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THE RELATIONSHIP BETWEEN OBSERVED POLLUTANT CONCENTRATIONS AND BUILDING VENTILATION SYSTEM DESIGN

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ABSTRACT

The relationship between the observed concentration of air pollutants at points within a building and the characteristics of the ventilation system is examined, and a basic set of analytical expressions showing these relationships is presented. The extension to large and complex systems is considered, and an example of the application of the equations to an actual air quality problem is given.

Introduction

The significance of observed concentrations of air pollutants in samples taken from a building is directly dependent upon the relationship between the point of observation, the pattern of pollutant release within the building, and the operation of the ventilation system. The instantaneous pollutant concentrations observed at any point within a building will depend not only upon the position, the amount and the timing of the pollutant releases but also upon the details of the air intake, exhaust, and circulation arrangements.

The accurate prediction by a system analyst of the impact of a given pollutant release profile upon the air quality at any given location is dependent on a full knowledge of the air movement patterns. The converse problem of interpreting observed concentrations to infer the origins of pollutants, or to establish a general concentration profile within a building on the basis of a few local observations is similarly dependent upon an analytical understanding of the pollutant release and ventilation system interactions.

It is, of course, apparent that any air quality observation requires informed interpretation. The same air sample analysis can have a totally different meaning depending upon the time and position at which the observation was taken. For instance, a high concentration observed near the air supply point in a space will imply at least as high a concentration throughout the space, whereas a similar observation near an exhaust position may indicate only a very local condition in a building otherwise free of objectionable pollutant concentrations. Also, of course, where pollutant releases are intermittent, concentrations observed can only be understood with respect to the time of measurement.

Designers of large office and commercial buildings, and those who must subsequently evaluate the performance of their ventilating systems in terms of the air quality maintained in the space, have specific requirements for information upon which to base their analysis. Primarily, they must know, in overall terms, the rates of removal of pollutants from the building as a whole, which are largely dependent upon the amounts of fresh air supplied. But they must also know the paths followed by the various air streams, and the amounts of mixing between air streams and of air recirculation within the building. And they must know, or be able to infer, the profile of pollutant introduction, to know whether these pollutants are uniformly released throughout the space, such as those generated by the occupants, or are injected at specific points. It is also necessary to know if these releases are intermittent or continuous, and if intermittent to know the times of release. And finally they must be able to express and assess the relationships amongst those factors.

In an effort to serve these needs we present here a set of equations which separately express most of the basic relationships, and which can be used singly or in combination to represent many quite complex pollution release profiles and ventilation systems. We have found these expressions to be useful in several engineering applications, and that they not difficult to adopt to specific special situations.

Fully Mixed, Isolated Space   Case A

Consider a building space, such as shown in Fig. 1, isolated from other areas, which has a fresh air supply of X kg/s (lbs./hr.) pressurizing the space so all airflow through vents and by filtration is outward. There are internal pollution sources, which for simplicity can be considered to release a single compound, located within the space and steadily releasing a total of Y kg/s (lbs./hr.) of the polluting gas. The air within the space is considered to be well mixed by internal circulation.

Under these conditions an equilibrium state will result in which the concentration of the pollutant gases everywhere in the space will be

$$C = Y/X \text{ kgs of pollutant per kg of air,}$$

assuming there is no internal absorption of the pollutant.

This can be thought of as the standard reference case. As long as we assume the steady, isolated, fully mixed condition the concentration resulting is independent of time, position, size and shape of the space, and distribution of the sources of pollutants. In this case the interpretation to be placed upon an observation taken at any time and at any point in the space is simple and invariant.

Simple Flow Path with a Steady Point Source   Case B

Consider a space having a simple airflow pattern as in Fig. 2. X kg/s (lbs./min.) of fresh air are introduced and flow along a well-defined path within the isolated space, and are exhausted at the end of the path. The air is considered to be mixed across the path at any point, but not along it. At some point $S = S_s$ along the path, a steadily emitting source of pollutant introduces Y kg/s ($^{\text{lbs.}}$/min.) of pollutant gas. The concentration C everywhere upstream of the source, $0<S<S_s$, will be zero. Everywhere downstream of the source, $S>S_s$, the concentration will be $C = {}^{Y}/X$ kgs of pollutant per kg of air. A sample taken upstream of the source will show no pollutant, while one taken downstream will show a concentration of $C = {}^{Y}/X$.

Simple Flow Path with a Distributed Source   Case C

Case C, as shown in Fig. 3, is similar to Case B, except that the pollutant source is uniformly distributed along the path, but releases in total Y kgs/s of pollutant vapours.

The concentration of pollutant found at any point will be in linear proportion to its distance along the path, given by

$$C = (S/S_T)\ (Y/X),$$

and thus varying from zero at the air entry (S = 0), to (Y/X) at the exhaust point ($S = S_T$). This type of uniform source is typical of occupant-produced contaminants. The significance of the concentration observed is directly related to the point of sampling.

Simple Flow Path with Recirculation and a Point Source   Case D

Consider Case D, shown in Fig. 4. This is similar to Case B, but has Z kg/s (lbs./min.) recirculated through an air conditioning unit that has no pollutent adsorption function. (Typical actual systems would have ratios of (Z/X) between 0 and 10). In this case the concentration upstream of the source, $0<S<S_s$, will be

$$C = (Y/X)\ (Z/(X + Z)) = YZ/(X^2 + XZ),$$

while that downstream ($S>S_s$), will be

$$C = Y/X.$$

As the rate of recirculation, $(Z/(X + Z))$, increases, the concentrations upstream of the source begin to approach those in the reference case, Case A.

Simple Path with Recirculation and a Distributed Source Case E

This case, shown in Fig. 5, is similar to Case D except that the source of pollutants of strength Y kg/s is considered to be uniformly distributed along the path. In this case the concentration of the pollutant is given by

$$C = (Y/X)\ (Z/(X + Z)) + (S/S_T)(Y/(X + Z))$$

Simple Path with Recirculation and Both Distributed and Point Pollution Sources Case F

This case is a combination of Cases D and E. As shown in Fig. 6, there is a pollution point source of strength Y_1 kg/s at position $S = S_s$, and a uniformly distributed pollution source of the same compound, with strength Y_2 kg/s, with a fresh air supply of X kg/s and a recirculation rate of Z kg/s. The concentration C at any point S along the path will be:

$$C = (Y_1 + Y_2)[Z/(X^2 + XZ)] + (S/S_T)[Y_2/(X + Z)]$$

$$\text{for } 0 < S < S_s$$

and $$C = (Y_1 + Y_2)[Z/(X^2 + XZ)] + (S/S_T)[Y_2/(X + Z)] + [Y_1/(X + Z)]$$

$$\text{for } S > S_s$$

Multiple Path with Recirculation and Both Distributed and Point Sources Case G

Case G, shown in Fig. 7, is an extension of Case F to include the effect of multiple parallel paths of the air flow through the occupied space. A total of N parallel paths is considered, taking proportions of the total flow P_1, P_2,--P_R,--P_N, such that $P_1 + P_2 + \text{--} + P_N = 1$. The uniformly distributed sources of total strength Y_2 exist throughout the space, and point sources of strengths Y_1^R are located in the passage such $Y_1^1 + Y_1^2 + \text{--}\ Y_1^R + \text{--}\ Y_1^N = Y_1^T$. Consider the case of the source of strength Y_1^R located on path R, which takes the fraction P_R of the total flow.

The concentration of the pollutant in the P_R passage will be:

$$C = (Y_1^T + Y_2)[Z/(X^2 + XZ)] + (S/S_T)[Y_2/(X + Z)]$$

for $S < S_s$ in the R passage, and $0 < S < S_T$ in other passages without point sources,

and $$C = (Y_1^T + Y_2)[Z/(X^2 + XZ)] + (S/S_T)[Y_2/(X + Z)] + Y_1^R/P_R(X + Z)$$

for $S > S_s$.

Pulsed Emissions

Pulses of a pollutant gas can be emitted in any system. Such pulsed emissions would usually not originate from a distributed source, but more or less from a single point, since they would typically originate from the opening or breaking of a vessel, or an emission from some apparatus. For an initial period following release at a point the concentration of the pollutant near that point will be very high. In well mixed air spaces this concentration will rapidly fall to the mixed decay concentration. We will consider cases in which initial mixing has diffused the initial high but transient local concentration.

Pulsed Emission in a Fully Mixed, Isolated Space Case H

This case is similar to Case A and Fig. 1, except that in addition to the steady emission from the source S of Y kg/s (lbs/hr.) there is a single pulse releasing P_o kgs (lbs) of the pollutant gas emitted at time t=0. The space has a total volume of V m^3 (ft^3) and an air density of ρ kg/m^3 (lb/ft^3). The concentration at every point in the space at any time t secs subsequent to the release will be

$$C = Y/X + \frac{P_o}{V\rho} e^{-(\frac{tX}{V\rho})}$$

Simple Flow Paths with Pulsed Emissions Case J

In once-through simple flow path cases, similar to Cases B and C, a concentration peak will pass downstream from the pulsed injection point and effectively disappear from the space within $V\rho/X$ seconds. The intensity of the peak as it passes any downstream position will depend upon the mass diffusivity of the pollutant gas in air, and on the amount of lateral mixing, and will weaken as it moves toward the exhaust point. Detailed modelling in such cases is difficult, and probably unnecessary in most applications.

Pulsed Emissions into Systems with Recirculation Case K

For systems with recirculation, such as in Cases D, E, and F, the concentration transient is much more persistent. With recirculation rates of Z/X substantially greater than unity, and assuming the usual turbulent mixing at the supply diffusers, and normal gas diffusivities, the additional concentration due to the pulsed injection of P_o kgs of pollutant gas will, everywhere in the space, be

$$C = \frac{P_o}{V\rho} e^{-(\frac{tX}{V\rho})} \qquad \text{for } t > V\rho/X,$$

where V is taken as the total volume of the system, including the volumes of the ducts and plenums in addition to that of the ventilated space.

Multiple Component Gases and Alternative Volume Units

While the discussion has, for simplicity, considered only a single pollutant gas, each component gas in a mixture can be treated in the same way by the same equations, since, to a good degree of approximation, they do not influence one another. It should also be noted that the equations are presented in mass units. They are equally expressible in volume units, following Leduc's Law, simply by introducing the specific volume, a form often favoured by engineers despite its conceptual difficulties.

The Importance of Ventilation System Design in Air Quality Control

Consideration of these relationships between ventilation systems and pollutant concentration identifies and quantifies some major differences to be found between alternative ventilation systems with respect to the air quality that results in the working spaces. For instance, we compared the systems in two outwardly similar large office buildings in the same city. For equal pollutant release loads and equal fresh air make-up amounts the two systems were in remarkable contrast.

Building One, with 12 nearly identical open floors, is zoned vertically. Each floor is similarly divided into six areas or sub-zones, corresponding to different external exposures. The set of corresponding areas on each of the 12 floors, one above the other, constitutes a single zone, and each of the 6 zones is served by an independent ventilation system. The supply air flows in parallel through the twelve areas of each zone, and the return air is collected in a common return. A fraction of the flow, usually about 20%, is exhausted and the balance mixed with fresh make-up air, conditioned and recirculated.

Although the six systems are mechanically separate and independently controlled, there is uncontrolled mixing between the six areas on each floor since they are open to each other. In consequence a pollutant released anywhere in the building is rapidly diffused throughout the structure. There is no effective way to isolate a given source, and although dilution is high, resulting in reduced concentration levels, the whole building is exposed to every pollutant emitted anywhere within the building. In modelling this system the matrix of subsystems would utilize Cases E, F and G.

Building Two, by contrast, with eleven open floors very similar to those in Building One, is served by 22 independent air handling systems. Each system serves one half of one floor, and consists of a recirculating air handling unit which takes about 20% fresh air from a common tempered air supply serving all 22 systems, and exhausts the corresponding amount to a common building exhaust system discharging to the outdoors. This system effectively isolates each floor, and minimizes even the mixing between the two zones on any floor, since with only 2 rather than 6 zones, there is only a limited shared zone boundary area. Each of these 22 subsystems is adequately described by Case G. When the pollutant release rate in a given zone in this building is increased, it is possible to increase separately its fresh air supply rate in response. This system, using no more make-up fresh air and energy than the system in Building One, nevertheless permits effective air quality control.

The contrast between these two buildings illustrates the importance of the ventilation system design and operation in air quality control.

General Extension

Almost every large office building will offer a special set of conditions with respect to fresh air supply, recirculation provisions, and air distribution and return patterns. Moreover, the internal pollution sources will have different patterns depending upon the specific uses of the space. However, even quite complex cases can be approximated by a combinatin of the cases that have been presented. To represent completely a large building system, with many differently arranged floors, with multiple sources of fresh air, and with complex supply, return and distribution manifolds, would require an extensive assembly of simultaneous equations of the types indicated. The formulation of such an extensive set of equations, while not difficult, requires care, and the work of solution is best carried out on a computer.

For simpler spaces, however, such as in smaller buildings, or in subsections of larger buildings, the various cases can be applied directly in the analysis of air quality problems. One such application, to a subsection of the building previously identified as Building Two, will be used in illustration.

Illustrative Example

In this example problem, air quality measurements had been made, using a gas chromotography methodology, at a very limited number of positions on one of the open plan office floors. The objective was to make a rational inference from these few observations of the air quality at any other point on that floor.

The layout of the subsection is shown, somewhat simplified for clarity, in Fig. 8. The supply air is distributed through 6 main duct systems, labelled A to F, each with many diffusers. The discharge rate from each of the diffusers was determined, and the total flow through each of the six duct sections was established. The boundaries of the return flow paths through the space were graphically determined on the basis of the flows being proportional to the available cross-sections of the paths. The boundaries so determined for the return flow paths of the air from duct A are shown by dashed lines. The position of a sampling point which fell within this return flow path is designated by SP in Fig. 8.

Lane A was found to carry the fraction $P_A = \frac{13210\ \text{SCFM}}{40830\ \text{SCFM}} = 0.32$ of the total flow to the space, where 13210 SCFM is the supply flow through duct A and 40,830 SCFM is the total air supply to the zone. Point SP was found to be at the distance ratio $S/S_T = 0.75$. There were no known point sources, such as duplicating machines, in the region served by duct A, and hence a uniformly distributed pollutant source distribution representation of intermediate density office occupation was assumed. This source typically includes a wide spectrum of organics of the early elating class. On an arbitrary scale assumed to be linear the observed level of pollutants was assigned a value of 0.75.

Case G will apply here, but in a simple form since there were no known point sources and $Y_1^T = 0$.

$$C = (Y_1^T + Y_2)[Z/(X^2 + XZ)] + (S/S_T)[Y_2/(X + Z)]$$

For the present example,

S_T = 8 arbitrary units of length measured on Fig. 8.

S = 6 arbitrary unit of length along path to SP

C = 0.75 assigned concentration, dimensionless, taken from chromotography readings expressed in arbitrary units.

X = 5400 standard cubic feet per minute or $5400 \times 0.075 = 405$ lbs./min. where $\rho = .075$ lb./ft^3

Z = 35,4300 SCFM = $35430 \times .075 = 2657$ lb./min.

Solving for Y_2, we obtain:

$$0.75 = (0 + Y_2)[2657/(405^2 + 405 \times 2657)] + (6/8)\ [Y_2/(405 + 2657)]$$

$$Y_2 = 334 \text{ arbitrary mass units.}$$

This value of Y_2 applies for use in the equation to evaluate the concentration at any point in the space. For instance, substituting for the point W where $S = 2$ units shows a concentration of $C = 0.70$ at that point. The small difference between concentrations at SP and at W is because of the high recirculation fraction in use in the section under examination. By repeating this simple procedure the concentrations everywhere in the space can be mapped.

Conclusions

Air quality observations taken in a building and not related to the design and operation of its ventilation system are incomplete and cannot be properly interpreted. Analytical expressions able to represent these relationships to a good level of engineering approximation have been presented.

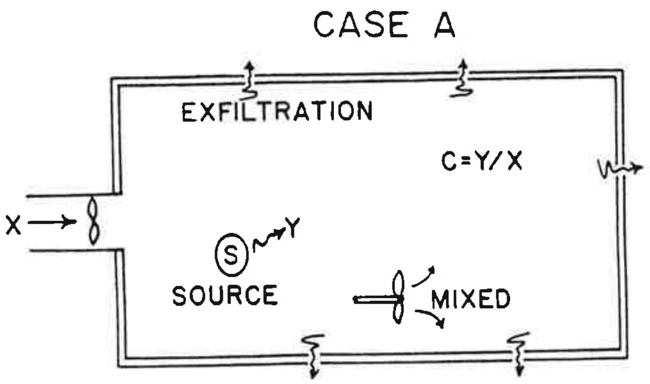

Fig. 1 Fully mixed condition in an isolated space. Case A.

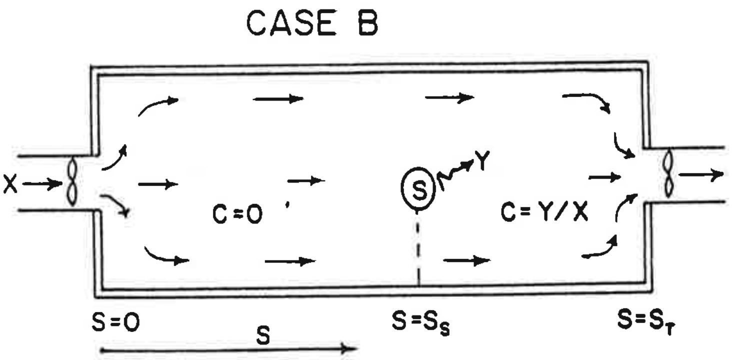

Fig. 2 Simple flow path with a steady point source. Case B.

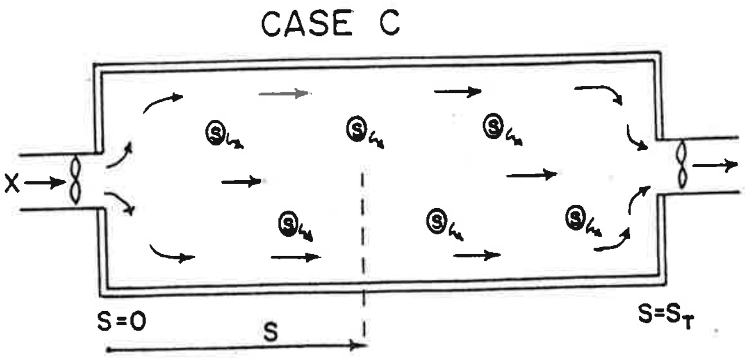

Fig. 3 Simple flow path with a uniformly distributed source. Case C.

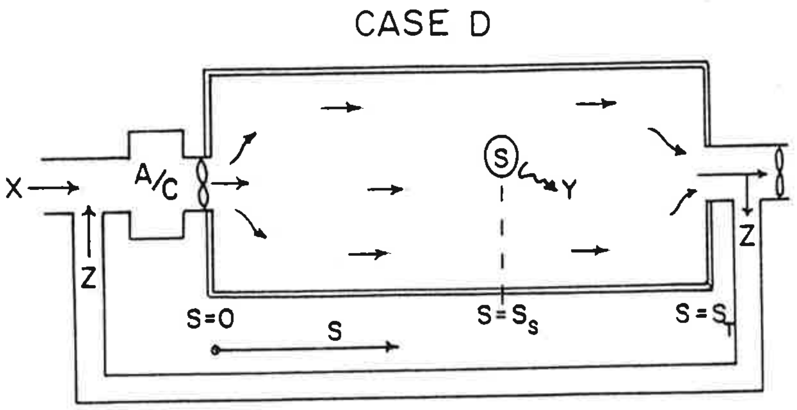

Fig. 4 Simple flow path with recirculation and a point source. Case D.

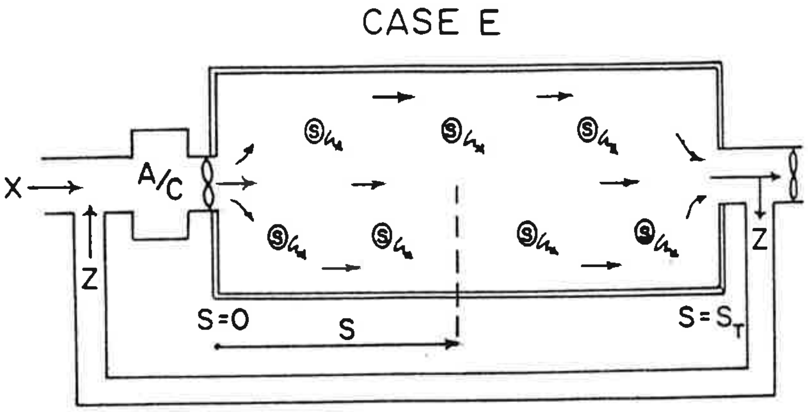

Fig. 5 Simple flow path with recirculation and a distributed source. Case E.

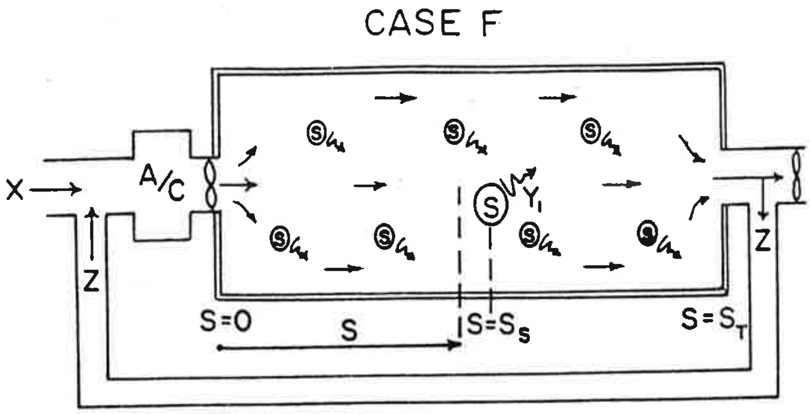

Fig. 6 Simple flow path with recirculation and both distributed and point sources. Case F.

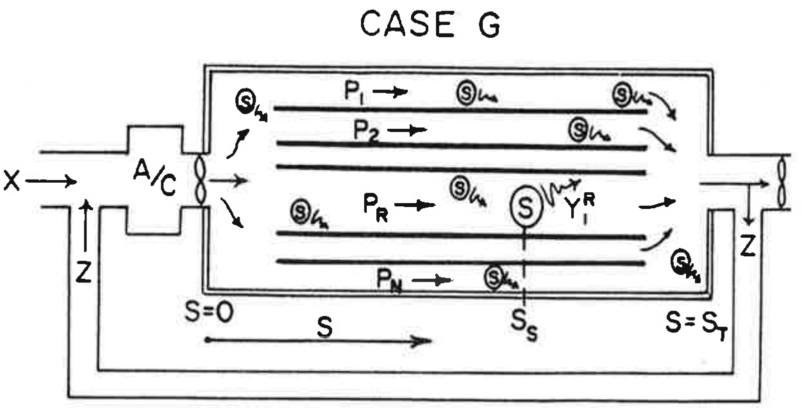

Fig. 7 Multiple flow paths with recirculation and both distributed and point sources. Case G.

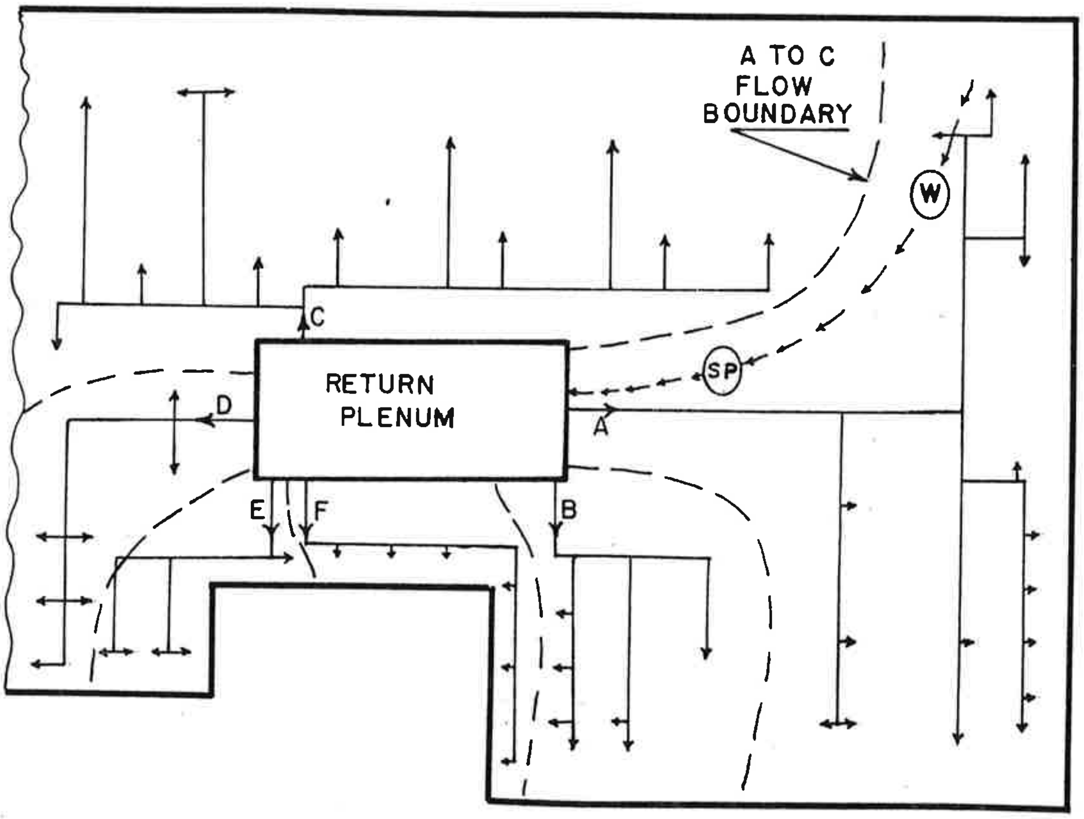

Fig. 8 Plan layout of ventilation subsystem taken in example.