FLÄKT WOODS LIMITED

Fans in Fire Safety

Fan Applications in Fire Smoke Control Systems

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Introduction

It is well known that the major cause of deaths at a fire is the hot toxic smoke, rather than the fire itself. The control and essential removal of this smoke from the building is, therefore, a vital component in any fire protection scheme. As our knowledge of the behaviour of fires increases, the traditional methods of exhausting the fire smoke via natural venting are sometimes shown to be inadequate; and systems using positive and readily controllable fan-powered units are often used instead. This paper examines the motivations behind these changes and discusses the requirements of the fans needed to power smoke-venting systems.

The demand for fans capable of handling hot fire smoke gases increased dramatically during the middle 1980s. To meet this new challenge Fläkt Woods Group Ltd. undertook a development programme designed to evaluate the Fire Smoke Venting market.

The programme addressed four main questions:

1. Why is it necessary to ventilate a fire?
2. How is it done and how are ventilation rates calculated?
3. Why are fans being increasingly used in preference to the more traditional natural vents?
4. What is expected of a fan? What should be its specifications?

The technology for designing Smoke Venting Systems was developed during the 1960s, but as late as 1985 the procedures involved were not widely known within the Heating and Ventilating Industry and were still concentrated in very few specialists hands. This paper outlines some of the basic principles involved in the design of ventilation systems for exhausting hot fire smoke.

Why Ventilate?

The outbreak of a fire results in the immediate production of hot toxic smoke. If left to its own devices, the suction action of the fire will fill a room with smoke in minutes and anyone caught in the room would not be able to see or breath. The first objective of any smoke venting system is to keep the escape passages free from smoke to assist in the evacuation of people (see fig. 1.).

In addition a well designed ventilation system can assist the Fire Brigade by making it easier for them to find the source of the fire, and by limiting the development of FLASHOVERS and BACKDRAUGHT.

FLASHOVERS can occur when the smoke temperature reaches 550°C/600°C. Radiated heat from the smoke layer will then be sufficient to ignite material away from the original fire source. In unventilated buildings temperatures can rise to twice this value.

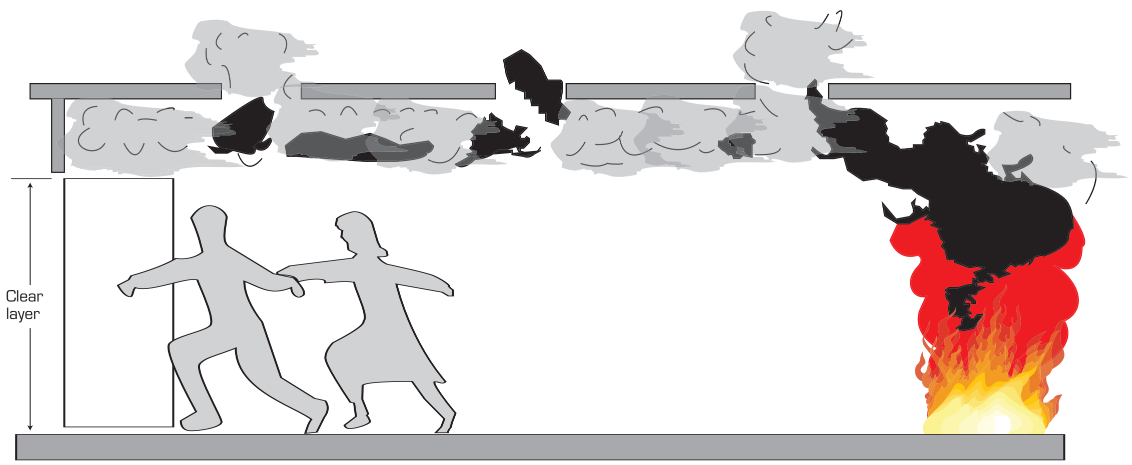
The dangerous phenomenon of BACKDRAUGHT arises when the oxygen in the room has fallen to a level where the fire is burning inefficiently. The high temperature smoke will then contain both unburnt residues and carbon monoxide. The introduction of more oxygen at this stage risks an explosion.

Smoke Production and Extraction

Unlike normal ventilation systems, extraction rates for fire-smoke venting have little to do with the size of the room. The amount of smoke produced depends mainly on the size of the fire. As the smoke plume rises, surrounding cool air is entrained into the plume and becomes so well mixed with the hot smoky products of combustion as to form an inseparable component of the smoke (fig. 2).

The quantity of smoke produced by a fire will depend on three factors:

- The perimeter of the fire.



1 Maintaining a clear layer for occupants to escape

- The temperature of the flames in the plume.
- The effective height of the column of hot gases above the fire.

Using the large-fire theory, outlined in Fire Research Technical Paper No. 7[1], the two most important factors are the perimeter of the fire and the effective height of the smoke column. These two factors affect the smoke production linearly, and to the power of 1.5, respectively. Smoke production only varies with the square root of the absolute temperature of the fire and, under the large fire theory, is much less important.

If we assume a flame temperature of 800°C and an ambient air temperature at 17°C (density 1.22 kg/m³) the production of smoke from a fire can be obtained by the simple expression [2]

$$M = 0.19\, PY^{1.5} \qquad (1)$$

where: M is the mass rate of smoke produced in kg/s,
P is the perimeter of the fire in metres, and
Y is the height of the smoke layer in metres.

The temperature of the smoke can be calculated using the formula[3]

$$\theta = Q_S/M \qquad (2)$$

where: θ is the temperature of the smoke in °C above ambient,
Q_S is the heat carried by the smoke in kW, and
M is the mass rate of smoke production in kg/s.

The specific heat is assumed to be close to 1kJ/kg/K.

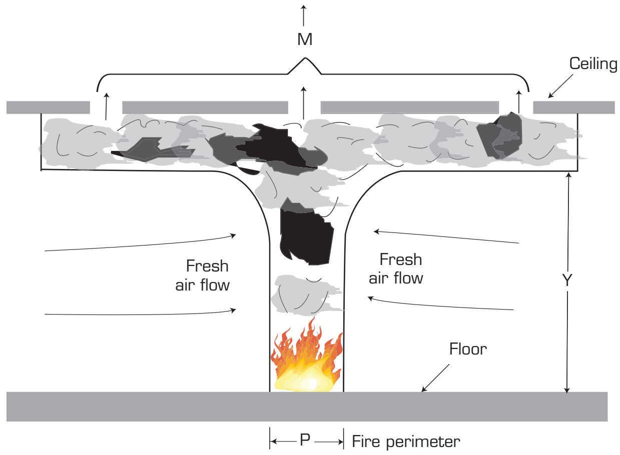
In the UK, normal seasonal temperatures range between about 0°C and 35°C. Since the ambient temperature in these formulae occurs only as an absolute temperature, the using of an average value at 17°C will give a maximum seasonal error of about 6%. This is trivial in design terms.

The total heat output power of a fire (Q_F) measured in kW is given by:

$$Q_F = B_R A \qquad (3)$$

where: B_R is the burning rate, measured in kW/m², and A is the fire area, measured in m²

The burning rate depends on several items. For a retail shop or factory premises 500kW/m² would be appropriate; in offices a maximum burning rate of 230kW/m² would be nearer the mark.[4]



2 Production of smoke in large volume, undivided buildings

Some limit must be put on the size of the fire. In sprinklered buildings a fire size of 3m x 3m has become the norm, even though larger fires do occur. This is usually equated to 10m², giving a total heat output Q_F, of 5MW. This is the origin of the so called 3m x 3m x 5MW fire which, for a time was being used as the design fire for all applications. The fact that this was incorrect will be discussed later.

Estimating the heat carried by the smoke, Q_S in eqn. (2), is more difficult. A fire burning in the open will lose about 25% of the generated heat by radiation, leaving a convective heat flux of 75%. A fire in a compartment or room, causing hot gases to issue from an opening, will also lose heat to the walls and ceiling. This loss depends on the temperature of the walls, therefore the overall heat loss can vary from 67% early on in the fire, falling to 33% for a steadily burning fire. It is probably adequate during design to assume a mid-point of 50% heat loss. This effect is important for offices opening onto an atrium or a shop opening onto a mall. These percentages apply in the absence of sprinklers[5].

The current convention is to take the convective heat flux leaving a shop unit as 5MW, this makes for a simple, worst case, rule-of-thumb approach; and will predict the maximum temperature in the smoke layer and hence the maximum extraction rate needed. Allowing for the 50% heat loss would produce the minimum smoke temperature and extraction rate. Thus it is possible to establish a range, for a given design, to assist in specifying the most economical fans and ventilation equipment required.

Eqn. (1) gives the mass of smoke produced in kg/s, but ventilation engineers require this to be expressed as a volume rate of smoke production. This can be done by using:

$$V = M\,(T_s + 273)/1.22\,(T_a + 273), \qquad (4)$$

where: V is the volume rate of smoke in m^3/s,
T_a is the ambient temperature, 17°C, and
T_s is the temperature smoke = θ + 17°C.

On substitution from eqns. (1) and (2) this equation becomes[2]

$$V = M(\theta + 290)/354. \qquad (5)$$

The foregoing formulae and discussion form the basis for all the tables and calculations throughout this paper. Where considered appropriate, both the minimum and maximum values of smoke temperature and extraction rate are given. Elsewhere the convention of using 5MW for the convective heat flux applies – unless otherwise stated.

Fire Size And Growth

How big is a fire? We have discussed a 5MW fire, but what does it mean? At the Fire Research Station, test fires are built using wood cribs. A typical crib will be constructed of 144 sticks, each 3ft x 2in x 2in, weighing 21lbs. When this crib is alight and every stick is flaming over its whole surface, it will require three cribs burning together to produce 5MW; this is equivalent to 17kg of wood burning away completely in one minute. A fire of this size is obviously a very large fire which will take time to develop. It is important to remind ourselves regularly, that the 3m x 3m x 5MW fire was never intended to be applied to all types of buildings. Often a much smaller heat output is appropriate.

The burning rate of $0.5MW/m^2$ should not be applied as a general rule to, say, an unsprinklered building, with the assumption that the whole area is on fire. This has been done, however, with fire sizes of 100MW plus being quoted.

A fire does not start at its fully developed size but ignites and grows; it only reaches its maximum burning rate after an interval of time has elapsed. This is an important statement and the effects of a spreading and growing fire on smoke temperature, need further consideration.

Spreading fire [6]

A 3m x 3m fire does not begin life covering all that area. It starts much smaller, for example, at a single chair in a furniture store, and slowly spreads to its final size[6]. Analysis of fire incident reports, supported by experiments, have established that the area of a fire doubles itself in equal time periods. This holds good until the fire approaches flashover, i.e., when the smoke temperature reaches 550 to 600°C. This time period is referred to as the Doubling Time; for an average fire it will be 4 minutes.

Fire growth

In most of the calculations in this paper we are assuming a constant burning rate of $0.5MW/m^2$. This is not entirely correct. In the same way as the fire begins small and spreads, the burning rate of a fire begins small and grows. All fires have a growth period, a maximum value period and a decay period. Tests on a large-scale fire of constant area, carried out at the Fire Research Station, have established the rate of growth of a fire which reached a maximum burning rate of $0.5MW/m^2$. From this, a curve of heat output against time was produced.

Spreading and growing fire

Table 1 details both the results of this work and its effect on smoke temperature during the early stages of a fire. Smoke temperature values assume a smoke layer height of 4m (one storey building) and 17°C ambient.

The results are tabulated in two groups:

1. using the simple proposition that a spreading fire has constant burning rate of $0.5MW/m^2$ – the basis of calculations throughout this paper, and
2. using the spreading and growing fire, discussed above, as the basis for calculating the smoke temperature.

From the table it will be seen that:

- for a constant burn rate, the fire takes 16mins to reach 5MW value,
- for a growing fire, the fire takes 22mins to reach the 5MW value,
- the smoke temperatures, at the early stages of both fires, are well below those reached at 5MW.

Both these periods are longer than the expected escape time for occupants, and the idea that a 5MW fire should be used as the design size for all fires is not realistic and could cause fatal error.

Table 1 - Effect of spreading and growing fires on smoke temperature

Time from ignition (mins)	Constant burn rate at 0.5MW/m2			Growing fire		
	Heat output (MW)	Fire size (m2)	Max. smoke temp (˚C)	Heat output (MW)	Fire size (m2)	Max. smoke temp (˚C)
0	0.3	0.6	80	0.1	0.4	43
8	1.2	2.4	144	0.4	1.5	66
16	5	10	277	1.5	6	118
18.5	8.5	17	356	2.6	10	152
20	10	20	384	3	12	159
22	-	-	-	4.6	18	195
22.5	-	-	-	5	20	201

From table 1 it can be seen that a spreading and growing fire may never reach a burning rate of 0.5MW/m^2. By the time it has reached 10m^2 in size its total heat output is only 2.6MW, giving a temperature in the smoke of 152˚C against 277˚C at 5MW. Alternatively if such a fire, say an unsprinkled fire, is allowed to grow to 5MW it will, in that time, spread to an area of 20m^2.

With a smoke layer height of 4m, a fire of this size would require 36.4m^3/s to ventilate it as against 29.0m^3/s for a 3m x 3m fire. Thus using 3m x 3m 5MW could result in insufficient extraction being provided.

This is thought provoking, and shows that we do need to be as specific as possible when calculating smoke temperature if we are to design smoke venting systems that work. Table 1 does provide some insight into the general behaviour of solid fuel fires and shows that such fires do take time to develop. In spite of the fact we now have information available to allow us to design systems on this basis, “steady state” fires continue to be used. Some typical fire sizes are given in table 2.

Table 2

Area	Sprinklers	Fire Size
Retail Stores	Standard	12 metres x 5 megawatts
	Fast Response	9 metres x 2.5 megawatts
Open Plan Offices	Standard	14 metres x 2.7 megawatts
Hotel Bedroom	Standard	6 metres x 4 megawatts
Motor Car (BRE 368)	Non	12 metres x 3 megawatts
Motor Car (BS7346-Pt 7)	Non	20 metres x 8 megawatts
	Standard	14 metres x 4 megawatts
Ladened Lorry		20 metres x 7 megawatts

Smoke Control In Buildings

Early smoke venting systems were designed around single storey factory buildings. Here, the height through which the smoke could rise was small. Hence, the smoke was thought to remain hot enough, when combined with a relatively deep smoke layer, to provide the buoyancy required to force it through the natural smoke vents provided. In larger and more complicated buildings, for example atria and shopping malls, adequate buoyancy cannot be assumed. During the critical early stages of a fire, when people are escaping, the smoke may be too cool to form a stable layer.

We have seen that as smoke moves and rises it entrains the surrounding air, grows in volume and cools. The effects of this on two typical modern buildings are discussed below.

Atria and Other High-Large area spaces

Many modern buildings are being designed around a central atrium to provide a light airy atmosphere in the occupied spaces. In this type of building form it is often difficult, if not impossible, to keep the fire smoke out of the high atrium area where it will rise and grow. Indeed, the top of the atrium is often the only convenient place from which to extract the smoke. A similar problem arises in other types of large open space buildings, Auditorium, Warehouses, Large-open spaced-2 storey stores.

Table 3 shows the effect of atrium height on smoke quantity and temperature from our basic 3m x 3m 5MW fire burning at the bottom of the atria or space, assuming ambient temperature of 17˚C. From table 3 we see that the higher we allow the smoke layer to settle up the atrium, the cooler it becomes and the larger the volume rate of extraction required to remove it. Indeed, in very tall atria the low temperature could mean that the smoke layer would not remain stable. To limit the extraction rate and thereby the size of any fans, we may have to allow the upper part of a high atrium to accumulate smoke. Hence the provision of physical means of escape via the atrium would have to be avoided. The venting of natural buoyancy-powered smoke from the top of a tall atrium becomes very difficult.

Table 3 - Atrium: effects of height on smoke quantity and temperature

Height of smoke layer (m)	Mass rate of smoke production (kg/s)	Volume rate of smoke production (m3/s)		Smoke temperature (˚C) *	
		Min	Max	Min	Max
4	19.2	23	29.9	147	277
8	55	52	59	63	108
12	100	89	96	42	67
24	280	236	244	26	35

* 17˚C ambient

Table 4 compares, at increasing heights, the volume-rate-of-flow by natural convection out of a vent opening of 20m² at the top of an atrium with the volume-rate-of-smoke-production from a 3m x 3m x 5MW fire. (The volume flow rates are based on a 4m deep smoke reservoir and an ambient temperature of 17°C). Table 4 makes it clear that in an atrium of 12m or higher (an 8m smoke layer plus a 4m smoke depth), the buoyancy-driven volume flow through 20m² of vent will be lower than the rate of smoke production. For the system to work above 12m a larger vent area is needed. This could be difficult to provide in the top of an atrium.

Mechanical ventilation is now frequently used in atria above 12m high. In very tall atria, where the smoke does not rise to the top of the atrium, smoke ventilation can be impossible without very careful design.

Table 4 - Atrium: natural convection out of a 20m² vent compared with smoke production

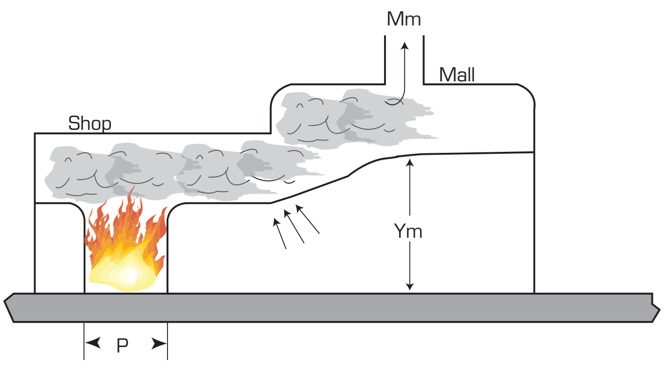
Height of smoke layer (m)	Max. volume of smoke production (m3/s)	Volume rate of flow from 20m2 vent (m3/s)
4	29.9	103.0
8	59.0	57.0
12	96.0	36.5
24	244.0	0

* 17°C ambient

Shopping malls

These present different problems as illustrated in fig. 3. Large shops, of 1000m² and above, must be provided with their own smoke venting system, calculated as already discussed. In the small shop units, along the malls, it would be impractical to provide individual systems and it has, therefore, become the norm to allow the smoke from the shop to enter the mall and then to exhaust it from the top of the mall. At the point where the smoke leaves the shop an additional large amount of air is entrained which effectively doubles the smoke mass, and rapidly cools it. Eqn. (1) for the calculation of the mass of smoke produced is thereby modified to become[3]

$$M = 0.34\ PY^{1.5} \qquad (6)$$



3 Production of smoke in shopping malls

Table 5 gives calculated extraction rates for the ventilation of both shops and malls. Volume flow and smoke temperature values are given both with and without an allowance for heat losses; the cooling effect of sprinklers is ignored.

Table 5 - Extraction rates for shops and malls

Height of smoke layer (m)	Shops					Malls				
	Mass rate (kg/s)	Volume rate (m3/s)		Smoke temp (°C)*		Mass rate (kg/s)	Volume rate (m3/s)		Smoke temp (°C)*	
		min.	max.	min.	max.		min.	max.	min.	max.
2.5	9	14	22	295	273	18	22	29	156	295
3	12	17	24	227	437	24	27	34	122	227
3.5	15	19	27	184	350	30	32	39	100	184
4	18.3	22	29	154	291	36.6	37	44	85	154
5	25.5	28	35	115	213	51	49	56	66	115
6	33.5	36	42	92	166	67	62	69	54	92
8	51.5	49	57	66	114	103	92	99	41	66
12	95	85	92	43	70	190	163	170	30	43

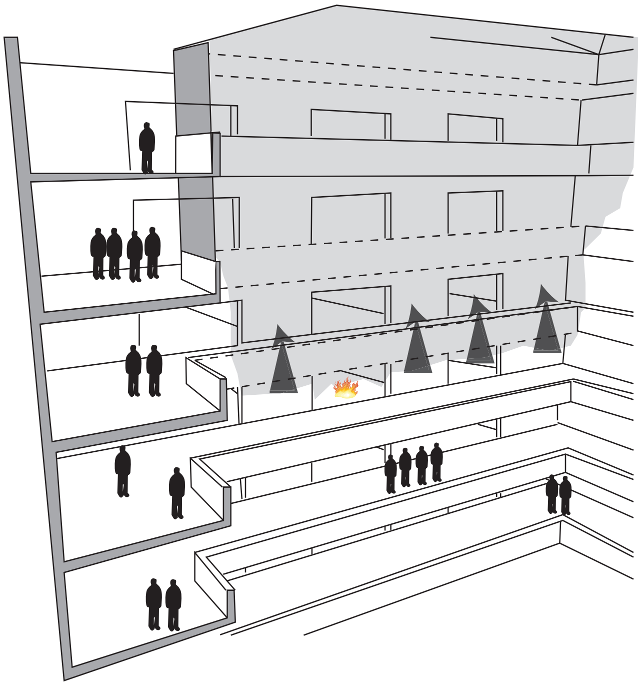
* 17°C ambient
In the temperature and volume rate column, the minimum allows for 50% heat loss, whilst the maximum is based on the full 5MW entering smoke layer. Minimum layer height should be 2.5m for goods etc and 3.0m for people.

Mechanical extraction is often the most suitable method of smoke extraction from all 2-storey shopping malls and this has become generally accepted, however, there will still be cases where natural systems would be quite acceptable. Developments more than 2-storeys high are treated, for smoke venting purposes, as if they were 2-storey blocks. In both these applications – atrium and shopping malls – quite low smoke temperatures are experienced, even when the fire is burning at its maximum rate. When this is linked with the knowledge that smoke temperatures, during the critical early stages of a fire, will be lower than had been assumed previously, then we can see why attitudes in the fire service on this subject are changing. Mechanical extraction will become the norm for fire smoke venting in the very near future.

Multi-Storey Malls-Edge Plumes

These present a third, and again, different problem, to those already discussed.

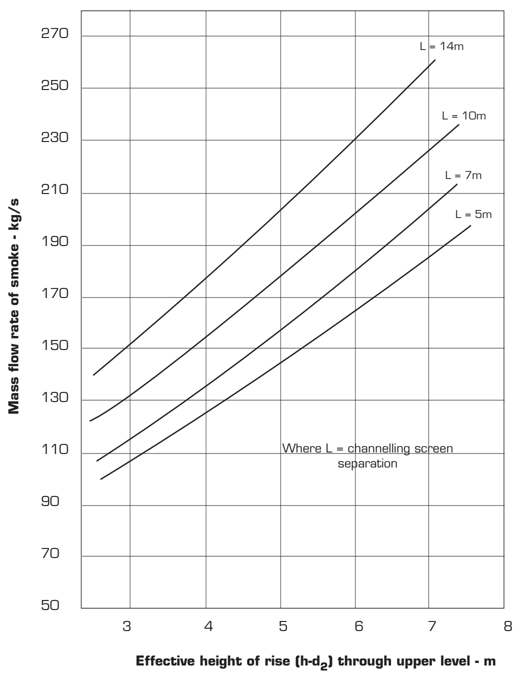
In a multi-storey-mall, the smoke from a fire in a ground floor shop will enter the mall from the underside of the walkways serving the first floor shops. Figure 4 illustrates this. The volume of smoke produced will depend on several factors, but perhaps the most important one is the length of the edge plume entering the mall, measured along the edge of the walkway.



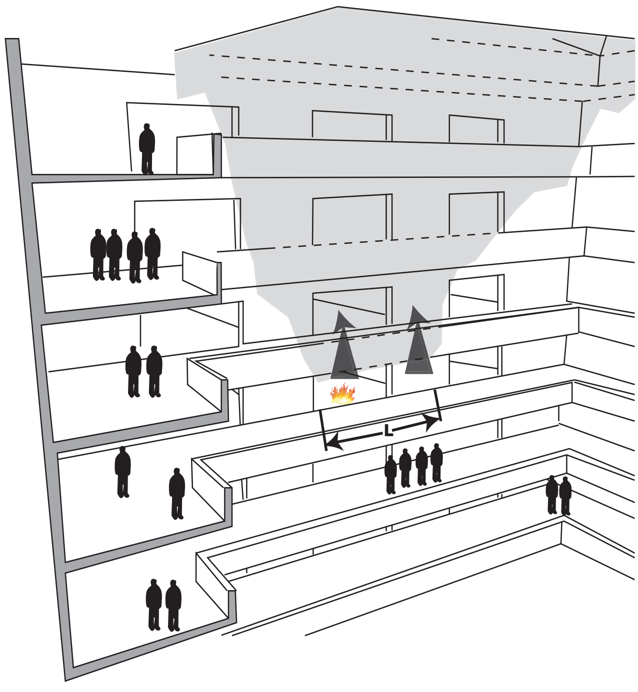
4 Smoke spreading sideways beneath a projecting canopy or balcony

Edge plumes produce large amounts of 'cool' smoke as shown at figure 5, and there are only two possible ways of limiting this smoke production:

1 by using channelling screens (smoke guides) under the walkways, figure 6 to restrict the length of the edge plume,
2 by keeping to an absolute minimum the height through which the smoke must rise within the mall – although this is often controlled by the need for safe evacuation.



5 Mass of smoke entering ceiling reservoir per second from a 5MW fire - large voids



6 Smoke confined to a compact 'spill' plume by channeling screens

A similar problem will arise with a fire under a mezzanine floor in a warehouse or two-storey retail shop. The smoke produced will enter the main building space, as an edge plume, from under the mezzanine floor with the same result, - large volumes of cool smoke.

Solving these problems is the task of qualified smoke control engineers.

Enclosed and Underground Car Parks

These present a very special problem for the smoke control engineer.

Car park ventilations systems have two functions:

1 to remove the fumes, mainly carbon-mon-oxide, produced by vehicles moving within the car park.
2 to have the capacity to at least remove the smoke produced by a car on fire in the car park.

The ventilation rates required to provide for these two requirements has long been proscribed in the Building Regulations as 6 air changes per hour, and 10 air changes per hour respectively.

As we have already discussed, the volume of smoke produced by a fire derives from the fire size, not the room size. Hence a system design based on air changes can only proved smoke clearance from the car park. 10 air changes will maintain a clear layer at one specific car park size.

BS7346-Part 7 [8] was introduced in 2006. This new standard retains the original prescription in the building regulations. In addition, it makes recommendations for the design of systems based on fire size, and specifies steady state design fires for this purpose, see table 6. Both the fire sizes recommended by the new standard are larger than the 12m perimeter x 3 megawatt fire that had been the accepted size since 1999, and specified in BRE368. This increase must raise doubts as to whether car park ventilation systems from before 2006 are now under designed and inadequate in their smoke ventilation mode.

Enclosed car parks can be regarded, for the purpose of calculating the volume of smoke produced by a car fire, as large open spaces with a low ceiling height. Equation 1 for the calculation of the mass of smoke produced is again modified to become[3]

$$M = 0.21\ PY^{1.5}$$

Table 6 gives the calculated ventilation rates for the three fire sizes and compares them with the extraction rate using 10 air changes per hour. Cooling effects of sprinklers, where appropriate, is ignored.

Table 6

Car park size m2	Ventilation Rates m3/sec			
	ADB 10 ac/hour	BRE 368 12m x 3 MW	BS7346 - P7 14m x 4 MW	BS7346 - P7 20m x 8MW
		One car	One car	Two cars
1000	8.34	13.30	16.60	28.54
2000	16.68	13.30	16.60	28.54
3000	25.00	13.30	16.60	28.54
4000	33.36	13.30	16.60	28.54
8000	66.72	13.30	16.60	28.54

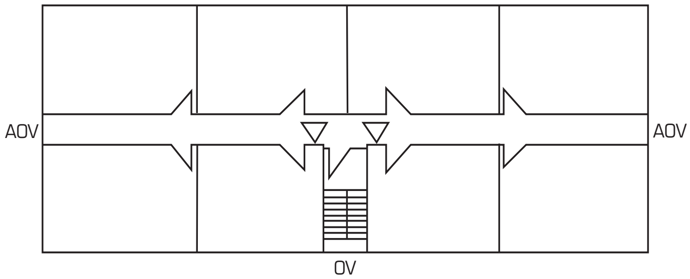
Effective height: 3 metres
Clear Layer: 2.25 metres
Heat Losses: 25%

Enclosed car park ventilation schemes are required to be powered by fans suitable for operation at 300˚C for not less than one hour, independent of the calculated smoke temperature. For further information on car park ventilation using jetfans see Fläkt Woods paper number 1.2 - 2006 [9]

Corridors and Lobbies

Historically, natural vents have been used as an acceptable method of disposing and venting fire smoke from the common access corridors and lobbies of blocks of flats over 2-storeys.

This was achieved by installing vents, of a specified size, in the corridor/lobby walls to outside, illustrated in fig. 7. The system relied on wind pressure, and to a lesser extent, smokes buoyancy to move the smoke through the corridor to outside. BS, - Code of Practice CP3 [10]. was published in 1971, and was met with immediate criticism.



7 Corridor access dwellings

Key: AOV Automatically opening vent (1.5m^2 minimum)
OV Openable vent for fire service use (1.0 m^2 minimum)

There was no scientific support for these proposals, and latter work carried out by the Fire Research Station, supported these criticisms. It showed that with openings of 1.5m^2, and the best alignment of the corridor to the wind direction, adequate smoke removal was achieved for only 53% of the year. All other situations were worse. In spite of this, the use of natural vents for smoke disposal and exhausting from corridors and lobbies continues to be used, in various forms, to the present day.

Fire Safety Engineers are now more aware of the shortfall of using natural vents and, as a result, are insisting that fans power these systems. Regulators will demand that these fans be high temperature smoke venting fans with a temperature rating of at least 200˚C or even 300˚C for 1 hour. They may also insist on 100% standby in common with the practice used on Pressurisation Systems.

Smoke Control by powered exhausting in this way, does not prevent the fire smoke from entering the corridors and other escape routes. It simply removes the smoke from the corridor. The only positive way of keeping smoke out of escape routes is by Pressurisation, as specified in European Standard – EN 12101 – Part 6 – 2005 [11]. Further information on Pressurisation Systems is to be found in Fläkt Woods technical papers WTP41 [12] and WTP42 [13].

There are several methods of calculating the volume exhaust rate to ensure the satisfactory performances of these powered systems, but all designs should try to arrange for the airflow direction to be from the stairwell through the corridors. This will help prevent smoke from entering the stairwell, the vertical part of the escape route, serving all floors of the building.

High-rise building with corridor smoke exhaust systems discussed above, often have a basement car park. This opens the opportunity for a smoke control package covering both areas.

Smoke Control and Smoke Reservoirs

As smoke moves and rises it entrains the surrounding air and grows. One of the main principles of smoke control, therefore, is to limit smoke movement as far as possible. Horizontal movement can be limited by hanging screens from the ceiling to form smoke reservoirs. The smoke is first contained in, and then extracted from, these reservoirs. Screens forming smoke reservoirs should be made of plasterboard, aluminium, or other specialist material and should reach the underside of the roof sheeting.

The object of any smoke-venting system design is to ensure a dynamic balance between the volume of smoke entering and the rate of extraction from the reservoir. It follows that the design and disposition of the smoke reservoirs forms as vital an element of a fire smoke venting system as the rate and means of smoke extraction, or the sizing of the air inlets. It is, therefore, worthy of further discussion.

Size of smoke reservoirs

In industrial premises, or areas of low occupancy, smoke reservoirs should never be larger in area than 3000m². With compartments larger than this the smoke could cool sufficiently to fall back to ground level[2]. Currently, reservoirs of 2000m² are preferred with the maximum length of any one side limited to 60m. For shopping malls, where the top of the mall is forming the reservoir, each reservoir is limited to 1300m², when mechanical extraction is being used, or 1000m² for a system using natural ventilation. Again, the maximum length of any one side is limited to 60m. This rule was later relaxed and replaced with a rule that people should be able to walk out from below the reservoir within 30m of any starting point below the reservoir.

Having first established the disposition of the smoke reservoirs, the extraction rate necessary to exhaust the smoke from the design fire size, must be provided to each reservoir.

Table 7 - Minimum depth (m) of smoke reservoirs

Extraction mass flow rates (kg/s)	Width of reservoir (m)					
	4	6	8	10	12	15
10	1.1	0.9	0.7	0.6	0.5	0.5
15	1.4	1.1	0.9	0.8	0.7	0.6
20	1.7	1.3	1.1	0.9	0.8	0.7
25	2	1.5	1.3	1.1	1	0.8
30	2.3	1.7	1.4	1.2	1.1	1
40	2.8	2.2	1.8	1.5	1.4	1.2
50	3.4	2.6	2.1	1.8	1.6	1.4
70	4.5	3.4	2.8	2.4	2.2	1.9
90	5.6	4.3	3.5	3	2.7	2.3
110	6.7	5.1	4.2	3.6	3.2	2.8
130	7.7	5.9	4.9	4.2	3.7	3.2
150	8.8	6.8	5.6	4.8	4.3	3.7

Minimum depth of smoke reservoirs

When hot smoke enters a reservoir it must flow towards the extraction points. This flow of smoke is driven by the buoyancy of the smoke and will cause the reservoir to fill with smoke to a depth related to the mass of smoke entering the reservoir, its temperature and the width of the reservoir[3]. The flow will be independent of the size of any downstream vent or the method of smoke extraction employed; provided that the vent is large enough to take all the hot gases able to flow towards it. Too small a vent will lead to a deepening of the layer. Table 6 gives the minimum permissible depth of a smoke reservoir, having a rectangular section for a specific mass of smoke flow into the reservoir produced by a 3m x 3m x 5MW fire. Any depth less than this will cause smoke to 'spill' into adjacent reservoirs.

Minimum number of extraction points in a smoke reservoir

The distribution of extraction points within the smoke reservoir must, as far as possible, be arranged to prevent the formation of stagnant regions. The number of extraction points from a smoke reservoir is equally important[3].

For a given depth of smoke layer, there is a maximum rate at which the smoke gases can pass through a vent of specific size which is independent of the type of ventilating being used. To exceed this extraction rate would only result in the drawing of air from below the smoke layer. Table 7 provides guidance on the minimum number of extraction points.

Use of ceiling void as a smoke reservoir

Voids above a false ceiling can be used as smoke reservoirs. Where the false ceiling has a free area of 25% and above, [7] smoke will pass freely into the void. Where the false ceiling is mainly solid, the minimum number of holes (grilles) through the false ceiling, for a single reservoir above, can be taken from table 7.

Table 8 - Minimum number of outlets from a smoke reservoir

Extraction mass flow rate (kg/s)	Depth of layer below extraction point (m)							
	1	1.5	2	3	4	5	7	10
9	5	2	1	1	1	1	1	1
12	6	3	1	1	1	1	1	1
15	8	3	2	1	1	1	1	1
18	9	4	2	1	1	1	1	1
20	10	4	2	1	1	1	1	1
25	13	5	3	1	1	1	1	1
30	16	6	3	1	1	1	1	1
40		8	4	2	1	1	1	1
50		11	5	2	1	1	1	1
70			8	3	2	1	1	1
90				4	2	1	1	1
110				5	3	2	1	1
130					3	2	1	1
150					4	3	1	1

Note: This table is based on the theory of point sinks, i.e. the extraction opening is small compared with the layer depth. Recent work suggests that it errs on the side of safety.

The extraction fan should not be sited directly above an opening in the false ceiling, but above an area of solid. This will both prevent air being drawn through the smoke layer, and ensure it passes over at least one sprinkler head before reaching the fan. Extraction fans must be selected to overcome any resistance through the false ceiling.

Cooling Effects of Sprinklers

The main purpose of installing a sprinkler system is to control the size of the fire and slow its growth within the fire effected area of the building.

However the action of the sprinklers will also cool the smoke layer, particularly in situations where the smoke layer is contained wholly within the room of origin or within a smoke reservoir.

With a powered smoke venting system, the fans will, to a reasonable approximation, remove a fixed amount of smoke irrespective of temperature. If the extent of sprinkler cooling is over estimated the system could be under-designed. The opposite is true using a system of natural ventilators. Consequently the effects of sprinkler cooling are often ignored when calculating the volume rate of smoke extract for sizing the fans.

The temperature of the smoke, in a sprinkler controlled fire, passing through the exhaust fan, will be cooler, and this could influence their temperature rating and hence, their cost.

The simplest way to estimate the resultant smoke temperature is on the basis of the average value between sprinkler operating temperature and the calculated initial smoke temperature, - assessing the number of fan intake points taking hot or cool smoke respectively, then calculating the average temperature of the extracted gasses. From this, the "new" volume extract rate and temperature can be determined.

Often, today, these calculations are carried out by computer programmes where the average smoke temperature is taken as being equal to the sprinkler operating temperature (say 72°C).

Independent of the method used to access the effects of sprinkler cooling, many UK codes of practice will specify that smoke venting fans be capable of surviving 300°C for 1 hour, at least.

Smoke Control And Air Inlets

It is obviously necessary to provide adequate air inlets to an area affected by fire in order to replace air that has been removed via the smoke vents. This replacement air must enter the area below the smoke layer and at low velocity to avoid disturbing the smoke layer. With natural ventilation schemes, the area of air inlet should be 1.5 to 2 times the extraction area in any one reservoir. Anything lower than this could seriously effect the performance of the natural vents.

With mechanical extraction, the inlet size is not so critical, provided that the fans are selected to overcome any resistance to the airflow which is created by the inlet port. The velocity of the incoming air should be no more than 5m/s, preferably 3m/s.

An inlet can be provided in different ways:

- through doors, any automatic door being arranged to fail open;
- automatic louvres, sidewall or roof mounted, and interlocks to pen when the fans are energised;
- from an adjacent smoke reservoir, via roof vents. This is permissible on the basis that smoke from a fire will only fill one reservoir at once. Roof inlets should be interlocked NOT to open in a smoke filled reservoir;
- using input fans with the discharge duct at a low level under the smoke layer; although this can present very difficult balancing problems.

Generally air supply systems for the normal ventilation requirements, inject air to the room at high level. Such systems must be arranged to switch off during a fire emergency.

Fan Requirements For Smoke Venting

There are two basic methods of providing for the adequate ventilation of hot fire smoke from a building.

- Natural vents – usually in the roof or at high level. These are buoyancy driven.
- Powered vents – fans and roof mounted extract units, usually electrically driven.

Technical and commercial considerations will determine which method is most suitable for a particular building. The final choice is therefore one for the system design engineer. Some of the advantages and disadvantages of both natural and powered systems are listed in table 8

Table 9 - Comparison of natural and powered extraction systems

Method	Advantages	Disadvantages
Natural	Lightweight (if aluminium)	Easily affected by wind
	Self regulating	Require large areas of inlet
	Easy to retrofit or reuse	Many large openings on roof
	Operate at high temperatures	Cool' smoke a problem
	Units on non-fire zones can provide replacement air	Not acceptable to all approving authorities
Powered	Guaranteed exhaust rate	Weight can cause a problem
	Few smaller openings in roof	Electrical supply and wiring
	Can handle 'Cool' smoke	Retrofit not always possible
	Small area of inlet required	Expensive if high temperature (above 400°C)
	Can be used with ducting	
	Can be sited away from risk area	
	Will provide normal ventilation for building (2 speed)	

Fan specification

The requirements of a fan in fire smoke venting systems can be listed as follows.

1 To extract the hot smoky gases for a sufficient period of time to enable occupants to escape from the building. This is paramount.
2 To keep the building free of smoke for long enough to assist the fire brigade in locating the seat of the fire (will usually do this whilst performing requirement 1).
3 If possible, to assist in clearing the residue smoke from the building after the fire has been extinguished.
4 To provide the normal ventilation requirements of the building.
5 To extract the cold smoke during the early critical stages of a fire.

As the first of these requirements is paramount it merits closer examination. Table 5 shows that from a 3m x 3m x 5MW fire the temperature in the smoke will only rarely exceed 300°C; often it is much lower. Furthermore, during the early stages of a fire the size and smoke temperature, will also be much lower. If we now add into this the cooling effect on the smoke of any sprinklers, we begin to understand why it has become generally accepted in the UK that a fan able to handle 300°C will be satisfactory for a large proportion of applications. Practical tests have shown that even the most complicated shopping centre can be evacuated of people within 20 minutes, provided that the means of escape are clear. Hence the life of a fan, when handling hot fire gases, need only be about 30 minutes. These are the facts that led to the '300°C for 1/2 hour' specification.

Within the London Fire Brigade area there was a bylaw which enables the brigade to require ventilation to assist with the fire fighting. Fan requirement 3) above, covers this category. To achieve this, using mechanical ventilation, the brigade demanded fan life of one hour when handling smoke. This modifies the basic specifications to 300°C for 1 hour in the London area. However, all these specifications are only benchmarks. If the smoke temperature by calculation is only 200°C, a fan, designed to handle 300°C for 1/2 hour, would have a life of two to three hours. Alternatively, a fan with a lower specification would function satisfactorily.

In certain other European countries, France and West Germany in particular, the 'benchmarks' were related to types of buildings and regulated by law. In France specifications of 400°C for two hours are common. In West Germany fans are required to handle up to 600°C for one and a half hours.

From these facts and considerations it is evident that, to provide for both flexibility and economy, a range of fan equipment is required having several temperature/time steps, in addition to the usual air duty variations. This would provide for both flexibility and economy. Existing axial flow fan technology can meet all these requirements.

An aerofoil fan has three main components – a casing, motor and impeller. By using variations of these components fans can be assembled to cover temperature/time specification up to 650°C for one hour. The temperature/time variations will provide the most economical smoke temperature of the particular system. The adjustable pitch impeller and wide choice of blade diameters of the aerofoil fans will allow a designer to select a fan accurately. Aerofoil fans are duct mounted and can be easily mounted on the roof, either externally or within a weathering roof cowl.

Fan Specifications

BS7346 – Part 2 [14] was published in 1990. This was the first national test standard for high temperature smoke venting fans. It harmonised, for the first time, the various benchmarks of temperature-time specifications.

BS-EN12101-Part 3 [15] later extended this harmonisation across all countries of the European Union.

Table 10 - Temperature-Time Classifications

Class	Temperature (°C)	Minimum Functioning Period (minutes)
F200	200	120
F300	300	60
F400	400	120
F600	600	60
F842	842	
Not Classified	Selected by sponsor	Specified by sponsor

This European Standard is supported by an accreditation scheme, under which approved fan manufacturers are authorised to use the CE Mark on their fans. The objective is that this standard becomes mandatory for all high temperature smoke venting fans installed in buildings throughout the EU.

Fläkt Woods high temperature smoke venting fans fully comply with these EU requirements. They have been independently tested and meet the temperature-time classifications, specified in BS-EN12101-Part 3, and shown in table 10.

Fan Selection

In selecting and using fans for fire smoke venting the following are recommend by Fläkt Woods.

1 Calculate the volume of smoke to be exhausted and the minimum smoke temperature, and decide the best type of system to be employed-mechanical or natural.
2 Select from the category higher than the calculated maximum expected smoke temperature.
3 Fans selected to handle smoke at the temperature calculated for at the height of the fire, will automatically remove some of the cooler smoke produced during the early critical stages of the fire.
4 Fan motors must be sized to have enough power to allow the fan to handle the heavier air which occurs at ambient temperature. Smoke venting fans will require periodic testing and this will be carried out at ambient temperature. If the fan motors have been derated to the power required to handle the hot fire smoke (say 300°C), then the motor windings could be damaged during the testing period. Equally, the actual smoke temperature will normally be lower than the fan temperature rating, and also the fan will, almost certainly, be called upon to handle relatively cool smoke during the early stages of the fire. Reducing the cost of fans by derating the motors could prove fatal.
5 All fans and roof extract units can readily be provided with two-speed motors. The low speed would provide normal ventilation of the building at low noise levels.
6 The electrical supply to smoke-venting fans must be from an independent, protected source, connected to the fan by fire-resistant cable, for example, Pyrotenax or other specially constructed cable.
7 Bifurcated fans have their drive motors mounted outside the hot gas stream in a compartment around which the gas divides as it passes through the fan. With this arrangement a supply of air at ambient temperatures (50°C max) is always needed for the motor compartment. For this reason bifurcate fans are best sited away from the potential fire zone.

Conclusions

In summary, when designing for smoke venting from buildings, Fläkt Woods suggest that the following points should be borne in mind.

1 It can take up to 22 minutes for a fire to reach its maximum size of say 5MW. During this early, critical, stage the temperature of the smoke will be correspondingly low and may not form a stable layer. Low temperature smoke can be removed only by positive mechanical fan-driven systems.
2 Not all the heat generated by the fire enters the smoke layers. A proportion (up to 50%) is lost by radiation.
3 As fire smoke moves through a building it increases in volume and cools. In atria above twelve metres high, and in two-storey shopping malls, it has been found that mechanical ventilation is often the most suitable method of smoke extraction.
4 The effect of any sprinklers is to limit the spread of fire. In addition they will further cool the smoke. Hot fire smoke could have its total output reduced by up to 1MW after passing one row of sprinkler nozzles.
5 As our knowledge increases, it becomes clear that, for a fire smoke venting system to perform satisfactorily at all times, it will have to be capable of handling both low and high temperature smoke. Of the two, the low temperature could be the more critical and difficult.
6 The greater use of positive, readily controlled, fan-powered, ventilation systems will result. These systems will often be required to provide for the normal ventilation of the building.
7 Fläkt Woods' existing axial flow fan technology can readily meet these requirements.

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Acknowledgements

- The contents of this paper should not be used for the purpose of designing fire and smoke control systems. Designers are directed to the references below, in particular Reference 3 and Reference 11.

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