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ABSTRACT

Characterization of smoke, factors influencing smoke production and experimental methods for measuring smoke production are discussed in this literature review. Recent test-based correlation models are also discussed.

Despite the large number of laboratories using different fire testing methods, published smoke data have been scarce. Most technical literature on smoke production from building materials is about experimental results in small scale tests. Compilations from cone calorimeter tests have been published for a few materials, e.g. upholstered furniture materials and some building products. Mass optical density data and compilations of gravimetric soot data are available for various materials as well as a number of smoke obscuration values. For a given material often a wide range of values of smoke output can be found in the literature and care should be excercised in applying the appropriate value in each case.

Little information is available in scientific literature concerning modelling or predictive correlations between small scale smoke data and real fires or large scale test results. The scale dependence of the rate of smoke production is generally not well known.

In laboratory experiments, the production of smoke and its optical properties are often measured simultaneously with other fire properties as heat release and flame spread. The measurements are usually dynamic in full scale, i.e. they are performed in a flow-through system. In small scale they may be either dynamic, as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. Small-scale tests are necessary as practical tools. Full-scale tests are generally considered to be more reliable and are needed to validitate the small-scale tests.

Quantitative prediction of the rate of smoke production using basic principles for commercially available construction products is not currently possible. Test-based correlation studies are therefore needed to enable the use of small scale test data in determining the fire hazard of products.

There seems to be some evidence that the early stages of certain full scale scenarios can be predicted, whereas post-flashover smoke production cannot yet be resolved. Flow-through systems have been suggested as one means of obtaining correlations between small scale and large scale data.

PREFACE

In recent years considerable research has been published attempting to quantify smoke production and the hazards due to smoke in a fire. This review of the research aims to make it easier for any newcomer to become acquainted with the basic concepts and the present level of knowledge.

The work was started on our own initiative and was funded by VTT Building Technology. The results have been used in a recent project funded by CEC/DGXII in which the scientific knowledge of reaction to fire phenomena was reviewed. The results have also been used in the document ISO WD 13390: Fire Safety Engineering - Initiation and Development of Fire and Fire Effluents, currently under preparation for ISO/TC92/SC4/WG2.

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CONTENTS

1 INTRODUCTION

Smoke production is one of the properties characterizing the hazard of construction products. The combustion conditions under which smoke is produced - flaming or smouldering - influence the amount and character of the smoke. The smoke emission from a flame represents a balance between growth processes in the fuel-rich portion of the flame and burnout with oxygen [Mulholland 1988].

Smoke is basically a product of incomplete combustion. The ISO Working Draft 13943 [1993] defines smoke as a visible suspension of solid and/or liguid particles in gases resulting from combustion. Essentially the same definition has been used also by Mulholland [1988], who defines smoke as the smoke aerosol or condensed phase component of the products of combustion. Sometimes, however, the evolved gases may be included in the definition as well (e.g. ASTM). This paper deals with condensed phase particles only.

Holmstedt et al. [1987] consider separately particles less than 0.3 μm which do not scatter light, and particles larger than 0.3 μm which do scatter light and which are therefore visible. The visible particles are generally what is called smoke. Troitzsch [1990] considers particles larger than 0.05 μm to be visible as smoke and those around 1μm to impair visibility most.

A distinction is sometimes made between *smoke* and *soot*, with the former being measured by optical means, while the latter is determined by actual weighing of particulates collected by gravimetric means.

Smoke particulates reduce visibility due to light absorption and scattering. Consequently, people may have difficulties finding escape routes. A practical way to determine visibility is to measure the distance at which an object is no longer visible. Depending on the smoke movements the hazardous area can be large and the smoky environment can expand very fast. The relation between the loss of visibility and peoples' ability to evacuate has been studied e.g. by Jin [1978].

All narcotic fire products occur in vapour phase, whereas irritant products may be either in gas or solid phase. The particle size determines how deeply particles penetrate into the respiratory tract. Reports on fire victims usually record smoke penetration well into the lungs [Purser 1988].

Corrosive effects on building structures and contents have become an area of great concern and have prompted a number of regulating bodies to restrict or prohibit the use of materials identified as generating corrosive smokes, i.e. halogenated cable and wire insulations [Hasegawa 1990, Tewarson 1993, Kessel et al. 1994].

A vast majority of the technical literature on smoke production from building materials is about experimental results in small scale tests. Little information is available in the scientific literature concerning modelling or predictive correlations between small scale smoke data and real fires or large scale test results. The scale dependence of the rate of smoke production is on the whole poorly understood.

The aim of this literature review is to provide basic information of smoke production. Characterization of smoke and experimental methods for measuring smoke production are briefly discussed, as are recent test-based correlation models.

2 AEROSOLS - BASIC CONCEPTS

An aerosol is a suspension of small particles in air or another gas. Primary gaseous emissions may react in the atmosphere to produce secondary species that nucleate to form particles or condense on pre-existing particles [Flagan & Seinfeld 1988].

The smallest particle diameter is often comparable to the distances that gas molecules travel between collisions with other gases. In actual aerosols the particles are not necessarily spheres and the density of the particles may not be known. For the purpose of describing the motion of such particles in flow fields and under imposed external forces a concept of an *aerodynamic diameter* has been introduced. This is a diameter of a hypothetical spherical particle with the same motion characteristics as the particle in question. The aerodynamic diameter is a measure of the reaction of a particle to inertial forces. In fact, particles with different sizes, shapes, and densities can have the same aerodynamic size. The most common aerodynamic diameters are Stokes diameter, classical aerodynamic diameter and aerodynamic impaction diameter [Flagan & Seinfeld 1988].

Particles suspended in any fluid undergo irregular random motion due to bombardment by surrounding fluid molecules. Phoretic effects produce a directional preference in this *Brownian diffusion* of aerosol particles. *Thermophoresis* is the migration of a particle away from the higher-temperature region and toward the lower-temperature region of the gas in which it is suspended. Unless the temperature gradient is very steep, thermophoresis can generally be neglected compared with the effects of other forces on aerosol particles. Aerosol particles experience an external force when subjected to an intense light beam. This phenomenon, called *photophoresis*, results from the non-uniform heating of the particles. *Diffusiophoresis* occurs in the presence of a gradient of vapour molecules that are either lighter or heavier than the surrounding gas molecules [Flagan & Seinfeld 1988].

The smallest aerosol particle can be defined in principle as that containing two molecules or monomers. Beyond a relatively small number of molecules (about 100) an aerosol population can be treated as if its size variation were essentially continuous. The total number of particles per unit volume of air of all sizes is then

$$N = \int n(D_p)dD_p \qquad (1)$$

where $n(D_p)dD_p$ is the number of particles per unit volume of air having diameters in the range D_p to $D_p + dD_p$.

Because particle diameters in an aerosol population typically vary over several orders of magnitude, it is often convenient to express the size distribution in terms of the logarithm of the diameter, either *ln* D_p or *log* D_p. The most popular distribution representing aerosol size distributions is the *log-normal distribution* [Flagan & Seinfeld 1988, Mulholland 1988].

The dynamic behaviour of an aerosol is described by a population balance equation that can be termed the *general dynamic equation*. In the most general form of this equation the independent variables are particle size and composition, although in most applications size is the only variable characterizing the aerosol [Flagan & Seinfeld 1988].

It has been shown [Mulholland & Ohlemiller 1982] that the minimum information required for a quantitative characterization of the evolution of the aerosol in the buyoant plume above the combustion process includes the mass flow rate, and size distribution of the aerosol at one position in the plume, the heat and mass flow rate from the source, and the thermal stratification in the environment. With this information the aerosol flow rate and size distribution, which are changing as a result of coagulation and air entrainment into the plume, can be predicted as a function of height in the plume.

Coagulation, agglomeration, or *coalescence* of two particles can occur as a result of several mechanisms by which two particles may be brought together. The particles may collide as a result of their mutual Brownian motion; they may be brought into contact by laminar or turbulent velocity gradients in the gas or they may collide due to differential settling velocities. In addition, when two particles get sufficiently close to each other, electrostatic, electrodynamic, and fluid dynamical forces between particles affect the actual rate at which the particles collide. Under typical atmosperic conditions and for particles smaller than a few microns in diameter, the dominant mechanism for agglomeration is Brownian motion. The coagulation coefficient for larger particles is relatively low because of their relatively small Brownian diffusivities [Flagan & Seinfeld 1988]. The effect of initial particle size distribution has been studied, e.g. by Mulholland and Baum [1980]. A practical model to take into account the coagulation when evaluating smoke detector response has been developed by Yamauchi [1988].

3 COMPONENTS OF SMOKE

Combustion processes emit large quantities of particles into the atmosphere. Particles formed in combustion fall roughly into two categories. The first category, referred to as *ash*, comprises particles derived from noncombustible constituents. The second category, referred to as *char, coke* and *soot*, consists of carbonaceous particles formed by pyrolysis. Particles produced by combustion

sources are generally complex chemical mixtures that often are not easily characterized in terms of composition [Flagan & Seinfeld 1988].

Ash is derived from noncombustible material. Some components of ash are highly volatile; examples include sodium, potassium, and arsenic. Since the enthalpies of typical ash constituents are high, the vaporization rates are a strong function of temperature [Flagan & Seinfeld 1988].

The carbonaceous *char* residue that remains after coal is devolatilized burns slowly by surface reactions. Heavy fuel oils may produce similar carbonaceous particles, called *coke*. Coke particles are relatively large, 1 to 50 μm in diameter, with smaller numbers of much larger particles [Flagan & Seinfeld 1988].

Carbonaceous particles can also be produced in the combustion of gaseous fuels and from the volatilized components of liquid or solid fuels. The particles formed by this route, known as *soot*, differ markedly from char and coke [Flagan & Seinfeld 1988]. Most commonly, soot particles are agglomerates of small, roughly spherical particles. While the size and morphology of the clusters can vary widely, the small spheres differ little from one source to another. They vary in size from 0.005 to 0.2 μm but most commonly lie in the size range 0.01 to 0.05 μm. The structural similarity between soot particles and the inorganic particles produced from volatilized ash suggests a common origin. The genesis of soot, however, is much less well understood than that of the inorganic particles due to the extreme complexity of hydrocarbon chemistry in the flame, as well as to the fact that soot particles can burn if exposed to oxygen at high temperatures [Flagan & Seinfeld 1988].

The smallest spheres that agglomerate together to form a soot particle consist of large numbers of lamellar crystallites that typically contain five to ten sheets containing of the order of 100 carbon atoms each. The structure within each sheet is similar to that of graphite, but adjacent layers are randomly ordered in a turbostratic structure. The platelets are also randomly oriented and bound by single sheets or amorphous carbon, giving rise to the spherical particles [Flagan & Seinfeld 1988]. In a fire, the particles may further form complex soot agglomerates [Mulholland 1988].

Soot particles are not pure carbon. The composition of soot that has been aged in the high-temperature region of the flame is typically C_8H, but soot may contain considerably more hydrogen earlier in the flame. Furthermore, soot particles adsorb hydrocarbon vapours when the combustion products cool, frequently accumulating large quantities of polycyclic hydrocarbons. The presence of soot in a flame gives rise to radiative heat transfer. Because of the high emissivity of soot particles relative to that of the gases in the flame, only a small quantity of soot is sufficient to produce an intense *yellow* luminosity. Without soot, hydrocarbon flames appear either *violet* due to emissions from excited CH radicals when fuel-lean or *green* due to C_2 radical emissions when fuel-rich. The high emissivity of soot translates into a high absorptivity at ambient temperatures, leading to its *black* colour in a plume [Flagan & Seinfeld 1988].

No generally applicable model has yet been formulated to predict soot formation as a function of fuel type and combustion conditions. Soot forms in a flame as the result of a chain of events that begins with pyrolysis and oxidative pyrolysis of the burning material into small molecules, followed by chemical reactions that build up larger molecules that eventually get big enough to become very small particles. The particles continue to grow through chemical reactions at their surface, reaching diameters in the range 0.01 to 0.5 µm at which point they begin to coagulate to form chain agglomerates [Flagan & Seinfeld 1988].

The propensity to form soot (as measured by the critical C/O ratio at which soot formation begins) is a complex function of flame type, temperature, and the nature of the burning material. There is a general agreement that the rank order of the sooting tendency of fuel components is naphtalenes > benzenes > aliphatics. However, the order of sooting tendencies of the aliphatics (alkanes, alkenes, and alkynes) varies dramatically with flame type. Much of the variability has been attributed to flame temperature. As the temperature increases, the oxidation rate increases faster than the pyrolysis rate, and soot formation decreases (Flagan & Seinfeld 1988].

The difference between the sooting tendencies of *aromatics* and *aliphatics* is thought to result from different routes of formation. The condensed aromatic systems are at present considered as the direct precursors of soot [Troitzsch 1990]. Other indications are that the conjugated polyenes which were also considered formerly as direct precursors of soot undergo cyclization to aromatic systems which then contribute to soot formation. Aliphatics appear to form soot primarily through formation of acetylene and polyacetylenes at a relatively slow rate [Flagan & Seinfeld 1988]. Solid particles such as minute carbon particles or inorganic fillers (in plastics) can also act as soot-forming condensation nuclei [Troitzsch 1990].

Once soot nuclei have been formed, particle growth occurs rapidly by surface reactions. Ultimately, the soot nuclei account for only a small fraction of the mass of soot formed; the remainder is material that has condensed or reacted on the initial nuclei. The yield of soot increases rapidly as the C/O ratio increases beyond the sooting threshold. Soot particle inception takes place very early in the flame, in a region where radicals are present in superequilibrium concentrations [Flagan & Seinfeld 1988].

4 SMOKE POINT

The smoke point of a fuel is generally defined by the critical laminar "candle-like" flame height (or heat release rate) at which smoke just begins to be released from the flame tip. Soot is formed in the lower part of the flame, transported by the rising gases, and oxidized in the upper part of the flame. For laminar flames at their smoke point, the competing mechanisms of soot formation and soot oxidation are in balance. For flames burning at or below their smoke point height, the soot is completely oxidized in the upper part of the flame before it can escape.

Fuels producing sootier flames have smaller critical smoke point residence times and correspondingly smaller smoke-point laminar flame heights, because the greater intensity of their radiative heat loss from the soot causes their flames to cool more rapidly, leading to earlier extinction by radiation [de Ris & Cheng 1994].

It has been established that the release of both thermal radiation and products of incomplete combustion from well ventilated buoyant turbulent diffusion flames are well correlated by the fuel's laminar flame smoke point value [de Ris & Cheng 1994]. Thus the smoke-point of a material provides an important measure of its flammability. Similarly, knowledge of the smoke point of a substance gives a good indication of its total release of unwanted non-thermal products of combustion (soot, tars, CO and others). The chemical composition of soot is generally thought to be similar for all C-H, C-H-O and C-H-N fuels, so that their chemical mechanism of soot oxidation is presumably independent of fuel type. This implies that the smoke point of a fuel is primarily a measure of its soot formation rate.

Figure 1 shows, according to Tewarson [de Ris & Cheng 1994], the incompleteness of combustion (heat of combustion of products divided by the fuel heat of combustion) for various fuels burning in air plotted against the fuel laminar smoke point flame height. The production of smoke is related to the incompleteness of combustion.
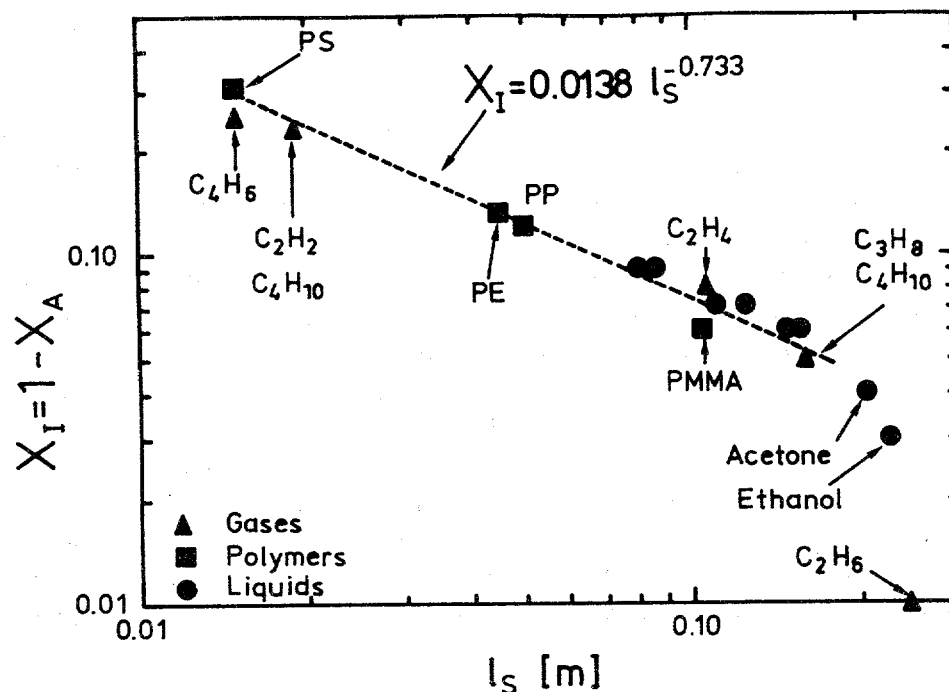

Fig. 1. Incompleteness of combustion vs. smoke point flame height according to Tewarson [de Ris & Cheng 1994].

11

A linear correlation has been found between the radiant fraction of the theoretical heat release rate for various fuels and the rate of heat release of the fuel's laminar smoke point flame [de Ris & Cheng 1994].

Standard methods are available for measuring the smoke points of gaseous and liquid fuels (e.g. ASTM D1322), but not for solid fuels. De Ris and Cheng [1994] have developed an apparatus for measuring the smoke points of charring and non-charring solid materials.

5 FACTORS INFLUENCING SMOKE PRODUCTION

5.1 COMPOSITION OF THE PRODUCT

Fire is intimately concerned with the process of oxidation. Air is not the only source of oxygen for the burning or fire process. There are many substances that contain oxygen and are capable of oxidizing other substances in a rapid manner by burning (such as pyrotechnics). These materials react and burn without the aid of the oxygen in air [Tuve 1976].

The chemical nature of the burning material has a systematic effect on the smoke production. Very few pure fuels (e.g. carbon monoxide, formaldehyde and methyl alcohol) do not produce smoke. Other organic materials burning under identical conditions give substantial amounts of smoke depending on their chemical nature [Östman 1992].

Oxygenated liquids (such as ethyl alcohol) and polymers (such as polyacrylates and polyacetals) make only a limited contribution to smoke production [Troitzsch 1990]. If the hydrocarbons are unsaturated, the smoke production is higher than with corresponding saturated hydrocarbons [Östman 1992]. The largest contribution is made by aromatics attaining the gas phase, which are converted into condensed polyaromatic systems, the direct precursors of soot [Troitzsch 1990]. Thermoplastics which decompose primarily to aromatics in the gas phase give rise to large amounts of soot (e.g. polystyrene and its copolymers SAN and ABS). Pyrolysis and combustion of thermosets results in minimal smoke development. This is due to the cross-linked structure of thermosets which renders them liable to char and liberate fewer decomposition products to the gas phase. A few thermosetting plastics do tend, however, to develop smoke strongly since they contain aromatic structures which are liberated in the gas phase (i.e. unsaturated polyester resins cross-linked with polystyrene, epoxy resins based on bisphenol A).

12

5.2 ENVIRONMENT

The smoke production may also depend on the burning environment. Experimental studies have shown smoke yield to be dependent on variables such as radiant heat flux, oxygen concentration, ventilation, sample orientation and geometry, and moisture content of the sample [e.g. Östman 1992]. Most of these conditions can also vary between different phases of fire. However, two distinct phases of smoke production should be considered, one related to the early stages of fire (pre-flashover, perhaps only a single item involved), and another related to the post-flashover fire (all items of a compartment are burning under ventilation controlled conditions).

The rate of burning and the area involved in burning must always be considered when determining the smoke production. A material or product producing rather small amounts of smoke per fuel area, may have a substantial smoke production due to a rapid surface spread of flames. This is of special importance when comparing fires (or tests) of different sizes.

5.3 COMBUSTION

In order to burn, organic molecules containing carbon and hydrogen must first break down, or pyrolyse, under the influnce of heat to produce simple, combustible gases and solids that will be oxidized in air [Tuve 1976].

Smoke is basically a product of incomplete combustion. While most materials can be pyrolyzed (decomposed), only a few materials, including cellulosic materials (wood, paper, cardboard etc.) and flexible polyurethane foam, are able to *smoulder*. The temperature during smouldering is typically in the range of 600 to 1100 K [Mulholland 1988]. In smouldering combustion, volatiles are evolved at elevated temperatures. Upon mixing with cool air they condense to spherical droplets, which appear as light-coloured smoke aerosol. Smoke from smouldering combustion is similar to that obtained from carbon based materials heated to temperatures at which there is chemical degradation and evolution of volatiles [Drysdale 1986]. The particle size of the spherical droplets from smouldering combustion is generally of the order of roughly 1 μm, i.e. larger than from flaming combustion.

Flaming combustion produces a black carbon-rich smoke, where particles have a very irregular shape. Smoke particles at flaming combustion are formed in the gas phase and in regions where the oxygen concentrations are low enough to cause incomplete combustion [Östman 1992]. For cellulosic materials the amount of smoke per unit mass is less with flaming combustion than with smouldering combustion [Drysdale 1986]. With plastics, however, no such generalization can be made [Mulholland 1988]. For wood and similar cellulosic materials the production of smoke is increased dramatically with restricted ventilation; for other types of fuels, little is known [Dod et al. 1989].

13

5.4 FIRE AND FLAME RETARDANTS

Fire-retarded or flame-retarded (FR) materials and products are supposed to produce "slower" fires. There are, however, no theoretical or systematic approaches to the "slow fire performance". A number of adjectives have been used to describe a product having a low contribution to a fire [Gann 1994]. Nonquantitative terms such as *fireproof, flameproof, self-extinguishing, non-burning,* and *non-combustible,* have been used. Once ignited an ignition-resistant material may burn with a higher density than a more easily ignited counterpart. Moreover, successful ignition-resistance test performance is not proof of fire prevention.

FR agents, mainly considered for wood, plastics and textiles, typically comprise halogenated and/or organophosphorous compounds, and inorganic compounds (e.g. based on B, Sr, Al and Mg).

If the flame retardants act in the gas phase by interrupting the radical chain mechanism, they almost always contribute to an increase in smoke levels since they suppress the oxidation reactions occurring during combustion and promote soot formation [Troitzsch 1990]. Flame retardants which are effective in the gas phase are used mainly in thermoplastics and cause dense smoke development even in those polymers which by themselves inherently emit relatively little smoke.

Systems which act in the condensed phase by e.g. cross-linking or protecting the substrate by coating, limit the formation of gaseous decomposition products and act simultaneously as flame retardants and smoke suppressants [Troitzsch 1990). They are of particular interest for those polymers which normally do not char (e.g. polystyrene).

Smoke data regarding FR treated materials or products are scarce. The overall impression with flexible polyurethane foams treated with bromine-based and phosphorous/chlorine-based FR agents was that the resistance to small ignition sources was improved, while actual fire performance, once ignited, was not much changed [Babrauskas 1992]. With polystyrene foams the rate of heat release was unchanged and ignitability was actually made worse. A systematic study by Jarvis et al. [Babrauskas 1992] showed that with PP and PMMA treated with organobromine/antimony oxide the modest benefits were outweighed by the roughly doubled emissions of toxic gases, smoke and soot.

Bench-scale cone calorimeter data [Babrauskas 1992] clearly showed substantial improvements in heat release performance at irradiance level 30 - 100 kW/m^2 with some selected plastics products treated with different FR agents. The yields of smoke and toxic gases, however, were in many cases higher. In real-scale tests it was demonstrated that if sufficiently effective FR agents are used, any effects of increased yields of smoke are more than compensated by decreased burning rates of polymeric materials. At the moment, however, we do not have universal predictive techniques of knowing whether an FR agent being used *is* a sufficiently effective FR agent.

6 MEASURED SIZE DISTRIBUTIONS

Smoke aerosols vary widely in appearance and structure, from light coloured, for droplets produced during smouldering combustion and fuel pyrolysis, to black, for solid, carbonaceous particulate or soot produced during flaming combustion [Mulholland 1988].

More than one instrument is necessary for a complete characterization of the smoke size distribution, because it is typically quite wide. The size distribution plotted in Figure 2 is based on electrical mobility analysis of the smoke aerosol. It should be noted that the size distribution and the mean size of the smoke particles depend on the weighting, e.g. whether one is expressing a number size distribution or a volume size distribution. The particle size distribution of smoke aerosols changes with time - the smoke particles coagulate as they age [Mulholland 1988]. Other sources of measured size distribution include Seader & Chien [1974], Bankston et al. [1977] and Welker & Wagner [1977] and Molière et al. [1978].
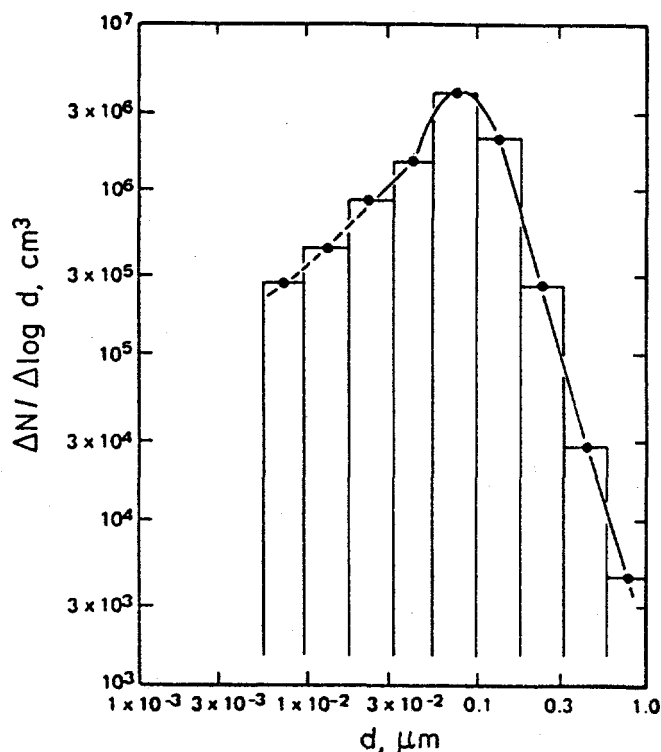

Fig. 2. Size distribution (geometric number distribution) of smoke generated by a smouldering incense stick as measured by an electrical aerosol analyser. There is a large uncertainty in the dashed portion of the curve [Mulholland 1988].

15

7 AVAILABLE SMOKE DATA

Despite the large number of laboratories using different fire testing methods published smoke data have been scarce. Compilations from cone calorimeter tests have been published for a few materials by Mulholland et al. [1988] and for upholstered furniture materials by Babrauskas and Mulholland [1988]. Examples of smoke data for some building products by Östman and Tsantaridis. [1991] are given in Table 1.

Table 1. Smoke extinction area (m^2/kg) from the cone calorimeter [Östman 1992].

BUILDING MATERIAL	IRRADIANCE LEVEL 25 kW/m^2	IRRADIANCE LEVEL 50 kW/m^2	IRRADIANCE LEVEL 75 kW/m^2
Rigid polyurethane foam	750	860	-
Textile wall-covering on rock-wool	220	210	290
Insulating fibre board	a)	70	100
Expanded polystyrene	NI	1360	-
Medium density fibre board	a)	80 b)	120
Wood panel (spruce)	a)	a)	80
Paper wall-covering on particle board	a)	a) 70	
Particle board	a)	60	90
Melamine-faced particle board	NI	a)	100 b)
Plastic wall-covering on gypsum board	370	60	70
Textile wall-covering on gypsum board	70	30	40
Paper wall-covering on gypsum board	20	30	20
Gypsum board	NI	20	20

a) Test termination according to mass loss criterion of 2.5 g/(m^{2}s) not obtained

b) Test termination according to mass loss criterion of 2.5 g/(m^{2}s) not quite obtained

Tewarson [1988] has collected mass optical density data for various materials. Compilations of gravimetric soot data are available for a smaller range of materials, including some building products [Östman 1992]. A large number of smoke obscuration values have been tabulated by Hirschler [1992]. References to the older literature on smoke evolution has been collected by Hilado and Kosola [1977].

Data on the smoke production of different materials are available mainly from small scale testing (specific optical density, mass optical density). However, when using such data, it should be noted that there are substantial differences for the same or similar materials under similar burning and testing conditions [Östman 1992]. It should be emphasized that these smoke data represent a general level rather than "absolute" properties for different materials and products. Measurement of smoke is essentially dependent on the equipment used, and interpretation of time-dependent curves is not very simple.

8 MEASUREMENT OF SMOKE PRODUCTION

8.1 GENERAL ASPECTS

Visibility in smoke has been related experimentally to the logarithmic expression of the attenuation of light per unit length of light path in the smoke. This property has been called *smokiness* and for a given smoke is directly proportional to the mass concentration of the particles in the smoke. The visibility is approximately inversely proportional to the smokiness (unless there are lachrymatory effects). Smokiness is routinely measured in fire tests and related to the smoke output of the fire on the basis of volume [Rasbash 1995b].

In laboratory experiments, the production of smoke and its optical properties are often measured simultaneously with other fire properties such as heat release and flame spread. The measurements are usually dynamic in full scale, i.e. they are performed in a flow-through system. In small scale, they may be either dynamic as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. Small-scale tests are necessary as practical tools. Full-scale tests are generally considered to be more reliable and are needed to validate the small-scale tests [Östman & Tsantaridis 1994].

8.2 SMOKE MEASUREMENT UNITS

Different units are used when measuring optical smoke density, with a resulting possibility of misunderstanding the unit used by various authors. In the following we first define the basic concepts and then introduce the conversion factors needed to use results published using other units.

Let us first consider a situation where a beam of light with initial intensity I_0 is passing through a cloud of particles with an effective absorption cross-section of

σ [m^2]. The particles are randomly distributed in space with a number density n = dN/dV [m^{-3}], where N is the total number of particles in volume V. If the thickness of the cloud is L, it is easy to derive the well-known Beer-Lambert´s law for attenuation of light:

$$I(L) = I_0 \exp(-\sigma \ln L) = I_0 \exp(-kL), \qquad (2)$$

where the **extinction coefficient** k [m^{-1}] is the total cross-section of particles per unit volume and is easily obtained by inversion of the logarithm,

$$k = (1 / L)\ln(I_0 / I). \qquad (3)$$

The total amount of smoke or the **total smoke production** - TSP - [m^2] can be defined as the total cross-sectional area of smoke particles produced (from a given piece of product in a given period of time, usually until complete extinguishment), i.e.

$$TSP = \sigma N. \qquad (4)$$

The **rate of smoke production** - RSP - [m^2/s] can be defined as the increase of the total cross-sectional area of smoke particles per unit time (i.e. **not** per unit volume), i.e. the time derivative of TSP;

$$RSP = \frac{d(\sigma N)}{dt}, \qquad (5)$$

where the latter form is valid if the effective cross-section is the same for all particles.

If all the particles produced are led through a duct with a volume flow rate of $V_f = dV/dt$, we get

$$RSP = \sigma \left(\frac{dN}{dV}\right)\left(\frac{dV}{dt}\right) = \sigma nV_f \qquad (6)$$

or

$$RSP = kV_f \qquad (7)$$

The rate of smoke production in this way is easy to apply. For example, if all the produced smoke is being led into a compartment of volume V, the rate of increase of the total cross-sectional area of smoke particles equals RSP. If the smoke is fully mixed, the average smoke density in the compartment is

$$k_{room} = \frac{\int k_{source} \, V_{f,source} \, dt}{V_{room}}.$$
(8)

In some older literature, the attenuation of light has been expressed using a common logarithm (base-10). The equation for attenuation is then

$$I / I_0 = 10^{-DL},$$
(9)

where D is the optical density of smoke. Thus

$$D = (1 / L) \log_{10} (I_0 / I) = k \log_{10} e = 0.434 \, k$$
(10)

or

$$k = D \ln 10 = 2.30 \, D.$$
(11)

In smoke detector technology the unit dB/m (decibel/m) has been used with the smoke density defined as

$$m = (10 / L) \log_{10} (I_0 / I) = k \, 10 \log_{10} e = 4.34 \, k$$
(12)

or

$$k = m \ln 10 / 10 = 0.23 \, m$$
(13)

Östman [1992] has discussed smoke measurement units and their derivatives in more detail. To avoid confusion, Rasbash [1995a, 1995b] recommends that for data involving light attenuation in smoke, units that clearly indicate the base of the logarithm should be used. He also points out that for a given material there is often a wide range of values of smoke output which can be found in the literature and care should be excercised in applying the appropriate value in a particular case. This has also been emphasized by Whiteley [1994].

8.3 EXPERIMENTAL METHODS

Here we briefly describe the commonest methods used for measurement of smoke production, as test-based smoke production models are inherently related to input data. Measurements in a flow-through system are dynamic [ASTM E 906, ASTM E 1354, ISO 5660, ISO 9705]. Cumulative or static methods are mainly performed in small scale and in closed systems [ASTM E 662, ISO DIS 5924, ISO DIS 5659].

ISO DIS 5924 (Dual Chamber Test) is a test method designed to measure the smoke production of essentially flat materials and products whose surface is exposured to thermal irradiences up to 50 kW/m². Horizontal orientation is used.

Smoke is generated in one compartment of a box using a modified ignitability test apparatus [ISO 5657] without the pilot flame. The smoke is then accumulated in a second chamber (volume about 1.2 m³) in which the smoke is stirred by a fan and the optical density measured by a horizontal white light beam. The maximum smoke density at five irradience levels from 10 kW/m² to 50 kW/m² is determined.

This test method is of static, cumulative type. The samples burn either by smouldering or by flaming combustion depending on the product and irradience level used. ISO TC 92/SC1/WG4 is carrying out a Round Robin to define the repeatability and reproducibility of the method. The results of that study will be available later.

ISO 5660 (Cone Calorimeter) currently specifies how the cone calorimeter is used to measure the rate of heat release. However, a method to measure smoke production is being developed using the ASTM E 1354 as a basis. In this test smoke is produced in the normal cone calorimeter test conditions (horizontal or vertical orientation, irradience usually between 25 and 75 kW/m²). The smoke is sucked into the exhaust duct where the light transmission (extinction coefficient) is measured by using a helium-neon laser. The extinction coeffient is measured as a function of time. Further analysis makes use of the mass loss rate and volume flow rate measurements. The average specific extinction area ($\sigma_{m,ave}$ or *SEA*) is defined as follows:

$$SEA = \sigma_{m,ave} = \frac{\left(\sum_i k_i \Delta t\right)}{\left(m_i - m_f\right)},$$

(14)

where V_i is volume flow rate in the exhaust duct, k_i is the extinction coefficient (according to Eq. 3), Δt is the sampling time interval, m_i is the initial specimen mass and m_f is the final specimen mass.

This method is of the dynamic type and is essentially related to flaming combustion, except that for certain products quite an important part of the smoke is produced before the sample ignites. The produced parameters (extinction coefficient, mass scaled extinction values, smoke production rates, total smoke production values) can be used in modelling to real scale fires/tests. A Round Robin arranged by ISO TC 92/SC1/WG4 gave the following results of repeatability (r) and reproducibility (R) for the average specific extinction area [Mikkola 1992]:

$$r = 30 + 0.16\sigma_{m,ave}$$

(15)

$$R = 50 + 0.41\sigma_{m,ave}$$

(16)

The multiplying factors 0.16 and 0.41 dominate the results, except for very low absolute values of smoke. In other words, the results mean that the repeatability value is slightly above 16% of the mean value of the parameter and the reproducibility value slighty above 41% of the mean. Giving these values as

20

standard deviation values would mean roughly 6% of the mean value for repeatability and 15% of the mean value for reproducibility. Such wide variation in the experimental results also indicates that there is no need, nor it is possible, to develop models which could predict the results to within a few percent.

ISO 9705 (Room/Corner Test) is a large scale room test for wall and ceiling linings. Smoke production is measured in the exhaust duct in a flow-through system, with white light and without mass loss determination of the burning products. Otherwise the measurement principles are the same as in the cone calorimeter. Smoke production rates and total smoke production values are the results obtained.

The method is of dynamic type. Available Round Robin values for rate of smoke production indicate the standard deviation of results obtained in different laboratories to be usually less than 10% [Mangs et al. 1991].

9 CORRELATION STUDIES

9.1 GENERAL ASPECTS

Quantitative prediction of the rate of smoke production using basic principles for commercially available construction products is not currently possible. Test-based correlation studies are therefore needed toenable the use of small scale test data in determining the fire hazard of products.

The prediction of smoke production has been much less studied than predictions of heat release, and with limited success so far [Östman et al. 1992, Heskestad & Hovde 1994]. However, there seems to be some evidence that the early stages of certain full scale scenarios can be predicted, whereas the post-flashover smoke production cannot yet be resolved. Flow-through systems have been suggested as one means of obtaining correlations between small scale and large scale data [Östman 1992].

Smoke data in units where the specimen mass is normalized are preferred for correlations with full scale, but are often hard to determine in full scale fires. In cases where mass normalized data have not been obtained for the full scale, parameters describing the burning rate should be included in correlations between small and full scale smoke production. An alternative is to normalize the smoke production in small and full scale to the heat release [Östman 1992].

9.2 MASS CONCENTRATION AND OPTICAL DENSITY

One possible way to develop useful correlations is to use yields of smoke mass (which have been tabulated, e.g. by Tewarson [1988]). The mass concentration information could then be translated into optical densities. Lee & Mulholland [1977] measured the properties of smouldering lamp wick smokes and heptane

black soot smoke in the UL 217 Standard Evaluation Chamber. The relation between measured optical density per meter and mass concentration in mg/m^3 is shown in Figure 3. Seader & Einhorn [1977] performed experiments with the NBS Smoke Density Chamber showing roughly similar correlations for a number of different smouldering or flaming materials.

Newman & Steciak [1987] found a correlation between the extinction coefficient at 0.4579 μm and a particulate volume fraction of smoke from a variety of materials. They also found that the extinction coefficient is inversely proportional to the wavelength of monochromatic light.
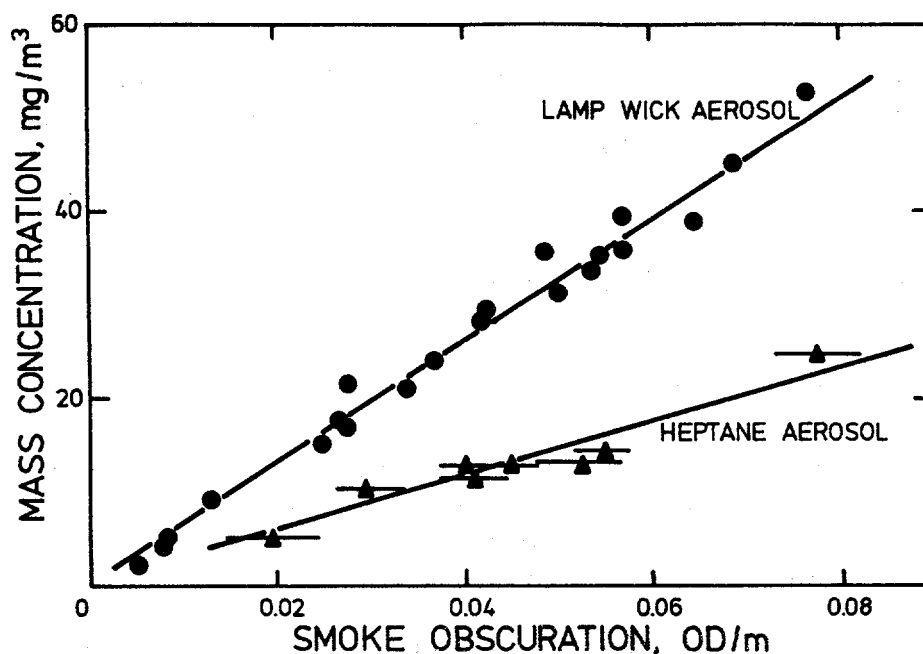

Fig. 3. Mass concentration versus smoke obscuration (optical density per meter) in the UL 217 Standard Evaluation Chamber [Lee & Mulholland 1977].

9.3 RATE OF SMOKE PRODUCTION AND RATE OF HEAT RELEASE

The smoke yield, i.e. the mass of smoke per mass burned, is a useful measure of smoke production propensity of a product under specific conditions. In large scale tests, however, it is not possible to measure the mass loss rate. One might, therefore, try to define a "yield" as the rate of smoke production per rate of heat release. An almost linear correlation (Figure 4) was found between the rate of smoke production and the rate of heat release in measurements including the cone calorimeter, room corner test and the large room test by Kokkala et al. [1992]. The rate of heat release ranged from less than 1 kW up to a maximum of 10 000 kW. Figure 4 indicates that in a fire the intensity of the fire is the dominant factor in the quantitative rate of smoke production. The differences between different types of products is much less important.

Since there are models available which successfully predict the rate of heat release in a large scale test (Wickström & Göransson [1987], Karlsson [1992]), one may try the following relation:

$$TSP_{pred} = \frac{THR_{pred}\,SEA}{EHC},$$

(17)

where the *EHC* is the effective heat of combustion in the small scale test. This principle has been shown to be only partially successful (Östman et al. [1992], Heskestad & Hovde [1994]). In the following we look at the results of Östman et al. in more detail.
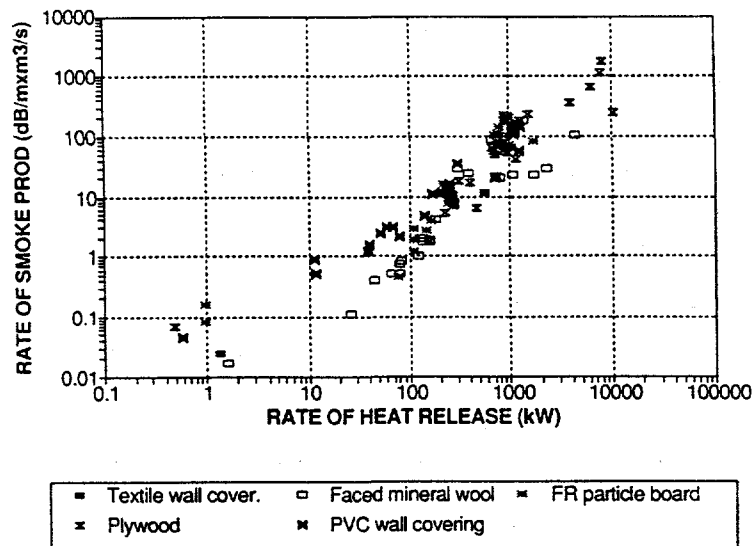

Fig. 4. Rate of smoke production as a function of rate of heat release in cone calorimeter tests and large room tests [Kokkala et al.1992].

9.4 CONE CALORIMETER AND ROOM FIRE TEST MEASUREMENTS FOR SURFACE PRODUCTS

Östman et al. [1992] analysed the smoke production in the full scale room fire test ISO 9705 [1990] and in the cone calorimeter for three sets of building products totalling 28 products. The cone calorimeter tests were performed according to ASTM E 1354 [1990]. Cone calorimeter data from the start of the test to 300 s after ignition was found to be most useful. The time before ignition was also included, since some products release a lot of smoke during that stage.

The smoke production in the room fire test could be predicted from the cone calorimeter data only for building products with more than 10 minutes to flashover in the room fire test. Average rate of smoke production and total smoke

production both had a correlation coefficient of 0.91, with only one outlier among the tested products (Figure 5).

The same products were identified as outliers in most correlations studied by Östman et al. [1992]. The outliers were either *composite products* or *thermoplastics* which are known to be difficult to handle in fire testing generally. The importance of relating problems with special products to product properties is emphasized instead of concluding that good correlations between small and full scale cannot be achieved. Some products simply have to be tested in full scale.
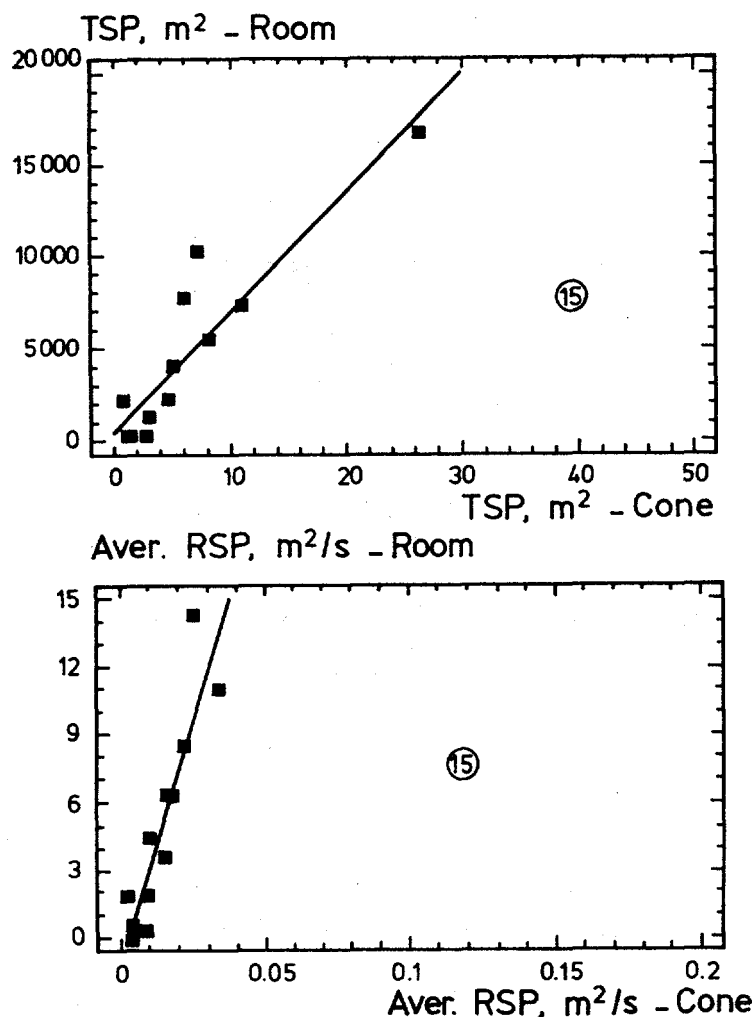

Fig. 5. Room scale - cone calorimeter correlations for products with more than 10 minutes to flashover [Östman et al. 1992].

Regression lines between total smoke productions in room-scale and in the cone, obtained for products with more than 10 minutes to flashover, might also be used for all products as a first rough estimate (Figure 6).

As a first estimate the following two relationships can be used to predict the smoke production in the room fire test from the cone calorimeter data. Both have a

correlation coefficient of 0.91 and are applicable to products with an estimated time to flashover of more than 10 minutes:

$$RSP_{room,>10\min to f.o.} = 420\ RSP_{cone, S3} \tag{18}$$

$$TSP_{room,>10\min to f.o.} = 640\ TSP_{cone, S3} \tag{19}$$

where *RSP* is the average rate of smoke production [m^2/s], *TSP* is the total smoke production [m^2] and *S3* is the time from start to 300 s after ignition. Another relationship can also be used with less accuracy to estimate the smoke production in the room fire test for all products independently of their estimated time to flashover:

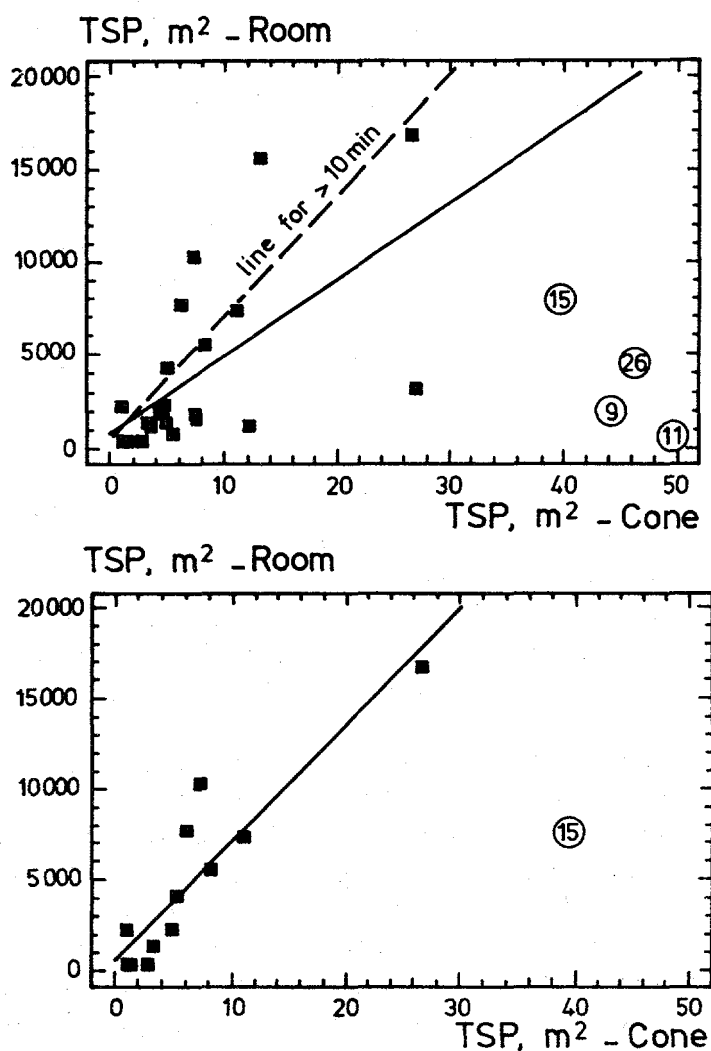$$TSP_{room} = 640\ TSP_{cone, S3} \tag{20}$$

Fig. 6. Total smoke production in the room fire test. The same regression line as for products with more than 10 minutes to flashover can also be used for all products but with less accuracy [Östman et al. 1992].

25

Recently, Heskestad & Hovde [1994] developed, in principle, similar correlations between the cone calorimeter and room corner tests. Their major finding was that a good correlation can be found for fully developed fires, i.e. when the surface area of the burning products is known. In the growing phase of the fire, the conditions may change due to secondary burning of soot in the upper layer, which does not occur in the early phases of fire.

10 CONCLUDING REMARKS

Many factors in the material and the environment affect the production of smoke and the smoke properties. The chemical nature of the burning material has a systematic effect on the smoke production. Variables in the burning environment include radiant heat flux, oxygen concentration, ventilation, sample orientation and geometry, and moisture content of the sample. The rate of burning and the area involved in burning must always be considered when determining the smoke production. A material or product producing rather small amounts of smoke per fuel area may have a substantial smoke production due to a rapid surface spread of flames. This is of special importantance when comparing fires (or tests) of different sizes.

When developing correlations between small and large scale tests, two distinct phases of smoke production should be considered, one related to the early stages of fire (pre-flashover, perhaps only a single item involved), and another related to the post-flashover fire (all items of a compartment are burning under ventilation controlled conditions).

In laboratory experiments, the production of smoke and its optical properties are often measured simultaneously with other fire properties as heat release and flame spread. The measurements are usually dynamic in full scale, i.e. they are performed in a flow through-system. In small scale, they may be either dynamic as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. Small-scale tests are necessary as practical tools. Full-scale tests are generally considered to be more reliable and are needed to validate the small-scale tests.

Correlations between particle / mass concentration and the optical density / extinction coefficient have been found. The rate of smoke production and rate of heat release have also been shown to correlate. Little information is available in the scientific literature concerning modelling or predictive correlations between small scale smoke data and real fires or large scale test results. However, there seems to be some evidence that the early stages of certain full scale scenarios can be predicted, whereas the post-flashover smoke production cannot yet be resolved. Unless developing correlations by statistical means only, a dynamic measurement system is needed with a known area of burning product and including a rate of mass loss and preferably also a rate of heat release.

Among small scale procedures, the dynamic cone calorimeter is most promising, even though its capability for smoke prediction in large scale has not yet been

fully proven. The advantages are several, e.g. also high irradience levels, mass-related smoke properties, known volume flow rate conditions, both rates and integrated data available, less restrictions in sample thickness or orientation, and the possibility of simultaneous and independent determination of other fire parameters. Some of these advantages can be obtained also by making modifications to the closed, cumulative system.

Correlations between small scale and large scale smoke results may be improved by adding parameters describing the burning rate and fire spread behaviour. The rate of heat release and ignitability data from the cone calorimeter test could be utilized in these studies.

The importance of relating problems with special products to product properties is emphasized instead of concluding that good correlations between small and full scale cannot be achieved. Some products simply have to be tested in full scale.

11 FUTURE DEVELOPMENTS

Test-based models to predict the smoke production of construction products are needed, since often the detailed chemistry influencing the fire properties is not known. To develop these models the following topics are suggested for future research:

- Knowledge of the effects of scale and ventilation conditions on smoke production is poor. Systematic studies are needed with experiments not only in small and large scale standard test methods, but also by varying the conditions systematically over a range of interest.

- Much of the research community has neglected the possibility of using smoke point measurements to characterize the smoke production of products. It has been demonstrated that the smoke point gives good correlations for at least some types of fuels. However, more work is needed to investigate the possibilities of using the concept for creating input data for predictive models and, subsequently, for ranking products.

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Title

Smoke production in fires

Abstract

Characterization of smoke, factors influencing smoke production and experimental methods for measuring smoke production are discussed in this literature review. Recent test-based correlation models are also discussed.

Despite the large number of laboratories using different fire testing methods, published smoke data have been scarce. Most technical literature on smoke production from building materials is about experimental results in small scale tests. Compilations from cone calorimeter tests have been published for a few materials, e.g. upholstered furniture materials and some building products. Mass optical density data and compilations of gravimetric soot data are available for various materials as well as a number of smoke obscuration values. For a given material often a wide range of values of smoke output can be found in the literature and care should be excercised in applying the appropriate value in each case.

Little information is available in scientific literature concerning modelling or predictive correlations between small scale smoke data and real fires or large scale test results. The scale dependence of the rate of smoke production is generally not well known.

In laboratory experiments, the production of smoke and its optical properties are often measured simultaneously with other fire properties as heat release and flame spread. The measurements are usually dynamic in full scale, i.e. they are performed in a flow-through system. In small scale they may be either dynamic, as in the cone calorimeter, or static, i.e. the smoke is accumulated in a closed box. Small-scale tests are necessary as practical tools. Full-scale tests are generally considered to be more reliable and are needed to validitate the small-scale tests.

Quantitative prediction of the rate of smoke production using basic principles for commercially available construction products is not currently possible. Test-based correlation studies are therefore needed to enable the use of small scale test data in determining the fire hazard of products.

There seems to be some evidence that the early stages of certain full scale scenarios can be predicted, whereas post-flashover smoke production cannot yet be resolved. Flow-through systems have been suggested as one means of obtaining correlations between small scale and large scale data.

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