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A Computer Model of Smoke Movement by Air Conditioning Systems (SMACS)

John H. Klote

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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General Services Administration
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Abstract

A computer model for simulation of smoke movement through air conditioning systems is described. A brief overview of air conditioning systems is presented. The methods of calculation of mass flow, smoke transport, fan flow and duct and fitting resistances are presented along with a general description of the program logic.

Key words: air conditioning, computer models, duct, fans, smoke control, smoke movement.

1. INTRODUCTION

There is much concern within the fire protection community regarding the hazards of smoke transported through air conditioning systems. These system are capable of moving smoke to locations remote from a fire and thereby endangering life. The Center for Fire Research (CFR) of the National Bureau of Standards is developing a computer model to predict the quantity of smoke transported by an air conditioning system which will help in evaluating the hazards due to smoke distributed by these systems and should be useful in evaluating the impact of the air conditioning system on fire growth and development. In similar models, Greuer [1] has developed a model simulating smoke transport by mine ventilation systems, and Bolstad, et al. [2] have developed another model particularly for nuclear facilities. However, an unique feature of the code under development at CFR is that it is intended to be a part of a larger model predicting smoke movement throughout a building. The code is called the model of Smoke Movement by Air Conditioning Systems (SMACS). The term 'air conditioning' is used in the broadest sense to include heating, ventilating and cooling. SMACS is modular in that it has been developed with the idea that it could be incorporated into any multi-room fire model, and it can be run by itself without a fire model. It is planned that SMACS will be incorporated into a future version of the FAST model [3]. Further, the model can be used to simulate the flow of any airborne contaminate through an air conditioning system. Thus it could have application in the area of indoor air quality.

2. AIR CONDITIONING SYSTEMS

It is to the credit of the air conditioning industry that most people can take their systems for granted. For this reason, a brief overview of these systems is provided for background information. More detailed information about these systems is available from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [4]. The industry classifies air conditioning systems into three types: all water systems, air and water systems and all air systems. The all water systems are not of much concern with regard to smoke transport. In most cases, the air portion of air and water systems can be regarded as all air systems for purposes of smoke transport analysis. Thus, the all air systems are of primary concern in the context of this paper. Figure 1 is a representation of a residential system. In this example return air from the living quarters is drawn in at one location, flows through filter, fan and coils, and is distributed at several locations throughout the residence.

Residential systems do not have the capability of providing fresh outside air needed for ventilation, and traditionally it has been considered that residences get sufficient outside air by infiltration through leakage paths in walls and cracks around windows and doors. The system illustrated in figure 2 for commercial buildings is probably the simplest system capable of providing ventilation air. All the spaces served by this system can be thought of as a single control zone because one thermostat (possibly in combination with a humidistat) control the temperature (and humidity) of the air supplied to the zone. Figure 3 shows a system which has a reheat coil arrangement to allow control for several zones. The energy conserving system of figure 4 has a

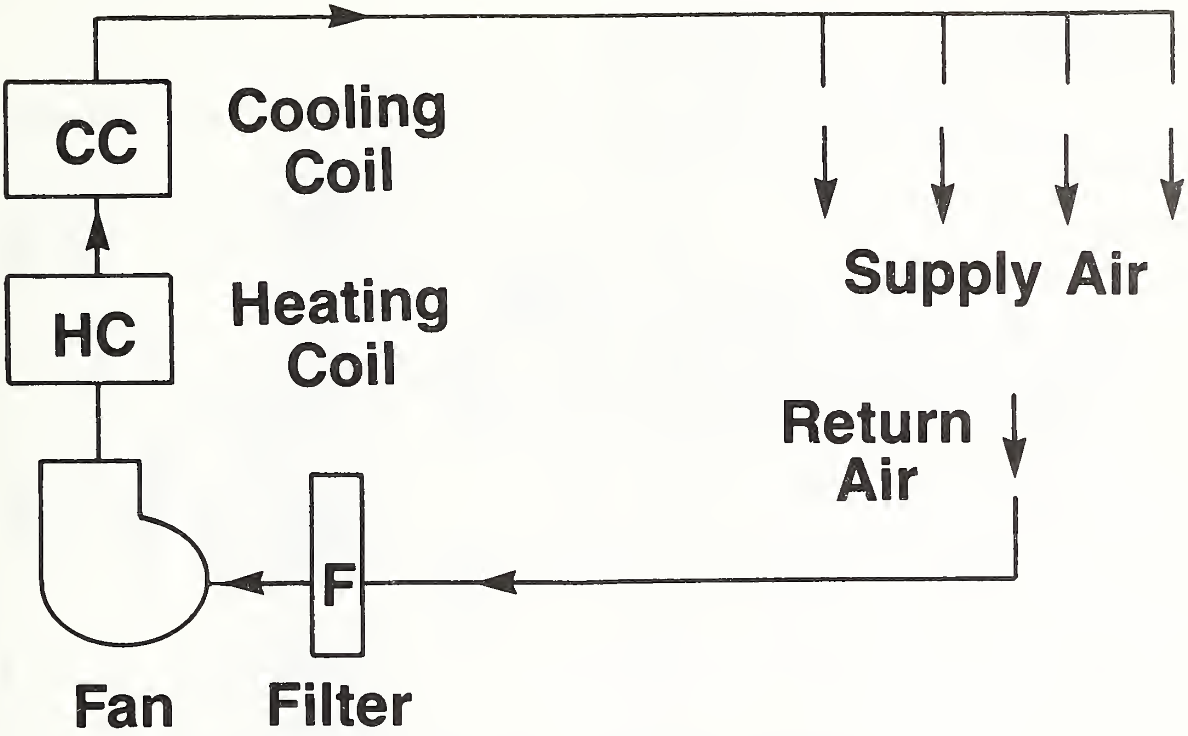


Figure 1. Residential Air conditioning system

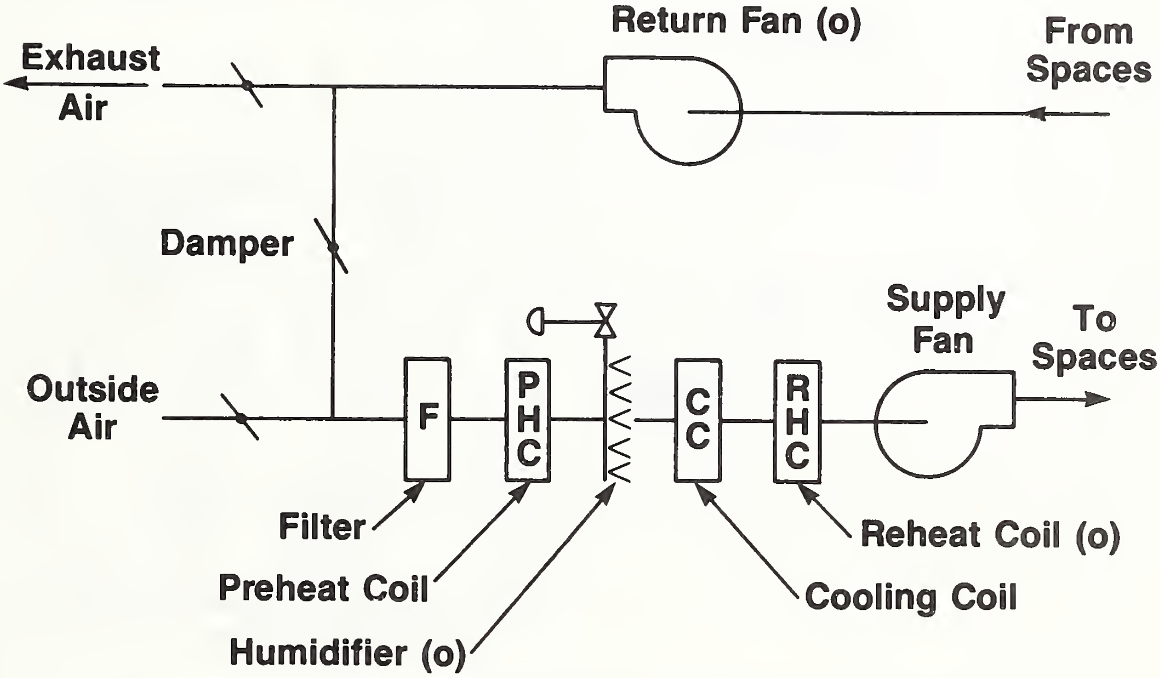


Figure 2. Constant volumetric flow, single control zone system

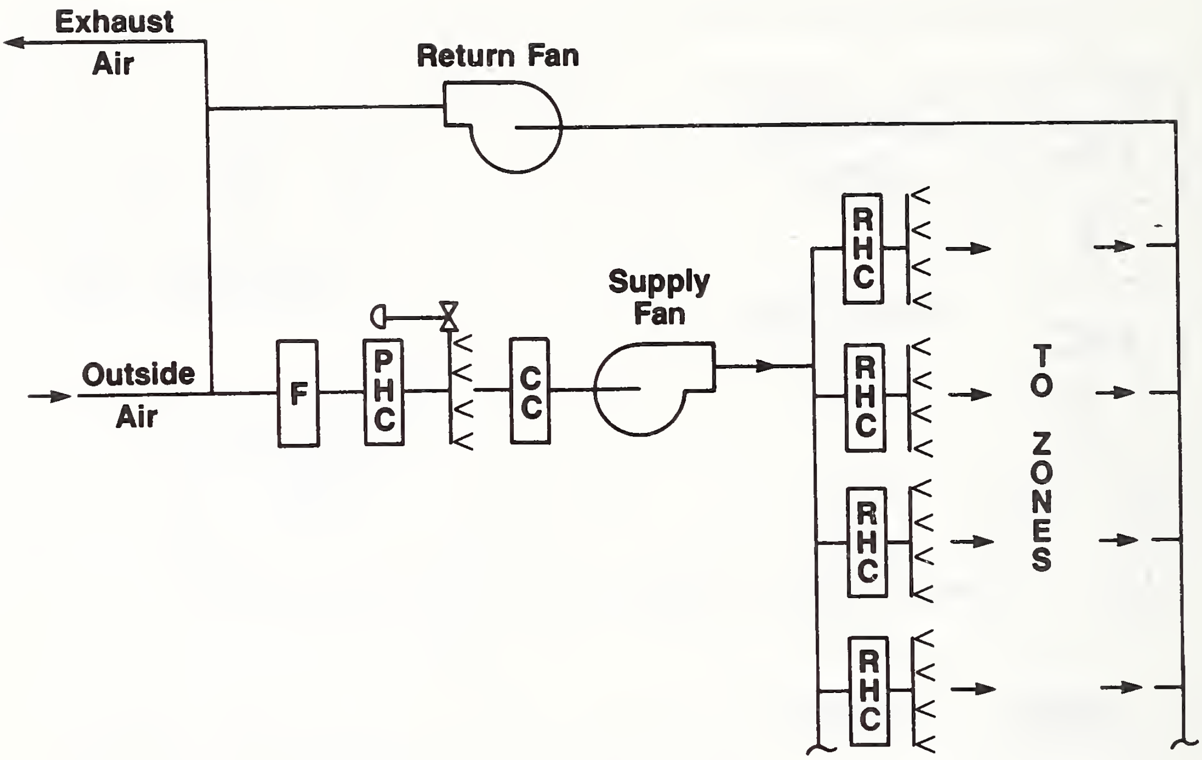


Figure 3. Constant volumetric flow system with terminal reheat

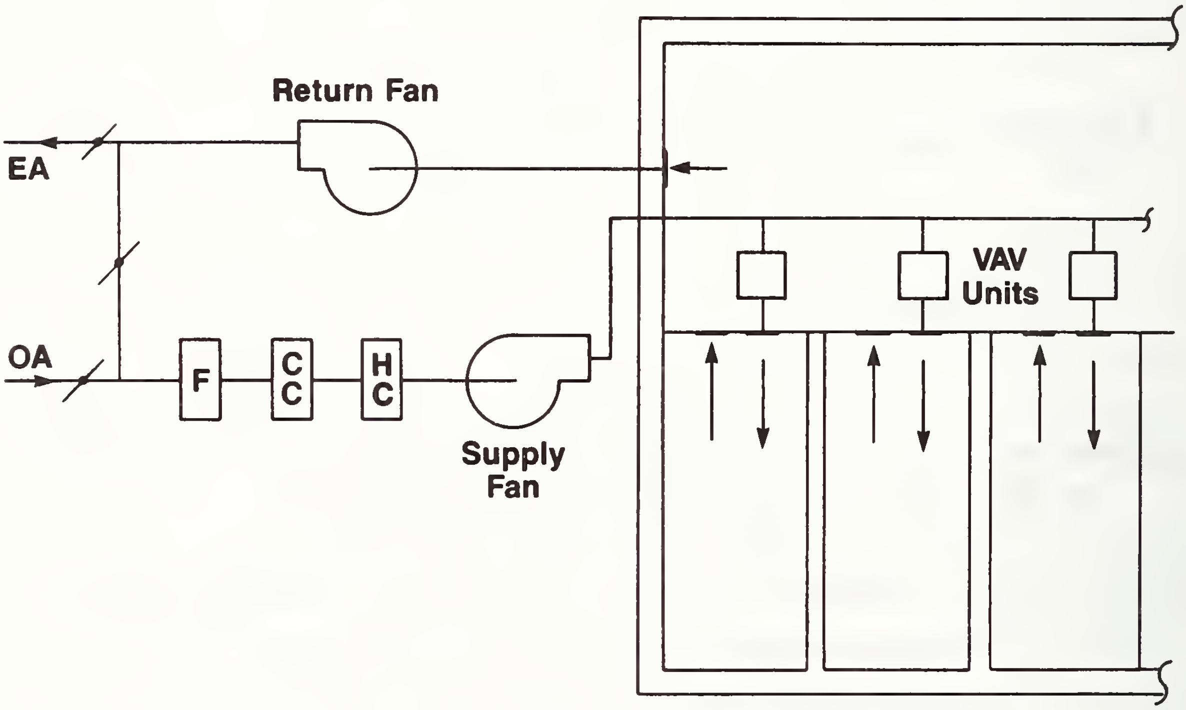


Figure 4. Variable air volumetric (VAV) flow system

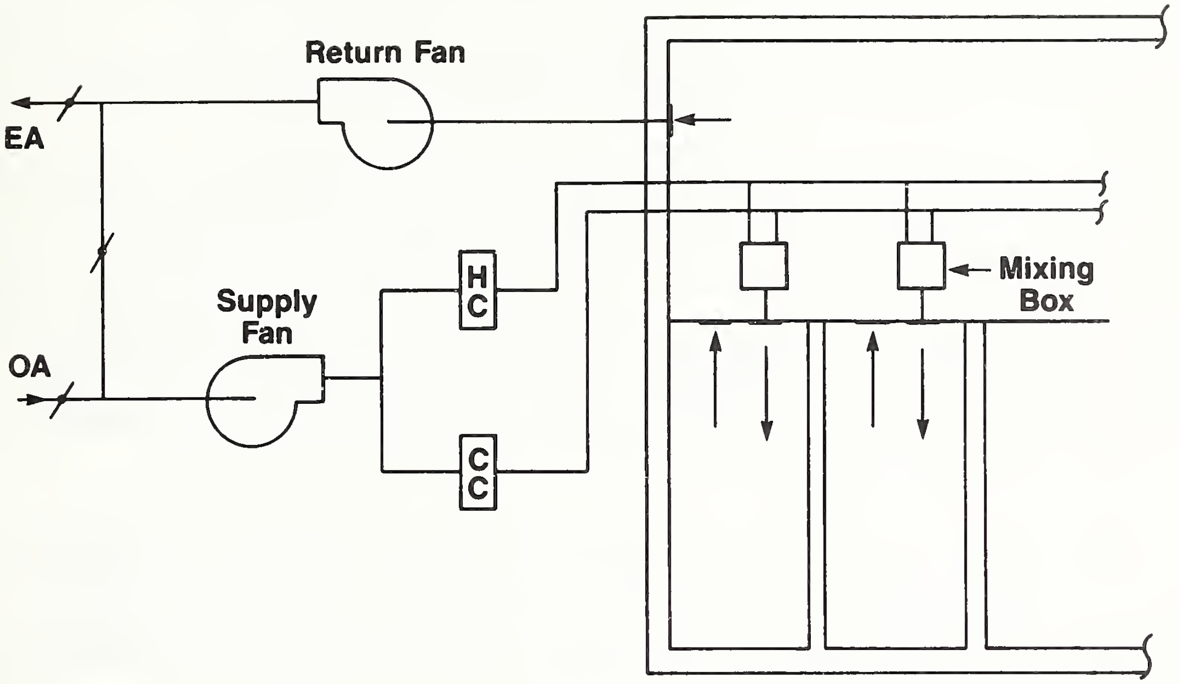


Figure 5. Dual-duct system

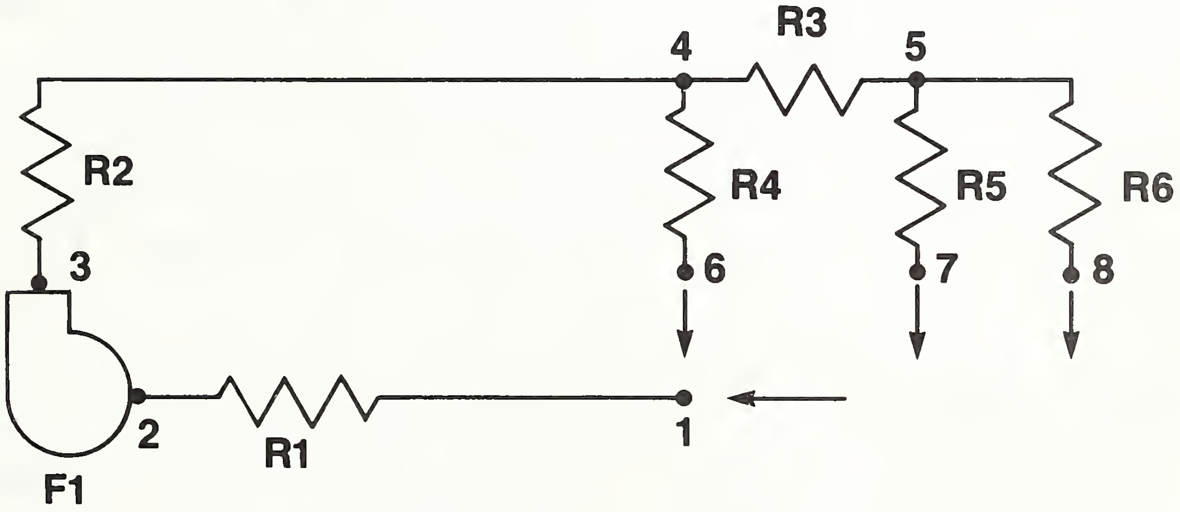


Figure 6. Network representation of residential system

variable flow rate fan arrangement which allows for multiple control zones. The system illustrated in figure 5 has both hot and cold air ducts, and mixing boxes provide the required flow rates to maintain conditions in many zones.

The systems addressed here are all general categories, and for each there are almost limitless variations of added, deleted or rearranged components. A common arrangement is to have one or more all air systems serving the building interior, and to have all water or air and water system serve the perimeter spaces of the building. In addition, different spaces like theaters, shops, offices and kitchens have different needs. Thus, many buildings have more than one air conditioning system.

It is obvious that an air conditioning model should be capable a simulating an almost limitless number of systems, and of simulating one or many systems in a building. The model described in the paper is modular and has the flexibility to accomplish this.

3. CONCEPT OF SMACS

The air conditioning system is represented as a network of nodes each at a specific temperature and pressure. The nodes may be connected by fans, ducts, fittings and other components. Except for fans, air flows through these components from nodes of higher pressure to nodes of lower pressure. For example, the residential system illustrated in figure 1. is represented in figure 6 as a network of six resistances and a fan. These resistances incorporate all the resistance to flow between nodes. For instance, the equivalent resistance, R_1, between nodes 1 and 2 accounts for resistances of the inlet, duct, filter and connection to the fan. For a given (short) time interval, pressures at the exterior nodes (nodes 1, 6, 7 and 8) are all supplied to SMACS by the main program. Because node 1 is an inlet to the air conditioning system, the temperature and concentrations of gases at this node are supplied by the main program. The model SMACS solves for the pressures at the interior nodes (nodes 2, 3, 4 and 5) and then calculates the mass flows, temperatures and concentrations throughout the air conditioning system.

The SMACS model is based on the following assumptions:

- the total mass flow through the system is quasi-steady,
- smoke movement within a duct behaves like plug flow,
- heat transfer to air conditioning components is insignificant with respect to the heat of the fire,
- the duct system is assumed to be perfectly insulated.

It is believed that the total mass flow through an air conditioning system is generally a very weak function of the pressures produced in a building fire. The considerable extent of leakage areas in residential and commercial construction is well known, and therefore, the pressures due to the expansion of gases in fires is not a concern for such construction. For a residential system, the pressure across the fan is on the order of a 500 Pa, the volumetric flow is on the order of 1 m^3/s, and the slope of the fan curve is about 1000 Pa per m^3/s. Thus it would seem that the pressure difference due to buoyancy of hot fire gases of about 20 Pa would have a maximum effect on the total flow rate of the system of about 2 %. Typically, air conditioning systems in commercial buildings operate at larger flow rates and pressure differences, therefore, these systems are effected by fire produced pressures less than residential systems. This supports the quasi-steady assumption for air conditioning systems that serve a large area such as an entire residence or a commercial building. Of course, research is needed to determine the actual extent of applicability of the quasi-steady assumption. Obviously, this assumption is not appropriate for small fan powered systems serving only one tightly constructed space in which there is a fire. Another model is being developed for this application.

In this paper, the term "smoke" is used in accordance with the ASTM [5] and NFPA [6] definition which states that smoke consists of the airborne solid and liquid particulates and gases evolved when a material undergoes pyrolysis or combustion. All the gases and particulates entering a section of duct flow through it like a plug and leave the duct after some time has passed. The air conditioning system is divided into control volumes, one for each effective resistance and fan. Even though the total mass flow rate is considered quasi-steady, transient calculations of temperatures and concentrations are made for each control volume.

Neglecting heat transfer to the air conditioning system components is appropriate for this model, because temperature differences due to the air conditioning system are on the order of 20 °C, while those of interest in a fire are at least an order of magnitude greater. Simulating perfectly insulated duct systems is supported by the fact that almost all ducts in commercial buildings are very well insulated for energy conservation. In the future the model may be extended to include uninsulated duct.

4. TOTAL MASS FLOW

The mass flow rate, $\dot{m}_{ij}$, to node i from node j can be expressed as a function of the difference in pressure , $P_j - P_i$, between the two nodes.

$$\dot{m}_{ij} = \dot{m}_{ij}(P_j - P_i) \tag{1}$$

The form of the function depends on the type of connection between the two nodes as will be discussed later in detail. The conservation of mass equation for node i can be written as

$$\sum_{j} \dot{m}_{ij} = 0 \tag{2}$$

By substitution of eq. (1) into eq. (2) and expressing in terms of pressure, a system of equations can be obtained for all n nodes.

$$
\begin{aligned}
&f_1(P_1, P_2, \ldots, P_n) = 0 \\
&\quad\vdots \\
&f_i(P_1, P_2, \ldots, P_i, \ldots, P_n) = 0 \qquad (3) \\
&\quad\vdots \\
&f_n(P_1, P_2, \ldots, P_n) = 0
\end{aligned}
$$

Thus the air conditioning system pressures, P_1 to P_n, are solved simultaneously by solving n number of mass balance equations. The number of pressures included in each equation $f_i = 0$ are only P_i and those of the nodes directly connected to node i. Because the form of the functions $\dot{m}_{ij}(P_j - P_i)$ are nonlinear, a Newton-Raphson method was employed for solution.

5. SMOKE TRANSPORT

Each section of duct is considered a control volume. Air enters a control volume at time, t, and leaves at time, $t + t_d$, where t_d is the travel time. The concentration of gas in the air leaving at time, $t + t_d$, equals the concentration that entered at time, t. This is expressed as

$$C_{ko}(t + t_d) = C_{ki}(t) \qquad (4)$$

where C_{ko} and C_{ki} are the concentrations of gas k at the control volume outlet and inlet respectively. For a control volume of uniform cross section, the travel time is L/V where L is the duct length and V is the average velocity through the duct. The average velocity is defined as $V = \dot{m}/\rho A$ where $\dot{m}$ is the total mass flow rate through the duct, ρ is the density of the gas in the duct and A is the cross sectional area of the duct. For a control volume made of sections of ducts of various sizes, the total travel time is the sum of the travel times for each duct ($t_d = \Sigma L_k/V_k$ for k = 1 to number of ducts). For perfectly insulated duct, temperatures are handled in the same manner as concentrations. This is similar to the approach that Greuer uses to model smoke transport in his mine ventilation model.

6. FAN FLOW

Fan manufacturers routinely provide typical data of volumetric flow rates through fans at various pressure heads across the fan. This data is either in tabular or graphical form. As indicated by Jorgensen [7], the use of a polynomial form of fan curve is common within the industry. The SMACS model simulates fan flow by the polynomial

$$Q = B_0 + B_1X + B_2X^2 + \ldots + B_nX^n \tag{5}$$

where Q is the volumetric flow rate and X is the pressure difference or pressure head across the fan. The coefficients can be entered as data or calculated by least squares regression from flow and pressure data. For incompressible fluids, eq. (5) is independent of temperature and pressure. For fan data at 20 ° C, compressibility effects amount to an error of about 6 % at a temperature of 200 °C. For this first order model compressibility is neglected.

7. EFFECTIVE RESISTANCES

The resistance, R, of a flow element can be defined as

$$R = \frac{\sqrt{\Delta P}}{\dot{m}} \tag{6}$$

where ΔP is the pressure loss through the element corresponding to a mass flow rate, $\dot{m}$. To reduce computation time, the conductance, G, is used in the SMACS model ($G = R^{-1}$ and $\dot{m} = G\ (\Delta P)^{\frac{1}{2}}$). The effective resistance between two nodes is always positive, however, sometimes one of the resistances between nodes can be negative as will be explained later. To account for this, $R = K^{\frac{1}{2}}$ is substituted into eq. (6) to give $\Delta P = K\ \dot{m}^2$. The total pressure loss, ΔP_t, from one node to the next is the sum of the losses, ΔP_i, through each flow element, i, between the nodes.

$$\Delta P_t = \sum_i \Delta P_i \tag{7}$$

The effective value, K_e, relates the total pressure loss to the mass flow rate as $\Delta P_t = K_e\ \dot{m}^2$, and K_i relates the pressure loss through element i as $\Delta P_i = K_i\ \dot{m}^2$. These pressure losses can be substituted into eq. (7), and canceling like terms yields

$$K_e = \sum_i K_i \tag{8}$$

Values of K_i are calculated for each element using equations developed later in the paper, and K_e is calculated by eq. (8). The effective conductance is calculated by $G_e = K_e^{-\frac{1}{2}}$.

8. STRAIGHT DUCTS

For a straight section of duct with constant cross sectional area, the Bernoulli equation incorporating pressure loss, ΔP_f, due to friction is commonly written

$$P_1 - P_2 = \Delta P_f + \rho g(Z_2 - Z_1) \tag{9}$$

where the subscripts 1 and 2 refer to the duct inlet and outlet respectively, P is pressure, Z is elevation, g is the acceleration due to gravity, and ρ is the density of the gas. The pressure los due to friction is expressed by the Darcy equation,

$$\Delta P_f = f \frac{L}{D_e} \frac{\rho V^2}{2} \tag{10}$$

where f is the friction factor, L is the duct length and D_e is the effective diameter of the duct. The commonly used hydraulic diameter concept is not used because more accurate relations have been developed specifically for rectangular duct by Huebscher [8] and for oval duct by Heyt and Diaz [9]. Using the definition of V, equations (9) and (10) can be expressed in terms of a duct conductance, G, as

$$\dot{m}_{ij} = G \sqrt{P_j - P_i + \rho g(Z_j - Z_i)} \tag{11}$$

and

$$K = G^{-2} = \frac{2 \rho D_e A^2}{f\ L} \tag{12}$$

where A is the cross sectional area of the duct. The friction factor can be evaluated by the Colebrook equation

$$\frac{1}{\sqrt{f}} = -\ 2\ \mathrm{Log}_{10} \left[\frac{\epsilon}{3.7\ D_e} + \frac{2.51}{R_e \sqrt{f}} \right] \tag{13}$$

where R_e is the Reynolds number (VD_e/υ where υ is the kinematic viscosity) and ϵ is the roughness of the inside surface of the duct. The ASHRAE handbook of fundamentals [10] lists values of ϵ for common duct materials and constructions. Equation (13) can be solved for f by the Newton-Raphson method.

9. OTHER RESISTANCES

The pressure loss, ΔP, through many other elements can be expressed as

$$\Delta P = C_o \frac{\rho V_o{}^2}{2} \tag{14}$$

where V_o is the average velocity at cross section o within the element, and C_o is a local loss coefficient. This equation is commonly used for inlets, outlets, duct contractions and expansions, heating and cooling coils, dampers, bends and many filters. For a large number of these elements, values of C_o have been empirically determined and are tabulated frequently as functions of geometry in handbooks [10 - 12]. Manufacturers literature also contains some values of C_o. Equation (14) and the definition of V can be used to obtain the following expression of K:

$$K = G^{-2} = \frac{C_o}{2\rho A_o^2} \tag{15}$$

where A_o is the area at cross section o.

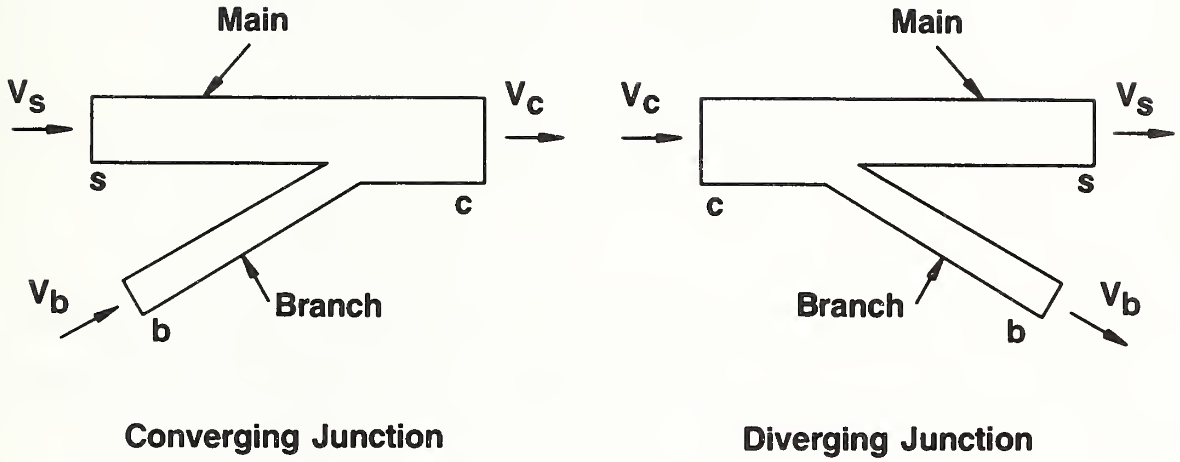
10. JUNCTIONS

Junctions may be either converging or diverging as illustrated in figure 7. For network representation, a node is located at cross section c of a junction. The pressure losses in the main section depends on the flow in it and on the flow in branch, and the loss in the branch depends on both the flow in it and in the main. The pressure loss in the branch is expressed as

$$P_b - P_c = C_{c,b} \frac{\rho V_c^2}{2} \tag{16}$$

and the pressure loss in the main is

$$P_s - P_c = C_{c,s} \frac{\rho V_c^2}{2} \tag{17}$$



Converging Junction

Diverging Junction

Figure 7. Diagrams of converging and diverging junctions

where $C_{c,b}$ and $C_{c,s}$ are local loss coefficients, P, ρ, and V are pressure, density and average velocity at cross sections b, c and s as illustrated in figure 7. Local loss coefficients for many junctions have been experimentally evaluated, and they are tabulated as functions of geometry and various flow ratios in handbooks along with values of C_o. Converging junctions may have negative local loss coefficients. For example when the flow in the main is much greater than that in the branch, the gas in the branch is pulled by the greater flow similar to the operation of a carburetor. As was done for the other elements, an expression for K in the branch is

$$K = \frac{\rho_c C_{c,b}}{2\rho_b^2 A_b^2}\left(\frac{\rho_b A_b}{\rho_c A_c} + \frac{\rho_s V_s A_s}{\rho_c V_b A_c}\right)^2 \qquad (18)$$

and for the main is

$$K = \frac{\rho_c C_{c,s}}{2\rho_s{}^2 A_s{}^2} \left[\frac{\rho_s A_s}{\rho_c A_c} + \frac{\rho_b V_b A_b}{\rho_c V_c A_s} \right]^2 \tag{19}$$

11. SMACS LOGIC

Figure 8 is a flow chart of the SMACS model. The first time through SMACS, data describing the air conditioning network is read, and arrays are set up and temperature and concentrations are initialized. The effective conductance, G_e, for each resistive connection between nodes is calculated using rough estimates of the flows. The system of equations (3) is solved using the approximate values of G_e. Because the initial values of flow are rough, multiple iterations are required to solve the system. The improved flows are calculated from the solution pressures. The process of calculating G_e's and solving the system of equations is repeated until two or less iterations are needed to solve the system. These flows are then used to calculate concentrations and temperatures.

12. FUTURE DIRECTION

A users manual and a program manual for the SMACS need to be developed. Experiments will be conducted to evaluate the smoke transport predictions of the model. Further, the need has been identified for a model of Smoke Movement through Air-Fan Systems (SMAFS). SMAFS would be a model of a system

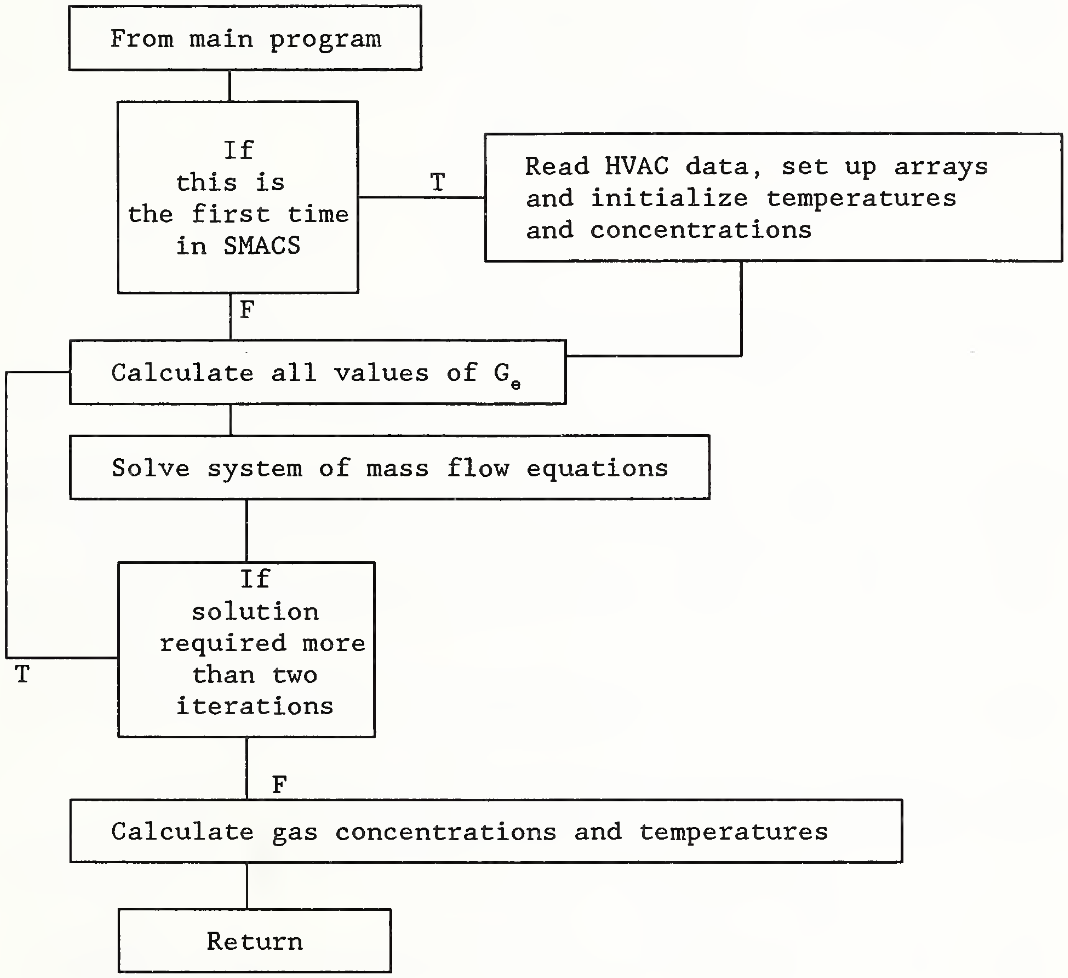


Figure 8. Flow chart of SMACS model

consisting of only one fan and one effective resistance. This simple system is used extensively in buildings, and SMAFS would be developed to simulate it with computational efficiency beyond the capability of SMACS. These subroutines will be used within fire models to study the interaction between air conditioning systems and smoke movement.

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14. NOMENCLATURE

A	area
C	local loss coefficient
D_e	effective diameter
f	friction factor
G	duct conductance
g	gravitational acceleration
K	square of duct resistance
$\dot{m}$	mass flow rate
P	pressure
Q	volumetric flow rate
R	duct resistance
T	temperature
V	average velocity
Z	elevation
ΔP	pressure loss
ϵ	roughness of interior duct walls
ρ	density

Subscripts

b	section b
c	section c
e	effective
f	friction
o	section o
s	section s

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A computer model for simulation of smoke movement through air conditioning systems is described. A brief overview of air conditioning systems is presented. The methods of calculation of mass flow, smoke transport, fan flow and duct and fitting resistances are presented along with a general description of the program logic.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air conditioning; air movement; computer models; ducts; fans; smoke movement; ventilation systems

13. AVAILABILITY

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