HOT SMOKE TESTS – LESSONS FOR BETTER DESIGN OF FIRE PROTECTION SYSTEMS

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ABSTRACT

Hot smoke tests are a useful methodology to verify the performance of an installed smoke control solution in buildings and other structures such as underground car parks, tunnels, metro stations etc. Although hot smoke tests in buildings typically utilize a heat source which is significantly smaller than the design fire for which the smoke control system was designed, they nevertheless provide the best available tool to check the adequacy of the smoke control strategy adopted at the building design stage and its implementation in the construction process. In most countries hot smoke tests are only carried out in large and complex buildings. However, such tests also offer a cost-effective method to check the suitability of the installed system in less demanding structures. This paper looks qualitatively at the results of over forty hot smoke tests carried out in Poland and the conclusions that can be drawn from them with respect to current construction practice as well as the recommendations contained in established design guidance documents and standards.

INTRODUCTION

Smoke tests are used as part of the commissioning of smoke ventilation systems in large and complex structures. They are commonly performed in tunnels, but also in some types of buildings such as large enclosed car parks, atrium buildings, shopping malls etc.

Full-scale smoke tests can be broadly divided into two groups: cold smoke tests and hot smoke tests.
In cold smoke tests artificial smoke is used simply as a tracer, with no significant heat generation. The source of such trace smoke can either be some sort of smoke bomb or a theatrical smoke generator. Such tests can be helpful in visualizing the air flows induced by mechanical smoke ventilation, but they cannot simulate fire conditions in which a buoyant smoke plume and a hot smoke layer are present.
Hot smoke tests aim to replicate as closely as possible actual fire conditions by producing both heat and visible smoke. This can be done in a number of ways: either by the controlled burning of a fuel (e.g. diesel in a metal pan) or by generating heat in a "clean" fire (e.g. methylated spirit or LPG fire) and then adding artificial smoke as a tracer. This later approach has the benefit of generating virtually no smoke damage in the space in which the test is being carried out. This is particularly important when the tests are carried out in spaces such as shopping malls or atria.

Numerous examples of hot smoke tests in road tunnels are described in the literature[1,2,3,4,5]. There is also a limited number of publications discussing the methodology and benefits of such tests in buildings[6,7,8]. Early examples include tests carried out in the nineties as part of commissioning process of the smoke ventilation system for Brussels Airport[9] and for the Espace Leopold Building of the European Parliament[10].

The methodology for carrying out hot smoke tests is not standardized worldwide. The document most commonly used as a reference is Australian Standard AS 4391[11] which is based on methodology developed in the nineties – this methodology will be further described in this paper. There is also a German guideline document VDI 6019: Part 1[12] covering engineering methods for the dimensioning of smoke removal systems, which includes recommendations for verification of the effectiveness of smoke control systems. This document contains reference to AS 4391 but also offers alternative methodologies based on a plume of heated air generated by a gas burner and a fan or an array of liquid-fuel burners which can be used to create a test fire with heat output of up to 1200 kW.

METHODOLOGY OF HOT SMOKE TESTS

All tests described in this paper were carried out using procedure set-out in AS 4391. The heat source in the test is industrial grade methylated ethanol burning in a steel tray of prescribed size (or a configuration of multiple such trays). The tray sizes described in the standard are based on ISO paper sizes A1 to A5. The heat output for the fuel tray configurations included in the standard ranges from 11 kW for a single A5 tray to 1500 kW for a set of four A1 trays. In principle, it is also possible to create a larger test fire by using more than four trays, the parameters of such configuration can be calculated based on the principles explained in the standard. Details of heat output and temperature rise in the smoke plume at a certain height above the fire are summarized in table 1.

Fuel tray size	**Amount of fuel for 10 minutes of steady state burn, L**	**Approximate heat release rate, kW/m²**	**Approximate heat output, kW**	**Temperature rise at 3 m above the trays, °C**	**Volume flow in the plume at 3 m above the trays, m³/s**
4 x A1	4 x 16 = 64	751	1 500	236	9.2
2 x A1	4 x 15 = 32	696	700	166	5.4
A1	13,0	678	340	117	3.2
A2	5,5	566	140	69	2.0
A3	2,5	471	60	41	1.3

Table 1. Test fire parameters for selected fuel tray configurations (source: AS 4391).

Each fuel tray is placed in a water bath which is essentially a larger metal tray filled with water. This serves to stabilize the temperature of the fuel in the tray and also as safety measure against fuel spillage.

Fig. 1 Example of a test set up for a hot smoke test in a warehouse with 1.5 MW test fire

As ethanol burns with very little visible smoke, artificial tracer smoke is produced by a generator and introduced into the plume just above the heat source. Such artificial tracer smoke must be relatively resistant to high temperature, otherwise it will be quickly vaporised once introduced above the flame. For practical reasons tracer smoke should not be toxic, it should have no strong odour and should leave no residue. In the tests described in this paper tracer smoke was generated using commercially available smoke generators which produce synthetic oil-mist smoke.

Fig. 2 Flowing hot smoke layer in a shopping mall (test fire in the adjacent retail unit)

Fig. 3 Spill plume at the edge of floor void in a two storey section of a shopping mall

It is important to stress that for practical and safety reasons the size (heat output) of the test fire will normally be significantly smaller than the size of the design fire selected as the basis of design for the given smoke ventilation system.

The size of the test fire should be selected taking into account the size of the space, the presence of fit-out elements which may be damaged by excessive temperature and the proximity of any combustible elements. Particular attention must be paid in spaces protected with automatic sprinkler or water mist installations, as such installations may inadvertently be activated during the test. In cases where the expected smoke temperature at the level of the sprinkler heads nearest to the test location is close to their activation temperature it is advisable to protect those sprinkler heads or to disable the fire suppression system for the duration of the test.

Each hot smoke test should be documented by video recordings and photographs taken during significant stages of the test. Where possible the temperature of smoke at the ceiling should also be measured and recorded.

Fig. 4 Hot smoke test in a multi-purpose hall (natural ventilation)

Fig. 5 Hot smoke test in an exhibition hall (mechanical ventilation)

DESIGN AND INSTALLATION PROBLEMS EXPOSED DURING HOT SMOKE TESTS

Hot smoke tests can help to identify problems with installed smoke control systems which are either a result of mistakes made at the design stage or a result of errors and deficiencies in the construction and installation of the system.

Design problems

Problems related to incorrect planning and sizing of the smoke control system are usually quite difficult to correct once the system is installed. A typical example of such a problem is insufficient capacity of the system, either in terms of smoke vent area (for natural systems) or insufficient extract capacity of fans for mechanical systems. Such inadequacy may be the result of a simple calculation error or an inappropriate selection of the calculation model e.g. sizing the system on the basis of an axi-symmetric smoke plume equation where a spill plume condition can occur, resulting in much higher volumetric flow rate of smoke into the reservoir.

Another problem quite commonly observed during hot smoke tests is the presence of stagnant smoke zones with insufficient rate of smoke extraction either by natural smoke vents or by smoke extract grilles. Smoke entering such dead-end zones cools down after a short period which results in of smoke settling and significant deterioration of visibility in the affected areas.

The proper functioning of a smoke control system often depends not only on a sufficient and well-spaced means for smoke extraction, but also on smoke curtains and other physical barriers which limit the spread of smoke and direct its flow towards the smoke reservoir. This is particularly important in complex, multi-storey spaces.

Fig. 5 Hot smoke test in an atrium space.
Performance of the system is hindered by the lack of smoke channelling screens.

In large, tall spaces with multiple smoke reservoirs an important parameter of the system design is the depth of smoke curtains. By increasing the total area of smoke vents or increasing the extract capacity of mechanical ventilation it is theoretically possible to raise the bottom of a smoke layer and consequently (in a room of given height) make the smoke layer very shallow. In reality the minimum depth of smoke curtains must be related to the height of the space in which they are located if the curtains are to be effective in preventing smoke spillage into adjacent smoke reservoirs.

The tests carried out suggest that smoke curtains with a depth less than 15-20% of the room height will not be able to contain all smoke within the smoke reservoir, even where the calculated necessary rate of smoke extraction is provided.

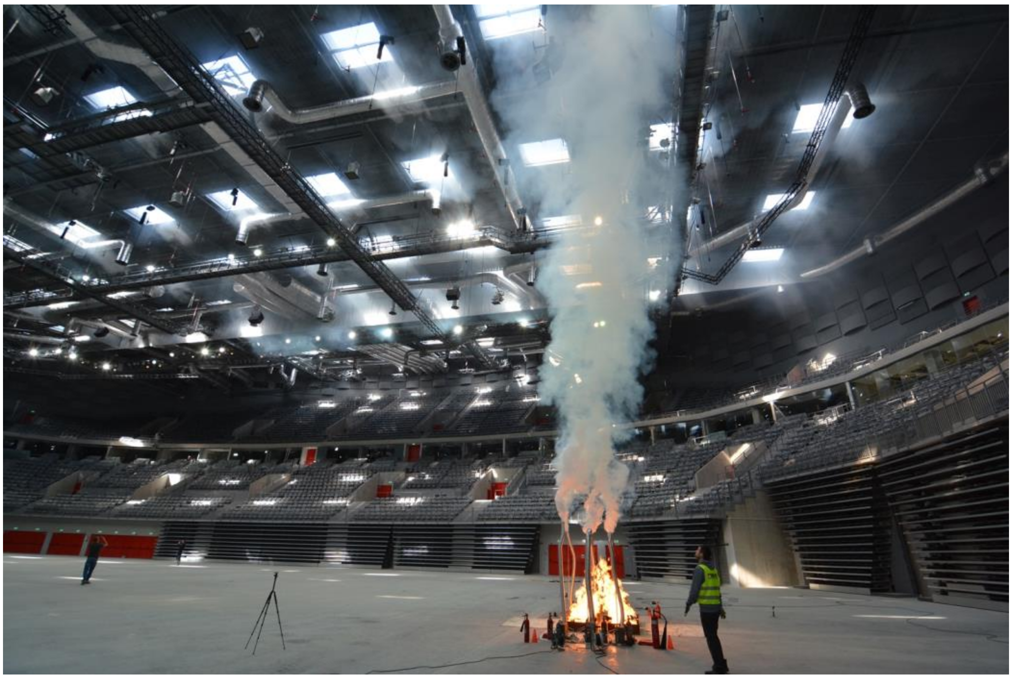

Fig. 5 Hot smoke test in a large sports hall.
Smoke migration to adjacent smoke reservoirs occurs due to insufficient depth of smoke curtains.

Fig. 6 Smoke plume in an atrium before (left) and after (right) a mechanical smoke extract system is turned on. Visible distortion of the plume by excessive velocity of replacement air coming from one direction.

One aspect of the design which has a huge influence on the overall performance of a smoke control system is the sizing and positioning of replacement air inlets / supplies. Existing design codes such as BS 7346-4:2003 or NFPA 204:2018 recommend limiting the air velocity to 1 m/s below the smoke layer and at the plume respectively. However this recommendation is often confused with the much higher limiting value of 5 m/s allowed for air velocity at inlets used for occupant evacuation i.e. doors or corridors. Introducing replacement air at such high velocity near the fire or close to the bottom of the smoke layer results in significant disturbance of the plume and /or the smoke layer.

Visual observations from many tests carried out by the authors suggest that it is crucial to introduce replacement air into the ventilated space from multiple directions (i.e. to avoid a single point of air inflow) and to limit the velocity of incoming air as much as possible. Rational provision of replacement air is also important for the correct operation of drop-down smoke curtains.
In spaces of limited height and / or volume such as enclosed car parks an improved performance of mechanical smoke removal system can sometimes be achieved by reducing the extraction rate and hence the velocity of incoming replacement air in the initial stages of fire growth, when evacuation is taking place – usually for the first 3 to 5 minutes after the outbreak of fire.

Installation problems

Problems related to the installation of smoke ventilation systems often concern the programming of the system, as described in the fire control matrix or a similar document. Such problems include for example incorrect direction of operation for reversible fans (e.g. jet fans in car park systems), incorrect operation of motorised smoke dampers in shafts serving multiple floors and premature activation of jet fans in car park smoke ventilation systems.

Another common problem is the lack of "locking" of the system in buildings with multiple smoke control zones served by independent smoke extract systems but shared replacement air inlets. Migration of smoke into adjacent detection (smoke control zones) can then result in one or more additional zones being activated and as a result the incoming air velocity becoming excessive.

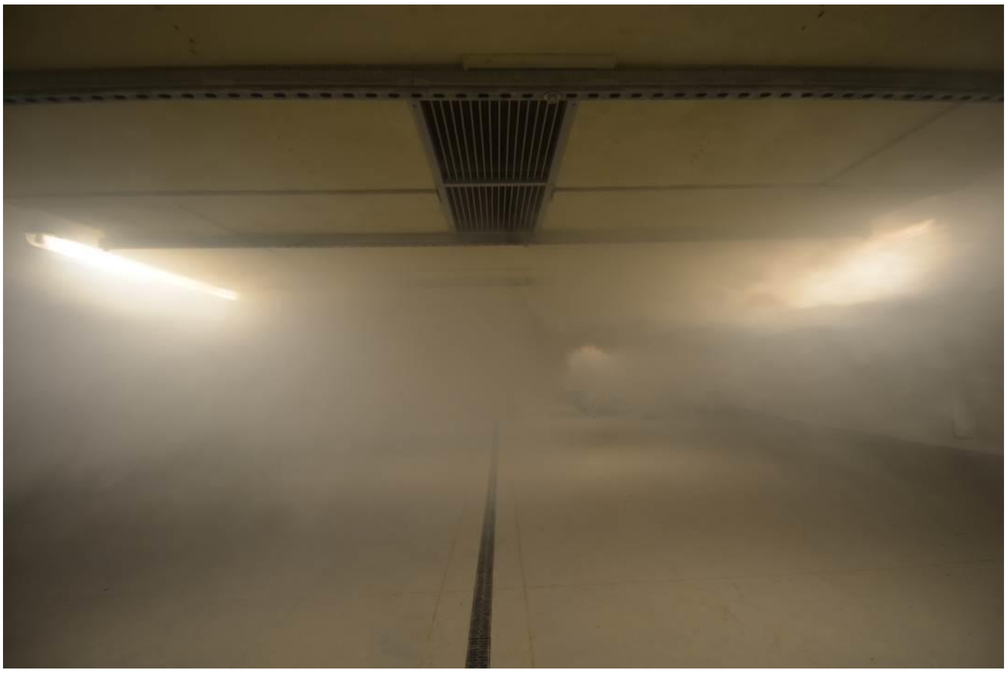

Fig. 7 Inefficient operation of a mechanical smoke extract system in a car park due to positioning of the extract grille at the bottom of the smoke duct

Other examples of on-site problems for smoke ventilation systems include the incorrect installation of smoke extract ductwork and grilles, excessive gaps in smoke curtains (both permanent and automatic) and introduction of replacement air through the smoke layer (i.e. from the ceiling).

SUMMARY

Hot smoke tests can play an important role in identifying deficiencies of both design and installation for smoke ventilation systems. Although tests utilizing a heat source of the same magnitude as the design fire are normally not feasible, even a reduced test fire can create smoke flow behaviour similar to that expected in an actual fire, particularly at the early stages of fire growth when evacuation is still taking place.

Based on personal experience the authors recommend that such tests should be performed more commonly, not only in very large and complex buildings but also in more ordinary spaces such as enclosed car parks, shopping centres and atrium buildings. In addition to the benefit of testing the system in conditions as close as possible to these experiences in actual fires they also offer huge educational benefits to the technical personnel witnessing them i.e. the designers, contractors and fire prevention officers.

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