Influence of vent positions on smoke clearance from a room

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Results of solutions to the equations governing the clearance of smoke in laminar and in turbulent flow from a single rectilinear room are presented for five different vent arrangements. These results show that the average smoke concentration in the room decreases in an approximately exponential manner with time at a rate that depends much more on room geometry (vent positions in the present case) than on whether the flow is laminar or turbulent. The benefit of this observation is that, provided the clearance air jet is disrupted by impingement on a solid surface within the room, the analysis of smoke movement can for many practical purposes be limited to consideration of laminar flow only. An exceptional case is when the jet is allowed to take a straight line path between the inlet and outlet vents. Here in the absence of the large scale eddies caused by jet impingement, the smaller scale eddies of turbulent flow become relatively important as a mixing mechanism and give higher clearance rates than in laminar flow. Even so, this type of geometry is best avoided. The appearance of the jet is shown in a graphic presentation of the numerical results for laminar flow.

Keywords: smoke clearance; vent positions; clearance air jet

Introduction

When fire breaks out in buildings, any resulting deaths are more likely to be caused by smoke than by the smoke-initiating fire. The fire is frequently confined to relatively small regions, such as a single room, whereas the smoke produced can rapidly be swept throughout the entire building by agencies such as the air-conditioning system and pressure differences caused by winds and "stack" effects. The control of smoke in the event of fire in a building is therefore of major importance to the safety of its inhabitants, and the development of any effective smoke clearance system must be conducted against a background of reliable data on smoke behavior. An element of this database is a knowledge of how smoke will clear from a single room and how the clearance rate may be influenced by the positions of the vents. This is the aspect of smoke clearance addressed in this paper, noting that the results will also be relevant to air conditioning in general.

Factors affecting smoke clearance

The rate at which smoke clears from a room depends on many factors, important among which are the detailed shape and the size of the room, the flow rate of clearance "air" which itself may have a nonzero smoke concentration, the time measured from the start of smoke clearance, viscosity, and the difference between the room temperature and that of the clearance air (buoyancy effects). When present, heat and smoke sources within the room and heat transfer through the room walls will also be important. The shape of the room for smoke clearance purposes is the gas-filled shape and therefore includes furniture and other equipment in the room. Also to be included in the room geometry are the shapes and positions of the clearance air inlet and smoke outlet vents. The size of the room is defined by some characteristic length scale, which for a given vent shape and clearance air flow rate fixes the velocity of the clearance air at the inlet vent which, in turn, can be used to define a Reynolds number for the smoke clearance process.

In the absence of smoke and heat sources and buoyancy effects, the average smoke concentration c in the room at any time t from the start of smoke clearance will satisfy a relation of the form:

$$\frac{c}{c_0}=f\left(\frac{Qt}{V}, \mathrm{Re}, \mathrm{Geom}\right)$$

where c_0 is the average smoke concentration at $t=0$, Q is the volume flow rate of clearance air, V is the smoke-filled volume of the room, Re is a Reynolds number characteristic of the flow system, and Geom is the list of length ratios necessary to define the shape of the room. The Reynolds number has a bearing on the turbulence level and distribution in the room, which will influence the smoke clearance rate through the mechanism of turbulent mixing. The Geom term is potentially the most troublesome in the relationship. For a typical room the list of variables subsumed under this umbrella term can be very long, and the labor of representing them precisely in the computer could be daunting. There are also the consequential demands on computer memory and speed, mainly because of the inevitable numerical grid refinement and therefore increased calculation load, needed to match any increase in geometric complexity.

Whatever the geometry, the problem of predicting c is not an easy one, because its rigorous determination requires the solution of the Navier–Stokes, continuity, and smoke concentration equations, together with some form of turbulence model when the flow is other than entirely laminar.

Idealized clearance

The presentation of results of such an analysis (for a simple geometry) is the principal purpose of this article. However, it is of some interest and utility to note at this point that exact

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solutions are immediately available for two limiting flow conditions: the extremes of zero mixing and perfect mixing of the clearance air with the smoke in the room.

Zero mixing

Zero mixing may be approximated in flows where buoyancy forces are dominant, as in the case where cold air is slowly admitted through a vent in the floor of a room filled with hot smoke that is allowed to leave through another vent in the ceiling. Conditions may be such that a rising horizontal interface exists and that the smoke concentration will remain constant at c_0 and zero for all points above and below the interface, respectively, and at a fixed point the concentration will change discontinuously from c_0 to zero as the interface passes through the point. It follows that the room will be completely clear of smoke when:

$$\frac{Qt}{V}=1$$

This expression is only one of a family of solutions for zero mixing in which the vent positions are parameters. Consider the consequence of having the outlet vent at a position on one of the walls midway between floor and ceiling. The smoke will clear from the room as in the first case until the level of the interface reaches that of the outlet vent, when further smoke clearance will effectively cease. Taking this example to an extreme, when the outlet vent is also in the floor then there will be practically no smoke clearance.

Expressed in terms of the average smoke concentration c for the room, and assuming small vents for simplicity, the family of solutions is given by

$$\begin{aligned}\frac{c}{c_0}&=1-\frac{Qt}{V} \qquad \frac{Qt}{v}<1\\ &=1-\frac{v}{V} \qquad \frac{Qt}{v}>1\end{aligned} \tag{1}$$

where v is that part of the room volume lying between the floor and the outlet vent level. Figure 1 summarizes the situation.

Yet another zero mixing approximation suggests itself. It occurs when cold air is admitted through a ceiling vent into a room filled with hot smoke for which the outlet vent is identical to, and vertically below, the inlet vent. Here we may imagine that the cold air falls through the hot smoke as a vertical column, initially displacing smoke ahead of it—a special case of the first zero mixing case discussed—before reaching the quasi-steady-state condition of a column of air surrounded by smoke. Mixing between the two is somewhat greater in this case through viscous action at the boundary of the jet. Note in this example that the stability of the column has little, if anything, to do with buoyancy but is due to the absence of external forces disposed to disturb it. If the momentum of the jet was imparted by a fan, say, rather than by buoyancy forces, the result would essentially be the same (and the alignment of the vents, in this case, need not be vertical). In the absence of disturbing influences within the flow itself, the alignment of the vents prevents the disruption caused by impact between the jet

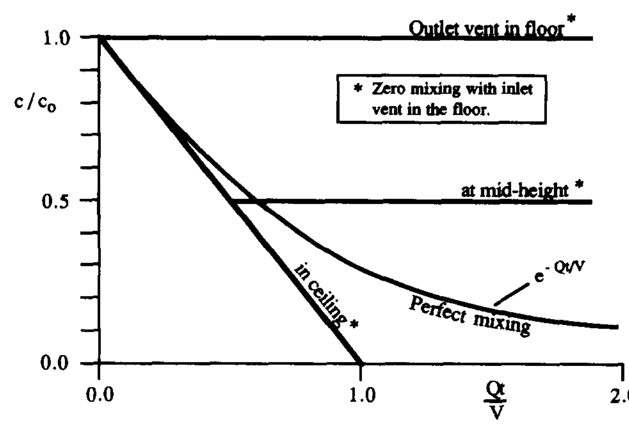

Figure 1 Idealized mixing

and the wall facing the inlet vent. Consequently, we may anticipate that when the projection of the inlet vent onto the plane of the outlet vent lies entirely within the outlet vent, the smoke clearance rate will be slow by virtue of the poor mixing between the clearance jet and the surrounding smoke. In short, perfectly aligned vents are a poor design feature.

Perfect mixing

In the opposite limit, perfect mixing, the smoke concentration is the same at all points in the room, and the rate of increase of smoke within the room is therefore given by

$$\frac{dN}{dt}=-\frac{QN}{V}$$

where N is the total number of moles of smoke in the room and N/V is the uniform smoke concentration $c(t)$ in the room and also in the exhaust volume flow rate Q. Dividing both sides by V and integrating gives

$$\frac{c}{c_0}=\exp\left(-\frac{Qt}{V}\right) \tag{2}$$

Equation 2 has the same form as that for the decay of a radioactive isotope species and, as in nuclear physics, it is convenient to characterize the decay rate by defining the "half-life" for the smoke clearance system as that time $t_{1/2}$ taken for the smoke concentration to fall to half its initial value, i.e., the time from commencement of smoke clearance for c/c_0 to equal one half. It follows that:

$$\frac{Qt_{1/2}}{V}=0.693$$

regardless of the initial concentration c_0. See Figure 1.

Actual mixing

Equations 1 and 2 are exact for the particular conditions prescribed. Of the two limiting types, zero and perfect mixing, the zero mixing limit seems a generally unsatisfactory basis for

Notation

c	Average smoke concentration
c_0	Uniform smoke concentration at $t=0$
Geom	List of length ratios needed to define room shape
Q	Volume flow rate
t	Time
V	Room volume
v	Air speed at inlet vent
v_f	Steady-state air speed at inlet vent
λ	Constant in equation for v

design. It looks only too easy to produce a nearly zero mixing design with a disastrously low smoke clearance rate (e.g., perfectly aligned vents); but it is unrealistic to assume that buoyancy effects will always be strong enough to maintain the horizontal interface with high inlet flow rates that would give the excellent clearance rates possible in this case—even if the designer always had the freedom to position the vents in the ceiling and the floor. A design for a high degree of mixing is much more realistic. Misalignment of vents will generally be easy to arrange, and provision for the clearance air jet to impinge on the solid surfaces of furniture, equipment, and, if necessary, specially placed baffles, will all be conductive to vigorous mixing. No stability problems will be encountered in trying to maintain a horizontal interface, and buoyancy forces, strong or negligible, are automatically accommodated. Perfect mixing, of course, will never be achieved at practical flow rates of clearance air, and there will inevitably be regions where smoke clears only slowly through molecular diffusion and viscous mixing effects, rather like the clearance mechanism in the case of perfectly aligned vents. The practical smoke clearance curve on the plane of Figure 1 is therefore likely to lie somewhere between a horizontal line through c/c_0 and the perfect mixing curve, more nearly approaching the latter as greater efforts are made to encourage mixing.

Actual clearance—computer analysis

To get some idea of the importance of Reynolds number and geometric effects, the complete system of governing equations has been solved numerically for the following simple cases: A single rectangular room of dimensions $6\,m \times 4\,m \times 2.5\,m$, with five different arrangements of one inlet and one outlet rectangular vent as shown in Figures 2–6. For reference purposes the rooms are labeled RMA, RMB, RMC, RMD, and RME. In RMA the vents are perfectly aligned (i.e., the clearance air jet can proceed in a straight line from inlet to outlet), the misalignment increasing progressively from RMA through RME. At $t=0$ the smoke/air mixture in the room is stationary and of uniform (and arbitrary) concentration. There are no buoyancy effects or smoke sources within the room. Smoke clearance is started at $t=0$ by a fan whose starting characteristic is

$$v=v_f[1-\exp(-\lambda t)]$$

where v is the clearance air speed at the inlet vent and v_f and λ are constants chosen here to be $1.0\,m\,s^{-1}$ and $0.1\,s^{-1}$, respectively ($v=0.99v_f$ at $t=46\,s$).

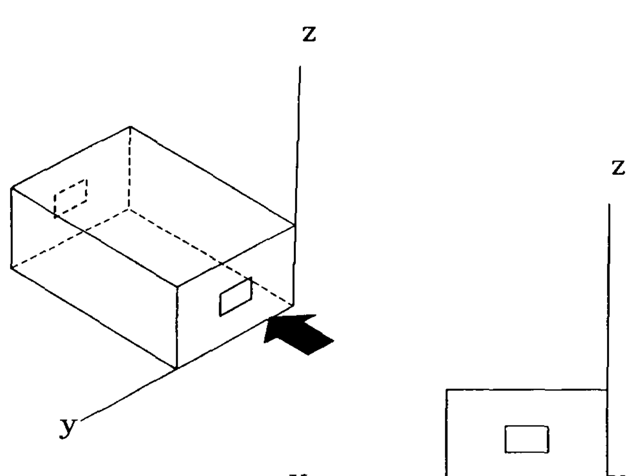

Figure 2 Room RMA

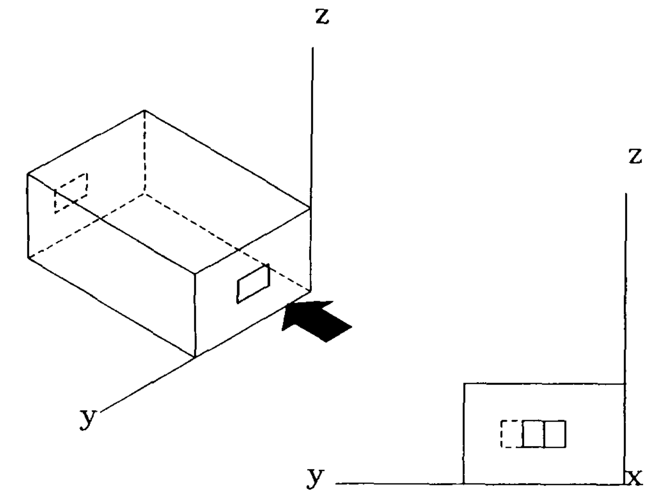

Figure 3 Room RMB

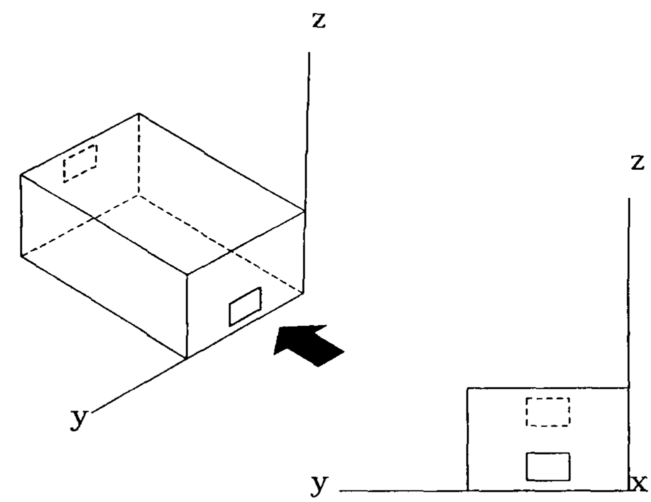

Figure 4 Room RMC

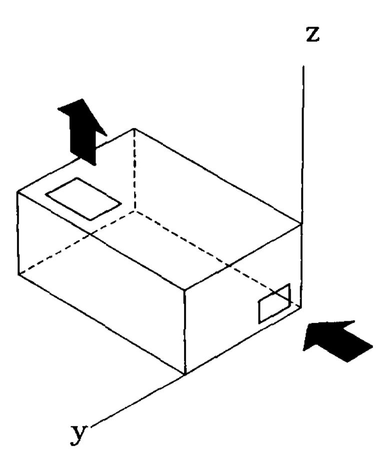

Figure 5 Room RMD

For each room configuration the smoke concentration was calculated as a function of time at every node in the numerical grid system for the cases where the flow within the room was (a) everywhere laminar and (b) everywhere turbulent. An outline of the calculation method is given in the Appendix. Leonard's[1] quick differencing method was used in the spatial

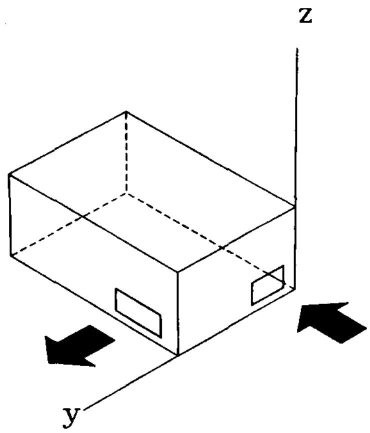

Figure 6 Room RME

discretization of the governing equations and Brian's[2] method was used for time stepping. In the turbulent flow calculations the k–ε model of turbulence was utilized.

Results

Average smoke concentration

A convenient, if incomplete, description of the smoke clearance process is to present the average smoke concentration for the room as a function of time. The average concentration $c(t)$ is defined as $\sum c_i v_i / V$ and c_i is the concentration for one of the control volumes v_i into which the room volume V is divided for calculation purposes, the sum being over all the control volumes v_i. Figure 7 shows the results for laminar flow, and Figures 8 and 9 show these results again with the turbulent flow results added for comparison.

The principal observation to be made from Figure 7 is that, the more tortuous the path forced on the clearance air by the room geometry, the faster the smoke clears. In room RMA the outlet vent is exactly opposite the inlet vent and the clearance air can take a straight-line path between the two. Because the flow is laminar, the clearance of smoke from regions of the room not lying directly between the vents relies on the weak mechanism of entrainment by molecular viscosity interaction, and consequently the smoke clearance is extremely slow. This is an example of a (nearly) zero mixing flow of a type qualitatively described previously, as will be made clearer presently. In room RMB the vents are still on opposite walls, as in RMA, but are slightly offset from each other, requiring a deflection of the jet for it to negotiate the misalignment. This introduces inertia effects that promote a vigorous mixing of the air and smoke in the room and therefore a marked increase in the clearance rate relative to that in RMA. The offset between the vents is successively increased in rooms RMC, RMD, and RME with a beneficial effect on mixing and therefore on the smoke clearance rate. Note, however, that the differences in the half-lives in these last three configurations are not nearly so great as between RMA and RMB. In other words, it does not require a very high degree of turning of the clearance air jet for nearly complete mixing to take place. Therefore increasing the deflection of the jet by increasingly displacing vents, while beneficial as the results show, has less and less potential for improving the degree of mixing.

The differences between laminar and turbulent flow results

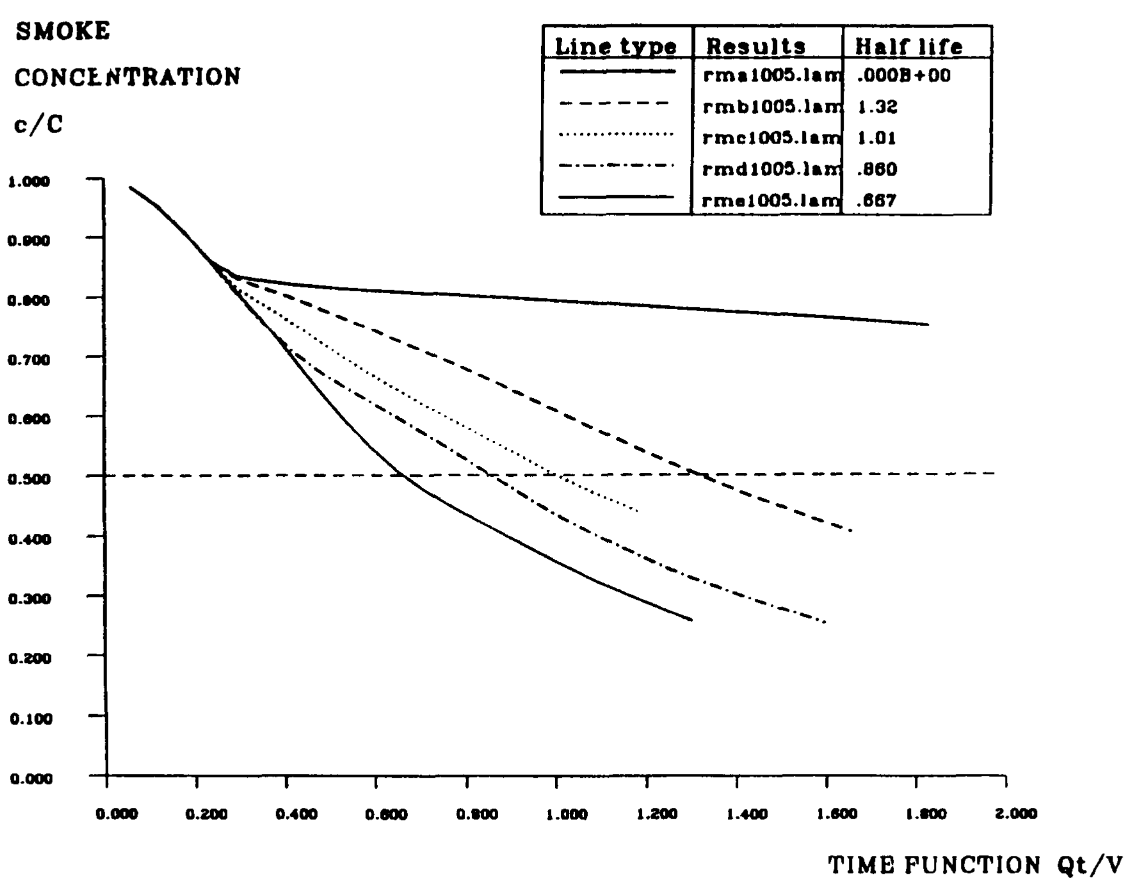

Figure 7 Decay of smoke concentration (laminar flow)

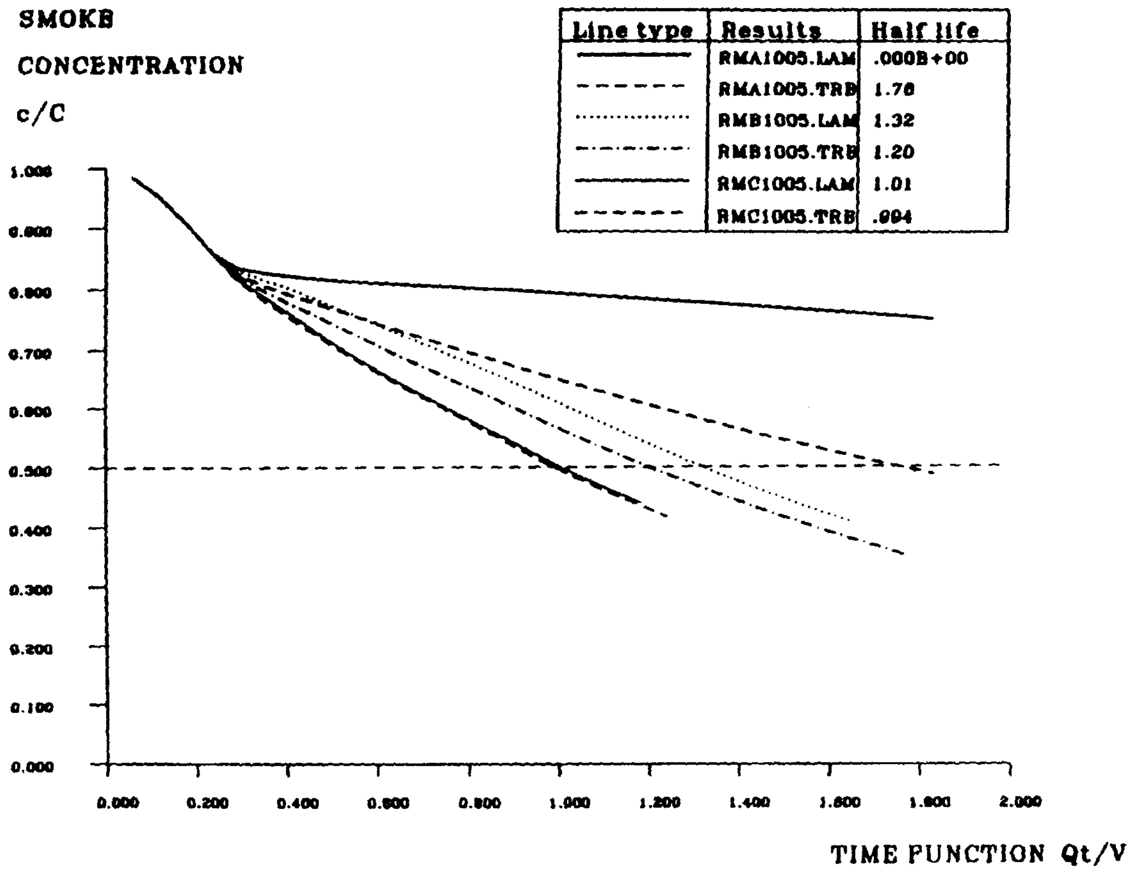

Figure 8 Comparison of laminar and turbulent results for smoke decay (RMA, RMB, and RMC)

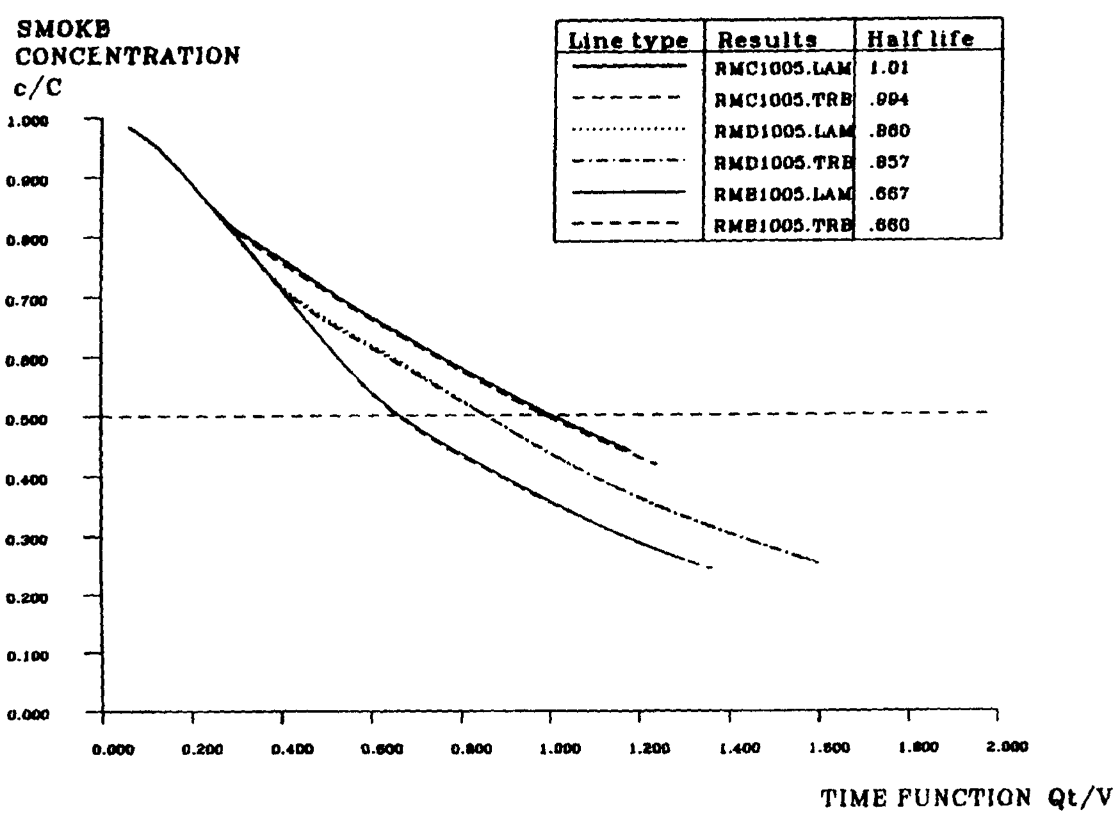

Figure 9 Comparison of laminar and turbulent results for smoke decay (RMC, RMD, and RME)

are shown in Figures 8 and 9. They demonstrate that there are two important mixing mechanisms, namely, turbulence and the disruption of the jet caused by its rapid deflection. In the case of RMA, where the jet is not required to turn, turbulence has a major influence on the smoke clearance rate. When the jet is forced to change direction, even slightly as in RMB, the consequent disruption causes such a high degree of mixing that the relatively small-scale fluctuations in turbulent flow are much less important. This phenomenon is very clearly shown by Figures 8 and 9, and it has the practical importance that, provided the inlet and outlet vents are not too closely aligned, the differences in the smoke clearance rates for laminar and turbulent flow are probably negligible. Thus the two types of flow need not be distinguished in calculation method. Analytically, it is simpler to work with laminar flow than with turbulent flow.

Two small additional points are worth mentioning in connection with the shapes of Figures 7–9. The first is to explain the almost identical starting sections from $Qt/V=0$ to about $Qt/V=0.25$, regardless of the geometry or whether the flow is laminar or turbulent. For some time after the fan is started, the smoke concentration near the outlet vent must in every case remain very near the initial value regardless of other factors. Therefore the rate at which smoke is exhausting is initially the same for all rooms, because the volume flow rates are the same. Eventually the different inlet air and smoke mixing characteristics caused by differences in geometry and flow type influence the smoke concentration at the outlet vent, and the rate at which smoke is exhausted changes accordingly. For example, in room RMA the incoming air hardly mixes with the smoke in the room and initially it more-or-less pushes a "tube" of smoke ahead of it through the outlet vent; the rate of smoke clearance in this time interval is just as rapid as for any other geometry. However, when the front of the clearance air jet reaches the outlet vent, and because of the poor mixing characteristic, the smoke concentration in the exhaust falls quite quickly to a low value; the rate at which smoke is leaving falls correspondingly, giving the very slow smoke clearance rate observed. The difference between RMA and the other rooms is that, in the latter cases, when the incoming air reaches the outlet vent, it is always well mixed with smoke (how well now depending principally on room geometry), so that the smoke thereafter exhausts at a higher rate than from RMA.

The second point concerns the slight S shape (or point of inflexion) seen in the curves. Very near $Qt/V=0$ the smoke is clearing only slowly. The concentration then falls more rapidly before slowing again to take up the exponential decay characteristic that might have been expected to hold all the way from $Qt/V=0$. The explanation is that, in the examples given here (and as in practice), the inlet air flow does not reach its maximum value instantaneously but rises from zero in the exponential manner already mentioned. With the fan characteristic adopted in the present work, the fan reaches 99% of its full flow rate only after 46 s from starting, which corresponds to $Qt/V=0.54$. Within this interval, particularly near the start, the increasing flow rate can be expected to have the distorting effect on the approximately exponential smoke clearance curve that would result from steady flow, and which is seen when the inlet flow does become steady.

Smoke distribution in selected planes

A better insight into the smoke clearance process, particularly the behavior of the clearance air jet, is assisted by a graphics package associated with the calculation program, which enables the smoke concentration distribution to be viewed on any room cross section at any time. The basis of the graphic method is to represent the smoke concentration at a point by a small

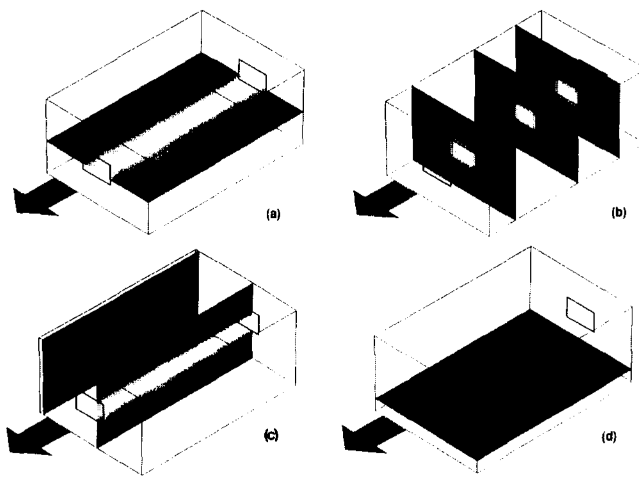

Figure 10 Smoke distribution in RMA ($Qt/V=2.4$)

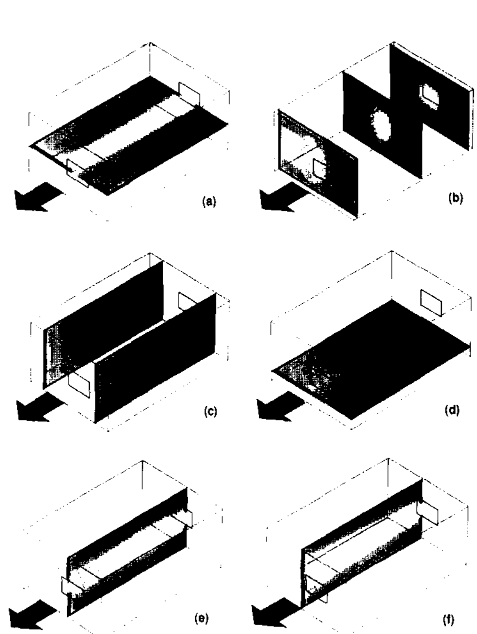

Figure 11 Smoke distribution in RMB ($Qt/V=2.4$)

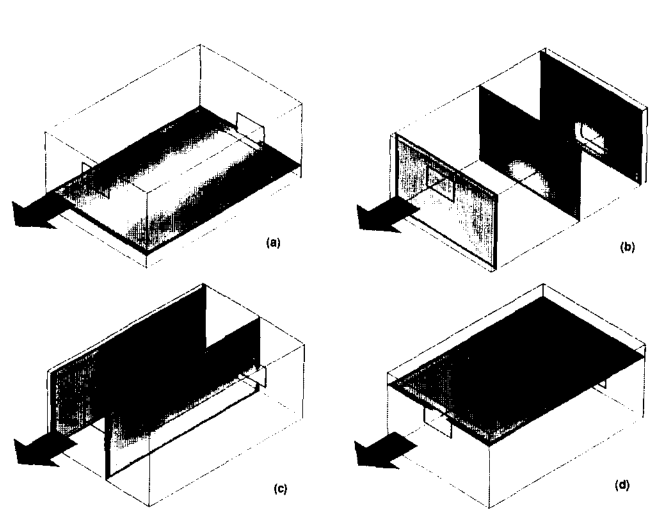

Figure 12 Smoke distribution in RMC ($Qt/V=2.4$)

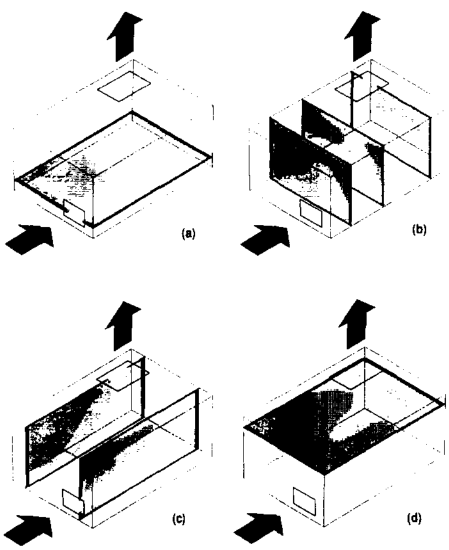

Figure 13 Smoke distribution in RMD ($Qt/V = 2.4$)

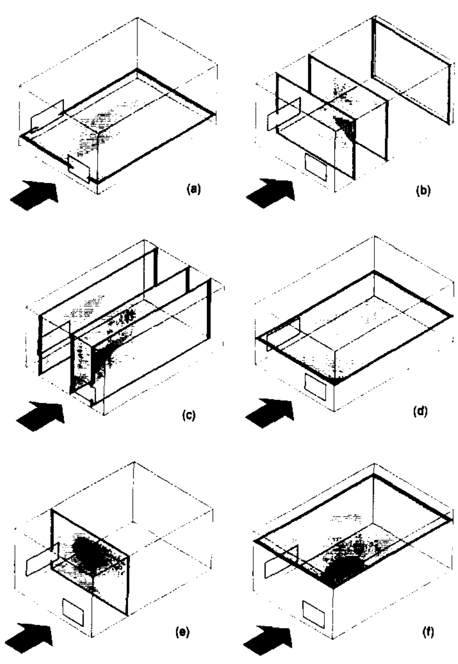

Figure 14 Smoke distribution in RME ($Qt/V = 2.4$)

patch shaded according to a gray scale varying linearly with concentration from black to white, these limits corresponding to $c = c_0$ and $c = 0$, respectively. Example cross sections are shown in Figures 10–14, the smoke distributions are all for laminar flow, and $Qt/V = 2.4$. They show that the clearance air jet tends to travel in a straight line from the inlet until disrupted by impact with the facing wall. Room RMA is a special case in which the vents are identical and exactly in line so that the jet passes through the outlet vent virtually undisturbed. This illustration clearly confirms the interpretation of the slow clearance rate noted for RMA in Figure 7 and the earlier reasoning that a nearly zero mixing type of flow like this could be realized. In this practical case, viscous effects at the boundary of the jet cause it to thicken slightly between the inlet and outlet. Because the vents are of the same size the "edges" of the jet do in fact strike the wall at the outlet causing a (rather weak) recirculation in the downstream half of the room, which sweeps some of the clearance air toward the side walls thereby encouraging a greater clearance rate in that vicinity. In RMB (Figure 11) part of the jet passes straight through the outlet, while the rest of it strikes the wall. Even this partial impingement causes a considerable disturbance in the flow to one side of the vent and results in the marked increase in the smoke clearance rate already seen in Figure 7. This general feature can be discerned in all of the results. When the recirculation following impact is sufficiently strong, it can, of course, influence the behavior of the jet before it strikes the wall. An interesting detail in this connection is shown in Figure 12(b) (Room RMC). The clearance air jet appears to be deflected slightly downward toward the floor, presumably by recirculation along the roof toward the inlet, which then turns downward onto the top of the jet.

Comment

The term "smoke" in this analysis and discussion can be interpreted as any gas, visible or otherwise, whose properties are similar to those of the clearance jet. In particular, the analysis applies exactly to an air-conditioning situation in which the concentration refers to, say, the volume (or mole) fraction of CO_2 in the room. Figures 10–14 then show graphically the distribution of fresh air and CO_2 (or "spent air") in the room and emphasize that, although the supply of conditioned air may be adequate in terms of air changes per hour, the air conditioning may still be unsatisfactory by virtue of poor vent positioning.

Conclusions

Smoke clearance air jets (and air-conditioning streams) should be caused to take a tortuous path between the inlet and outlet vents, and perfectly aligned vents should be strictly avoided. Provided this is observed, the smoke clearance rate does not depend on Reynolds number, i.e., on the level of turbulence within the room, because the dominant mixing mechanism is jet disruption caused by impingement on solid surfaces.

A useful measure of the effectiveness of a smoke clearance arrangement is the value of Qt/V when the average smoke concentration reaches half its initial value. For the room geometry considered here, a rule of thumb value is 0.7, or thereabouts, for a smoke clearance design that promotes good mixing. Nevertheless, it should be kept in mind that local clearance rates vary throughout a room.

The presentation, which has been couched in terms of smoke as the offending substances to be cleared, applies equally to air conditioning. Smoke clearance, indeed, is just another example of air conditioning.

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Appendix

Outline of numerical solution

The computational method adopted involved the numerical solution of the time-averaged Navier–Stokes equations, the continuity equation, and the mass concentration equation. The time-averaged Navier–Stokes equations remain the exact momentum equations in the case of laminar flow but must be augmented for turbulent flow by some form of turbulence model, most commonly the k–ε model that was used here.

A Cartesian x, y, z coordinate system is most appropriate to the present task. All of the governing equations may be represented by the single generalized form:

$$\frac{\partial\phi}{\partial t}+\frac{\partial(u\phi)}{\partial x}+\frac{\partial(v\phi)}{\partial y}+\frac{\partial(w\phi)}{\partial z}-\frac{\partial}{\partial x}\left(\Gamma_\phi\frac{\partial\phi}{\partial x}\right)-\frac{\partial}{\partial y}\left(\Gamma_\phi\frac{\partial\phi}{\partial y}\right)-\frac{\partial}{\partial z}\left(\Gamma_\phi\frac{\partial\phi}{\partial z}\right)=S_\phi$$

where t is the time and u, v, w are the velocity components in the x, y, z directions, respectively; ϕ represents any of the variables u, v, w, k, ε, c, where k is the kinetic energy of the turbulent fluctuations, ε is the rate at which k is being dissipated to internal energy by viscous action, and c is the smoke concentration. The "exchange coefficient" Γ_ϕ and the "source" S_ϕ are particular to ϕ, in accordance with Table A1.

The constants c_v, $c_{\varepsilon1}$, $c_{\varepsilon2}$, σ_k, and σ_ε have the widely accepted values 0.09, 1.44, 1.92, 1.0, and 1.3, respectively, recommended by Launder and Spalding.[3] The equation system is closed; that is, there are as many equations as there are unknowns. Thus it can be solved numerically subject only to the appropriate boundary conditions.

A finite volume method is adopted. For the purpose of computation the room is divided by three orthogonal sets of planes, the common intersections of the planes forming nodes at which a staggered grid system is constructed, as indicated in Figure A1. The u, v, w velocity components are evaluated at the centers of the faces of the control volume common to all of the other variables. This approach is particularly convenient when dealing with these other variables, because it is precisely at these locations that values of the convecting velocities are needed.

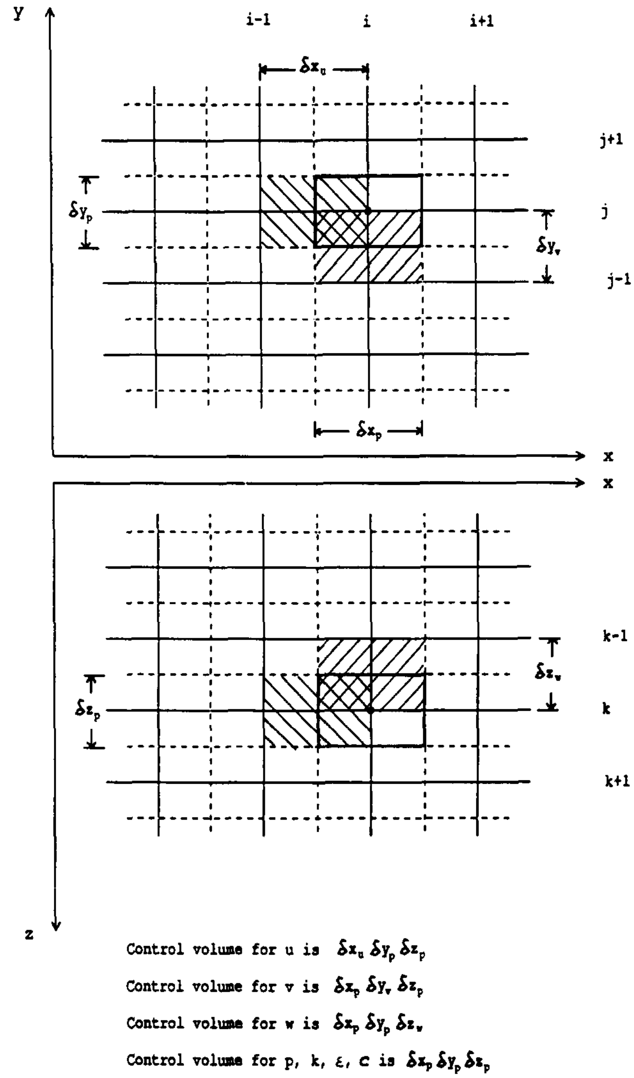

Figure A1 Staggered grid system

Table A1

Equation	ϕ	Γ_ϕ	S_ϕ
Continuity	1	0	0
x momentum	u	ν	$-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left(\nu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial w}{\partial x}\right)$
y momentum	v	ν	$-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\partial}{\partial x}\left(\nu\frac{\partial u}{\partial y}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial v}{\partial y}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial w}{\partial y}\right)$
z momentum	w	ν	$-\frac{1}{\rho}\frac{\partial p}{\partial z}+\frac{\partial}{\partial x}\left(\nu\frac{\partial u}{\partial z}\right)+\frac{\partial}{\partial y}\left(\nu\frac{\partial v}{\partial z}\right)+\frac{\partial}{\partial z}\left(\nu\frac{\partial w}{\partial z}\right)$
Turbulence energy	k	ν_t/σ_k	$P_k-\varepsilon$
Energy dissipation	ε	ν_t/σ_ε	$(c_{\varepsilon1}P_k-c_{\varepsilon2}\varepsilon)\frac{\varepsilon}{k}$
Concentration	c	ν_t/σ_c	0

$$P_k=\nu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\frac{\partial u_i}{\partial x_j}$$

ν = kinematic viscosity
ν_t = turbulent viscosity = $c_v k^2/\varepsilon$

Choice of the differencing method used to replace the differential equations with approximate algebraic counterparts suitable for computation is based on some compromise between intrinsic accuracy, stability in the proposed application, and convenience. Two differencing methods are required for the unsteady-flow problem considered here: one for the spatial and one for the temporal terms. With regard to the spatial discretization, only the convective terms in the momentum equations cause problems. For all other terms it is almost universal practice to use central differencing for its accuracy and simplicity; it is the method used here. When it is applied to the convective terms, instability arises with central differencing unless impractically small grid spacing is used and is therefore unsuitable. Instead, two other candidates have been considered for the convection terms. These are Leonard's quadratic upwind interpolation method,[1] commonly called the Quick method and the well-known and, until recently, widely used upwind differencing (UD) method. Of these, Quick is characterized by high accuracy but is prone to instability problems. UD is unconditionally stable but is less accurate than Quick, particularly when the flow direction is skewed with respect to the computational grid system, as will be a common occurrence in the smoke clearance situation. As a compromise, a composite scheme was adopted in which the convected variable ϕ at any face of a control volume is approximated by

$$\phi = \gamma\phi^{Q} + (1-\gamma)\phi^{U}$$

where ϕ^{Q} and ϕ^{U} are the approximations made in Quick and UD, respectively, and γ is a weighting factor, $0<\gamma<1$. No stability problems were encountered in using Quick alone ($\gamma = 1$), and consequently all the results presented here derive from its use.

When spatial discretization is complete, the equations are reduced to first-order differential equations with respect to time. To complete the transformation to algebraic forms, Brian's temporal differencing method[2] was used. The resulting equations were then solved by an adaptation of the method proposed by Brian.