TECHNICAL
REPORT

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Fire safety engineering —

Part 5:
Movement of fire effluents

Ingénierie de la sécurité contre l'incendie —

Partie 5: Mouvements des effluents du feu

Reference number
ISO/TR 13387-5:1999(E)

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Contents

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The main task of ISO technical committees is to prepare International Standards, but in exceptional circumstances a technical committee may propose the publication of a Technical Report of one of the following types:

- type 1, when the required support cannot be obtained for the publication of an International Standard, despite repeated efforts;
- type 2, when the subject is still under technical development or where for any other reason there is the future but not immediate possibility of an agreement on an International Standard;
- type 3, when a technical committee has collected data of a different kind from that which is normally published as an International Standard (“state of the art“, for example).

Technical Reports of types 1 and 2 are subject to review within three years of publication, to decide whether they can be transformed into International Standards. Technical Reports of type 3 do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful.

ISO/TR 13387-5, which is a Technical Report of type 2, was prepared by Technical Committee ISO/TC 92*, Fire safety*, Subcommittee SC 4, *Fire safety engineering*.

It is one of eight parts which outlines important aspects which need to be considered in making a fundamental approach to the provision of fire safety in buildings. The approach ignores any constraints which might apply as a consequence of regulations or codes; following the approach will not, therefore, necessarily mean compliance with national regulations.

ISO/TR 13387 consists of the following parts, under the general title *Fire safety engineering*:

- *Part 1: Application of fire performance concepts to design objectives*
- *Part 2: Design fire scenarios and design fires*
- *Part 3: Assessment and verification of mathematical fire models*
- *Part 4: Initiation and development of fire and generation of fire effluents*
- *Part 5: Movement of fire effluents*
- *Part 6: Structural response and fire spread beyond the enclosure of origin*
- *Part 7: Detection, activation and suppression*
- *Part 8: Life safety — Occupant behaviour, location and condition*

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Introduction

Fire effluent, i.e. smoke and gaseous species, cause a substantial threat to life and property. One of the fire safety objectives when designing a building is to ensure that the occupants are ultimately able to leave the building without being subject to hazardous or untenable conditions. In premises with significant financial or cultural value, one of the fire safety objectives is to prevent the damage to property. To meet these objectives one may either limit the generation of fire effluent or control the flow of fire effluent. The former is discussed in ISO/TR 13387-4, whereas the latter is the topic of this Technical Report.

Assessment of fire effluent flow within a building, and assessment and design of smoke control and venting systems is a common feature in fire safety design of a building. In most of the existing fire safety regulations measures are taken to control the movement of fire effluents. Typically in prescriptive codes, the requirements are set as the minimum effective area of smoke vents as a percentage of the total roof area. The required smoke vent area may vary within the range of 0,25 % to 5 % of the roof area.

Engineering methods for the design of smoke control systems have been available for a long time in the form of nomograms or calculation methods (see reference [1] of the bibliography). In both approaches, however, the design of smoke control is treated as an isolated form from the rest of the fire safety design, although in real fires the movement of fire effluent highly depends on the interaction with other features of the design.

Phenomena controlling smoke movement have been actively studied during recent decades. Calculation methods and computer codes have been developed to make the necessary evaluations. At the same time advances in experimental techniques have made it possible to produce input data for the calculation methods and to run large-scale tests for assessing the validity and limitations of the models.

This part of ISO/TR 13387 is intended for use together with the other Technical Reports produced by SC 4 as described in clause 5. For some applications this document alone may be sufficient.

Clause 6 of the report describes and provides guidance on the methods available to describe the processes involved in movement of fire effluent.

Clause 7 describes and provides guidance on the use and evaluation of different types of engineering methods available to describe the movement of fire effluent, i.e. hand calculations, zone models, field or Computational Fluid Dynamics (CFD) models, and experiments.

Clause 8 briefly describes different techniques available to control movement of fire effluent. The quantitative information may be related to specific test conditions and/or specific commercial products, and the application of data under different conditions may result in significant errors.

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Fire safety engineering —

Part 5:
Movement of fire effluents

1 Scope

This part of ISO/TR 13387 is intended to provide guidance to designers, regulators and fire safety professionals on the use of engineering methods for the prediction of movement of fire effluents within and outside of a building. It is not intended as a detailed design guide, but could be used as the basis for the development of such a guide.

This part of ISO/TR 13387 also provides a framework for critically reviewing the suitability of an engineering method for assessing the potential for movement of fire effluent during the course of fire. The document also provides guidance on the means to assess the effectiveness of fire safety measures meant to reduce the adverse effects of movement of fire effluents. The methods for calculating the effects of design fires for use in the design and assessment of fire safety of a building are also addressed.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of ISO/TR 13387. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of ISO/TR 13387 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO/TR 13387-1, *Fire safety engineering — Part 1: Application of fire performance concepts to design objectives.*

ISO/TR 13387-2, *Fire safety engineering — Part 2: Design fire scenarios and design fires.*

ISO/TR 13387-3, *Fire safety engineering — Part 3: Assessment and verification of mathematical fire models.*

ISO/TR 13387-4, *Fire safety engineering — Part 4: Initiation and development of fire and generation of fire effluents.*

ISO/TR 13387-6, *Fire safety engineering — Part 6: Structural response and fire spread beyond the enclosure of origin.*

ISO/TR 13387-7, *Fire safety engineering — Part 7: Detection, activation and suppression.*

ISO/TR 13387-8, *Fire safety engineering — Part 8: Life safety — Occupant behaviour, location and condition.*

ISO 13943, *Fire safety — Vocabulary*.

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3 Terms and definitions

For the purposes of this part of ISO/TR 13387, the definitions given in ISO 13943, ISO/TR 13387-1 and the following apply.

3.1
ceiling jet
horizontal gas stream under a ceiling

3.2
extinction coefficient
a constant determining the decay of light intensity in smoke per unit path length, given by $K = (1/l) \ln(l_0/l)$

It is expressed in m^{-1}.

3.3
fire effluent
all gaseous, particulate or aerosol effluent from combustion or pyrolysis

3.4
opening factor
$A_\mathrm{v} (h_\mathrm{v})^{1/2}/A_\mathrm{T}$

It is expressed in $\mathrm{m}^{1/2}$.

3.5
plume
buoyant gas stream above a localized fire

3.6
vent
an opening for passage of fire effluent out of an enclosure

3.7
ventilation factor
$A_\mathrm{v} (h_\mathrm{v})^{1/2}$

It is expressed in $\mathrm{m}^{5/2}$.

4 Symbols and abbreviated terms

A_fuel	surface area of fuel, expressed in m^2
A_T	total area of bounding surfaces in an enclosure, expressed in m^2
A_v	area of an opening, expressed in m^2
C_i	concentration of species i, expressed in $\mathrm{kg/m}^3$
C_in	concentration of species i in a flow into an enclosure, expressed in $\mathrm{kg/m}^3$
c	specific heat capacity, expressed in J/(kg·K)
f_X	yield of species X, where X = CO, CO_2, ...
g	acceleration due to gravity, expressed in $\mathrm{m/s}^2$

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h_v	height of an opening or height of a shaft, expressed in m
I	intensity of light after passing through smoke, expressed in W/m^2
I_0	intensity of light in clean air, expressed in W/m^2
K	extinction coefficient, expressed in m^{-1}
k	thermal conductivity, expressed in W/(m·K)
$\dot{m}_{\text{fuel}}$	mass loss rate of fuel, expressed in kg/s
$\dot{m}_X$	generation rate of species X, where X = CO, CO_2, ..., expressed in kg/s
$\dot{Q}$	heat release rate, expressed in W
P	pressure, expressed in Pa
T_g	gas temperature or outside ambient temperature, expressed in K
T_0	initial surface temperature or inside temperature, expressed in K
t	time, expressed in s
V_{encl}	volume of enclosure, expressed in m^3
ρ	density, expressed in kg/m^3
Δ	difference (as in ΔP or $\Delta\rho$)

5 Subsystem 2 of the total design system

The approach adopted in the work of ISO/TC 92/SC 4 is to consider the global objective of fire safety design. The global design, described in more detail in the framework document ISO/TR 13387-1, is sub-divided into what are called subsystems of the total design. The key principles of the global design approach are that interdependencies among the subsystems are evaluated and that pertinent considerations for each subsystem are identified.

In the framework document, the total fire safety design is illustrated by an information bus analogy (see Figure 1). The information bus has three layers: global information, evaluation and process buses. The information bus analogy of Subsystem 2 (SS1), movement of fire effluents, is illustrated in Figure 1. SS2 draws on other subsystems for a prescription or characterization of fire. SS2 provides information on movement of fire effluents for the other subsystems to be employed.

SS1, for example, provides information on heat, smoke and species generation, which then is applied by SS2 for the calculation of smoke movement out of the room and in the building. The information may then be used by SS5 to assess evacuation and rescue provisions. The prediction of activation of fire detectors, sprinklers or smoke vent opening devices is provided by SS4. The prediction of spread through barriers or openings beyond the room of fire origin is provided by SS3.

The evaluations and the processes needed to do the evaluations are discussed in detail in clause 6.

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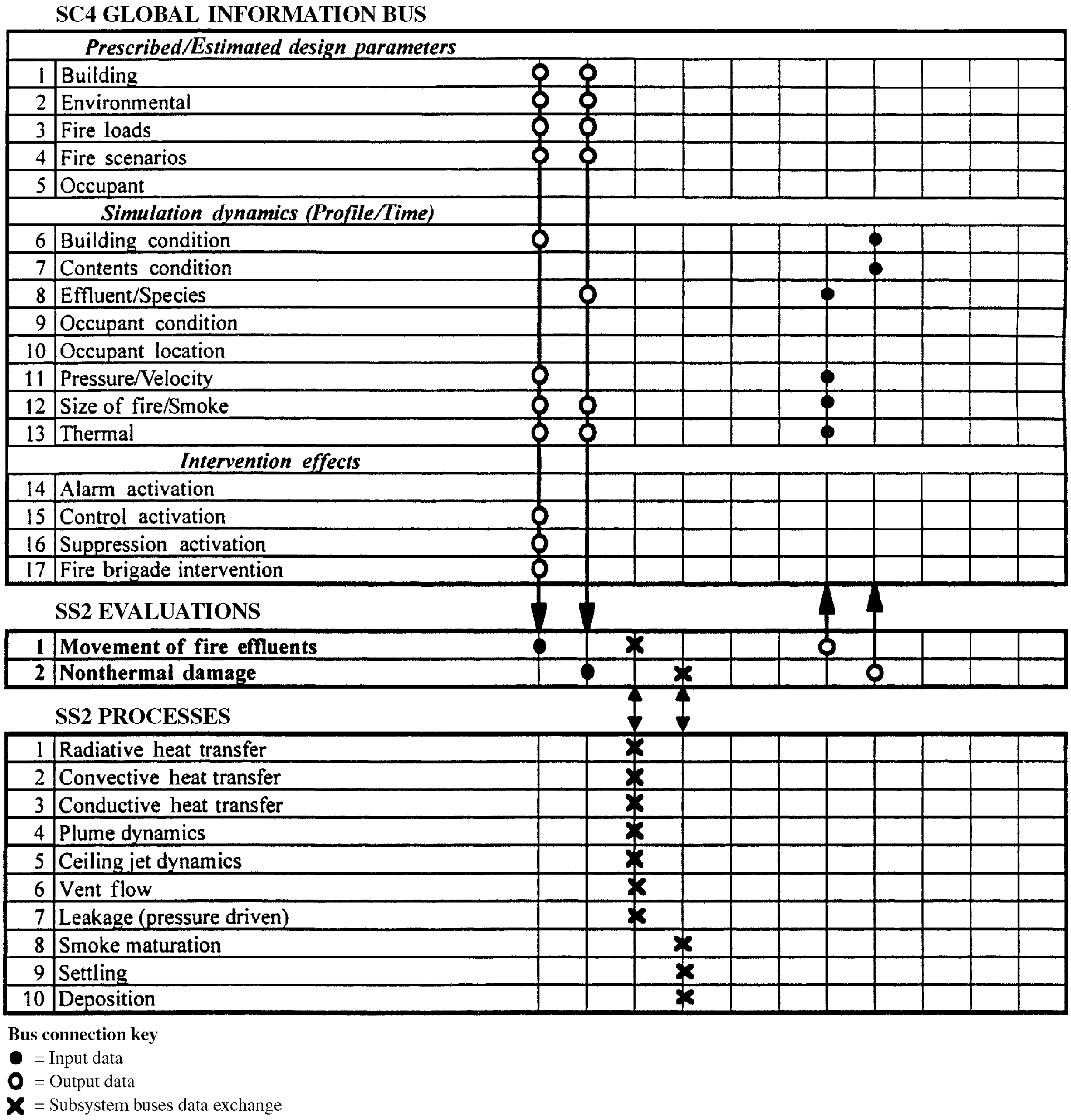
ISO TC 92/SC 4 FIRE SAFETY ENGINEERING BUS SYSTEM

Subsystem 2 (SS2) — Movement of fire effluents



For explanations of terms used in conjunction with the global information bus, see ISO/TR 13387-1.

Figure 1 — Illustration of the global information, evaluation and process buses for SS2

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6 Subsystem 2 evaluations

In this clause various processes of movement of fire effluents and the threat to life, property and environment shall be discussed. The required input information and the possible output information shall be identified. Areas for which shortages in engineering methods and lack of knowledge are known to exist will be addressed. The text will make reference to existing acknowledged literature, whenever such is available.

6.1 Movement of fire effluents

6.1.1 Role in fire safety engineering design

The flow chart in Figure 2 outlines the main stages of evaluating the movement of fire effluents within and beyond the room of origin. In using the flow chart it is assumed that all the source terms needed for evaluating movement of fire effluents shall be given by SS1 (ISO/TR 13387-4) or as design fires described in ISO/TR 13387-2.

6.1.1.1 Input

The evaluation of movement of fire effluents (see Figure 1) may require as input information the following:

- building parameters (for example, thermal properties, geometry, location of openings, etc.);
- environmental parameters (for example, velocities and prevailing direction of wind, outside temperature, temperature distribution in the building, internal air movements caused by mechanical ventilation systems);
- size of fire/smoke (for example, rate of heat release of the fire, plume mass flow, smoke generation rate);
- thermal profile (for example, temperature distribution in the plume);
- pressure/velocity profile (for example, pressure profile in the room of origin);
- effluent species profile (for example, species generation rate, mass flow of species in the plume).

6.1.1.2 Output

The evaluation of movement of fire effluents (see Figure 1) provides information about the following:

- size of fire and/or smoke (for example, smoke density distribution in the building);
- thermal profile (temperature and heat flux distribution in the building);
- pressure/velocity profile (for example, pressure at smoke vents, flow through vents, velocity in the corridor jet);
- effluent species profile (for example, gaseous species concentration distribution in the building);

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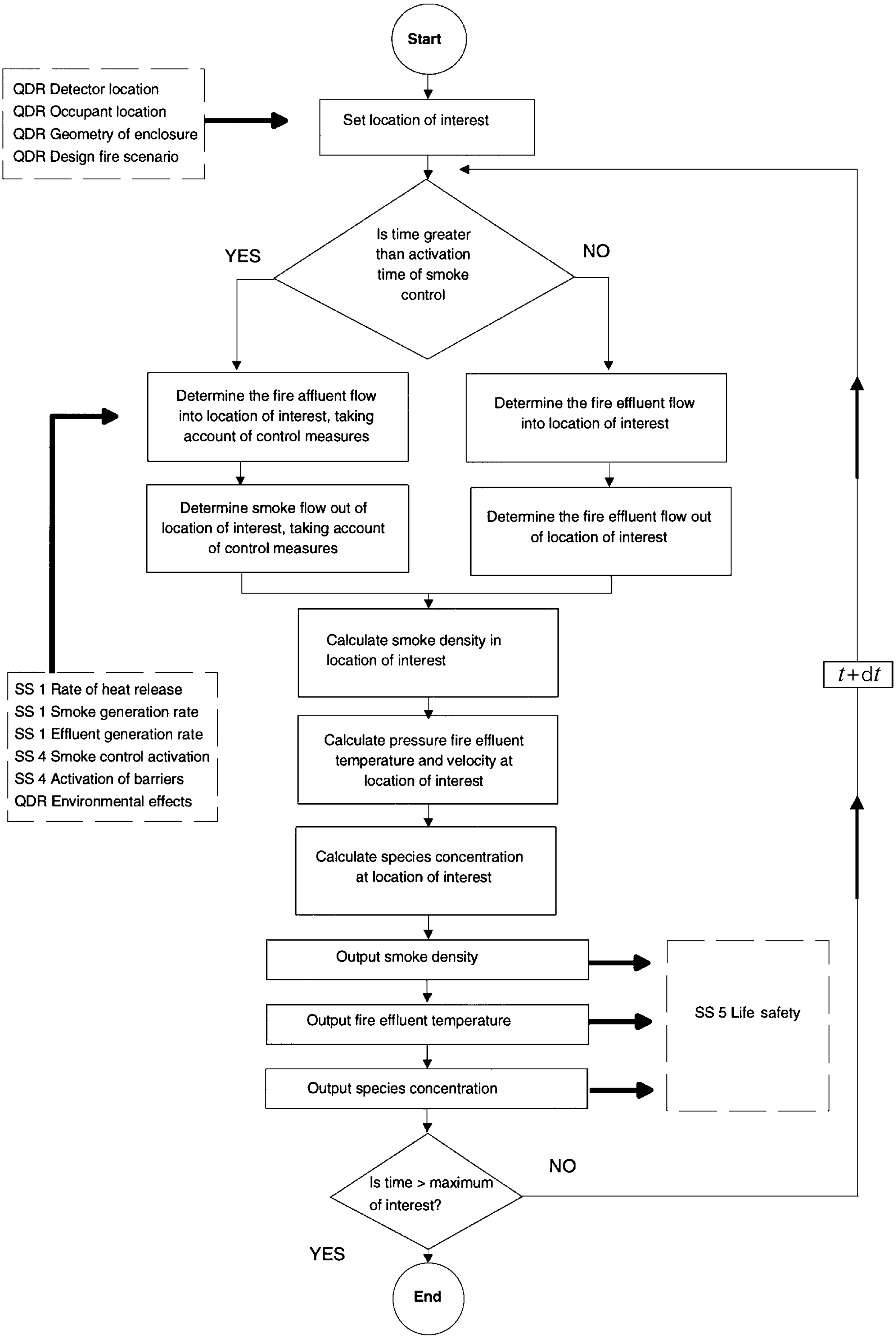

The dark arrows indicate interaction with the global information in Figure 1.

QDR = Qualitative design review has been discussed in ISO/TR 13387-1.

Figure 2 — Flow chart for movement of fire effluents

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6.1.2 Processes of movement of fire effluents

6.1.2.1 General

The spread of a fire effluent is caused, primarily, by its buoyancy and the increase in volume resulting from the entrainment of air. Its spread can be controlled by means of smoke barriers, smoke extraction and opposing flows (pressure differentials). The techniques most commonly used to limit the extent of smoke spread are summarized in clause 8.

The temperature of a fire effluent, and hence its buoyancy, depends on the rate of heat release of the fire and the entrainment of cool air into the smoke plume. Entrainment reduces both the concentration of smoke particles and the temperature. This increases visibility but also increases the volume of smoke.

The effluent plume from a fire within an enclosure will rise to ceiling level and then spread horizontally to form a layer beneath the ceiling. Generally, the mass flow of the burnt fuel is so small compared with the mass flow of the entrained air that for practical purposes it may be ignored. For smooth ceilings or ceilings of limited extent the entrainment is small during horizontal flow and can usually be ignored. However, when the smoke flows around obstacles (for example, beams) or through apertures (for example, a doorway), the rate of entrainment increases.

Smouldering fires typically have low buoyancy and the smoke may never form an upper layer due to higher initial temperature close to the ceiling or forced flow in the enclosure.

6.1.2.2 Plumes

The buoyant gas stream above a localized burning area is called a fire plume. The fire plume is characterized by its temperature and velocity distribution, which can be transformed into mass and energy flows at various heights above the source.

Plume models have been a subject of active research especially in the early 1980's. By simplifying approximations to basic laws and fits to experimental data, a number of semi-empirical plume models have been developed. General discussions on fire plumes have been presented, for example, in detail in reference [2] and in a summarized form in references [3] and [4]. Useful reading to the user of plume models is also the review paper[5] in which various expressions describing plume and ceiling flows are compared and discussed. Several papers comparing the results obtained by plume models have been published in journals or presented in conferences during the last ten years; one of the most recent and useful ones is reference [6].

Many of the plume models used in fire-safety engineering describe the fire as a point source. The effect of the finite diameter of the fire is taken into account by assuming the fire is a virtual source below or above the actual fuel surface depending on the diameter and the rate of heat release of the fire, i.e., the ratio of the buoyancy and the momentum of the gas stream. Expressions can be found, however, also for sources of other geometries. At one extreme a fire source can be regarded as a two-dimensional line source. Non-circular flat fuel sources, which are almost square, can be treated as circular sources with an effective diameter resulting in the same area as in the real source. For some burning objects like rack storage the depth of the fire source cannot be neglected. Semi-empirical equations are derived for these special cases.

If the burning object is close to a wall or a corner, the plume equations for circular fire sources are transferred by using a virtual source extending as a mirror image on the other side of the wall. The simple imaging method results in temperatures which are close to those measured in wall or corner plumes, although the effects of the wall surfaces on the turbulence are neglected. For finite sources adjacent to the wall, the plume expressions are scarce, and considerable engineering judgement is needed when analysing such fire scenarios, for example, by zone models (see 7.3).

When selecting a fire plume one should pay attention to the assumptions made when developing the plume expression. Usually, the heat release rate in the plume property expressions equals the convective fraction of heat release rate. The convective heat release rate is typically assumed to be 70 % of the total heat release rate. However, the commonly used McCaffrey plume expressions use the total heat release rate[7]. The expressions are always fitted to a limited set of experimental data and therefore the empirical coefficients may not be applicable to the scenario under consideration. The most commonly used plume models have been originally calibrated against small fire (heat release rates < 1 MW). It is necessary to be particularly careful when extending the application to a

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larger scale, because extrapolation may lead to systematic errors. There are, however, a large number of examples in which the plume models implemented in zone models have been able to produce results which compare favourably with experimental data.

The plume expressions have usually been derived from steady-state fires under quiescent ambient conditions. In real buildings significant cross winds can be present either due to air flows existing before the fire or generated by the fire itself. These usually cause better entrainment and therefore lower temperatures but bigger mass flows in the plume. Whether this is can be considered safe or unsafe will depend on the purpose of the calculation.

In engineering applications, if no information of the exact fire location exists, it should be assumed that the fire source is directly below the object of interest.

Expressions are also available for plumes emerging from windows with or without balconies.

6.1.2.2.1 Input

The input information in plume flow expressions are:

- rate of heat release (total and convective fraction);
- diameter of the base of the fire;
- ambient temperature.

6.1.2.2.2 Output

The outputs of plume expressions are:

- average temperature and velocity at various positions in the plume;
- mass flow in the plume at various heights.

6.1.2.3 Ceiling jets

When the plume hits the ceiling, a ceiling jet is formed carrying the combustion products away from the line of fire axis. The ceiling jet is characterized by the same quantities as the vertical plume. However, considerably less work has been done to develop semi-empirical expressions for ceiling jet flows than for plume flows.

The most commonly used ceiling jet expressions were published in the early 1970's[8],[9]. Reference [9] also contains expressions for maximum temperatures and velocities in t^2-fires under an unconfined ceiling and in steady fires under confined ceilings.

Transient flow of a ceiling jet is especially important in corridors, because it may produce the first cue of the fire at a remote location and determine when hazardous conditions begin to be formed. Reference [9] includes also a brief discussion on the phenomena and appropriate references to scientific literature.

Friction between the ceiling jet and the ceiling slows the velocity near the ceiling surface. The reduced velocity may be significant for the response of ceiling mounted detectors or sprinklers. Detailed analytical expressions exist for the flow profile in the ceiling jet, but as a crude estimate the maximum occurs at a distance of 2 % of the distance from the fire source to the ceiling.

6.1.2.3.1 Input

The input information in plume flow expressions are:

- heat release rate (total and convective fraction);
- diameter of the base of the fire;
- ambient temperature.

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6.1.2.3.2 Output

The outputs of plume expressions are:

- averaged temperature and velocity at various positions in the ceiling jet;
- mass and energy flux in the ceiling jet at various radial distances.

6.1.2.4 Hot upper layer formation

Due to buoyancy the hot combustion products collect in the upper part of the room. For ease of calculation it is commonly assumed that the upper layer is sufficiently homogeneous so that it can be characterized by a single temperature. The depth and the temperature of the layer depend on the mass and energy flow into the layer, the heat losses to the bounding walls and the lower part of the room as well as the mass and convective energy flow out of the room. The formation of a homogeneous upper layer is usually assumed by zone models.

The assumption of a homogeneous upper layer may not be valid if the fire grows rapidly, i.e. if the temperature of the plume as it enters the layer is always considerably higher than the average temperature of the layer. The hot plume penetrates the layer and the warmer combustion products modified by turbulent mixing always form a new layer close to the ceiling. Therefore, there may be a continuous temperature gradient in the layer. The homogeneous layer concept may not hold true if the floor area of the enclosure is small compared to the area of the fire source or the width of the plume before it hits the upper layer. At the other extreme, if the floor area of the enclosure is large, the temperature in the ceiling jet may decrease considerably close to the walls resulting in significant temperature differences at different radial positions. Unfortunately, no quantitative limits have been established to determine when the homogeneous layer assumption is to be applicable.

A useful discussion on the processes relevant to hot upper layer formation can be found, for example, in references [10] and [11].

When evaluating the formation of the upper gas layer, it is important to consider any enclosure characteristics that may have an effect on the plume. In high-ceiling and large-volume enclosures with temperature stratification, the entrainment of cool air into the plume may cause the plume temperature to become so low (relative to the enclosure temperature) that the relative buoyancy will be insufficient for the plume to reach the ceiling. In such cases, the upper layer will stratify at some level below the ceiling until additional thermal energy is added to the plume. Should stratification occur, it is unlikely that fire signatures will reach ceiling-mounted fire detection devices, and initiation of active fire protection measures may be significantly delayed[11].

The likelihood of stratification can be evaluated by comparing the maximum plume temperatures and the maximum ambient ceiling-level temperatures at the location of interest[12], [13]. The maximum ambient ceiling-level temperature is highly dependent on the height and volume of the enclosure, on the building construction, on the interior finish materials, and the building location (i.e., exterior environmental conditions). It has been reported, for example, that the difference in ambient temperature from floor to ceiling can be of the order of 50 °C in some atria with glazed ceilings[11]. A useful discussion relevant to stratification and fire detection can be found in reference [11].

If the plume temperature is high enough, the plume may hit the ceiling and a radial ceiling jet is formed. The temperature of this primary flow may be considerably higher than the average upper zone temperature. For thermal detectors and sprinklers this means a faster response but for structures the higher local temperatures may cause critical conditions (ignition, collapse) to occur much faster than if estimated based on average upper layer temperatures.

In structural design, the possibility of localized higher temperatures should always be considered. If no location specific information is available, one should assume the fire source to be right below the structural component of interest.

In the case of smoke vents in the ceiling, a fire directly under the vent may cause the vent to open and the majority of the hot plume to be exhausted. Under these conditions, detectors or sprinklers at a distance from the vent may not respond as early as expected because the ceiling jet may remain too weak. Under some circumstances, the fire

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may be able to grow beyond the capacity of protective systems. However, this problem is far from being fully understood and no unanimous opinion exists about the significance of the potential of this type of hazard.

6.1.2.4.1 Input

The input information to describe the upper layer formation includes:

- mass and convective energy flow of the fire plume;
- vent flows in and out of the compartment;
- heat loss characteristics of the bounding surfaces;
- initial temperature and flow profile in the building;
- size of compartment.

6.1.2.4.2 Output

The output of the hot upper layer formation is:

temperature and thickness of the hot upper layer.

6.1.2.5 Vent flows

Openings like doors and windows allow fire and the combustion products to spread outside the room of origin. The vents also allow air to reach the combustion zone and thus influence the size of the fire. Flow through vertical vents is relatively well understood and analytical expressions are available to estimate the mass flow when the temperature (under one-zone or two-zone assumptions) in the room is known. Further discussion on flows through vertical vents can be found in reference [14].

Little quantitative information on flows through horizontal vents is available, particularly for the scenario where all air enters through the same opening as the combustion products are exhausted. Horizontal vent flows with a model commonly used in two-zone fire models have been discussed in reference [15].

6.1.2.5.1 Input

The input data needed to calculate the flow through an opening include:

- building parameters (size and orifice coefficient of the vents and other openings);
- environmental parameters (external wind and temperature);
- thermal profile in the enclosure;
- pressure and/or velocity profile in the enclosure.

6.1.2.5.2 Output

The output of the vent flow calculation is:

the mass, volume and energy flow through the opening.

6.1.2.6 Powered ventilators

Powered ventilators may exist in a building both to generate a comfortable indoor climate during normal use and to extract smoke out of the building in the event of fire. Because of wide differences in mechanical ventilation system design, analysis of the potential for smoke spread by the subject system requires detailed knowledge of the design criteria and accurate information about the "as-built" performance of the system. It is important to note that the method of designing ventilation capacity in terms of the number of air exchanges per hour — common practice

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when designing air conditioning systems — cannot be readily applied to the design of powered smoke-venting systems, because the pressure gradients created by fire may significantly affect the performance of the system.

Various techniques of control of the movement of fire effluents by powered ventilators are specified in clause 8. Further information on the design of smoke control systems can be found, for example, in references [12], [16] and [17].

6.1.2.6.1 Input

The input data needed to calculate the flow through powered ventilators include:

- building parameters (duct network to which the ventilators have been connected, openings, tightness characteristics, capacity-versus-pressure-difference curves of fans; dimensions of structures);
- environmental parameters (external wind and temperature);
- thermal profile in the enclosure;
- pressure/velocity profile in the enclosure.

6.1.2.6.2 Output

The output of the vent flow calculation is:

the mass, volume and energy flow through the vents.

6.1.2.7 Stack effects

The stack effect induces an upward movement of air or fire effluents in building shafts, such as stairwells or elevator shafts, the temperature of the outside ambient air is less than the temperature within the shaft. If the temperature difference is reversed, the air movement is downwards. The movement is caused by a pressure difference

$$\Delta P = \Delta\rho \times g \times h_\mathrm{v} = \rho_0 \times T_0 \times g \times h_\mathrm{v}\left(\frac{1}{T_0} - \frac{1}{T_\mathrm{g}}\right) \quad (1)$$

where

$\Delta\rho$ is the difference of gas densities between the inside and the outside;

T_0 is the inside temperature;

T_g is the outside gas temperature;

h_v is the height of the shaft.

The volume flow rate depends on the size of the openings at both ends of the shaft.

Further discussion about stack effects in relation to smoke control can be found in reference [10].

6.1.2.7.1 Input

The input data needed to evaluate the stack effect are:

- building parameters (height and width of the shaft, size of the openings);
- thermal profile (temperature distribution inside and outside of the shaft).

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6.1.2.7.2 Output

The output is:

volume and mass flow rate in the shaft.

6.1.2.8 Movement of effluents through ventilation duct

The ventilation system is often designed to operate under specified pressure and temperature conditions. The fire environment will upset the balance between air source and exhaust both within the enclosure of origin and in adjacent enclosures, if served by the same system. This imbalance will be particularly acute where natural ventilation paths do not exist or are inhibited.

In enclosures where power ventilators are the sole source of air supply, the stratification of fire effluents may be affected. Consequently, the two-zone model may not be applicable since thermal gradients and species distribution can be completely different from those produced by natural ventilation.

The flow of fire effluents through ventilation ducts can be evaluated by considering the pressure distributions created in fire. This should be done even if the strategy were to shut down the ventilation in case of fire. Fire dampers may be installed in the ducts to close the path to smoke and hot gases in the event of fire. It should be noted, however, that dampers are seldom tight enough to prevent all flow of effluents.

The performance of heating, ventilating and air conditioning systems under fire exposure have been discussed briefly in reference [18].

6.1.2.8.1 Input

The input data needed to evaluate the flow through ventilation ducts include:

- building parameters (location and size of ventilation ducts, properties of powered ventilators);
- environmental conditions (external temperature and wind direction);
- thermal profile in the enclosure of fire origin and in the rest of the building;
- pressure and/or velocity profile in the enclosure and in the rest of the building.

6.1.2.8.2 Output

The output is:

volume and mass flow of fire effluents in through the ventilation ducts.

6.1.3 Smoke and species profiles

Fire effluents may contain substantial amounts of particulate causing loss of visibility or gaseous, possibly toxic, species. The generation of these has been discussed in ISO/TR 13387-4 (SS1). In this clause the methods available for assessing the smoke density or species concentration at a location far from the fire origin are discussed. In one- and two-zone models, a well-stirred volume is assumed, i.e. the particulates or the species concentrations are assumed to be fully mixed within the volume in which the temperature is constant, too. In field models, more detailed smoke and species profiles can be obtained. The effects of smoke and the gaseous species on people are discussed in ISO/TR 13387-8 (SS5).

In case of a smouldering fire or if the location of interest is far from the point of fire origin, the temperature of the fire effluent may not be high enough for stratification to occur. Smoke density and species profiles can then be estimated by assuming the space to be well-stirred. If we assume no gases leak out from the room, the concentration C_{i} of species i can be obtained by integration

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$$C_i(t) = \frac{1}{V_{encl}} \int_0^t \dot{m}_i(t) dt \qquad (2)$$

where

$\dot{m}_i$ is the rate at which the species “i” is introduced in volume V_{encl}

If the volume flow rate $\dot{V}$ into and out of the enclosure and the concentration C_{in} in the incoming flow are known, the concentration in the enclosure can be obtained by integration

$$C_i(t) = \frac{1}{V_{encl}} \int_0^t [C_{in}(t) - C_i(t)] \dot{V}(t) dt \qquad (3)$$

The same principle can be used to estimate the smoke density, because as a first approximation the optical smoke density (extinction coefficient) is proportional to the mass concentration.

The two-zone models usually conserve mass of chemical species. Once the species or smoke yields are given as input, the models can trace the concentration at any location. If the conservation of mass is not included, a relationship can be derived for the mass fraction of a species and the adiabatic temperature rise.

Equation (3) can be applied also in the case of the two-zone approach by replacing the volume of the enclosure with the volume of the upper hot zone.

The use of two-zone models with their limitations are discussed in clause 7.

The analytical expressions for plumes and ceiling jets, and the field models based on computational fluid dynamics are similar in the way that they both give as output the temperature and flow velocity profiles. If the models do not include conservation of species, the concentrations can be estimated in the same way as for zone models, i.e., by assuming a known relationship between temperature rise and species concentration.

CFD models with a combustion submodel make it possible to calculate the species generation rate and the subsequent concentrations as part of the solution of the conservation equations.

6.1.3.1 Input

The input information needed for the assessment of smoke density and visibility at any location far from the fire include:

- generation rate of visible smoke and gaseous species;
- concentration of smoke and gaseous species in the inflow;
- volume flow rate into the enclosure.

6.1.3.2 Output

The output information is:

- concentration of species in the enclosure as a function of time;
- smoke density (extinction coefficient) as a function of time.

6.2 Non-thermal fire damage

The production of acid gases in fire effluent may cause corrosion of steel used to reinforce concrete in buildings which can lead to weakened structural performance and the need for replacement. The deposition of soot from a wide range of materials (halogenated and nonhalogen; organic and inorganic) may cause shorting in electrical

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switches and conductive bridging on electronic microcircuits in control panels, computers and telephone exchanges. The deposition of super-toxicants on surfaces can also be regarded as non-thermal damage.

Non-thermal damage to property can include surface corrosion, structural damage, electrical malfunctions, discoloration, odours. Non-thermal damage depends on the chemical nature, physical characteristics, transport, and deposition of fire products on the building surfaces, structures, furnishings and equipment. The severity of non-thermal damage often increases with time and humidity[19].

NOTE 1 For corrosion protection, galvanized zinc or zinc chromated finishes represent a major portion of the structural components of telecommunication and computer equipment as well as HVAC duct work. Consequently, all zinc surfaces are sensitive to attack by acid gases. On exposure to acid gases, zinc forms zinc chloride, which is very hygroscopic and absorbs moisture from air at humidities as low as 10 % RH to form an electrically conductive solution. The solution flows on the surface, drips down or runs onto equipment, resulting in very serious electrical shorting problems. In some major fire losses at telephone central offices, zinc chloride has played a key role in both the rate of restoration as well as the ability to salvage equipment[20], [21].

NOTE 2 Non-thermal fire damage assessment is not logically part of SS2: Movement of fire effluents. Due to the significance of the subject, a decision has been made to discuss it in connection with SS2, although it mat be transferred later to a possible subsystem on property protection.

6.2.1 Input

The input information needed to estimate the non-thermal damage include:

- concentration of corrosive fire effluents as a function of time;
- properties of the deposition surfaces.

6.2.2 Output

At present state of knowledge no accurate predictions of the magnitude of non-thermal damage can be made. The principle information obtained is:

potential for non-thermal damage (contents response, including loss of equipment functionality).

7 Engineering methods

7.1 General

A large variety of engineering methods of different levels of complexity are available to evaluate the movement of fire effluents[1],[20]. Like for other evaluation tasks, the engineering methods may be divided into estimation formulae, computer programmes simulating the phenomena in more detail, and experimental methods. Various types of methods will be discussed in 7.2 to 7.5.

Before using any method, make sure the model treats the fundamental processes delineated in the bus of Figure 1. In the case of movement of fire effluents, make sure the model treats the following phenomena in a manner appropriate to the application:

- heat release rate from the fire;
- mass loss rate;
- flame spread over the burning object(s), horizontal and vertical;
- heat transfer due to flame radiation;
- entrainment of air into plume;
- mixing between gas layers;

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- pressure distribution in the room(s);
- radiative and convective heat transfer between zones, plumes, objects and building components;
- optical smoke density;
- generation and transport of toxic products;
- material data k, ρ and c.

The limitations of models proposed for design use should be identified in terms of criteria set out in ISO/TR 13387-3.

7.2 Estimation formulae

Many formulae are available for estimation of the movement of fire effluents. These formulae are normally approximations based on empirical equations and rule of thumb, that can be used for simple estimates and for checking more advanced methods. The user should, however, be aware of the limits of the use of each specific model and input parameter, as use beyond limitations may lead to incorrect results.

Some of the phenomena that can be treated with simple formulae have been discussed in clause 6. Text books and handbooks such as references [20], [22], [23] include a large number of additional formulae and references to the original publications. User-friendly computer programs with collections of analytical equations are also available.

7.3 Zone models

7.3.1 General

Zone models are used to predict the development of a fire in an enclosure by considering the actual fire load, the geometry of the enclosure, the effect of openings, and the thermal feedback from the enclosing structures.

In zone models, the enclosure is divided into a limited number of compartmental volumes. Normally the room is divided into two compartmental volumes with an upper hot layer and a lower cold layer during the development of the fire. When the fire becomes fully developed, the model usually will change into one zone. Each zone is treated as a homogeneous volume, meaning that all variables, for example, the temperature, reflect the mean value for each volume. As the number of zones are limited, the equations of the zone models can be solved by personal computers, but note that use of the results is limited. For more precise results, the volume should be divided into several compartments where each compartment is considered on its own.

The zone models are based on solving equations of conservation of mass, energy and momentum as a function of time. If there are openings in the room to other rooms or the surroundings, interchanges with these are also considered. The theory behind the models is described in literature, for example, in references [10] and [24].

7.3.2 Input

The needed input data varies among zone models. They will, at minimum, require a description of:

- the building geometry, i.e. floor area, ceiling area, room height, position and size of openings leading to other compartments or to the surroundings;
- the building materials used, i.e. specific heat capacity, density and heat conductivity for each material. In addition surface characteristics, such as heat transfer coefficients and effective emissivity are often required;
- the design fire given as the heat release rate (HRR) and the locations of the fire. HRR can be defined in many ways. The simplest being the definition of HRR as a function of time based on mathematical formulae, for example, t^2 fire growth. Many models also allow the user to specify a range of data points for the HRR based on full-scale experiments.

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Some models also allow the user to specify heat detectors, smoke detectors, installation of smoke ventilation, installation of mechanical ventilation, etc..

Input data should generally be chosen in agreement to ISO/TR 13387-2.

7.3.3 Output

Based on the input data given by the user, the zone model will then be able to predict:

- compartment smoke filling as a function of time, i.e. the depth of the hot smoke layer;
- average smoke layer temperatures as a function of time;
- velocity, mass and heat flow out of openings.

Some models also calculate average smoke densities and oxygen depletion.

7.3.4 Application of results

Zone models are suitable for predictions of smoke filling and the development of a fire in an enclosure including time to flashover. This means that the results are directly applicable for rescue models (SS5). The results can also be used for detection and activation (SS4), but one should check which values are being used as this can differ from model to model. If only the values from the upper zone of a single room are used, very conservative results are often obtained.

For structural responses (SS3) the results from zone models can be used but the designer must be aware of how the gas temperature is derived and if it is appropriate to use this temperature on the given structural element. Because the upper layer temperature is an average temperature in the whole upper part of the room, the maximum temperatures and the consequent thermal exposures may be much higher locally.

The zone models publicly available today do not include validated algorithms for predictions of reaction to fire, for example, spread of flame on lining materials.

7.3.5 Limitations of zone models

Designers need to carefully examine whether a zone model's assumptions are appropriate for a particular design situation. The use of zone models may not be appropriate for applications where the flow field is considered important. For example, if the fire plume is close to a wall, the model must account for the fact that entrainment of air is no longer axisymmetric. Furthermore, the two zone assumption may not be appropriate for situations where fire suppression causes significant mixing in the enclosure.

These effects may be expressed as limitations on zone models related to:

- enclosure length/width/height ratios;
- enclosure height and floor area considerations;
- heat release rate relative to the dimensions of the enclosure.

7.4 Field models

7.4.1 General

Field modelling is the term used for the application of computational fluid dynamics (CFD) to the simulation of the growth and spread of fire. In CFD codes the fundamental equations of conservation of the mass, momentum and energy are solved subject to the boundary and initial conditions that represent the particular fire scenario under consideration[24], [25], [26].

Field models make fewer a priori simplifications than zone models about the heat and mass transfer processes that occur during a fire. However, some assumptions are necessary to deal with phenomena not directly covered in the

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fundamental equations. Of particular significance is the modelling of turbulence, where a number of empirical equations are commonly used to represent the phenomena.

The combustion process is extremely complex. The change from reactants to final products includes many intermediate reactions involving the formation and interactions of numerous short-lived species and free radicals. In most instances, these intermediate products and their rates of creation and destruction are not known. Turbulence greatly complicates the situation by influencing the mixing of reactants and products.

Consequently, in fire field models the combustion process is simplified using one of several techniques. The simplest approach represents the fire as a volumetric heat and mass release rate. In this approach, the combustion process is ignored and represented as a source of heat and mass. A second approach models combustion using global one-step chemical reaction mechanisms in which fuel reacts with oxidant to give products. The rate of reaction is controlled solely by turbulent mixing of gaseous fuel and oxidant which is determined from calculated flow properties. Although the combustion process is only approximated, this approach gives satisfactory results for simple gaseous fuels. Other finite-rate reaction models are available, however, they are also limited to simple gaseous fuels. The prediction of flame spread over solid surfaces is currently beyond the scope of field-modelling technology and is receiving interest from some research groups.

Calculations of radiative heat transfer are often treated by simplified algorithms that may not be adequate to represent such complex heat transfer mechanisms. Proper representations require consideration of soot concentration, emission characteristics and gas phase absorption. Inaccuracies may also result from the computational algorithm leading to numerical diffusion and inadequately converged results. The simplifications commonly adopted can lead to inaccuracies in the computed temperature, species concentration and flow fields.

The technique has been most successfully employed to simulate the movement of the gaseous products of combustion (smoke) throughout enclosures. The method is suitable for a range of problems that a zonal approach cannot cover. For example, the influence of pre-fire temperature gradients throughout the enclosure can be included as can the influence of external wind pressures. Although in principle the method can be used to study the whole range of fire processes including fire growth and spread, such techniques are still in the research phase and are not yet developed to the extent that they can be used as practical fire safety engineering studies. For this reason the discussion given here on field modelling of fire will be restricted to its application to heat and mass transport.

7.4.2 Model predictions

The primary output of this kind of model is a series of timed events for each of the variables — i.e., gas velocities, gas temperatures, fuel, oxidant and combustion product concentrations together with pressures — at each elementary control volume throughout the range of calculation. Furthermore, mass fluxes through ventilation openings as well as convective and radiative heat fluxes across the solid boundaries are provided.

Secondary variables can be deduced from primary ones by the use of further assumptions. However, deductions of these secondary variables are heavily dependent on the initial assumptions made and are in the spirit of the zonal modelling approach. The validity of these assumptions must always be kept under review.

7.4.3 Acceptance of the solution

Before any engineering judgement is made on a numerical solution, it is important that an acceptable level of convergence be demonstrated for it. Convergence is the term that describes whether the solutions of the discretized form of the equations approach the true solution of the partial differential equations having the same initial and boundary conditions. The numerical mesh is refined as the number of numerical iterations increase. The true solution is not known for, if it were, the numerical solution would not be needed. The solution is determined for a given mesh from inspection of the behaviour of the “residual” errors in each of the conservation equations as iterative solutions proceed. These residual errors are the magnitudes of imbalance between right and left sides of the discretized equations using the latest solution of the guess-and-correct operation for each variable. It is not sufficient to simply demonstrate that the solution which does not change as iteration proceeds is the true solution. For example, when considerable under-relaxation is used in an attempt to produce convergence, the solution can become frozen but not converged.

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Furthermore, it is important to examine the sensitivity of a solution to grid refinement. This can be an expensive task. Refining a grid by a factor of two in each coordinate direction will increase computational cost roughly by a factor of eight, so it is often necessary to strike a compromise between cost and accuracy.

Most general-purpose CFD packages provide diagnostic information on the progress of residual errors for each of the equations solved. However, it is important to be satisfied that overall mass and energy balances for the whole domain are within acceptable bounds. Compartment mass outflows must balance mass inflows and heat lost into the structure taken together with heat lost from the compartment through its openings must balance that generated by the fire.

It is important to ensure that the solution is “well-behaved”. This might include inspection, for example, to ensure that it is free from spurious oscillations and that predicted downstream temperatures away from areas of chemical reaction are lower than those at the source. If problems of this nature do not occur then consideration should be given to reducing the grid spacing and/or the time step.

There will be occasions where the computer simulation using field modelling may suggest unexpected behaviour. If a physical simulation were to produce something unexpected, the engineer would need to exert his ingenuity to explain what he has seen or what he has measured and to relate it to the practical problem at hand. However, with numerical simulation such an unexpected behaviour is more disturbing since it can have two explanations; either it is genuine and would have been observed in a physical simulation or, alternatively, it is a misleading numerical artefact.

The possibility of a misleading numerical artefact cannot be completely discounted with such complex numerical simulations as those involved in CFD. It is therefore essential to ‘shadow’ the numerical simulation, where possible, with known simple calculation methods.

7.4.4 Mode of working for safety assessment

In applying CFD to fire problems, it is important that both fire-safety engineering and CFD principles are appropriately applied. This may mean that a multi-disciplinary team is required to oversee a project and to ensure that the problem is properly posed and that the results produced make practical sense.

7.5 Experimental methods

In some cases the efficiency of smoke extraction systems can be evaluated by running full-scale experiments using hot smoke. One procedure has been described in an Australian Standard[27].

Small-scale models can also be used to assess the movement of fire effluents. For example, salt-water modelling has been used with success to study complicated buildings[28].

When setting up ad hoc tests or when the objective is to assess movement of fire effluents, the general guidance given in ISO/TR 13387-4 is appropriate. The document ISO/TR 13387-2 gives guidance on selection of design fire scenarios and design fires. This guidance is also applicable when selecting the design fire for tests.

8 Techniques to control movement of fire effluents

Smoke containment relies on physical barriers to limit the spread of smoky gases from one space in a building to another. Passive compartmentation, such as doors, walls, floors, etc., can provide a level of protection against smoke ingress. The extent to which smoke will leak through these barriers will depend on the size and shape of leakage paths and the pressure differentials across the paths.

Smoke clearance describes any method of removing relatively cool, smoky gas from a space in a building when smoke is no longer entering or being created in that space. This may be achieved by providing natural cross ventilation, for example, by openable windows or by powered systems.

Smoke dilution describes any method of mixing the smoky gases with enough clean air to increase the visibility and reduce the threat from toxic combustion products.

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Smoke exhaust ventilation is a method to provide a separation between an upper layer of smoke and a lower layer of relatively clean air. This is achieved by continuously exhausting smoke from the buoyant smoke layer using either natural or powered ventilators by replacing smoke with clean air from the lower layer.

Pressurisation is a form of smoke control using pressure differentials, in which the air pressure in the spaces being protected is raised above that in the fire-affected area. Airflow through the leakage paths prevents infiltration of smoke to the high-pressure side, i.e. the protected area.

Depressurization is smoke control using pressure differentials in which air pressure in the space containing the fire is reduced below that in the adjacent spaces requiring protection.

The efficiency of any smoke management system may be adversely affected by wind and outside temperatures. The pressures generated by wind may hamper the extraction of smoke by providing a positive pressure at the extraction point. Internal climatic conditions may also be important, especially in rooms of large volume, such as exhibition halls, where forced-air circulation may initially prevent smoke of low buoyancy reaching high level detectors. Stack effect in tall buildings and temperature inversion may also need to be considered.

A general discussion on the principles of smoke control can be found, for example, in the SFPE Handbook on Fire Protection Engineering [12], [16].

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