. ■

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