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Measurement of smoke from fires : The present trends

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Summary — Smoke from fires poses hazards to life due to obscuration of vision, panic and the toxic effects of decomposition products. In this article methods used for smoke measurement are described with their drawbacks. It is pointed out that smoke may either be measured by accumulation in a chamber (static method) or by allowing it to flow across a sensor (dynamic method). One of the main drawbacks in most of the widely accepted methods is the use of a polychromatic light source. The present trends in smoke measurement are highlighted which lay emphasis on specific methods for materials, products and structural items. Examples of each type of method are discussed. Reference to a new method specially suited to the study of fire retardant smoke suppressant products is also made.

Introduction

Smoke generated from the burning of materials poses danger to human life, particularly in the initial phases of a fire, due to the loss of orientation caused by sight obscuration. This can lead to panic and irrational behaviour which makes the escape as well as fire fighting difficult, often with fatal results. A large number of investigations have been carried out to define criteria for predicting the smoke forming properties of materials. Different test methods have been reported for smoke measurement, however, the results obtained by one method are usually not comparable with those obtained with the other methods because of the inherent differences in various test procedures and the apparatus used therein. In the present communication, different methods used for measuring smoke density have been reviewed and the present trends have been explored.

Smoke Generation

Increasing use of synthetic materials in our day-to-day life has resulted in a dramatic increase in the number of serious fires. Organic polymers have a tendency to ignite and burn when exposed to an ignition source. The main fire hazards associated with the polymers are the emission of smoke and toxic products of combustion. Visible smoke precedes the formation of critical concentrations of toxic products of combustion and thus hinders the escape due to obscuration of light. This results in disorientation and panic, thereby delaying or preventing the escape until the combustion products and temperature become critical. Particulate smoke results from incomplete combustion. It comprises mainly soot and carbonaceous particles, which are responsible for light obscuration. Smoke is a dispersion of solid and liquid particles in carrier gases consisting of combustion products. ASTM[1] has defined smoke as, "An aerosol constituted of molecules of gaseous products, the liquid droplets and the solid particles, formed during thermal decomposition of a material or during combustion". Gross *et al.*[2] have defined smoke as, "Gaseous products of burning organic materials in which small solid and liquid particles are also dispersed". This indicates the role of organic materials over the inorganic ones as potential smoke generators. In the presence of sufficiently intense heat, a polymer pyrolyses, breaking down into lower molecular weight species. These species, in dispersed phase, comprise smoke in the absence of flames. If the oxygen is not available in sufficient quantity, solid smoke constituents are formed at higher temperatures, particularly in the form of soot in the flame zone. Soot, the main constituent of smoke, is generated both in the smouldering and the flaming combustion, although the nature of particles and their mode of formation are different. In general, the extent of smoke formation increases with increasing carbon-hydrogen ratio in the fuel, so that aromatic hydrocarbons produce copious quantities of smoke. Since the flames of the organic polymers are essentially diffusion flames, the smoke producing propensity of different polymers is fairly directly related to the nature of the gaseous decomposition products formed by them[3]. Theoretically, soot will be formed only if oxygen is not present in sufficient quantity to convert the carbon contents of the fuel to carbon monoxide, i.e. when carbon-oxygen ratio is > 1.0 (ref.4). Under these conditions, some of the carbon containing species in the flame undergo pyrolysis rather than oxidation, leading ultimately to the formation of minute carbonaceous particles (dia. ≤ 10 nm). These are the precursors of smoke. Different mechanisms for soot formation have been reviewed by Hirschler[5] who concluded that no single mechanism can completely describe the complex mechanism of soot formation.

Smoke Measurement

Detection and control of smoke have attained high priority in view of the phenomenal increase in the use of plastics, leading to the accentuation of the problem of smoke in fires. Methods for the measurement of visible smoke from various materials have been reviewed by many authors[5-12]. These include methods based on mechanical, electrical and optical techniques. The most frequently used tests, however, are based on optical methods, i.e. on the principles of attenuation of light beam.

Mechanical Methods

In these methods smoke particles are collected on a filter paper by passing a known volume of air through it. The resultant smoke spot on the filter paper is classified either in terms of the degree of blackness, or by gravimetric method. The 'Arapahoe Smoke Box' is a standard test method (ASTM D 4100) based on the gravimetric technique but it has not received the practical importance and is used only as a laboratory screening test for plastics. Another standard test method utilizing the gravimertric technique is ASTM E 162. Mechanical methods are generally not suitable for assessing the smoke hazards during fire since they do not relate to the light obscuration.

Electrical Methods

Smoke production can also be measured by ionization chambers. This principle is widely used for smoke measurement in smoke and fire detectors. Little use of this method has been reported for the evaluation of materials.

Optical Methods

The smoke measurements are mostly conducted utilizing the principles of attenuation of light beam by smoke particles. The degree of attenuation of light due to smoke depends largely upon the number and size of smoke particles and the length of light path. It also depends upon other parameters such as the extent of ventilation in test chamber, refractive index of gases, ignition source, size and conditioning of the samples, temperature, etc. In practice, this complex phenomenon is simplified by assuming the particle to be of uniform size, using a monochromatic light and combining both absorption and scattering in an empirical extinction coefficient, σ, based on the Beer-Lambert law:

$$I = I_0 \, e^{-\sigma X}$$

where I is the intensity of light attenuated by the smoke layer; I_0, the intensity of light at source; σ, the attenuation coefficient, and X is the path length through smoke.

$$\text{or } D = \log 10 \, I_0/I = \sigma X / 2.303$$

where D is the optical density, a measure of smoke concentration.

All the smoke density test apparatuses in use today operate on Beer-Lambert law; however, they differ as a result of the conditions laid down for each test method, mainly for the following reasons:

(i) They can run under static (accumulative) or dynamic (flow) conditions,
(ii) The light source may be mono (laser) or polychromatic (tungsten filament lamp),
(iii) Orientation of the light source and/or the specimen may be vertical or horizontal, and
(iv) Energy input may be radiant heat and/or open flame.

Some of the widely used methods for smoke measurement are given in Table 1. Optical methods of smoke measurement can be grouped as the static (accumulative) and the dynamic (flow) methods.

Static Method of Smoke Measurement

The method using NBS smoke density chamber (ASTM E 662, NFPA 258- T-34 BS 6401) is the one used most frequently for measuring the smoke generated by solid materials. The ISO smoke box [ISO/DIS 5659 {Single chamber test} and ISO/DIS 5924 {Dual chamber test}] are some other equipments used for the static type, wherein smoke is accumulated in a closed chamber and measured. In all these apparatuses a tungsten filament lamp, polychromatic in nature, is used in vertical orientation as the light source. Use of traditional white light (polychromatic) in smoke measurements introduces errors in the results[16-20].

The other methods based on smoke accumulation include Rohm and Hass smoke chamber technique and the Fire Propagation Box method. In these methods, the specimen and light source are mounted in a horizontal position. The methods, however, do not take into account the settling of smoke due to aging. The latter method is basically for determining the fire propagation index of materials. The smoke generated during the test is accumulated in a 18 m^3-chamber where it is measured.

Table 1 — Methods of smoke measurement

Method	Type	Smoke measurement	Energy input	Orientation of Specimen	Orientation of Light source	Reference
Traditional Methods						
NBS Smoke Chamber	S	P	R±F	V/H	V	ASTM E 662
Rohm and Hass Smoke Chamber	S	P	F	H	H	BS 5111 Pt 1 ASTM D 2843
Steiner Tunnel	D	P	F	H	H	ASTM E 84
Radiant Panel Test	-	G	R+F	30°	-	ASTM E 162
Araphoe Smoke Box	-	G	F	-	-	ASTM D 4100
Michigen Test	D	P	F	V	H	13
Fire Propagation Test	S*	P	R±F	V	H	14 and BS 476 pt 6
Recent Methods						
ISO Single Chamber	S	P	R±F	H	V	ISO/DIS 5659
ISO Dual Chamber	S	P	R	H	V	ISO/DIS 5924
OSU-RHR	D	P	R±F	V	H	ASTM E 906
Cone Calorimeter	D	L	R	V/H	H	ASTM E 1354
Fumenometer	D	P	R	H*	H	15

S = Static, S* = Smoke collected in a seperate chamber

D = Dynamic

P = Photometric System (Tungsten Filament Lamp)

L = He-Ne Laser

G = Gravimetric

F = Pilot flame

R = Irradiance

H = Horizontal, H* = Specimen in powder form

V = Vertical

± = With or without

Drawbacks in Accumulative Systems

The smoke obscuration has been measured for a long time by the NBS smoke density chamber (ASTM E 662). It measures the obscuration inside a static chamber, after a sample has been exposed, vertically, to 25 kW/m^2 radiant heat source. The method suffers from the following inherent deficiencies [21,22].

- Combustion takes place in a closed box; therefore the air available to the specimen is depleted of oxygen. Thicker and composite sample tend to extinguish as the oxygen level drops below 14%.
- The smoke re-circulated through the heater and flame, and thus gets recombusted.
- History of the specimen cannot be traced due to lack of a loadcell.
- Only a single irradiation level of 25 kW/m^2 and a single orientation of the specimen (vertical) are available. This results in lower values for thermoplastics which have a tendency to melt and flow and hence the quantity of specimen responsible for smoke generation is relatively lower. A very large difference is observed when specimen are exposed

Table 2 — A comparison of smoke density in NBS chamber under flaming conditions for vertical and horizontal sample configurations[23*]

Materials	Average D_m	
	Horizontal	Vertical
Thermoplastics		
Polypropylene	398	57
Polyethylene	286	35
Nylon 6, 6	264	48
Paraffin wax	228	83
Non-Thermoplastics		
Phenolic impregnated paper	155	140
Vulcanized fibre	52	63
Balsa wood	16	8

*All materials tested in 0.15 cm thickness in NBS smoke density chamber
D_m = Maximum specific optical density

in either the horizontal or the vertical orientations (Table 2).

- The light source is polychromatic while only monochromatic light is required for applying Beer-Lambert law, and
- Time dependency of the results cannot be established.

Seader and Ou[24] studied a number of materials, ranging from wood to inorganic boards to synthetic polymers, for their smoke generation characteristics. The equipment used was NBS smoke density chamber under the flaming and the non-flaming modes. The equipment, however, had a rather poor repeatability and reproducibility. Improvement might be achieved if smoke yield is measured on the basis of mass loss from the original sample[12,25]. ISO smoke box suffers from the drawback of non- availability of pilot flame for ignition.

Improvisation in the NBS Smoke Density Chamber Method

In the improved version of NBS smoke density chamber method (ISO/DIS 5659 and ISO/DIS 5924)[12,26] some of the drawbacks have been overcome. The improvisations include:

- Irradiance levels vary from 10 to 50 kW/m^2, in place of single level of 25 kW/m^2.
- Horizontal as well as vertical orientations of the specimen are provided, and
- Load cell has been installed for weight loss studies.

Some latest models of NBS chamber have also been provided with a stirrer or fan for mixing the smoke generated during a test. However, Morgan and Geake[27] have opined that such a system is not desirable as it changes the particle size distribution from the one initially generated from the burning specimen.

Dynamic Methods of Smoke Measurement

Standard methods using dynamic system for smoke measurement include those of Steiner Tunnel, Ohio State University Rate of Heat Release (OSU-RHR) Calorimeter, Room/Corner Test (ASTM E 603) and Cone Calorimeter (ASTM E 1354). In all these methods, the smoke is not collected in a box but is allowed to flow through an exhaust duct where it is measured under dynamic conditions.

In Steiner tunnel test (ASTM E 84), a relatively large specimen is mounted with face down on the ceiling of a rectangular horizontal duct. Light transmission is recorded horizontally and dynamically in the exhaust gases, photometerically.

In the OSU-RHR calorimeter, the sample is mounted vertically, and the smoke obscuration is measured dynamically and horizontally in exhaust gases, photometerically.

Though the cone calorimeter was developed originally for measuring the rate of heat release in an improved manner, it has been updated for use in smoke measurements as well[28], wherein a monochromatic light source (He-Ne laser beam) is used.

A method known as Michigen Test uses Limiting Oxygen Index (LOI) (ASTM D 2863) flammability apparatus for igniting the specimen. A chamber fitted with an exhaust fan is provided above the chimney for smoke collection. Smoke is measured in this chamber horizontally using a polychromatic light source.

Drawbacks in Dynamic Methods

In the Michigen test, though provision is made for an exhaust fan in the chamber, the smoke is measured inside the chamber where it is accumulated for a short while and therefore most of the drawbacks of static methods are applicable to this method also. OSU-RHR uses a photometeric system for smoke measurement while the tungsten filament lamp being polychromatic in nature does not fulfil the requirements of the Beer-Lambert law.

It is noteworthy that there is no correlation between the maximum smoke density in NBS smoke density chamber (static test), flaming mode, and the obscuration in full scale tests (dynamic test) in the series of experiments reported by Hirschler[29] (Table 3).

Polychromatic Light Source and Its Disadvantages

The photoelectric equipment registers the extinction but does not differentiate between the absorption and scattering of light. This can be of major importance in a fire incident since people while trying to escape are more disoriented by strongly reflective smoke than by the reduced vision due to black smoke. Most of the smoke measurement equipments are based on optics and use incandescent lamp as a light source, which gives polychromatic light. Beer-Lambert law being valid only for monochromatic light, the error introduced in smoke measurement could be up to 25%, if a non-monochromatic light is used[17]. Moreover, emission from a lamp is related to the colour temperature of its filament. Gross error is likely to be introduced if the colour temperature of this filament vary. The studies at Fire Research Station, UK[30], have revealed that a change in operating wavelength from 1.0 to 1.5 μ results in 50% reduction in apparent optical density for white smoke and 30% for black smoke. Use of monochromatic light source has been investigated by many workers [18,20,31]. Studies have been reported where He-Ne laser was used along with the white light in NBS smoke chamber [18,20] as well as in dynamic systems[32,33]. Appreciable differences have been reported in smoke density values in both the cases (Tables 4 and 5).

Table 3 — Smoke generation in a room corner testa and NBS smoke chamber[29]

Material	Thickness (cm)	Max. smoke (OD/m)	Soot (g)	Smoke hazard (MJ/m^3)	NBS smoke (F/D_m)
Control[b]	-	1.6	106	7.9	-
Polycarbonate	0.24	>15.1	>2900	>305.9	247
ABS FR	0.23	>15.1	>1460	>160.6	900
Oak panel	0.58	9.6	750	130.6	106
FR acrylic	0.24	7.7	398	>83.7	435
Generic PVC[c]	0.23	8.3	384	39.9	780
Low smoke PVC[c]	0.12	1.5	93	17.8	94
CPVC[c] (chlorinated PVC)	0.12	1.5	75	6.9	53

a : A 6.3 kg wood crib was used in all room corner burn experiments; Total panel area 6.6 m^2

b : Refers to smoke generation by fuel only

c : PVC material used in these experiments were unplasticised

FR : Fire retardant

OD : Optical density

F : Flamming mode

D_m: Mximum smoke density

Table 4 — Transient values of optical density of smoke measured by white light and He-Ne laser in NBS smoke chamber (Static method)[20]

Time	Optical Density	
min	White Light	He-Ne Laser
30	0.0	0.0
60	0.02	0.02
90	0.02	0.05
120	0.38	0.08
150	0.8	0.6
180	1.2	1.3
210	1.2	1.8
240	1.4	2.0
270	1.8	2.08
300	2.4	1.8
330	2.8	2.2
360	3.2	2.8
390	4.15	4.2
420	5.2	5.2

Present Trends in Smoke Measurement

Conventionally, for measuring smoke generation propensity, a material is taken in the form of a product, i.e. in the form of sheet, slab or film, etc. The test equipments employed for such evaluations have many inherent disadvantages, as discussed earlier. One of the major drawbacks has been the poor reproducibility and lack of correlation with actual fire situations. Since more and more new materials are entering the market everyday, it is desirable to know about their fire behaviour in advance. Hence, the present trend is to measure the smoke generation from materials at three different levels: (i) raw materials level, (ii) first transformation, i.e. product level, and (iii) component or structural level. Here, the raw material refers to the

Table 5 — Smoke measurement using laser and white light (Dynamic method)[32]

Sl. No.	Quantity of PVC burnt(g)	Minimum transmission %			Peak optical density OD			Smoke Index		
		Laser	White light	Difference	Laser	White light	Difference	Laser	White light	Difference
1	2.9	44.5	67.0	-22.5	0.352	0.174	0.178	71.0	23.0	48.0
2	4.9	24.0	65.5	-41.5	0.620	0.184	0.436	61.6	31.2	30.4
3	6.3	9.7	8.5	1.2	1.013	1.070	-0.570	136.0	124.6	11.4
4	7.3	11.2	11.0	0.2	0.951	0.959	-0.008	142.6	122.4	20.2

Table 6 — Various paramenters that can be studied by a Fumenometer

Parameter	Type of output
Optical density	Direct display
Kinetics of optical density	Direct plotting
Smoke potential*	Automatic computation
Equivalent mass**	Automatic computation
Smoke potential as a function of temperature	Can be computed

* Smoke potential : Equivalent mass for a volume of 1 M^3

** Equivalent mass : Mass of material, the combustion of which gives 50% opaqueness

ingredients of a chemical formulation, product refers to material in the form of sheet, slab or film, etc. and the component represents items like sandwich panels used for doors/partitions, cable trays, etc.

Equipments like 'Fumenometer' are mainly employed for smoke generation studies on raw materials. A new test method developed by the author[31] also serves this purpose in addition to its specific application in the area of flame retardant smoke suppressant materials and products. Cone calorimeter and ISO smoke box attempt to correlate the results with real fire situation[21] and are mainly used for smoke generation studies on products and components. The three metre cube method is solely devoted to smoke generation in 'full scale fire studies'.

Fumenometer

Fumenometer[15] is an apparatus designed by Societe Eternite Recherches Techniques, France and developed by Prodemat, France,for continuous measurement of the opaqueness of smoke emitted during pyrolysis of a specimen. A small quantity of sample is introduced into a non-aired furnace whose temperature can be controlled up to 900°C. A fan homogenizes the smoke and reduces dispersion in the measurement. An optical device enables continuous measurement of opaqueness of smoke. It is mainly devoted to smoke evaluation from raw materials; however, small pieces of products as well as structures may also be assessed for their smoke generation propensity. The apparatus can also be used to detect white smoke. Like most of the modern test equipments, it is also connected to a computer and a lot of useful data can be generated. The different parameters that can be studied by this apparatus are listed in Table 6.

Method of Sharma et al.

In a new method (Fig. 1), reported by Sharma *et al.*[31], samples are used in the shape of strips or rods; powder and liquid forms may be studied using a modified specimen holder. The specimen are ignited in a flammability unit (FTA/HFTA) of Stanton Redcroft, UK, at oxygen levels higher than the LOI of the specimen. The smoke is drawn through a duct with the help of an exhaust fan. A smoke measurement system (Fig.2) comprising a He-Ne laser beam projected across the exhaust duct is used. The output of the monochromatic light is monitored by a silicon diode photodetector. The smoke generation data are reported, both in terms of peak optical density and the smoke yield. This method is specially suited for assessing the effectiveness of fire retardants and smoke suppressants.

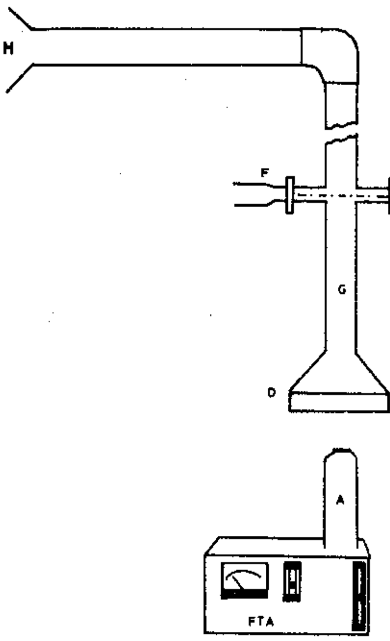

Fig.1 — Apparatus for smoke generation and its measurement by flow system — A schemetic view (FTA-Flammability test apparatus, A: Chimney; D: Hood; E: He-Ne laser source: F: Laser radio-meter, G: Duct; and H: Exhaust fan)

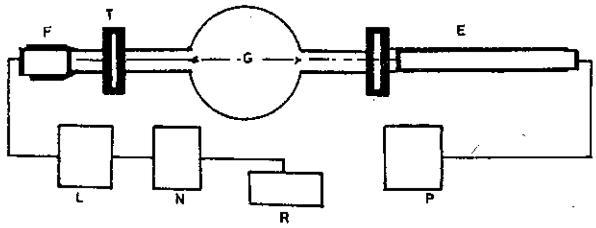

Fig.2 — Smoke monitoring using He-Ne laser (F: Radiometer; T: Optical filter; G: Duct; E: Laser source ; L: Radiometer readout; N: Integrator; P: Power supply; and R: Recoder)

Cone Calorimeter

Cone Calorimeter (Fig.3) was initially designed for measuring heat released by bench scale specimens [34], wherein 100 × 100 mm specimen are irradiated by a cone shaped heater, and hence the name 'cone calorimeter'. Irradiance can be set at any desired level between zero and 110 kW/m^2. A high voltage electric spark is used for igniting the specimen externally, if required. The specimen is mounted on a load cell for mass loss studies. A smoke measuring system is used which comprises He-Ne laser beam projected across the exhaust duct. The monochromatic light is monitored by a solid state detector. A second detector serves as a reference to guard against the effect of drift and of laser power fluctuations. The optical system is described in details elsewhere [35].

ISO Smoke Box

Two types of smoke boxes have been recommended by ISO. ISO/DIS 5659 refers to an improved version of NBS chamber. This method is called the 'single chamber' test method. A 450 W radiant cone heater is used to irradiate the specimen assembly mounted in a horizontal or vertical orientation. The irradiance levels range between 10-15 kW/m^2. These improvements are highly valuable in studying the smoke emission characteristics of thermoplastics which are often underestimated when tested only in vertical orientation due to melting. The method developed by Teichgaeber and Topf (cited in reference 12) at the university of Munich is known as 'Dual Chamber' method (ISO/DIS 5924). The apparatus (Fig.4) consists of two interconnected chambers, one for the sample decomposition and the other for smoke measurement. Smoke is generated in the first compartment and passes into the second chamber where its optical density is measured. The specimen mounted horizontally are irradiated between zero and 50 kW/m^2 by a cone heater. The test is repeated at the irradiance level which causes the highest maximum optical density of smoke (Dhm) during preliminary tests. The disadvantage of this method as compared to the NBS method is the absence of a pilot flame in the decomposition chamber to induce ignition. However, Prager and Mueller [36] have demonstrated that smoke generation is not influenced significantly by the ignition source such as pilot flame or a spiral heating element.

Three Metre Cube Chamber

The Three Metre Cube chamber [37] is used mainly for large-scale studies. It is extensively used by the cable industry. The chamber uses various fire models, depending on the material under consideration. It is provided with a fan for homogenization of smoke and to avoid its stratification. The three fire sources used are: industrial methylated spirit, ethyl alcohol and English soft wood charcoal soaked in alcohol. The smoke measurement system consists of a light source and a photocell placed horizontally in the mid plane of the cube at a height of about two metres. The light source is a halogen lamp with a tungsten filament. Results are reported as the standard absorbance which is defined as the absorbance produced across the opposite face of a cube of side one metre when one unit of the material is burnt under the specified conditions.

Concept of Mass Optical Density (MOD)

A direct comparison of smoke intensities without qualification of sample size or mass, test orientation or burning behaviour can be misleading. Seader and cowork-

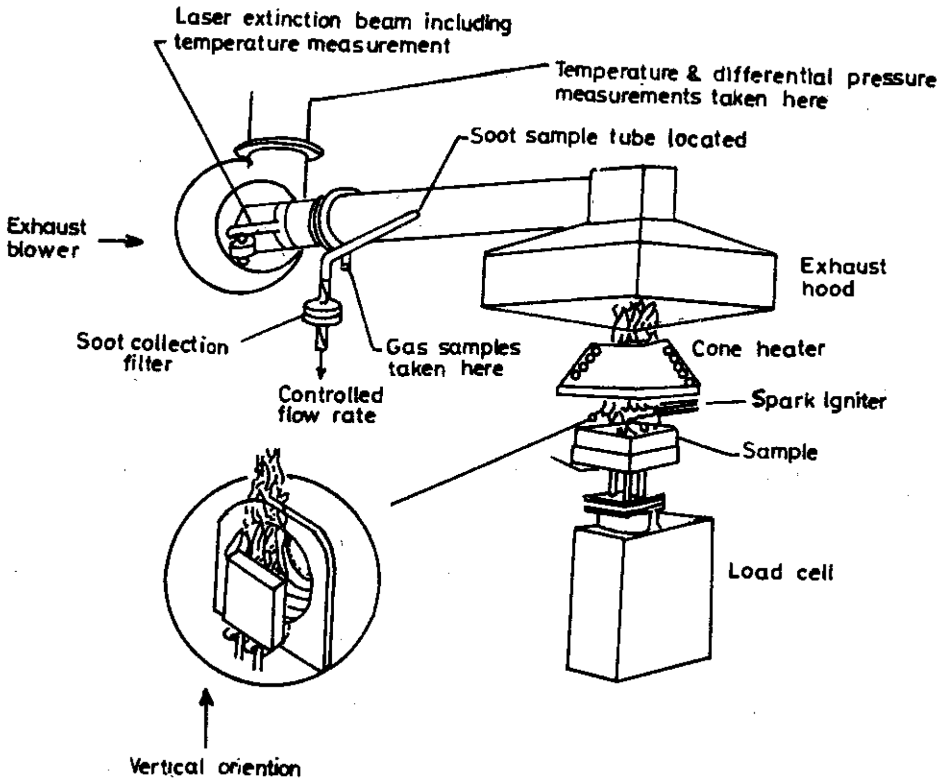

Fig.3 — Conceptual view of cone calorimeter

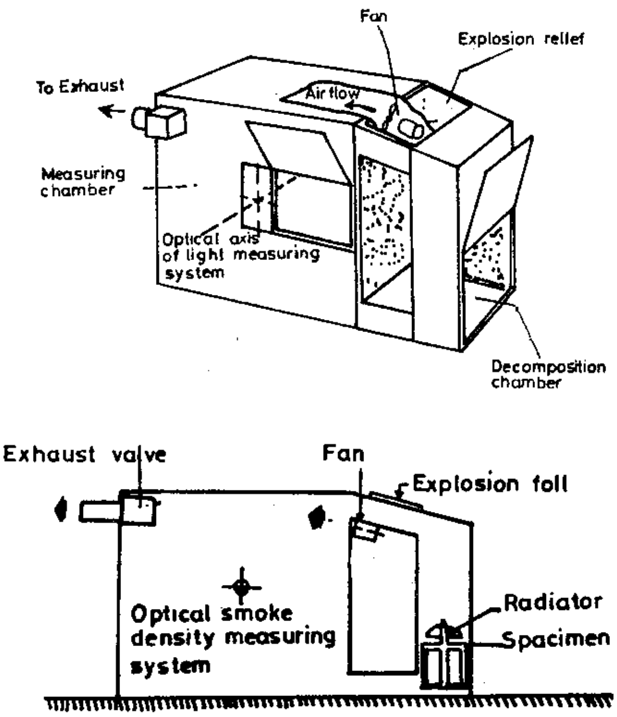

Fig.4 — ISO smoke box — A general view

ers[24,38] have demonstrated the utility of mass optical density (MOD), for correlating smoke generation characteristic of material using NBS smoke density chamber. MOD is defined as:

$$\text{MOD} = \frac{D_s}{M/A} = \frac{DV}{ML}$$

where D_s is the specific optical density; D, the optical density; M, the mass loss of test specimen; A, the surface area of test specimen; V, the volume of smoke chamber; and L is the length of light path. MOD can be applied to other static methods as well. These methods can be categorized according to their applications, as given in Table 7. To ensure a proper comparison of results of different fire properties, they should be measured under identical test conditions. Use of the same apparatus is one of the ways to ascertain this. Simultaneous evaluation of various burning behaviour characteristics of a material under identical conditions is possible by two recently developed calorimeters-OSU-RHR and Cone calorimeter. Since it is not always possible to employ the same appartus, it is pertinent to decide the form in which the results of the test will be most suitable for a particular end use situation, as for example given below, before deciding in favour of a particular method.

Table 7 — Smoke measurement methods and their applications

Method	Type	Application	Reference
Fumenometer	Dynamic- photometric system	Raw materials, Products, Structures	15
Method by Sharma *et al.*	Dynamic-Laser	Raw materials, Products, Structures, FRSS* Compositions	30
Cone calorimeter	Dynamic - Laser	Products, Structures	33
ISO smoke chamber	Static - photometric system	Products, Structures	ISO/DIS 5659, ISO/DIS 5924
Three metre cube chamber	Static-photometric system	Products, Structures, Cables	36

* FRSS : Fire Retardant Smoke Suppressant

- Which is more important, rate of smoke production or the total smoke yield?
- Should smoke yield be measured as optical density or as a mass of particulate matter?
- Should smoke generation be expressed in terms of a unit surface area, as in case of NBS chamber test or as unit mass of airborne product?

Conclusion

Several factors are important in assessing smoke propensity of material. The present trend, therefore, is to measure smoke from material at different stages of its preparation, e.g. raw material, product, component/structural units. Smoke measurements may be carried out by either accumulative or flow methods, depending on the specific end use of the results. Use of laser over conventional light sources is recommended.

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