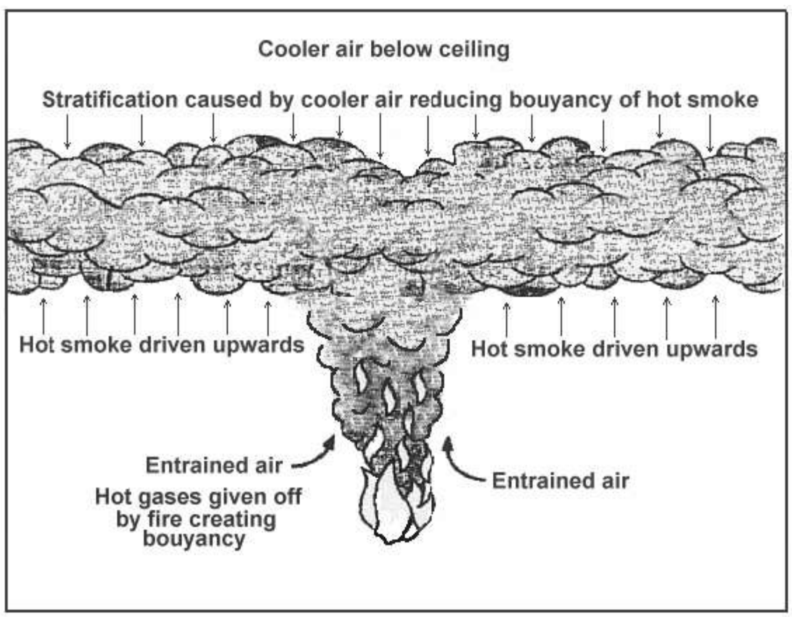
The Stratification of Smoke

by Tony Botha – Fire Engineering Consultant

Stratification – the phenomenon where the upward movement of smoke and gases ceases due to the loss of buoyancy.

The dynamics of stratification of smoke is not always appreciated in terms of fire protection and especially in relation to the placement of fire detectors and ventilation in buildings. The reason this concept is not always appreciated in fire protection measures is that it is not a common occurrence in most facilities. The wider use of high bay storage and atriums in recent years has resulted in more emphasis being placed on the probability of stratification of smoke. This article provides a basic overview of the concept of smoke stratification (smoke layering). In addition, other references are included which can be used to further study the concept. Figure 1 below illustrates the concept of smoke stratification.

Figure.1 Illustration of smoke stratification



Fire produces a buoyant smoke plume which rises above the source of the fire until it reaches the upper layer which invariably is a ceiling or roof in a confined area. Stratification occurs when the buoyancy forces lose momentum before reaching a ceiling or roof. Because the hot gases from a fire will rise owing to buoyancy forces, combustion products will initially be stratified near the roof of an entry. As this stratified gas layer moves away from the fire, the resultant cooling and dilution will eventually produce a well-mixed flow of combustion products.

The upward movement of smoke in the plume is dependent upon the smoke being buoyant relative to the surroundings. The potential for stratification relates to the difference in temperature at the ceiling and floor levels of the open space. There is a maximum height to which plume fluid (smoke) will rise, especially early after ignition, depending on the convective heat-release rate and the ambient temperature variation in the open space.

Stratification occurs when air containing smoke particles or gaseous combustion products is heated by smoldering or burning material and, becoming less dense than the surrounding cooler air, rises until it reaches a level at which there is no longer a difference in temperature between it and the surrounding air. The smoke plume as it rises encounters colder air which absorbs heat and slows the upward movement of the smoke. This process is more prevalent in the incipient stages of fire development where the buoyancy forces generated by a fire can more easily be restricted by colder upper layers. As the fire develops and heat release rate increases, the hot gas layer rises higher due to the differential air temperature between the smoke plume (ceiling jet) and the colder upper layer being reduced. The smoke plume will eventually be forced upward until it reaches the underside of the ceiling or the maximum theoretical height of the smoke plume.

As smoke and heat rise from a fire, they tend to spread in the general form of an inverted cone. Therefore, the concentration within the cone varies inversely as a variable exponential function of the distance from the source. This effect is very significant in the early stages of a fire, because the angle of the cone is wide. As a fire intensifies, the angle of the cone narrows and the significance of the effect of height is lessened.

A simple illustration of this process is the traditional camp fire which is started on an early winter morning. The smoke layer will tend to drift just above the ground and as it moves further away from the source it will be forced downward by the colder morning air. The same fire if made later in the day, when the surrounding air is warmer, will have a much higher smoke plume trajectory.

The probability of stratification of smoke needs to be considered in the placement of fire detectors and smoke management systems especially in high bay warehouses, atriums, service ducts and stairwells.

Validity of Test Methods

Test methods have been used historically in instances where the authority having jurisdiction requires additional testing. These test methods have limited value in evaluating certain system performance, and their validity as a method of testing a smoke management system or placement of fire detectors is questionable. As previously discussed, the dynamics of the fire plume, buoyancy forces, and stratification are all major critical elements in the design of the smoke management systems and fire detector placement. Therefore, to test the system properly, a real fire condition would be the most appropriate and meaningful test. But there are many valid reasons why such a fire is usually not practical in a completed building.

Open flame/actual fire testing might be dangerous and should not normally be attempted. Any other test is a compromise. If a test of the smoke management system for building acceptance is mandated by the authority having jurisdiction, such a test condition would become the basis of design and might not in any way simulate any real fire condition. More importantly, it could be a deception and provide a false sense of security that the smoke management system or fire detectors would perform adequately in a real fire emergency. Smoke bomb tests, smoke generators and other chemical smoke producing devices do NOT provide the heat, buoyancy, and entrainment of a real fire and are NOT suitable in evaluating the real performance of the system. The smoke generated by these devices is `cold' smoke that does not display the same dynamics of a hot smoke plume generated by a fire.

At the present time, a theoretical approach to establishing an effective verification of the determination of stratification of smoke is limited due to the following influences:

- variations in types of fire exposure
- rate of involvement of a material in a fire
- ventilation characteristics of the compartment
- degree of stratification of the accumulated smoke

These are, in most instances, undetermined variables that greatly influence the development of smoke layers. A complete analysis of the potential fire relating to the facility is required to provide a suitable determination of the probability of stratification of smoke.

One of the options is the wider use of computer fire models, however, this technique needs to be further developed in South Africa. The use of computer fire simulation models requires that a number of simulations of the various fire scenarios, determined by analysis of the fire potential of the facility, be developed before a reasonable assessment can be made.

Designing Smoke Management Systems

Where it is possible and practical pan fires can be used under controlled conditions to visually verify the extent of smoke stratification. Small or full scale tests at recognized testing institutions may be necessary if further verification is required.

Where the potential for stratification of smoke or smoke layering exists appropriate measures need to be implemented in the design of smoke management systems and the placement of fire detectors or the selection of fire detection systems. A fire detection system should meet specific performance objectives, considering the individual building/room characteristics, potential fire growth rates, and damageability characteristics of the targets (e.g., building occupants, equipment and contents, or structures).

Early warning of a fire incident is generally dependent on detection of products of combustion in the incipient stage of fire development. Stratification of smoke can compromise the performance objective of providing early warning of a fire incident. As the ceiling height increases, a larger-size fire is necessary to actuate the same detector in the same length of time. In view of this, the designer of a fire detection system calling for fire detectors, should consider the size of the fire and rate of heat release that may be permitted to develop before detection is ultimately obtained. When stratification occurs, the smoke/heat being transported from a fire might not be able to reach detectors mounted at a particular level above the fire. The fire designer needs to adjust to these conditions in the type of fire detection system proposed and more particularly in the placement of the fire detectors or sensing device used.

Stratification of air in a room can hinder air containing smoke particles or gaseous combustion products from reaching ceiling-mounted smoke or fire-gas detectors. In installations where detection of smoldering or small fires is desired and where the possibility of stratification exists, consideration should be given to mounting a portion of the detectors below the ceiling. In high ceiling areas, projected beam-type or air sampling-type detectors at different levels should be considered. The configuration of the large--volume space should be considered in selecting the type of detector to be used to activate the smoke management system. The size, shape, and height of the space needs to be evaluated.

These factors vary widely among atrium designs and need to be considered carefully in selecting detectors for a large-volume space. In addition, the envelope of the large-volume space needs to be evaluated for its contribution to temperature stratification. The height of the large-volume space and its architectural features, such as skylights, will be dominant factors in determining stratification.

The following references provide more detailed information on the dynamics of smoke stratification.

Morton, B. R.; Taylor, Sir Geoffrey; and Turner, J.S. "Turbulent Gravitational Convection from Maintained and Instantaneous Sources, " Proc. Royal Society A, 234, 1-23, 1956.

Heskestad, G. "The Initial Convective Flow in Fire: Seventeenth Symposium on Combustion. " The Combustion Institute, Pittsburgh, PA (1979).

Fires, of the 2nd International Mine Ventilation Congress. The designer is advised to be thoroughly familiar with Chapter 41, Fire and Smoke Control, in the ASHRAE Handbook.

Klote, J. and Milke, J. "Design of Smoke Management Systems, "American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA 1992.

Cooper, L. Y., Harkleroad, M., Quintiere, J., and Rinkinen, W., An Experimental Study of Upper Hot Layer Stratification in Full-Scale Multiroom Fire Scenarios, Paper 81-HT-9, The American Society of Mechanical Engineers (1981).