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Air infiltration and indoor air quality models — a review

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SYNOPSIS

Several mathematical models have been developed to study air infiltration and indoor air quality in buildings, and to develop control strategies. This paper first describes the methodology and then gives the capabilities, limitations and assumptions of some of these models.

INTRODUCTION

Mathematical models have been developed for estimating air infiltration rates, and predicting air movement, dispersion of contaminants and fire induced smoke migration in buildings. These models can be grouped into two categories: detailed models for predicting air flow and contaminant distribution patterns in rooms (Room air movement models) and simplified models for predicting such in buildings consisting of one or several "well- mixed" zone or zones (Building air movement models).

Room air movement models are capable of predicting two- or three-dimensional air flow and contaminant distribution patterns in a room. The governing equations are the continuity, momentum, energy and mass diffusion equations. The turbulence effect is either described by the k-ε model which employs two equations representing the kinetic energy of turbulence, k, and its dissipation rate, ε, or the mixing length model [1, 2]. These models are expensive to run and their application is limited to one or two zones. However, the results can be used as the basis for making simplifications in developing simplified models.

Building air movement models use a network approach. Nodes representing zones of differing pressure, temperature and contaminant concentration are interconnected by leakage paths. Uniform and instant mixing is assumed for each zone. Depending on the level of detail required, a node may represent a building (single-cell model) or a section of a building such as a room or a storey (multicell model). Although the level of analysis is not nearly as detailed as a room air movement model, building air movement models are easy to use and can provide an overall picture of air flow and contaminant concentration patterns in the modelled building, and hence are more frequently used. Therefore, only building air movement models are considered here. Nine models were identified and selected for this study. This paper describes briefly the network approach and presents an assessment of the nine models.

THE NETWORK APPROACH

The use of network technique in electrical engineering dates back to Kirchoff. Since then this approach has been applied to many areas such as mechanical systems, hydraulic networks and energy systems [3, 4]. In this approach the air movement in a building is viewed as a network of interconnected nodes and each node (zone) is assumed to be at a specific uniform pressure and temperature. The

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nodes are connected to each other through a line which is called an element (opening). Each element can be easily assigned to its electrical analog, mainly resistance and capacitance. As an example, flow friction through openings and doorways are treated as resistances.

To fully describe the physics of air movement in buildings, the model should take into account the driving forces that cause air movement. The major driving forces are: the stack effect, wind pressure, and Heating Ventilating and Air-Conditioning (HVAC) systems. These driving forces will be briefly discussed.

The stack effect. This is due to the difference in air temperature between the zones, and/or the temperature difference between the inside air and outside air. The pressure difference, ΔP, due to the stack effect can be obtained by:

$$\Delta P = P_j - P_i = (\rho_j - \rho_i)\, h g \qquad (1)$$

where ρ_j and ρ_i, and P_j and P_i are the air density and pressure in zone j and i, respectively, and h is the distance from the neutral plane. Using the ideal gas law Equation 1 can be rewritten as:

$$P_j - P_i = \frac{P}{R}\left[\frac{1}{T_j} - \frac{1}{T_i}\right] g h \qquad (2)$$

where T_j and T_i are the air temperatures in zone i and j.

The wind pressure effect. The air flow around a building creates a positive pressure on the windward face of the building, and a negative pressure on all other sides. This pressure distribution causes a horizontal air movement in the building. The wind pressure at each point on the building is generally expressed in terms of a wind pressure coefficient and the wind dynamic pressure [5]. The pressure created by wind on the j surface is:

$$P_j = \tfrac{1}{2}\, C_{pj}\, \rho_a\, V_o^2 \qquad (3)$$

where C_{pj} is the pressure coefficient, ρ_a is the ambient air density, and V_o is the wind velocity at the site. Wind velocities are generally recorded at open areas at an elevation of 10 m above the ground. The wind velocity at the building site may be determined from

$$\frac{V_o}{V} = \beta \left(\frac{H_o}{H}\right)^{\gamma} \qquad (4)$$

where V_o and V are the wind velocities at the site, and that monitored at the weather station; H_o and H are the heights at the site and at the weather station, and β and γ are constants which depend on the terrain. The constants β and γ are determined for several terrains. For example, for rural areas with low buildings, $\beta = 0.85$ and $\gamma = 0.2$ are recommended [6].

Wind pressure coefficients were determined by the testing of several building models in wind tunnels [7]. In all these tests a reference height of H_o = 10 m was selected, V_o was measured at these heights, and the wind pressure coefficients were determined with respect to this value of wind velocity. The direction that wind blows into the surfaces of a building affects the pressure distribution over the exterior surfaces [6].

The air movement could also occur by mechanical systems such as a fan, or by an unbalance in the air supply or exhaust systems. Air movement in a mechanically ventilated building is more stable than in a naturally ventilated building. The air movement in a mechanically ventilated building can be disturbed by the air movement caused by the stack effect and the wind pressure.

The relationship between air flow and pressure difference. This depends upon the size and shape of the opening. The openings can be placed into three categories:

(1) purpose-provided openings such as an air vent or windows;
(2) component openings which are identifiable cracks that occur in doors and windows;
(3) background leakage areas which are the openings that remain after the first two types of openings are sealed, such as cracks between walls and floors.

The geometry of the first two openings can be measured but that of the third type of opening cannot be easily identified. The last two types of openings are collectively referred to as adventitious openings. Fresh air entry through these openings is called infiltration. The term ventilation is applied for the air flow through the purpose-provided openings.

Crack flow equations. The component and background leakage areas of buildings may be characterized fairly well by an effective open area and can be described by the crack flow equations. Two forms of flow equation are usually used, the quadratic form and the power law form. The quadratic equation forms the basis of simple models and is defined by:

$$\Delta P = a q_j + b q_j^2 \qquad (5)$$

where q_j is the volume flow rate, and a and b are constants for a given geometry e.g. the shape and size of the opening.

Another versatile way of describing the relationship between air flow and pressure difference is by:

$$q_i = C_f\, A\, [P_j - P_i]^n \qquad (6)$$

where C_f is flow coefficient and is a function of Reynold's number and ratio of the opening size to the entire surface, A is the area of opening, and n is the flow exponent. Normally n is taken in the range from 0.5 to 1 depending on the type of the flow path; n = 0.5 for turbulent flows (purpose-provided opening), and n = 1 for laminar flows.

The amount of air flowing through any opening j may be expressed by:

$$q_j = (P_j - P_i)\, R_{ji} \qquad (7)$$

where R_{ji} is the flow resistance of the opening j and P_i is the air pressure (in excess of the atmospheric pressure) inside the zone [8]. It is clear that the internal pressure P_i, and the air flow rate q_j vary with changes in the wind speed or direction, temperature or flow resistance.

Mass flow rate balance. In a network approach the air flow at each node (zone) is obtained by balancing the mass flow rate into and out of each space. For the "ith" zone, the mass balance equation may be expressed as:

$$\sum_{j=1}^{n} q_{ij} = V_i \frac{d\rho_i}{dt} \qquad (8)$$

where q_{ij} is the mass flow in the element (opening) connecting zone i to zone j, V_i is the zone volume, and $d\rho_i/dt$ is the rate of change of density with time.

Besides the flow equation (8), two more sets of equations can be employed to describe pollutant concentration and the temperature distribution in the building.

The distribution of pollutant can be calculated by writing a mass balance for each zone in the building:

$$\sum_{j=i}^{n} (q_{ij}\, C_{ij}) + G_i = V_i\, \rho_i \frac{dC_i}{dt} + V_i\, C_i \frac{dI_i}{dt} \qquad (9)$$

G_i is the pollutant source in zone i. The source strength depends on the type of the source e.g. stove or fireplace, the type of ventilation system, and the ventilation strategies.

Temperature distribution. The distribution of temperature is determined by performing an energy balance for each zone in the building:

$$Q_c + \sum_{j=1}^{n} (q_{ij}\, \rho_i\, C_p\, T_{ij}) + Q_i = V_i\, C_p \frac{d(\rho_i\, T_i)}{dt} \qquad (10)$$

where T_{ij} is the temperature of the flow in the element joining zones i and j, Q_i is the heat generated within the zone i, C_p is the specific heat and Q_c is the energy convected from internal sources. The pressure differences, flow, pollutant concentration, and energy equations can be set up to compute the air movement, pollutants concentration and temperature distribution in the building. To obtain the unknown, an iterative technique is required since the pressure in each zone is initially unknown and the flow equation (8) in nonlinear. Then the pollutant concentration and temperature are calculated from equations (9) and (10) respectively.

As stated earlier, the network approach assumes complete and instant mixing of air in each zone. The mixing factor is an important parameter which is not only effecting the indoor air quality but also describing the ventilation efficiency. Ventilation efficiency represents how quickly contaminants are removed from a particular zone in a room, and depends primarily on the type of pollutant sources, their location in relation to the breathing and occupancy zones, and type of distribution methods.

Two types of distribution method, total displacement air flow and total mixing air flow, have been thoroughly analyzed for their capability to remove contaminants and change air in buildings. In total displacement air flow, the air flow is unidirectional and the contaminants are spread as little as possible. In the total mixing air flow method, the temperature and concentration of contaminants are evenly distributed within the room.

Several air movement simulation programs have been developed during the past two decades [9–25], although not all of these are freely available in the open literature. A critical assessment of some of these programs is given below.

INFMR MODEL

This model was developed at the Institute of Gas Technology [9, 10] to estimate the air infiltration characteristic of buildings using weather and construction data, and furnace installation parameters. INFMR is a single zone model and in order to calculate the air infiltration, it first computes the magnitude and height of the neutral zone and then uses this value and other parameters such as effective crack length, shielding and permeability factors. The air infiltration is calculated by:

$$\text{infiltration} = \int_0^{Y} K_x\, (\rho_0 g h - \rho_i g h)^{0.5}\, dh + \int_0^{Y+Z} K_1\, (\rho_0 g h - \rho_i g h)^{0.5}\, dh \qquad (11)$$

where K_x and K_1 are the flow coefficients for leeward and windward side, Y is the leeward side "neutral" plane, and Z is the difference between windward and leeward wall "neutral" planes.

For envelope pressure above the neutral zone, i.e., when the indoor static pressure is greater than the outdoor pressure, exfiltration will occur as defined by:

$$\text{Exfiltration} = \int_0^{H-Y-Z} K_1\, (\rho_0 g h - \rho_i g h)^{0.5}\, dh + \int_0^{H-Y} K_x\, (\rho_0 g h - \rho_i g h)^{0.5}\, dh \qquad (12)$$

where H is the height of building.

This model has been validated with experimental data [9–11]. The results showed that this model can moderately well simulate the actual physical conditions.

LBL MODEL

This is a single-cell model developed by Lawrence Berkeley Laboratory [12, 13]. This model requires actual pressurization data. Experimentation is required on site to obtain the effective leakage area. This model does not require the standard ASHRAE crack length data to calculate the rate of infiltration due to stack effect and wind pressure difference. These rates of air flow are calculated by:

$$q_{stack} = A_0 \, f_s^* \, \Delta T^{1/2}/T$$
$$\text{and } q_{wind} = f_w^* \, A_0 \, V \qquad (13)$$

where f_s^* and f_w^* are stack and wind parameters respectively and include the influence of geometry, leakage distribution, and terrain sheilding classes, and they are independent of weather variables. Since these parameters take into consideration the effect of terrain and sheilding, the wind speed can be taken from any weather station in the area, f_s^* and f_w^* parameters convert the temperature difference and wind speed into an equivalent pressure across the opening.

To calculate the total infiltration rate the LBL model uses the superposition law:

$$q = (q^2_{stack} + q^2_{wind} + q^2_{vent})^{1/2} \qquad (14)$$

where q^2_{vent} is the air flow through the exhaust vent.

The main assumption in the development of this model is that the directional effects are not important. As stated in the paper [23], the directional effects could be very important in buildings where the leakage of the walls varies from wall to wall, or if the sheilding varies from side to side. Also, this model assumes that the floor and ceiling are unaffected by the wind, which is not a valid assumption.

The LBL model has been validated with experimental data [14]. This model is the most successful single cell model in simulating the experimental data.

J.K. CIRCUS MODEL

This program was developed at Lund Institute of Technology specifically to study the air flows in building components [15]. This is a multi-cell model used to predict room pressures, flow between the rooms, flow through ducts and flows through the envelope.

The model characterizes a building by a network of nodes and interconnected components, and employs a modified program designed for analysis of electrical circuits to solve the set of flow equations. In this model a component may be defined as:

a) A pressure difference between two nodes due to an active component such as a fan,

b) A piece of permeable material; the relationship between pressure difference and flow rate in a permeable isotropic material is discribed by:

$$\Delta p = U_m \frac{L}{B_0/\eta} \qquad (15)$$

where L is the length of the element in the flow direction, B_0 is the fluid permeability coefficient, η is the dynamic viscosity, and U_m is the average velocity,

c) A piece of duct; Duct pressure losses are described by:

$$\Delta p = \frac{f}{D_H} \frac{\rho \; U^2_m}{2} \qquad (16)$$

where f is the friction factor and D_H is the hydraulic diameter.

d) A single resistance; single resistances, such as a bend, influence the pressure loss in the following way:

$$\Delta p = \xi \frac{\rho \; U^2_m}{2} \qquad (17)$$

where ξ is the specific loss factor. ξ is strongly dependent on the flow region and is a non-linear component.

The JK-CIRCUS program uses a successive linear approximation approach to calculate the flow using a Gaussian elimination technique, the convergence criterion is expressed in terms of the percentage-wise value.

As a steady-state model, JK-CIRCUS lacks the effect of the dynamic behaviour of air flow. The model also lacks the consideration of the stack effect. This could be questionable because it might lead to substantial errors in the prediction of air flow in tall buildings. This model has not been validated against experimental data.

TARP MODEL

TARP uses ASHRAE techniques to model air flows and pressures in multi-room and/or multi-storey buildings [16, 17]. It considers a building as a network of interconnected nodes each at a specific uniform temperature and pressure. Nodes pressures and flow rates through all the openings are calculated by solving the set of flow equations, taking into account the combined effect of the wind and stack effects and the operation of air handling systems. To describe the air flow through cracks and large opening, TARP uses the following equation:

$$W_i = P \; \Delta P^n \qquad (18)$$

where W_i is the mass flow rate and P is the density of incoming air. The pressure difference due to the stack effect and wind effect is calculated by:

$$\Delta P = \rho \; g \; \Delta H$$
$$\Delta P = \rho/2 \; V^2 \qquad (19)$$

The set of flow equations is solved using a Gaussian elimination technique. TARP calculates the room air temperature based on a heat balance on the room air, and considers a steady-state condition for room air, $dT_i/dt = 0$, $d\rho_i/dt = 0$. TARP does not calculate the spread of pollutant throughout the building.

TARP also assumes the wind speed is constant and neglects its fluctuation effect. As a result, it does not consider the reversal air flow through the opening.

The TARP model is composed of several routines. INITAIR initializes variables and reads in data from the file, "Control DATA". AIRMOV calculates the room densities, pressures due to wind and stack effects, and SOLVZP calculates air flows and then computes the mass and energy flows for each zone. In the air flow calculations, SOLVZP computes the Jacobian matrix and net air flow matrix, and solves for room air pressures in an iterative fashion using a Gaussian elimination routine which calculates the Newton correction coefficient used in solving for the room air pressures.

BRITISH GAS MULTI-CELL MODEL

This is a multi-cell model for predicting individual room air flow rates as well as the whole house air flow rates. This model uses two flow equations to describe the flows through the three different types of opening [18, 19]. For purpose-provided openings, the flow equation is given by:

$$q = C_2 \; A\left[\frac{2\Delta p}{\rho}\right]^{1/2} \qquad (20)$$

where q is the mean volume flow rate, C_2 is the discharge coefficient and A is the opening area. Flow rates through component cracks (i.e. gaps in doors) and the background are calculated by:

$$CAq^2 + \frac{BZL^2}{4\rho} \mu \; q - \frac{2 \; A^3 \; \Delta p}{\rho} = 0 \qquad (21)$$

where C and B are empirical constants and dependent on crack geometry, Z is crack depth, L is crack length, and μ is air viscosity. This model also accounts for the pressure fluctuations resulting from wind turbulence which can cause reversal air flow even when the mean pressure difference is equal to zero (ΔP_i). This effect can be described by:

$$q_T = 0.4 \, F \sqrt{\frac{2}{\mu}} \; \Delta P_{IRMS} \frac{8 \; A^3}{B^2 \; L^2 \; \mu} \qquad (22)$$

where ΔP_{IRMS} is the root-mean-square of the fluctuating component of $\Delta p_i(t)$. $\Delta p_i(t)$ is assumed to have a Gaussian distribution, and F is a factor which includes the effect of mean pressure difference. The stack pressure is defined by:

$$P_i = 3462 \left(\frac{1}{T_E} - \frac{1}{T_i}\right) (H_i - N) \qquad (23)$$

where T_E is the external temperature, T_i is the internal temperature, H_i is the height of the opening above reference level, and N is the height of the neutral plane of the zone in which the openings appear. The neutral plane is determined for each cell.

This model also accounts for the air flow and pressurization caused by mechanical systems. This model has been validated by the experimental data, and the prediction was within 25 percent of the measured data [14].

CP-37 MODEL

This multi-cell model for predicting the air movement in a building was developed by the National Research Council of Canada [20]. This model takes into account the combination of the wind effect, stack effect and the operation of air handling systems. The supply and return air by the air handling system is considered to be constant and independent of building pressures.

In this model the building is modelled by a series of vertically stacked compartments interconnected by vertical shafts. Each shaft may have two vents to the outside and may be located at any desired floor level. The supply and return air by the air handling system are provided to each vertical shaft and each floor. CP-37 uses Equation (5) to define flow through each opening. The flow coefficient and the flow exponent has to be provided by the user. This model assumes that the indoor temperature is constant at 24°C, and the outdoor temperature is given as another constant. This model is a steady-state model, and therefore lacks the dynamic behaviour of the air movements. CP-37 also lacks the capacity for subdivision horizontally to account for variations in pressure from one zone to another on the same level.

This model is composed of two main subroutines; one for calculation of air flow rates and the other for calculation of smoke concentration. First, for given initial conditions, the steady-state air movements through the building are calculated by the air flow subroutine. Then, the smoke routine uses these values to calculate smoke concentration in all compartments using the following equation:

$$\Sigma \; (q_{ij} \; C_{ij}) = V_i \frac{dC_i}{dt} \qquad (24)$$

This model has been also used in NBSLD simulation program for predicting the heating and cooling loads in buildings [21], and its performance has been tested against the experimental data [13]. The result of this comparative evaluation indicated that the CP-37 was the most successful model in predicting the experimental data.

CP-45 MODEL

This model [22] is an extension of the CP-37 model described above. It can predict air movement, dispersion of contaminants and smoke migration in a building. CP-45 takes into account the effects of outside weather, the progress of a fire, the building characteristics, the operation of stair and elevator doors and the operation of the smoke control system. Like CP-37, this model also consists of two main subroutines, one for air flow calculations and the other for smoke concentration calculations. The air flow routine is the same as in CP-37 and will not be discussed further.

CP-45 uses two different equations to predict the smoke concentration in a compartment. To calculate the smoke concentration in a fire compartment, CP-45 uses the following equation:

$$C_f(t) = C_f\ (tn) + (t - t_n) - \left[\frac{C_f\ (t_{n+1}) - C_f(t_n)}{t_{n+1} - t_n}\right] \qquad (25)$$

where C_f is the smoke concentration. To estimate the smoke concentration in a compartment other than the fire floor, CP-45 uses this equation:

$$\sum_{k=1}^{n} q_{ik}\ C_k - q_{ki}\ C_{i,t} = V_i\ C_{i,t}\ \frac{d\rho_i}{dt} + V_i\ \rho_i\ \frac{d_{ci,t}}{dt} \qquad (26)$$

where $C_{i,t}$ is the smoke concentration in zone (i) at time t. The assumptions made in this model are similar to the CP-37.

OSCAR FABER MODEL

This model is a multi-cell simulation model for predicting air flows through a building envelope and could be used for calculating ventilation rates [23]. Air flow through cracks and large openings is described by:

$$q = K\ \Delta P^n \qquad (27)$$

where the exponent value depends on the flow path type and K is flow coefficient. This model can predict both steady-state and transient behaviour of air flows, pressure and smoke (pollutant) in a building. The Oscar Faber model calculates the pressure due to the wind action and stack effect on the external wall by:

$$\Delta P = C\ \frac{\rho_o}{2}\ V^2$$

$$\text{and } \Delta P = (\rho_o - \rho_i)\ g\ (H - H_o). \qquad (28)$$

The model applies a quadratic polynominal to simulate the air flow in the mechanical ventilation duct systems:

$$q = a + b\ \Delta p + c\ \Delta p^2 \qquad (29)$$

where a, b, and c are the coefficients defining the fan characteristics of the mechanical ventilation system.

This program can predict the smoke and heat movements in a cell using modified versions of Equations (8) and (9). This model has been verified against measured data from full scale experiments [24].

CONTAM86 MODEL

Contam86 is a multi-cell air quality model [24]. This model has been developed for studying contaminant dispersal behaviour in buildings.

Three contaminant mass flow rates are distinguished for an element connecting nodes i and j. W^e is the element flow rate, W^e_i the mass flow rate entering the element at node i, and W^e_j is the mass flow rate entering the element at node j. Thus, W^e_i and W^e_j are not necessarily equal. The relation between the three element flow rates and filter efficiencies η is given by:

$$\{W^e\} = \left\{\begin{matrix} W^e_i \\ W^e_j \end{matrix}\right\} = \left\{ \begin{vmatrix} W^e_i \\ W^e_j \end{vmatrix} * \begin{vmatrix} 1 & 0 \\ -1 & 0 \\ 0 & -1 \\ 0 & 1 \end{vmatrix}_e \times \begin{vmatrix} 1 & 0 \\ \eta-1 & 0 \\ 0 & \eta-1 \\ 0 & 1 \end{vmatrix}_e \right\} \qquad (30)$$

The relation between element concentration C^e_i, C^e_j and the node concentration C_i, C_j is given by a "Simple Boolean Transformation":

$$\begin{vmatrix} C^e_i \\ C^e_j \end{vmatrix} = B^e * \{C_1, C_2, \ldots C_n\}^T; \qquad (31)$$

where B^e is an n × 2 Boolean Transformation matrix consisting of zeros and ones, where n is the number of system nodes. $B_{ij} = 1$ if element e is connected to system node j; $B_{ij} = 0$ if element e is not connected to node j.

The system equations that govern the contaminant dispersal behaviour of the system are obtained from contamin mass balance using Equation (9). Contam86 model can distinguish between the nodes for which concentration is specified C_0 and those for which generation rate is specified, G_i.

The main disadvantage of Contam86 is that this model does not incorporate air flow analysis into its framework. Thus, air flow data of each element must be specified.

GENERAL OBSERVATIONS AND CONCLUSIONS

A review of nine available models of infiltration and indoor air quality has been presented. They can be categorized as (a) multi-cell vs single cell, (b) steady-state vs dynamic or (c) deterministic vs stochastic.

Multi-Cell vs Single Cell. Multi-cell models take the form of a flow network in which the nodes representing zones of different pressure are interconnected by flow paths. The interior of the building is divided into individual rooms or zones of different pressures. These models can accommodate detailed flow networks and can be used to analyze air movement in buildings. Thus, multi-cell models not only can be used to determine whole building and individual room change rates, but they also have application in, predicting interzonal air movement, indoor air quality studies, smoke and fire movement and finally energy calculations. The multi-cell models can be used to investigate the ventilation efficiency. The flow non-uniformity and pollutant source variations in buildings can cause localized zones within buildings that are not well ventilated even though the overall building ventilation (air exchange) rate meets acceptable standards. These models are a powerful tool to study the room ventilation efficiency and contaminant control. The main disadvantages of these models are that they require substantial data input to describe flow network and also need main-frame computing facilities.

Liddament and Allen [14] validated and compared these multi-cell models (except TARP) with actual air infiltration measurements data available from 3 test homes. They concluded that the performance of these models are more or less similar to each other and they were able to predict the infiltration rate within 25 percent of the measured value.

In the case of single-cell models, the entire building is assumed to be at a single uniform pressure and is considered as one node. These models are simple and effective for predicting whole building air infiltration rates. Hence, they cannot predict interzonal air movement, and they are not applicable to buildings in which internal partitioning restricts air movement. The results of Liddament and Allen's comparative evaluation of models showed that single-cell models were more successful in predicting the air infiltration rate than multi-cell models. They also concluded that the level success of single cell model depends on modelling techniques. Based on this study, the LBL and IMFR were the most successful models to calculate the air infiltration. LBL model needs pressurization data, but INFMR uses the standard ASHRAE crack length data. The main disadvantage of these models is that they assume a uniform internal pressure and as a result they cannot be used to calculate air movement.

Steady-State vs Dynamic. In steady-state models, the zones of the buildings are considered to make the change by transferring from one state to another. Between two consecutive states, the air flow is assumed to stay constant. In dynamic models, the change of states are considered as continuous. The air flow rates are usually obtained by solving differential equations.

All models, except the Oscar Faber, consider a steady-state condition for room air, and as a result they cannot fully describe the dynamic behaviour of air movement.

Deterministic vs Statistic vs Stochastic. Deterministic models do not consider the fluctuations of the input parameter values, such as wind speed and direction. All the models, except the British Gas multi-cell model, ignore the effect of the fluctuation of wind which can cause reversal air flow.

In the stochastic methods, the parameter values such as pressure, wind speed, wind direction are considered to have a certain probability. The values are defined as random processes. Recently a method for predicting the uncertainties in the analysis of indoor air quality was suggested [26, 27]. This method is based on Ito stochastic differential equations which provides the statistical characteristic of variables of interest.

TARP and Oscar Faber appear to be the most extensive models. They can predict indoor air temperatures and air movements either in given zones or throughout the building. The remaining models lack the capability of predicting indoor air temperature, which is given as input. CP-37 also cannot consider variable ventilation air supply.

Of these models reviewed, CP-37 and Oscar Faber were developed to study the dynamics of smoke/air movement in building. Recently, a review of smoke control models was published [28].

The only attempt to date at developing an air quality model has been made by Axley [25]. This model can be integrated by any air infiltration model.

The main inherent disadvantage of the network approach to modelling would appear to be the assumption of perfect air mixing in each zone. This could lead to errors when modelling large spaces, especially if they are divided with partitions or when dealing with point source [29].

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Water-cooled air-conditioning systems for energy and power saving

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SYNOPSIS

The paper presents the results of an experimental investigation to compare the performance of water-cooled and air-cooled air-conditioning systems. Two identical chilled water air-conditioning systems, incorporating air-cooled and water-cooled condensers, were used independently to supply the cooling demand of a space. All other components of the two chillers were identical and of the same make. The chillers were operated on alternate days and their cooling production, power and energy needs were measured for the 24 hour period on a day-to-day basis during the summer of 1988. The results show that the water-cooled system requires 40% less peak power and 25% lower electrical energy. The energy requirements can be reduced further if seawater is used for condenser cooling in place of desalinated seawater.

INTRODUCTION

Air-conditioning in Kuwait, as in most countries of the region, is essential for summer cooling in residential, commercial and public buildings. Kuwait has a long summer season, extending from April to October. The ambient temperature during this period is very high. Daily average temperatures often go above 40°C. These harsh weather conditions demand an excessive amount of cooling to maintain comfort. The performance of most commonly used cooling systems with air-cooled condensers deteriorates drastically with high ambient temperature thereby increasing the electricity demand. For these reasons the annual electricity consumption to provide cooling to a given area of a building is perhaps greater in Kuwait than anywhere else in the world. The performance of cooling systems using water-cooled condensers is, on the contrary, much better. Such systems reject heat to the water in a shell and tube heat exchanger. The thermal energy is transferred to the ambient air through a humidification process (cooling tower). The controlling factor in this case is thus the ambient wet bulb temperature. The temperature difference between the peak dry and wet bulb temperatures for the summer months is about 20°C. Thus, air-conditioning systems using water-cooled condensers are expected to perform more efficiently since both systems have similar differences between the condensation and the sink temperatures and the energy equivalent of water used up in the cooling tower is not large, although soft water in Kuwait is produced by seawater desalination [1].

In spite of the obvious advantage in the form of peak power demand and annual electricity consumption, most of the air-conditioning systems in Kuwait at present, are of the air-cooled type [2]. The most likely reason for preferring air-cooled systems is the misconception that the

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