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## **Behavior and Control of Smoke in Fire**

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The objectives of smoke control are primarily two fold:

One is to help occupants to escape safely from the danger of smoke in fire.

The other, to help fire brigades to search and rescue of occupants who have failed to escape and to suppress fire.

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This is an example of smoke venting system, mechanical, equipped in a department store in Japan.

First, escalator shaft, or any other vertical space connecting multiple floors, is compartmented by fire shutters etc.

Second, a space exceeding the area limit is subdivided by fire wall or automatic closing fire shutters.

The fire compartment is further divided into smoke partitioned area within 500m<sup>2</sup> each by smoke curtain hanging 50cm from ceiling.

In each anti-smoke area, equipped is a smoke vent which is connected with horizontal duct, then shaft and eventually with smoke exhaust fan.

The intention is that, should a fire breaks out, smoke from fire is captured and removed through the venting system. However, there is a degree of effectiveness of this system, and the same is true for natural smoke venting method.

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In order to discuss the nature and efficiency of smoke venting, we need to know the nature of fire plume. What is a fire plume?

This picture shows a huge fire plumes rising from city of Kobe, which was hit by a strong earthquake in 1995. Multiple fires broke out simultaneously due to the earthquake. The heat released by the burning of buildings produced a large buoyant flow above the fires. These also belong to fire plumes.

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Then, shown by this is a picture of a building scale fire taken at a real scale experiment.

Heat generated at the fire source is transported to the upper part of a room through the fire plume.

The fire plume, as it rises, entrains air from the surrounding and thereby increases the flow rate. The theory to deal with such a fire plume has been developed based on the concept of 'fire plume above a point heat source'. This assumes all the heat release is concentrated at the virtually considered point. Such an assumption may seem too unrealistic but from a far high up point even a large fire, like a city fire we already saw, may seem as a point. Therefore, as long as discussion is limited to the plume behavior far distant from the source, the point heat source assumption is not so inadequate as it may seem.

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The properties of fire plume above point heat source has attracted many studies and been investigated fairly well.

These figures, from Yokoi, Japan, plot the temperatures and upward velocities in a plume measured in experiments. Both the temperatures and the velocities at each height are

normalized by those on the plume axis at the same height and plotted versus the distance from the axis normalized by the height from the point heat source.

The fact that all the measurements thus plotted collapse to a single line implies that the fire plume develops similarly as illustrated on the left.

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As for axial properties of fire plume, the axial temperature distribution with height from fire source  $z$  is known to be negatively proportional to  $5/3$  power of  $z$  as shown in this figure from Yokoi. And the axial velocity is negatively proportional to  $1/3$  power of  $z$ .

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There is ample study on fire plume above a point heat source, experimentally and theoretically. In summary, equations for plume half-width, axial temperature and velocity, and flow rate are almost established as shown here.

These equations, expressed in non-dimensional form, can be used commonly irrespective of units.

$Q^*$  here is called non-dimensional heat release rate and often appears in many other equations concerning fire phenomena.

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Plume flow rate plays important role in smoke layer development in building spaces.

If we use SI unit to the plume flow rate equation in the previous slide, we have an equation as you see here.

This form will be easier to use for most of practical fire engineers.

For some more accurate calculation, the plume flow rate equation is adjusted using the offset called virtual point heat source distance. There are a certain number of equations proposed for estimating the distance. Shown here is the one from Heskestad, which is one of the most popular ones. Notice here that the plume flow rate is much more dependent on height than heat release rate of a fire source.

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This pictures show a smoke filling experiment conducted in a dome structure that was built for Tsukuba International Exposition in 1985 and demolished soon after it.

The fire source was ethanol in a pan and smoke was generated by smoke candles.

At first smoke layer is so thin that you can see the ceiling through the smoke layer and that stratification is not evident.

But upper smoke layer gradually get to be thick to reveal clear stratification.

This is because the fire plume above the source entrain mostly fresh air at the early stage but as the upper layer develops the plume turns out to entrain less fresh air and more smoky gases from the upper layer.

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This shows the comparison between measured and predicted smoke layer height and temperature for the smoke filling experiments.

The left side of the center line is the thermocouple measurements and the right side is the prediction by BRI2 of the temperatures.

By the way, BRI2 is a two layer zone smoke spread model for multi-room buildings.

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Many sort of physics, including energy conservation, are involved to govern the smoke layer properties.

A computer model such as BRI2. CFAST (by NIST) etc. need be used to totally simulate the layer behavior.

However, by assuming that smoke layer density is approximately constant during the smoke filling process, we can have a practically convenient calculation formula for smoke filling. In

this case, layer mass changes only by mass addition through fire plume so the mass conservation equation for the layer becomes as shown here.

And invoking constant density assumption, we obtain the differential equation for smoke layer in a room with constant horizontal section area as shown in the last.

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The differential equation can be solved only when the dependence of  $Q$ , heat release rate, on time  $t$  is simple enough.

Among such simple  $Q(t)$ , one that is useful in practical fire safety design of building is such as this. For this  $Q$ , the differential equation can be integrated to yield the following formulas.

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The types of fires that are practically important as the design fires are constant fire and t-square fire.

For constant fire,  $n=0$ , and for t-square fire,  $n=2$  can be used in the former formula to yield the following simple formulas for each fire source.

Not that smoke filling time increases proportionally to floor area in case of constant heat release rate, and  $2/3$  power of floor area in case of t-square fire.

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This compares the prediction by the simple formula and the measurements from full-scale test of smoke filling with time. The experiment was conducted using the full-scale fire test facility of Building Research Institute.

The ceiling height is 26m and heat release rate is 1.3MW.

As you see in this figure, the smoke filling is very fast at the initial stage but gradually slow down as time elapses. This is due to the nature of plume flow rate, which is very dependent on height.

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It is of course necessary that occupants in the room of origin can exit the room before they are exposed to smoke.

However, as we have already seen, smoke filling slows down at the later stage, unless a fire continues to develop infinitely. Accordingly the case that occupants in the room are endangered to be exposed to smoke filling is that they reside at upper part of the room such as theater with balcony seats and atria connecting with floors at multiple levels.

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Iroquois theater fire in Chicago, 1903, which is a well known fire that claimed 602 fatalities, is one of such fire that almost victims were found from the occupants on the upper level.

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In this fire, the vent at the top of the stage, which was supposed to exhaust smoke in the event of fire, was nailed down for some unknown reason. The asbestos curtain, which was supposed to shutdown, did not close due to inadequate maintenance.

And opening the doors behind the balcony seats and a vent at roof for evacuation ironically induced strong draft from the stage to evacuation occupants.

However it was the panic of the occupants scared by the smoke rather than the smoke hazard itself that induced such a formidable disaster.

The fire eventually burned seats on the ground floor but the damage to structure was very trivial. Also, no death was reported from this level.

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Smoke filling can be stopped or delayed if a certain kind of smoke venting is equipped.

The most typical way of smoke venting are natural smoke venting and mechanical smoke venting.

Natural smoke venting system consist only of a smoke vent at upper part of the interested space. If a fire breaks out in such a space, smoke layer at elevated temperature develops under ceiling. Then the difference in temperature between the smoke layer and the outdoor causes the pressure difference profile along height as illustrated here. Smoke venting rate is determined as a function of the smoke vent area and the pressure difference at the height of the vent.

You might think that the larger the smoke vent the larger the smoke venting rate.

But this is only half true. Things are not such simple.

Size of air inlet at lower part of the space is involved in the efficiency of the smoke venting. Because the rates of smoke exhaust through the smoke vent, the plume flow and the air inflow through the air inlet have to be basically the same according to the mass conservation law: exactly the same at steady state, and approximately at transient state.

As the result, if air inlet is small the pressure difference increase to let the same mass of air as that of smoke vent pass. And this in turn reduces the pressure difference at the smoke vent.

On the contrary, if the air inlet is large the pressure difference can be small to let pass the same amount of mass so the pressure difference at the smoke vent increases.

The emphasis here is that air inlet should not be disregard when designing a natural smoke venting system. In addition, it is obvious that the pressure difference at the height of smoke vent is dependent on smoke layer thickness, therefore natural smoke venting is not very efficient in low ceiling spaces.

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The basic characteristics of natural smoke venting is more clearly understood by considering steady state condition than complicated transient conditions. So we consider here steady state fire and flow in the room of origin.

In terms of physics, natural smoke venting is governed by mass conservation, energy (or heat) conservation, opening air and smoke flow rate as a function of pressure difference, and gas state, which is omitted here for it is too clear.

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The former system of basic equations can be solved by employing rather easy trial and error iteration method.

This figure compares the predictions by solving the coupling equations and the experimental measurements for steady state smoke layer height and the pressure difference distribution.

The agreement can be said satisfactory considering the simplicity of the equations.

By the way the smoke filling dashed curve in this figure is for without venting, which is shown for reference. The system of steady state equations can only predict smoke layer height and temperature, smoke and air flow rate, and pressure difference at steady state.

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Researchers tend to be interested in and proud of being able to predict things under arbitrary conditions. However, designing a smoke control system is not a research but engineering practice. The interest of engineers dealing with smoke control system will be to know the required vent area to meet the acceptance conditions.

If the critical smoke layer height,  $z_c$ , is given as the criterion to meet, the calculation turn out to be straightforward. You can calculate the required smoke vent area just by following the procedure one after one.

- 1) Plume flow rate at the critical height,  $z_c$ , is at the same time, the required mass smoke venting rate and air flow rate at air inlet according to the mass continuity.
- 2) Therefore from heat conservation, we get the smoke layer temperature.
- 3) Now that we have temperature, layer gas density,  $\rho$ , can be calculated from the equation of ideal gas state

- 4) Using mass flow rate,  $m$ , we also obtain the pressure difference at the height of air inlet
- 5) Using the results of the above calculations, we finally obtain the required smoke vent area  $A_e$

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In case of smoke extraction too, the practical interest is to know the required extraction rate. The plume flow rate, mass and heat conservation, state of gas, and opening flow rate are common with natural smoke venting.

In terms of mass, calculation of the required smoke extraction rate is straight forward.

Note, however that this smoke extraction induce pressure across air inlet given by this formula. So, if ordinary exit is expected as air inlet, caution must be exerted in that this pressure does not cause difficulty in door opening by evacuees.

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In terms of mass, calculation of the required smoke extraction rate is straight forward as already mentioned. But the extraction rate in volume is required in ventilation engineering, which means smoke layer temperature need to be known.

Thus almost the same relationship as those in natural smoke venting turns out to be necessary.

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The procedure to obtain the required smoke extraction rate can be developed if the critical layer height is given. This is much simpler than the case of natural smoke venting, that is

Note, however, that any flow rate may be achieved in case of mechanical smoke extraction but as the critical layer height get greater, the required extraction rate un-proportionally increase due to the nature of fire plume, which may demand huge fans.

So in case high critical layer height need to be attained natural smoke venting is more economical than mechanical smoke extraction.

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Although the number of applications to real buildings is not significant in Japan, the idea of combination of smoke vent and pressurization may be considered.

It will be understood by this figure that pressurization to this space will increase the pressure of the space including the pressure difference at the smoke vent and smoke ventilation can be enhanced. Although due caution must be taken not to fan the fire inside, this method may find its application to smoke control in stairwell vestibules, corridors or atria, where live combustible is insignificant.

(slide 27) (slide 28)

The governing equations and calculation procedure can be developed for this system but the explanation is omitted here due to the limitation of time.

(slide 29)

The other important phenomena concerning smoke behavior in building fire is stack effect. Stack effect is particularly important in the event of fire in high-rise buildings.

High-rise buildings inevitably involves vertical shafts, such as stairwells, elevator shafts etc. for the transport of occupants, utilities across floors.

In the event of fire, such a well like space can be a dominant passage of smoke spread to upper floors and the smoke spread is intensified by stack effect.

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Sen-nichi-mae building fire broken out in Osaka, 1972 is one of the examples that people in Japan recognized the hazardous aspect of vertical shafts on human lives involved in a building fire.

This building housed a department store from the 1-6th floor, and a theater on the 6th floor and a nightclub on the 7th floor.

This fire started on 3rd floor and due to the deficiency of compartmentation of escalator shaft and duct shafts.

It was at evening that the fire started. The department was already closed and only the night club was open.

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It was the night club where the fire claimed 118 fatality and 81 injury out of about 200 occupants in there.

Smoke got in through HVAC duct whose fire damper did not close and through most of stairwells.

92 of the killed were found inside the club and 52 jumped to death. The only relief of the tragedy was that 53 were rescued by the courageous effort of Osaka fire brigades.

(slide 32)

MGM Grand hotel Fire is an example out of a number of high-rise fires worldwide for which stack effect played an important role to result a large number of victims.

In this case, the smoke from the fire that is originated and spread in casino area on ground floor spread to whole building through elevators and stairs.

The guests in the hotel were trapped in rooms or frantically tried to escape through stairs, where most victims were found.

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Stack effect is caused by the difference in temperature between a shaft and the outdoor.

The temperature difference, hence air density difference, cause the pressure difference like this between the shaft and the outdoor.

If openings are distributed uniformly along the height, as a typical opening type of shaft, neutral zone of pressure is formed about the middle height.

Below the neutral zone outside air flows into shaft is induced and above the neutral zone shaft air flows out to the outdoor.

If the neutral zone height is known, the outflow and inflow rates are calculated by the well established theory.

Then, how can you know the neutral zone height?

It can be obtained by invoking mass continuity law to result as shown here.

It is known by this equation that the neutral zone height is formed almost at mid height of shaft unless the shaft temperature is extremely higher than the outdoor.

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As another typical opening type, let's consider the case where a shaft has an opening at the top and the bottom.

Likewise using orifice flow rate equations and mass continuity, the neutral zone height and mass flow rate can be obtained.

The notable difference of the neutral zone height in this array of the opening is that it heavily depends on the sizes of the two openings.

If the opening at the top is larger than that at the bottom, the neutral zone is formed at higher position and if the opening at the bottom is larger, the neutral zone is lower.

When neutral zone is at low position, shaft is as if pressurized, and the neutral zone is at high position it is as if depressurized.

(slide 35)

Needless to say, shafts are not independent in the air but connected with floor areas in a building. What is important is that the pressures of the floor areas at each level are determined unexceptionally between the pressures of the shaft and the outdoor.

It implies that if a fire breaks out below the neutral zone the pressure act to push its smoke into the shaft, and above the neutral zone the pressure act to push the smoke in the shaft out into the floor area.

This is a reduced scale experiment to visualize the smoke spread in a multi-story building. It has 10 floors and a shaft. The fire is located on the 1st floor.

You see the upper half floors, above the neutral zone, are clogged with smoke while the lower half is free from smoke due to the inflow air.

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It is said that the higher the temperature and the larger the height of a shaft, the stronger the stack effect. But what is the measure of the strength of stack effect?

Perhaps the flow rate is the adequate candidate measure for it.

Based on this, it follows that the stack effect strength is proportional to  $\frac{1}{2}$  power of temperature difference for both typical opening cases.

And proportional to opening area and to  $\frac{1}{2}$  power of shaft height.

(slide 37)

This figure is from Building Code by National Board of Fire Underwriters in 1915.

In order to protect escape stairwells vital to human safety in fire, smoke-proof tower concept was introduced in the USA in early 20<sup>th</sup>.

This stairwell had a balcony or a lobby widely opened to the outdoor as well as separated from floor area by fire walls. By entering into the stairwell via an open air balcony, this stair is made perfectly free from smoke.

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The smoke-proof tower concept is introduced in Japan as Special escape stairs as you can recognize in this figure.

(slide 39)

In modern buildings, for the sake of economy, the smoke-proof performance of stairs is gradually degraded. The lobbies of special escape stair in this high-rise office building are used as a part of corridor in normal time. The lobbies are formed by automatic closing doors relayed with smoke detectors.

(slide 40)

As an extreme case, the lobby of this condominium is located in the midst of dwelling units. The doors of the lobby are entrance doors of the dwelling units.

(slide 41)

Because smoke-proof performance of escape stairwell tend to be sacrificed in modern buildings to make the most of the limited spaces, smoke control system is introduced to compensate the deficit of the performance.

Typical smoke control methods to protect escape stairwell are smoke extraction in stairwell lobbies, stairwell pressurization and lobby pressurization.

Stairwell pressurization seems to be popular in the US partly because it is allowed to employ it as the alternative to arranging lobbies.

In Japan, smoke extraction and pressurization at lobbies re most popular probably because lobbies are not exempted by employing a stairwell pressurization and stairwell pressurization system is not prescribed in the regulation so it requires special permission by Ministry in charge.

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The goal of pressurization smoke control system is to achieve smoke stop condition at an opening between the fire room and the spaces to be protected for evacuation of fire service operation.

The spaces to be protected are firstly vertical shafts such as escape stairwells, elevator shafts, etc. which are important for safe evacuation of whole building as well as for fire brigade's approach to the fire floor.

Secondary, stairwell lobbies are to be protected as temporary refuges of the occupants on the fire floor and as the base of fire brigades, from which they dispatch to hazardous area for search as rescue as well as for fire suppression.

Thirdly, it is desirable to keep corridors free from smoke until completion of evacuation of the fire floor. This figure illustrate sthe idea of smoke control system to attain such goals.

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This schematic explain smoke stop condition at doorway in terms of pressure. Two types are considered depending on the scenarios of the spaces contaminated by smoke.

Two layer scenario corresponds to that the space on the fire room side is stratified into an upper smoke layer and lower air layer such as the fire room itself or a corridor relatively early stage.

On layer scenario corresponds to that the space on the fire room side is fully contaminated by smoke such as the fire room or a corridor at later developed stage.

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The smoke stop condition at door way can be expressed in a couple of ways. The useful expressions are shown here, that is: pressure difference at floor level, average pressure difference and doorway flow rate.

Note that these three expressions are all identical. If there is a pressure difference across an opening, there is always flow through the opening. Average pressure difference over an opening is convenient when flow calculation involves multiple rooms.

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The temperatures of spaces in a building may be greatly different under fire conditions. This induces pressure distribution along the height of an opening and complicates the calculation of the flow rate.

The idea of average pressure difference is to approximate the actual pressure difference into a uniform pressure difference.

The definition is given as here. Note that opening mass flow rate in this treatment is considered in terms of net flow rate. The good thing of using such average pressure is that opening flow rate under any condition can be calculated simply by this orifice formula.

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In the calculation of smoke control involving multiple spaces, air flow calculation through multiple opening is needed.

Let's consider here for a simple example that two openings exist between two spaces, I and K for generality, whose pressures are known.

Noting the relationship on pressure differences between intervening space, j, and the mass continuity, the opening flow rate can be calculated using the known pressures and the areas of the two openings.

The last equation is generally called as effective opening area, and can be extended to cases with more openings in the similar form.

(slide 47)

The average pressure treatment assumes that the heights of the openings involved in the flow calculation are not very different. But in some cases such as the flow calculation

involving a tall shaft, buoyancy effect due to temperature difference with outdoor cannot be neglected.

Examining the relationship among the pressures involved we have this equation.

Using the opening flow rate formula in this equation, we can obtain the flow rate equation for such a case, which is only different from the preceding equation by the buoyancy term on the right hand side. Note here that  $A_e$  is again the effective opening area.

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Using the preparatory knowledge explained up to now, let us consider a simple example of smoke control calculation for two rooms configuration to understand the basic procedure of the calculation.

The example is, as shown here, the problem to calculate the rate of air supply required to stop smoke at the door in the wall between the fire room, R, and the adjacent room, L.

Firstly, we notice some relationship holds, that is:

For pressure, the pressure of room L is the pressure of room R plus the pressure difference across the doorway  $\Delta p_{LR}$ , of course.

For mass continuity, in and out flows for room L are the same, and the total of the outflow rates from the room equals the air supply rate,  $W_L$ .

And the opening mass flow rate at each opening is a function of corresponding pressure difference are as follows.

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The other key point in the smoke control calculation is that the pressure difference across the doorway is fixed by the smoke stop condition, that is, in terms of average pressure difference:

Hence, the flow rate through the opening is at the same time fixed as:

Therefore, from the mass continuity of room R and the relationship between rooms R and L we obtain:

Using  $\Delta p_{LR}$ , we can of course calculate the air leakage from room L to the outdoor,  $m_{LO}$ ; So from the mass continuity of room L, we get the required air supply rate.

The interesting feature to note in the smoke control calculation is that the calculation procedure is made straightforward by that the pressure at a doorway is pre-fixed by the smoke condition imposed.

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The outline of the calculation procedure is demonstrated in the following slides. But I stop here for limitation of time.

However, the outline is retained in the handout distributed to the audience. So if you are interested, please, look into it later.

Finally, I would like to note the good point of simple calculation method.

Of course, computer fire models are widely used for fire safety design practices. But such computer models tend to be blindly used, not exactly knowing what the model are predicting.

On the other hand, designers are always aware what they are addressing in case they use simple calculation procedure. Also they can clearly identify the degree of importance of various factors involved in the design.

Thank you.