Combined Heat, Air, Moisture, and Pollutants Transport in Building Environmental Systems*

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Combined heat, air, moisture and pollutants transport (CHAMP) exists across multi-scales of a building environmental system (BES): around the building, through the building shell/envelope, inside a multizone building, and in the micro-environments around occupants. This paper reviews previous work and presents a system model for simulating these transport processes and their impacts on indoor environmental quality. Components of the system model include a multizone network flow model for whole building, a room model for air and pollutant movement in ventilated spaces, a coupled heat, air, moisture, and pollutant transport model for building shell, an HVAC model for describing the dynamics of the heating, ventilating and air-conditioning (HVAC) system, and shared databases of weather conditions, transport properties of building materials, and volatile organic compounds (VOCs) emissions from building materials and furnishings. The interactions among the different components, and challenges in developing the CHAMP system model for intelligent control of BES are also discussed.

Key Words: Heat and Mass Transfer, Building System Model, Multizone Model, Computational Fluid Dynamics Model, Indoor Air Quality, Room Air Distribution, Material Emissions, Sorption, Intelligent Control

1. Introduction

A building environmental system (BES) can be viewed as a nested multi-scale system involving personal/micro-environment around a person, individual room environment, and the whole building environment. Various control and management strategies can be applied at each scale for achieving optimal indoor environmental quality (IEQ), high energy efficiency and adequate building security (Fig. 1). As controls and management are applied from the whole building down to the personal scales, the BES can satisfy the environmental and safety needs of a diverse individual occupants who may have very different preference for environmental conditions, and hence increase the occupants satisfaction to a higher percentage value than the currently adopted industrial standards for ventilation, IAQ and thermal comfort[(1),(2)]. The objective of this study is to review previous work and develop a mathematical modeling and computer simulation framework for combined heat, air, moisture and pollutant transport (CHAMP) in buildings in support of the design optimization and intelligent control of BES. In the following sections, we provide an overview

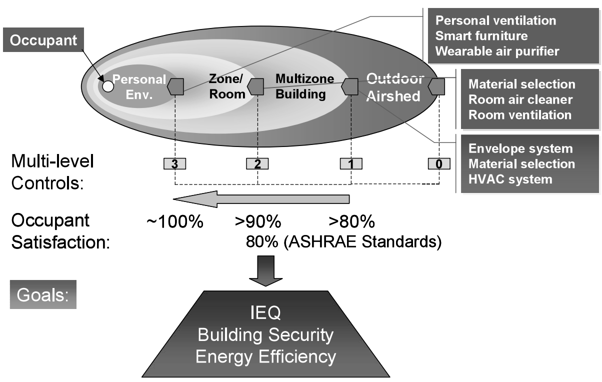

Fig. 1 Conceptual model for BES control/management

* Received 30th November, 2004 (Review)
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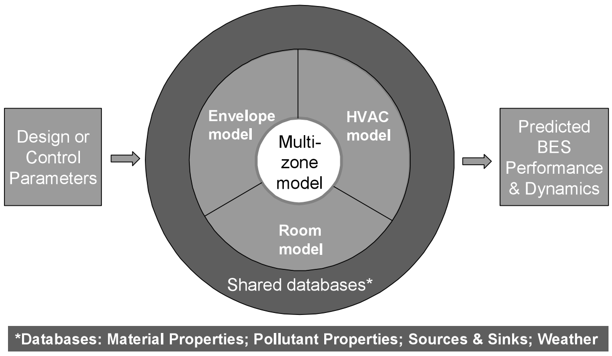

Fig. 2 CHAMP simulation system architecture

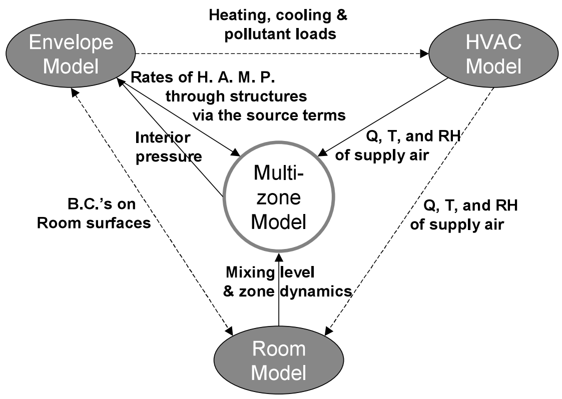

Fig. 3 Interaction among the component models

of the CHAMP simulation system architecture and the models involved, and discuss the model applications and challenges in the model development.

2. Simulation System Architecture

The proposed CHAMP simulation system includes a multizone model, an envelope model, a room model and an HVAC model, which are supported by several shared databases (Fig. 2). While each model can be used for simulations within its own problem domain, it can also interact with the other models through boundary conditions, source and sink terms (Fig. 3). The multizone model has the additional ability to integrate outputs of the other three component models to predict the overall performance of the building environmental system.

3. Multizone Model

A whole building can be divided into multiple zones, each representing a space or aggregated spaces (office workstation/cubical, room, corridor, stair shaft, elevator shaft, etc.) whose environmental conditions can be represented by averaged values, and controlled through a single controller such as a thermostat or an "airstat"[*1]. Lumped parameters are defined for each zone including the pressure, temperature, relative humidity and pollutant concentrations. The primary purpose of the multizone model is to capture the interactions among the different zones of a building, and the ambient weather conditions, and provide a system level prediction of the building performance. In addition, it should also be able to use the outputs from the other component models in order to predict the building performance more accurately. Existing multizone contaminant transport models such as COMIS[(3)], BREEZ[(3)], and CONTAMW[(4), (5)] belong to this model category[(6)], but they do not include thermal analyses. In the following, we introduce a mathematical formulation that includes heat, air, moisture and pollutant transport.

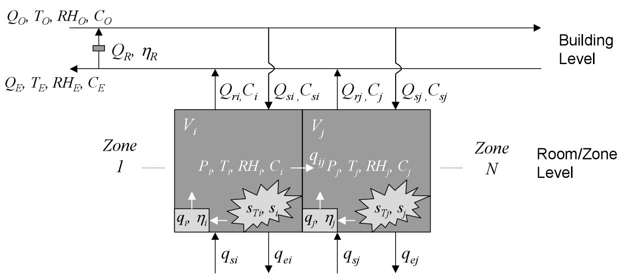

Fig. 4 Schematic of a multizone model

Consider a BES with N zones including the ambient zone (Fig. 4). Each zone has a defined air volume (V_i) in which perfect air mixing is assumed. State variables of the BES are pressure (P_i), temperature (T_i), and moisture or pollutant concentration (C_i) for each zone (i). The source generation rate for heat and moiture/pollutants in Zone i is designated as s_{Ti} *and* s_i, respectively. These source (considered as "sink" if negative) are broadly defined to include both the internal and those transmitted from adjacent zones except those by bulk air movement between zones. Each zone is served by a general (building level) heating, ventilating, and air conditioning (HVAC) system with supply and return airflow rates of Q_{si} and Q_{ri}, respectively. The building HVAC system has an outdoor airflow rate of Q_O, exhaust flow rate of Q_E, and return flow rate of Q_R with a filter efficiency of η_R. Each zone may be equipped with a local air supply and exhaust unit for local ventilation and pressure control, which may operate at a given supply and exhaust flow rates of q_{si} and q_{ei}, respectively. They may also have a local air purification/dehumidification unit operating at the flow rate of q_i and contaminant/moisture removal efficiency of η_i. The state variables in Zone i (i.e., P_i, T_i, RH_i, and C_i) are governed by the following equations:
Heat balance:

$$V_i\frac{d(\rho_i c_i T_i)}{dt} = Q_{si}\rho_{si}c_{si}T_{si} - Q_{ri}\rho_i c_i T_i + q_{si}\rho_{qsi}c_{qsi}T_{qsi}$$

[*1] In analogy to a "thermostat", "airstat" is introduced here as a device with a sensor and information processing algorithm (e.g., compare measured value with a "setpoint" and send our control signals to actuators such as an air cleaning or ventilating device).

$$-q_{ei}\rho_i c_i T_i+\sum_j^N \eta_{Tji} q_{ji}\rho_j c_j \Delta T_{ji}+s_{Ti} \quad (1)$$

Air balance:

$$Q_{si}\rho_{si}-Q_{ri}\rho_i+q_{si}\rho_{oi}-q_{ei}\rho_i+\rho_j\sum_j^N q_{ji}=0 \quad (2)$$

$$q_{ji}=f(\Delta P_{ji})=f(P_j-P_i) \quad (3)$$

Pollutant or moisture (water vapor) balance:

$$V_i\frac{dC_i}{dt}=Q_{si}C_{si}-Q_{ri}C_i+q_{si}C_{oi}-q_{ei}C_i$$
$$+\sum_j^N \eta_{ji}q_{ji}C_j-q_i\eta_i C_i+s_i \quad (4)$$

Where,

C_i : the concentration of the pollutant/moisture in zone i, kg/m^3
C_{oi} : the concentration of the pollutant/moisture in ambient air, kg/m^3
C_{si} : the concentration of the pollutant/moisture in supply airflow, kg/m^3
N : the number of zones
Q_{ri} : the return airflow rate in zone i, m^3/s
Q_{si} : the supply airflow rate in zone i, m^3/s
P_i : the static pressure in zone i, Pa
P_j : the static pressure in zone j, Pa
q_{ei} : the exhaust airflow rate, m^3/s
q_i : the airflow rate of the air cleaner in zone i, m^3/s
q_{ij} : the leakage airflow rate from zone i to j, m^3/s
q_{si} : the supply airflow rate of local HVAC system in zone i, m^3/s
s_i : the generation rate of the pollutant/moisture in zone i, mg/s
s_{Ti} : the generation rate of the heat in zone i, Watt
t : the exposure time, s
V_i : the volume of zone i, m^3
ΔP_{ij} : the pressure difference between zone i and j, Pa
ρ_{si} : the density of supply air for zone i, kg/m^3
ρ_{oi} : the density of outside air for zone i, kg/m^3
ρ_i : the density of air in zone i, kg/m^3
η_i : the removal efficiency of the air cleaner in zone i
η_{ji} : Pollutant/water vapor penetration factor in path (j, i) to accont for the sorption/deposition or filtration in the path.
η_{Tji} : Heat transfer factor in path (j, i) to acount for the heat loss from the air as it flows through the path

For a given building, the multizone model can predict the dynamic changes of temperature, humidity, pollutant concentrations, and pressure in each zone as functions of time as affected by weather conditions, internal and external heat and pollutant sources and HVAC operating conditions. The time scale of the dynamics of the processes modeled here may range from minutes (pollutant dispersion), to hours (daily temperature changes, occupancy and HVAC operating schedules), to months or years (VOC emissions and moisture accumulations). With appropriate simulation time steps, the time required for completing a simulation using a personal computer is generally smaller than the time scale of the processes of interests in a particular application. Therefore, the multizone model is generally sufficiently fast for real-time predictive control purposes. For example, it has been applied to predict the effects of HVAC system control on the dynamics of pollutant dispersion in buildings for the purpose of devising optimal evacuation strategies in case of internal or external pollutant releases(7).

The multizone model, has however, the limitation of being not able to predict the dynamic dispersions of pollutants in zones where the perfect mixing assumption is not valid. Such a zone may include corridor, large ventilated spaces, or where non-mixing type space air diffusion systems (such as displacement or task ventilation systems) are used. In this case, a room model will be needed to provide the mixing level and zone dynamics (Fig. 3).

The source terms in the multizone model can include the rates of heat, air, moisture, and pollutant influxes calculated by the envelope model, while the flow rates, temperature, and relative humidity of the supply air can be determined by the HVAC model (Fig. 3).

4. Envelope Model

The envelope model simulates the coupled heat, air, moisture and pollutant (using VOC as an example) transport across the building shell. It includes equations that describe: 1) heat, moisture and VOC diffusion; 2) sorption isotherms (moisture and VOC storage) as a function of relative humidity and VOC concentration; 3) moisture and VOC transport by liquid flow (significant only in the initial painting process for VOC); 4) moisture and VOC transport by leakage airflows; 5) Boundary conditions between two adjacent material layers, and between solid material surfaces and air; 6) Initial moisture content and VOC concentrations in each material layer; and 7) Effects of temperature and humidity. Several hygrothermal performance models currently exist for simulating heat, air and moisture transport (e.g., Delphin(8), LATENITE(9), WUFI(10), and hygricIRC(11)). Multilayer VOC transport models have also been developed(12). In the following we present the similarities of the model equations for both moisture and VOC calculations(13).

4.1 Sorption

Moisture storage/sorption capacity of porous materials can be described by:

$$u=f(RH,T) \quad (5)$$

$$RH=RC=P_v/P_{v,sat}(T) \quad (6)$$

where u = moisture content [kg-water/kg-dry material]; RH = relative humidity (or relative concentration of water vapour) [%]; and T = temperature [K]. Similarly for

VOCs the storage capacity of the compounds can be presented as a function of relative concentration of VOC and temperature

$$u_{VOC} = f(RC, T) \tag{7}$$

where RC (Relative Concentration) corresponds to Relative Humidity for moisture. Often the temperature dependency is ignored, however, e.g., for wood the temperature dependency exists (higher the temperature, the less moisture wood can store).

The concentration in the ambient air and in the air inside the pores of the porous material is

$$C_a = P_v M / RT \tag{8}$$

where P_v = vapor pressure [Pa]; M = molecular weight [g/mol]; R = the universal gas constant [J/molK]; and T = temperature [K].

The so-called partition coefficient is another way of presenting the storage capacity of VOCs in porous materials for a given temperature under low VOC concentration conditions

$$K_{ma} = C_m / C_a \tag{9}$$

where C_a = the VOC concentration in air at the air-material interface [kg/m^3]; and C_m = the VOC concentration in the porous material at the air-material interface [kg/m^3]. Note that,

$$u_{VOC} = C_m / \rho_0 \tag{10}$$

and

$$RC = P_v / P_{v,sat} = C_a / C_{a,sat} \tag{11}$$

where, ρ_0 = material's density [kg/m^3], $C_{a,sat}$ = saturated VOC concentration for the given temperature. Therefore,

$$\begin{aligned} u_{VOC} &= K_{ma} C_a / \rho_0 = K_{ma} C_{a,sat} RC / \rho_0 \\ &= K_{ma} P_{v,sat} M \cdot RC / (\rho_0 RT) \end{aligned} \tag{12}$$

4.2 Transport by diffusion

The same equations can be applied for moisture and VOC transport by diffusion. The commonly used equations for moisture are based on either vapour pressure or pore air concentration

$$q_{m,vapor} = -\delta_p \nabla P_v \quad or \quad q_{m,vapor} = -D \nabla C_a \tag{13}$$

where δ_p = vapour permeability [kg/msPa]; and D = effective moisture diffusivity [m^2/s]. Equations for VOC transport often use VOC content in the porous material C_m as the potential

$$q_{m,VOC} = -D_m \nabla C_m \tag{14}$$

This type of equation is often used in moisture modelling for liquid transport. It works in isothermal conditions also for vapour transport but in varying temperature conditions or under temperature gradients the equation will have difficulties. Because the VOC concentrations in porous materials are typically very low, the primary transport mechanism can be assumed to be vapour diffusion. Vapour diffusion is dominated by the concentration in the pore air, which depends on the local temperature via evaporation-condensation locally between the pore air and the surfaces of the porous space. VOC content C_m in the porous volume does not take this into account.

Diffusion transport can be modeled in isothermal conditions either by using C_m or C_a (or vapour pressure) as the potential.

4.3 Transport by liquid flow

Liquid flow for VOCs can be assumed negligible at the concentration level typically found for these compounds in porous materials. Water-soluble VOCs, salts and impurities may however be transported along with moving liquid moisture. This area will be addressed at the later stage of research when the CHAMP modelling system will be expanded to include the movement of salts through the porous materials.

4.4 Transport by airflow

Air flowing through a porous material can transport moisture or VOCs and can be presented for both with the equation:

$$q_{m,air} = \rho_{dry\ air} \vec{v} c \tag{15}$$

where v = velocity [m/s].

However, the challenge lies in the modeling of transport by airflows through cracks and cavities in envelope systems where the exact leakage paths are often difficult to determine.

4.5 Mass balance equation

After conversions from different forms of equations describing the same phenomena the final equations to solve either moisture or VOC transport and storage will look the same and are for moisture

$$\rho_0 \frac{\partial u}{\partial t} = -\nabla \cdot q_{m.vl} - \nabla \cdot q_{m,air} + S \tag{16}$$

and for VOCs

$$\frac{\partial C_m}{\partial t} = \rho_0 \frac{\partial u_{VOC}}{\partial t} = -\nabla \cdot q_{m,VOC} - \nabla \cdot q_{m,air} + S \tag{17}$$

where S = source [kg/m^{3}s].

For particulate transport, additional equations will need to be added to account for the particle movement in air, and deposition on surfaces along the flow paths. This will be addressed in future studies.

The envelope model can predict the detailed distribution of temperature, moisture/pollutant content across the building shell as functions of outdoor weather conditions and indoor climate conditions. The pressure calculated by the multizone model, and indoor climate conditions from the room model can be used as boundary conditions for the simulation (Fig. 3). The processes simulated by the envelope model have time scales ranging from minutes (pollutant transport through leakage flows), to hours or days (heat transfer), to months or years (VOC and moisture diffusions). Time required for simulating an entire year may take a few minutes to several hours or days for a PC depending on the complexity of the envelope assembly and if the airflow in the cavities are simulated in detail. While the envelope model has largely been used for evaluating and comparing different envelope designs under various outdoor and indoor climate conditions, it should be sufficiently fast for modeling the outdoor to indoor pollutant transport for the purpose of real-time controls of BES.

Currently, major challenges in developing the envelope model are 1) modeling the effect of leakage flows on the moisture and VOC transport due to the difficulty in characterizing leakage paths; 2) determining the material transport properties of the materials, especially when the directional variations are considered. Research is underway to overcome these difficulties[(14)–(16)].

Syracuse University is developing a coupled heat, air, moisture, pollutant and salt (CHAMPS) transport software in collaboration with the Technical University of Dresden of Germany. The processes included in the software are: 1) Heat and moisture transport and sorption including the effects of evaporation-condensation of moisture; 2) VOC transport and sorption; 3) salt transport; and 4) Temperature difference and air pressure driven flow of air through cracked or non-cracked porous materials and cavities[(17)].

5. Room Model

The purpose of the room model is to resolve spatial distributions of temperature, relative humidity, air speed, and pollutant concentrations in zones that require more accurate assessment of the thermal and air quality conditions than the lumped parameter model. Computational fluid dynamics (CFD) techniques have been most widely used for this purpose[(18),(19)]. Other types of room models include zonal or (sub-zonal) models[(20)] and, most recently, the proper orthogonal decomposition models[(21),(22)]. We limit the following discussions to CFD models due to their generic and less-empirical nature. CFD model simulations can provide detailed flow characteristics, and can be the starting point for developing more simplified or empirical approaches.

5.1 Governing equations

A CFD model numerically solves the partial differential equations that governs the conservation of air mass, momentum in three directions, and moisture/pollutant mass (assuming incompressible fluid):

For air mass:

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{18}$$

$$u_i = \overline{u_i} + u_i' \tag{19}$$

where, u_i is instantaneous velocity, m/s; x_i defines the Cartesian coordinates; $\overline{u_i}$ denotes the ensemble average of u_i for a steady flow and u_i' is the fluctuation velocity, measured as the standard deviation of u_i.

For momentum in three directions:

$$\rho\frac{\partial u_i}{\partial t} + \rho u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + F_i \tag{20}$$

where, t is the time, s; ρ is the density of the fluid, kg/m^3, p is the pressure, Pa; F_i is the body force, N/m^3; τ_{ij} is the viscous stress tensor defined as,

$$\tau_{ij} \equiv 2\mu s_{ij} \tag{21}$$

where, μ is viscosity, s_{ij} is the strain rate tensor and defined as,

$$s_{ij} \equiv \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{22}$$

For moisture or pollutant mass:

$$\frac{\partial C}{\partial t} + u_j\frac{\partial C}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\Gamma\frac{\partial C}{\partial x_j}\right) + S \tag{23}$$

where, C is the instantaneous concentration of a pollutant of water vapor, kg/m^3; Γ is diffusivity of the pollutant or water vapor in air, m^2/s; and S is the source (or sink term), kg/(m^{3}s).

5.2 Turbulence modeling

Air movement in a ventilated space is complex and involve laminar, transition and turbulent flows. Boundary layer flows over the room interior surfaces can be stagnant or have weak and strong turbulence[(23)]. Ensemble averages are taken on the above governing equations in order to obtain equations for the averaged quantities of interests including mean velocity, mean temperature, mean concentrations of pollutants or water vapor, and mean pressure. As an example, the ensemble average of the momentum conservation equation becomes:

$$\rho\frac{\partial \overline{u_i}}{\partial t} + \rho\overline{u_j}\frac{\partial \overline{u_i}}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial(2\mu\overline{s_{ij}} - \rho\overline{u_i'u_j'})}{\partial x_j} \tag{24}$$

which is the Reynolds-Averaged Navier-Stokes (RANS) equation[(24)]. On the right hand side of the equation, the $-\rho\overline{u_i'u_j'}$ term is called the Reynolds stress tensor. Determination of this term constitutes the well-known closure problem in turbulence modeling. A significant portion of turbulence research has focused on tackling the closure problem by proposing various turbulence models such as RANS-based models (eddy diffusivity model, Reynolds stress model, and algebraic stress model), Large Eddy Simulation (LES) model and direct numerical simulation (DNS) model.

Among the RANS models, the two-equation variants of the $k-\varepsilon$ model appear as the popular ones in industrial applications for simulating steady mean flows and scalar species transport[(25),(26)]. This model employees two additional transport equations to describe the turbulence kinetic energy (k) and its dissipation rate (ε) in order to determine the turbulent eddy viscosity (μ_t) as a function of the flow characteristics[(27)]. Reynolds stress or algebraic stress models generally give better predictions because anisotropic effects of turbulence are taken into account[(28)–(30)], but the improvement over the $k-\varepsilon$ model for room airflows are not always significant[(31)–(33)].

For room airflows that are intrinsically transient, the time-dependent RANS simulations often fail to resolve the flow field in the temporal domain. Large Eddy Simulation (LES) is a method that directly calculates the time-dependent large eddy motion while resolving the more universally small-scale motion using Subgrid Scale (SGS) modeling[(26),(34),(35)]. LES requires significantly more computational time than RANS, but due to the advancement of computer technology, it can now be applied to room airflow simulation for relatively simple geometries[(36),(37)]. An excellent introduction to this promising CFD technique is given by Ferziger (1997)[(35)].

Direct Numerical Simulation (DNS) calculate the turbulence effects directly using statistical method. It can be used as a benchmark to validate other CFD techniques like the RANS and LES models. However due to its significantly higher demand on computational power, DNS is usually used to study flow motion with simple geometry and confined within a small spatial and temporal domains[(26)] and for investigating flow mechanism such as multiphase flow[(38)] and droplet evaporation[(39)].

The first CFD predictions of room air movement were made in 1970s[(40)], and has been studied extensively, especially since 1990s due to the advancement in computing technology[(41),(42)]. The time scales of the processes simulated by CFD models corresponds to the frequecies of the velocity fluctuations in the turbulent room airflow and relatively slow speeds of molucular diffusions in air, and typically range from milli seconds to miniutes. The time required for completing a steady state simulation on a currently fast PC could, however, take hours (zero-equation turbulence model), days (eddy $k-\varepsilon$ model), weeks (Reynolds stress model), months (LES model), or even years (DNS model) for a realistic room ventilation flow. Therefore, CFD models are generally not sufficiently fast to be used directly for real time flow control applications[(7)]. However, CFD models can be used to pre-calculate the flow and pollutant field for sufficient number of scenarios that may be foreseen in a particular control application to provide the data required in developing a reduced-order model such as the Proper Orthogonal Decomposition model[(22)].

6. HVAC Model

The purpose of the HVAC model is to simulate the effect of HVAC system operation on the CHAMP processes, and on building performance. It is particularly important for predicting the effect of intelligent control strategies on IEQ, safety, and energy consumption.

A complete HVAC system model should include the primary system (i.e., the central cooling and heating plant) and the secondary system (i.e., all parts of the HVAC system except the central cooling and heating plant)[(43)]. Both the primary and secondary HVAC systems have been modeled extensively in several energy simulation programs that are available for free download on the Internet: eQUEST[(44)], EnergyPlus[(45),(46)], and ESP-r[(47),(48)].

These models can simulate the performance of HVAC components and systems on a hourly or shorter time basis taking into account the variations in the building heating and cooling loads due to the variations in weather and internal heat gains/losses. However, they do not typically consider the dynamic response characteristics of fans, airflow dampers, air cleaners, heating/cooling and humidifying/dehumidifying devices or other actuators, which can be important from the BES control point of view, especially in dealing with emergency situations such as in the cases of fire or intentional or un-intentional chemical or biological releases in or outside a building.

The proposed HVAC model will include the dynamic response characteristics of the HVAC components as well as other performance aspects such as pressure and flow delivery of fans, efficiency of air cleaners, and flow resistance of air dampers, and energy consumptions. The time scales of the processes to be simulated by the HVAC model would range from less than a second (e.g., damper shutting off the airflow), to minutes (e.g., electrical heater, heating/cooling coils, air cleaners), to hours or longer (supply fluid conditions from the central plants), but the simulation model are mostly algebraic equation based, and hence can run on PC or HVAC system controllers fast enough for real-time controls.

7. Databases

Several databases are needed for the simulation models including:

- A weather database on hourly changes of outdoor temperature, humidity, wind and solar radiation conditions for various locations. This information is shared by the envelope model, the HVAC model and the multizone model.
- A database of material transport properties that are needed for the envelope model.
- A database of indoor pollutant sources and sinks that is needed for the room model, envelope model and the multizone model. An example of such a database is the material emission database that contains source emission rates of volatile organic compounds from building materials and furnishings[(49)].
- A database of fundamental properties of typical air pollutants present indoors, but could come from either indoor or outdoor sources, or chemical reactions indoors. The information is needed for extrapolating the material transport properties for the "reference" chemical compounds in the database to compounds whose transport properties are not yet readily available.

8. Applications and Challenges

Applications of the CHAMP model are countless, and may include, but not limited to:

- Development of intelligent building environmental systems (i-BES) for large high performance buildings;
- Development of i-BES for personal or micro-environmental control that would satisfy every individual's environmental needs while achieving high energy efficiency;
- Optimal placement of distributed sensors for intelligent control of BES;
- Locating pollutant sources;
- Understanding of the indoor-outdoor interactions, and their impacts on IEQ and energy consumption of buildings;
- Understanding and prediction of the material emission characteristics and their impact on IAQ;
- Understanding and prediction of the hygrothermal performance of buildings and its impact on energy consumption and IAQ (prevention of mold growth through proper moisture control);
- Development of new materials for built environments that have the required transport properties for heat, air, moisture and pollutant control in buildings;
- Design optimization of building environmental systems for both normal and emergency operating conditions.

Primary challenges in terms of CHAMP model development lies in three areas:

- Fundamental understanding of multi-scale transport phenomena ranging from laminar to fully developed turbulence flows, and their relationship to gaseous pollutant sorption/desorption, particle deposition and resuspension. Of particular interests is the transport through building envelopes and in the micro-environment around occupants where forced, natural and mixed convection flows can be all important at times. Novel experimental method such as the multi-Particle Image Velocimetry (MPIV) technique[50] for simultaneous measurements of the airflow fields ranging from a micro-region (e.g., airflow in the breathing zone) to a full-scale cubical or room are also necessary for improving the understanding of the flow characteristics and providing reliable data for model validation.
- Development of reduced-order models (e.g., the POD model) for real-time prediction of transport processes. These models will enable the development of predictive control algorithms that are needed for dynamic optimization of the BES in real time for either normal building operation or in response to extra-ordinary situations.
- Effective integration among the different model components.

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