Use FDS to Assess Effectiveness of Air Sampling Smoke Detection in Large Open Spaces

Ming He, Yun Jiang[1], Cesar Perez[2]
Vision Fire & Security

ABSTRACTS

Traditionally, a simple calculation is applied to assess the performance of a point type smoke detector in terms of activation time. Fire Dynamics Simulator (FDS) may be used to evaluate smoke obscuration level after the fire is fully developed so the tenability can be taken into consideration. There is very little research conducted on the topic of how a computational simulation model is used to calculate smoke propagation at its early development stage. This is becoming an important topic in performance-based design where early fire detection is paramount to facilitate orderly and safe human evacuation and prevent asset losses.

Very high sensitivity Air Sampling Smoke Detection (ASD) technology and smoke dilution have not been modelled and usually are not well understood. This paper presents a case study, a systematic approach to use FDS to model very high sensitivity smoke detection using VESDA® ASD detectors. This paper highlights a process to model, predict and validate the ASD response time using Computational Fluid Dynamic (CFD) via real design fire tests.

ASD was considered for a major building complex redevelopment in Hong Kong - K2-Redevelopment project. The entire complex is separated into three areas, a 54-story office building, a 60 meters high Grand Atrium and the rest is a shopping mall with cinema, restaurants and shops.

Considering ASD as part of the fire safety system to protect the Grand Atrium area, which is a large open spaces (LOS) application, VESDA ASPIRE® is used to design the pipe network. To optimise the location of smoke detectors and their sampling holes in such an environment for early fire detection, a set of computer simulations were carried out using FDS which calculate smoke movement in the atrium, detection performance and the overall protection in accordance with performance-based fire safety system design methodologies.

INTRODUCTION

Large Open Spaces (LOS) protection is traditionally a very challenging issue. Some of these challenges are the distance from a potential fire hazard to the detection points, smoke being quickly diluted in a sheer volume of space and a large number of occupants usually found in LOS. The fire protection industry has been searching for optimal solutions to adequately meet building and life safety design objectives. Standards such as NFPA92B [1] have been developed and adopted specifically for LOS application. However, many LOS are usually part of a landmark building involving extensive innovative design ideas to accomplish visual, energy sustainability and useability goals. These unique features have not been exhaustively considered in the existing codes and standards.

A fair percentage of commercial/non-commercial buildings exhibit the characteristics of a LOS. These include atria in office buildings/serviced apartments, hotels, convention and exhibition centres, museums and public libraries, main railway and airports terminals, sport stadiums, halls (municipals, universities, churches, etc.), entertainment and in-door

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[1] Vision Fire & Security, Australia
[2] Vision Fire & Security, Europe

recreation facilities, large warehouse type structures such as aircraft hangers, hardware/furniture stores, shopping malls, arcades, industrial sites and so on. When considering the best fire protection solution for such building types, the following aspects must be taken into consideration: (1) the key attributes of the building layout (i.e. ceiling height and interface to outside ambient environment), (2) ventilation (i.e. natural or mechanical), (3) airflow dynamics (i.e. building leakage, air supply and return vents and air handling unit (AHU) operation). Examples of the impact on fire growth and smoke propagation are the possibility of stratification, the extent of smoke dilution and uncertainty of smoke plume forming.

Beam detectors have been used in LOS such as warehouse applications mainly due to the fact that many other conventional point detectors such as ionisation or photoelectric type are not sensitive enough when mounted at a usually very high ceiling level. However, over the years, recommendations for beam detectors design and installation have been changed to reflect the need for detailed design considerations in order to achieve the level of protection required. As stipulated in BS5839-1:2002 revision [2], additional considerations include smoke plume forming, the need to provide ceiling level detection, etc. This highlights two important issues in regards to the effectiveness of LOS protection using beam detectors. The first issue is how to position the beam detectors when close spacing is required. The second is how to assess the system design so different fire scenarios, hazards and locations can be covered.

Today, performance-based building code has been in use in many countries such as Australia. It provides great incentives for safer and more innovative building designs and also encourages the application of advanced technology. In contrast to the prescriptive “deemed-to-satisfy” (DTS) approach, the cost of the solution is optimised when the building safety margin is maintained or even enhanced.

Because of the new performance-based approach, many computer tools have been developed so a fire safety system design can be validated. FDS is one of the leading CFD models, which was developed by the Building and Fire Research Laboratory, NIST [3]. This model has been used extensively for the purpose of fire and smoke growth, flame spread, tenability conditions and structural integrity [4]. As apart of the transition from prescriptive to performance-based designs, it becomes a necessity to be able to quantify the performance of the system in order to assess against set of design criteria.

For the past number of years, very high sensitivity ASD has been proven to be a fit-for-purpose solution for LOS applications. This is due to a number of key attributes of the technology such as highly sensitive and cumulative sampling, and ease of maintenance. However, there is still a need to be able to model smoke detection capability using CFD so fire engineering objectives can be assessed.

This paper gives an insight into how FDS and other CFD based computer models can be applied to quantify the performance of ASD in terms of response time in different fire scenarios for LOS applications. Just like any other computer model, a systematic validation is needed, especially when there is lack of information in such area. A case study – VESDA detectors for a 60-meter high atrium in Hong Kong K2 Redevelopment is used to work through the process of design, verification, real hot smoke tests and validation.

VERY EARLY WARNING FIRE DETECTION SYSTEMS

In their simplest form, ASD systems continually draw samples of air from the equipment or area requiring protection and assess these samples for the presence of smoke. The detector is a form of nephelometer – an air pollution monitor having remarkably high sensitivity, typically hundreds of times higher than conventional smoke detectors.

Such high sensitivity is required to detect the earliest traces of airborne particles or aerosols released due to the overheating of materials. One particular interest is how these systems handle fires in LOS or high airflow environments in which the smoke density and heat intensity can be dramatically reduced, preventing many conventional detection technologies from functioning effectively. Many ASDs can actively aggregate lower density smoke from sampling points to minimise the dilution effect.

As shown in Figure 1, an ASD system is typically implemented as a number of small-bore pipes distributed across a ceiling (above or below) with sampling holes drilled into each pipe at suitable intervals. Air is then continuously drawn into the pipe network via the holes to the centrally-located detector using an air pump or aspirator.

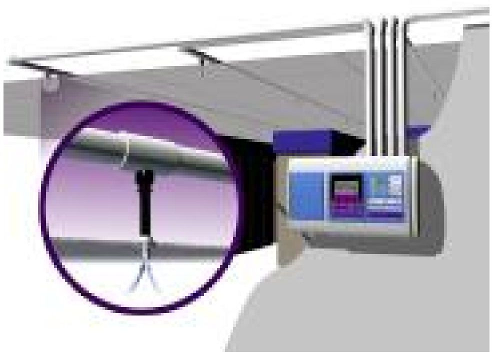


Figure 1: Air Sampled through a capillary and sample point

The location of the pipe network and the sampling holes is generally governed by local fire codes and standards such as Australian Standard AS 1670 [5], BS 5839 [2] or NFPA 72 [6]. Typically, the pipes and holes are laid out according to a grid pattern that places each hole where a conventional point detector would otherwise be located to meet the prescriptive codes. The true effectiveness of air sampling systems is through to be its flexibility in application. Placing the sample holes at points where smoke is most likely to travel (i.e. affected by mechanical air conditioning) provides the most effective means of very early warning smoke detection, typically at return air grilles.

It is also possible to use these systems to initiate fire suppression systems at a much later stage in the fire development cycle.

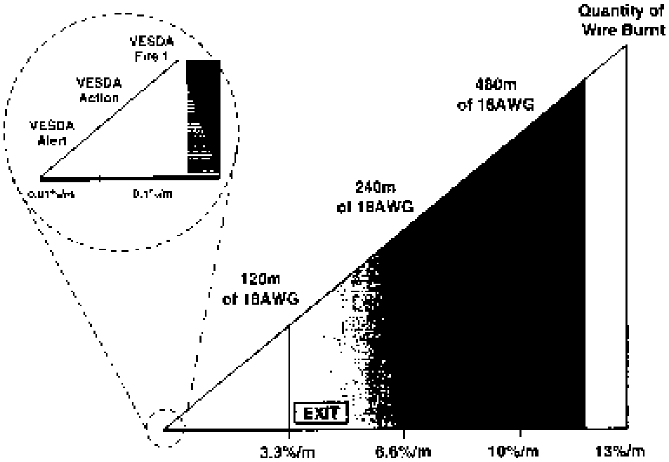


Figure 2: Smoke Obscuration measured based on a Burning wire within a 1000m^2 room

How sensitive can ASD be? VESDA, a Very Early Smoke Detection ASD system, for example can set alarm levels from 0.005% Obscuration/m to 20% Obscuration/m. Obscuration is the effect that smoke has on reducing visibility. Higher concentrations of smoke result in higher obscuration levels, lowering visibility. Figure 2 shows the relative smoke density and its affect on a typical EXIT sign. At 3% Obs/m visibility of the EXIT sign is already hampered [7].

ASD can provide warning alarms at around 0.005% Obs/m, some hundred times more sensitive than conventional detection systems. Staged alarms and associated time delays ensure these systems are quite immune to nuisance alarms.

The provision of staged alarms allows for activation of controlled and escalated responses. For example the ***Alert*** (i.e. the first alarm) condition may be used to call authorised staff to investigate an abnormal condition. Should the smoke condition continue to increase, the ***Action*** (i.e. the second alarm) condition could activate smoke control measures; begin warning sequences via the evacuation system and notify further staff members. ***Fire 1*** (i.e. the third level) alarm indicates that a fire condition is very close or has started. At this stage the environment is evacuated. With the provision of a ***Fire 2*** alarm level, ASD can initiate suppression systems.

DEFINITIONS AND ASSUMPTIONS

1. Definitions

- **Fire Growth Rate and Size**:

  Two types of fire growth rates, Ultra-fast and Fast, were chosen as “Design Fires”. According to NFPA 72 [6], these two types of fires follow T-square curve and reach 1055kW/m^2 at 75 and 150 seconds respectively. A Heptane burner with an open section of 1m x 1m (1m^2) was used as the fire source in the simulation. The heat release rate was set to 5000kW/m^2 to represent the fire size of 5MW.

- **Smoke Propagation Time, T_{sp}**:

  The time taken for smoke to move from the fire source to the sampling holes in one protected zone that reach alert or action level measured in seconds.

- **Smoke Transport Time, T_{st}:**

  The time taken for smoke to travel from a sampling hole to the detector under a nominal airflow rate of 30 to 60l/min, measured in seconds. The maximum smoke transport time, $T_{st(max)}$, is the time for smoke travel from the last far end sampling hole to the detector.

- **Estimated VESDA Detector Response Time T_{rt}:**

  The calculation for the estimated VESDA response time is given in following section. To be conservative, the response time (i.e. worst case) can be expressed as:
  $T_{rt(max)} = T_{sp} + T_{st(max)}$

2. Assumptions

- **Openings**:

  Openings including doors, air return sections and ventilations are assumed connected to the ambient environment.

- **Object Shapes**:

  Airflow and structure dimensions are approximated. To meet the FDS requirements, all objects in the domain are converted into rectangles.

- **Minimum Geometry Grid**:

  Due to the limitation of the computer computational capability, the minimum grid was set to 330mm to speed up processing time. Therefore all the thermal properties including the smoke level within each 330mm grid are assumed to be evenly distributed.

ASD SMOKE OBSCURATION MEASUREMENT AND CALCULATION

The most widely measured smoke property is the light extinction coefficient. In FDS, this parameter can be simulated as an output item *K*, (1/m). Bouguer's law [8] has lead to the following relation:

$$\frac{I_\lambda}{I_\lambda^0} = e^{-KL} \tag{1}$$

where, I_λ^0 is the intensity of the incident monochromatic light of wavelength λ;

I_λ is the intensity of the light transmitted through the path length, *L*, of smoke.

The extinction coefficient, *K*, can be expressed as the product of an extinction coefficient per unit mass, K_m, and mass concentration of the smoke aerosol, *m*.

$$K = K_m \times m \tag{2}$$

Here K_m is a function of a number of factors such as the mass size distribution, the ratio of particle diameter to the wavelength of light, particle density, etc. Seader and Einhorn [9] gave K_m values of 7.6 m^2/g for smoke produced from flaming combustion of wood and plastics, and 4.46 m^2/g for pyrolysis smoke products. In FDS, the first value was adopted for all the combustion phenomena.

Another widely used item in engineering is light obscuration, S_x in %, which is used to describe the visibility in a smoky enclosure. The definition of the light obscuration is given as follows:

$$S_x = 100(1 - \frac{I_\lambda}{I_\lambda^0}) \tag{3}$$

I_λ^0 and I_λ have the same definition as in formula (1). Then obscuration per meter, *OB*, can be obtained from below equation:

$$OB = \frac{S_x}{L} = 100(1 - e^{-KL}) / L \tag{4}$$

For an ASD system, the smoke obscuration level measured in a detector's chamber is a function of the smoke concentrations from a number of sampling holes, flow rates and transport time within the ASD pipe network. The flow rate and transport time from each sampling hole can be calculated by a CFD software named ASPIRE®, developed by Vision Fire & Security [10]. The smoke concentration profile at any given time at each sampling point is obtained from FDS fire model. Hence, the smoke obscuration for an ASD system can be calculated as follows:

Assume there is a number of *m* sampling holes in an ASD system, and each hole is marked as i where $1 \le i \le m$. The smoke transport time for each hole, calculated from ASPIRE®, is $T_{st,i}$. The flow rate ratio contributed from each sampling hole is F_i. The smoke concentration, which is also a function of $T_{sp,i}$, expressed as the extinction coefficient *K*, at a given time *j* (second) at each sampling hole is $K_{i,j}$. Then the extinction coefficient in the detector's chamber at time *t*, $K_{ASD,t}$, can be expressed as shown below:

$$K_{ASD,t} = f(K_{i,j}, F_i, j) \tag{5}$$

Finally, the smoke obscuration per meter can be obtained by substituting calculated $K_{ASD,t}$ into the equation (4). The time for this obscuration level to reach a pre-set value, for example 0.05%/m as ***Alert*** level for VESDA, is the response time of an ASD system.

FDS VALIDATION: SMOKE DEVELOPMENT

FDS has been widely validated in fire engineering on modelling heat transfer, gas movement and combustion phenomena, etc [4] [11]. It has also been used widely to assess untenable conditions such as the upper hot layer temperature and visibility in a fire scenario. However, there is no report so far on evaluating the performance of a smoke detection system via FDS simulation directly. Therefore it's necessary to validate FDS simulation by a series of real fire/smoke tests before any serious application.

At Vision Fire & Security, a series of fire and smoke tests and simulations were carried out for validation purposes. The fuel materials tested include liquid (i.e. Heptane) and solid (i.e. timber and paper). The enclosure sizes involved in the tests vary from about 80m^2 with a ceiling of height 3.6m (i.e. similar size to a standard test room specified by UL 268 standard [12]) to over 550m^2 with a ceiling height of 8m in a real warehouse. In order to model the early and very early detection ability that the VESDA system possesses, some very small fire sizes were investigated in these environments. The minimum fire size tested and simulated is as low as few hundred watts.

In the smaller enclosure, the simulation results of smoke properties were compared point by point at ceiling height with VESDA detectors measurements. Figure 3 indicates that the differences between the simulation and detector measurement at each location are within 20% for a 3kW Heptane fire. These results are quite satisfactory. When FDS was developed to simulate industrial scale fires, it has achieved about 20% accuracy on gas velocity and temperature prediction [3].

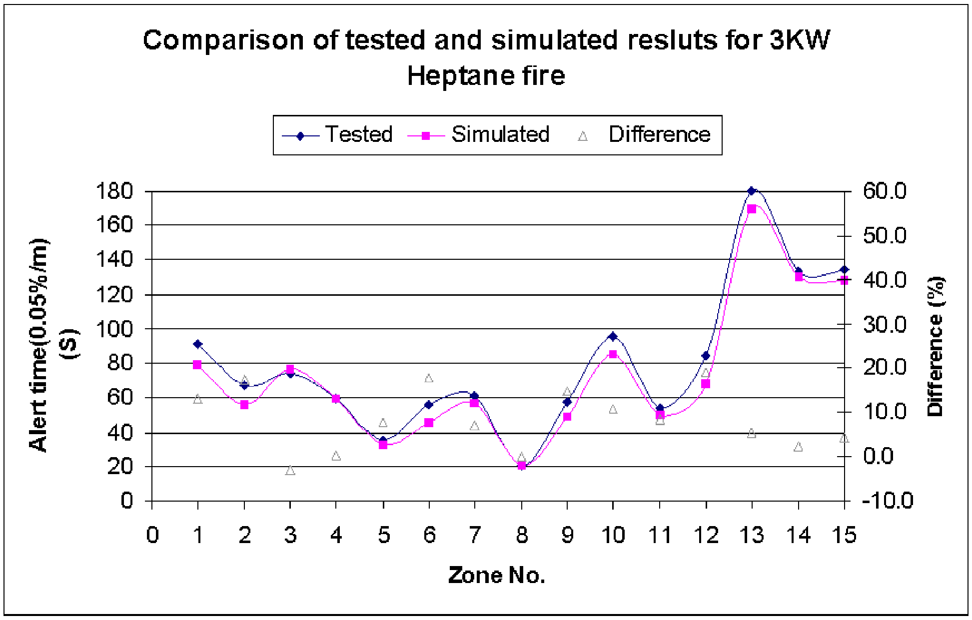


Figure 3: Comparison of response times at 15 points

The simulation results are even better when compared with the measurements taken from a standard VESDA pipe network design. In this case, the smoke collected from the above 15 sampling holes was sent into a single VESDA detector. The measured smoke level was then compared to calculated value based on above computation methodology. Figure 4 shows an example of model validation using a very small fire size.

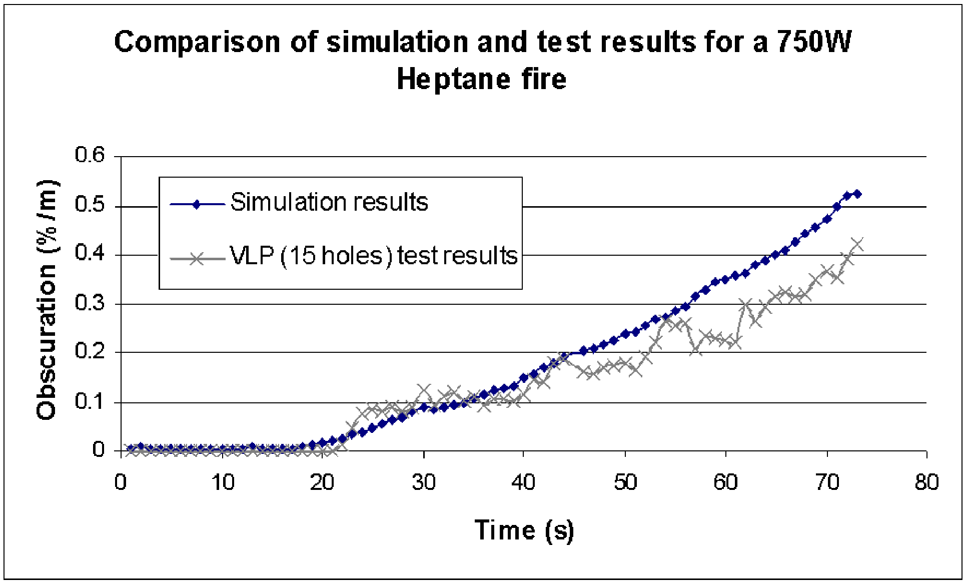


Figure 4: Comparison of smoke levels from simulation and a VESDA detector for a 750W fire

The model validation can be summarised as follows:

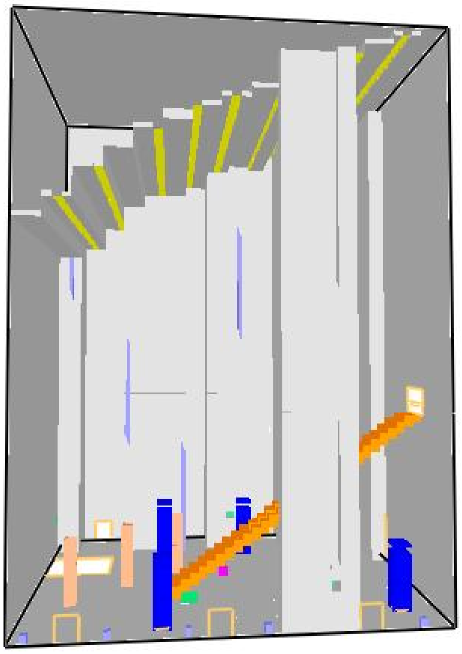
(1) FDS is capable of simulating selected fuel materials and small fire sizes;
(2) To evaluate ASD system performance, FDS simulation results can be combined with other CFD models such as ASPIRE to calculate the detector's response time. The accuracy of simulation and test results is to industrial accepted standard;
(3) Further validation for large fire sizes and in LOS is still necessary.

ATRIUM LAYOUT & SIMULATION MODEL

To apply FDS simulation to a LOS application, the 60m high Grand Atrium at K2 Redevelopment project in Hong Kong was chosen as a case study. The building geometry, airflow characteristics and detector sampling hole locations are all estimated and in some cases simplified. The simplified floor plan is shown in Figure 5.

The atrium has a ventilation capacity of two Air changes per hour. The total air out flow is 23,890 l/sec distributed by five vent columns, approximately 4,800 l/sec each. The total air-return is 18,000 l/sec. The difference in airflow is assigned to all openings evenly.

The purpose of this case study is twofold. Firstly, the simulation results are to be used to verify the VESDA system design, especially for those protection zones closer to the air vents. Secondly the simulated performance is compared with in-situ hot smoke tests.



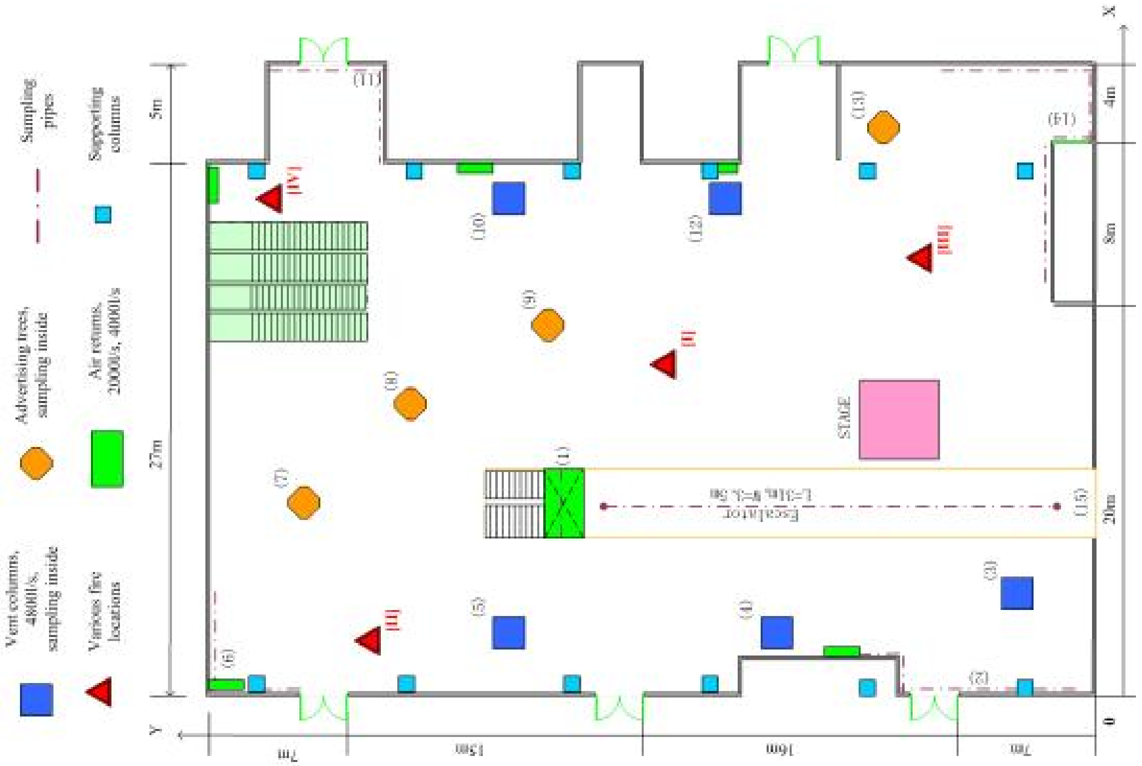


Figure 5: Protection zones on the bottom part of the atrium

SIMULATION & PERFORMANCE ASSESSMENT

An Ultra-fast fire up to 5MW is used to assess the VESDA's detection performance according to the initial design, taking into account the Christmas trees during the festival season [13]. Using 60 and 90 seconds as benchmarks, the VESDA detector activation and the response time vary when the fire location is changed. A total of four fire locations are selected. These locations are considered as "worst-case" scenarios in terms of airflow dynamics and the distance from the VESDA detector sampling holes.

The simulation results for the detection zones near the bottom of the atrium for the 5MW fire at different locations are illustrated in Table 1. The response times are all calculated based on the maximum transport time representing the worst case. Only results for the zones that activated within 90 seconds are listed here. The locations of these protection zones can be found in Figure 5.

Table 1: VESDA response time *Alert* (0.05%/m) *Action* (0.1%/m), 5MW ultra-fast growth fire

Fire location	I			II		III		IV
Sampling zone (design No.)	Zone 1 (1)	Zone 2 (15)	Zone 14 (9)	Zone 4 (6)	Zone 12 (7)	Zone 6 (14)	Zone 15 (13)	Zone 5 (11)
No. of sampling holes	18	16	8	7+7	8	7+7	8	7+7
Tst(max) (sec)	5	50	9	20	9	20	9	20
Tsp (sec)	25	33	32	5	47	55	42	52
Trt - Alert (sec)	30	83	41	25	56	75	51	72
Trt - Action (sec)	35	84	43	26	57	77	52	74

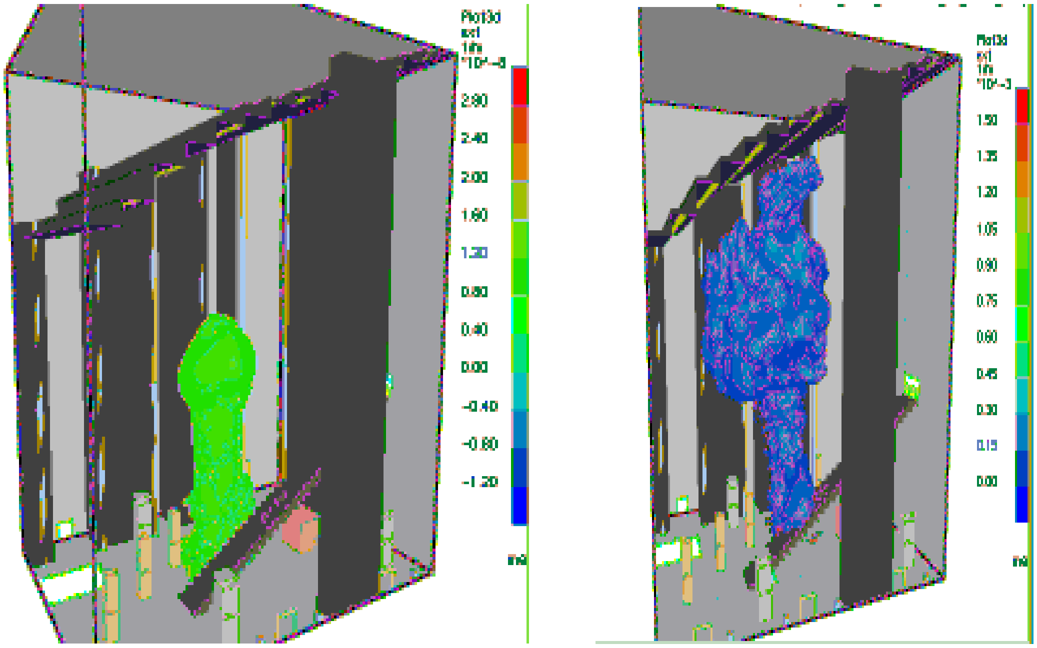
Note that "7+7" means detectors using 2 branches, each with 7 sampling holes. For ceiling detection and also investigating the effect of the upper hot layer stratification, additional simulations for three VESDA detection zones installed at the ceiling level were conducted.

These simulations involved fire sizes ranging from 500kW to 2MW fast growth fire. The stratification condition in FDS simulation is set at a maximum temperature of 38^{o}C at the ceiling (i.e. 60m high) and descending downwards at a gradient -0.3^{o}C/m to ambient temperature (i.e. 20^{o}C). Simulated VESDA response times for a 1MW fire are shown in Table 2.

Table 2: VESDA response time *Alert* level (0.05%/m), *Action* (0.1%/m), 1MW fast growth fire

Stratification	No			Yes		
Sampling zone	Zone S1	Zone S2	Zone S3	Zone S1	Zone S2	Zone S3
Location in the domain	Lower ceiling	Middle ceiling	Higher ceiling	Lower ceiling	Middle ceiling	Higher ceiling
No. of sampling holes	27	26	30	27	26	30
Trt - Alert (sec)	94	62	82	98	67	>110
Trt - Action (sec)	95	63	83	99	68	>110

Figure 6 shows a 3D illustration of the stratification effect.



(a) At 20 seconds (b) At 50 seconds

Figure 6: 3D smoke contour from a 1 MW fire

A 2MW liquid fire placed near location I in Figure 5 was simulated for a comparison with the in-situ hot smoke tests. Ethanol was chosen as fuel according to the real testing fuel configuration. However, a 10 times higher Soot Yield ratio was adopted to simulate a smoke machine used during the test. The simulation results are shown in the following section with test results.

SMOKE TESTS & PERFORMANCE VERIFICATION

The in-situ tests involved a number of preliminary "mock-up" tests and a final formal fire test. The final test was carried out in accordance with Section 2.1 of the Hot Smoke Test procedure detailed in Australian Standard AS 4391-1999 [14]. The fire source consists of six A1 size fuel trays containing denatured industrial grade methylated spirit (Grade 95). The fuel trays were placed in a metal rig.

Since the selected fuel results in a clean combustion without visible smoke, an external smoke source is necessary to generate sufficient smoke in order to simulate a 2MW ultra fast growth fire. The device is a Pepper Fog Smoke Generator, typed Mark-XII-D.

From previous testing experience, a liquid fire configured as above normally has a growth rate that is close to ultra-fast T-square curve and even has a faster burning rate at the initial stage. Therefore, this 2MW testing fire was simulated as an ultra-fast fire.

The simulated smoke profile for the first activated VESDA detector installed to cover the middle ceiling area is shown in Figure 7. It was recorded from the fire test that this VESDA detector activated in just over 60 seconds after the ignition had occurred. This agrees very well with the simulation results.

The smoke obscuration level in the chart was calculated using formula (4) and (5).

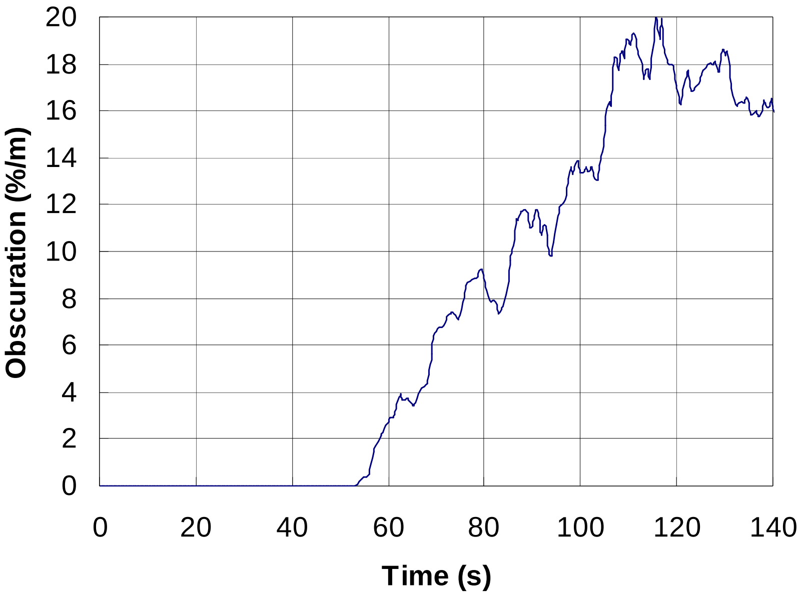
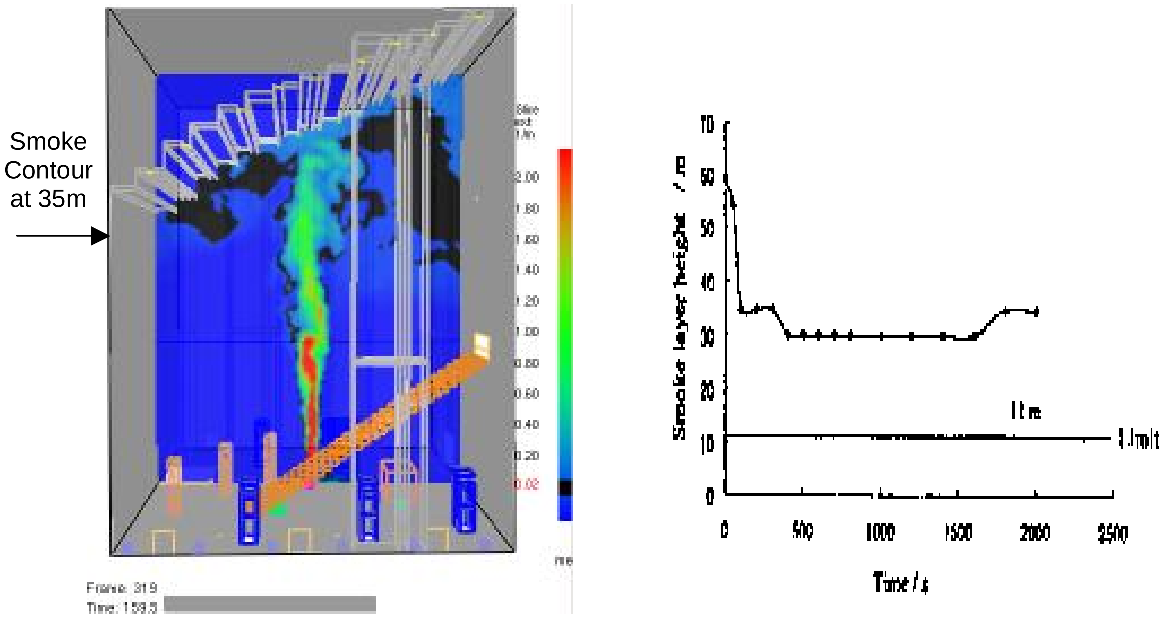


Figure 7: Smoke profile simulated for a VESDA detector for the 2MW ultra-fast fire

A comparison of the upper hot layer height from the simulation and actual testing [15] for a 2 MW liquid fire is also performed. Figure 8 illustrates a comparison of the simulated upper hot layer height against the one from the testing. It can be seen that the simulation result also agrees very well with the in-situ test measurements.



(a) Simulated upper hot layer height at 160s (b) Measured upper hot layer height

Figure 8: Comparison of simulated and tested upper hot layer height

During the test, it was observed that such fire configuration did not give a smoke plume stratifying at the outer edges at middle-level of the atrium. This result is also evident in simulation as shown in Figure 9.

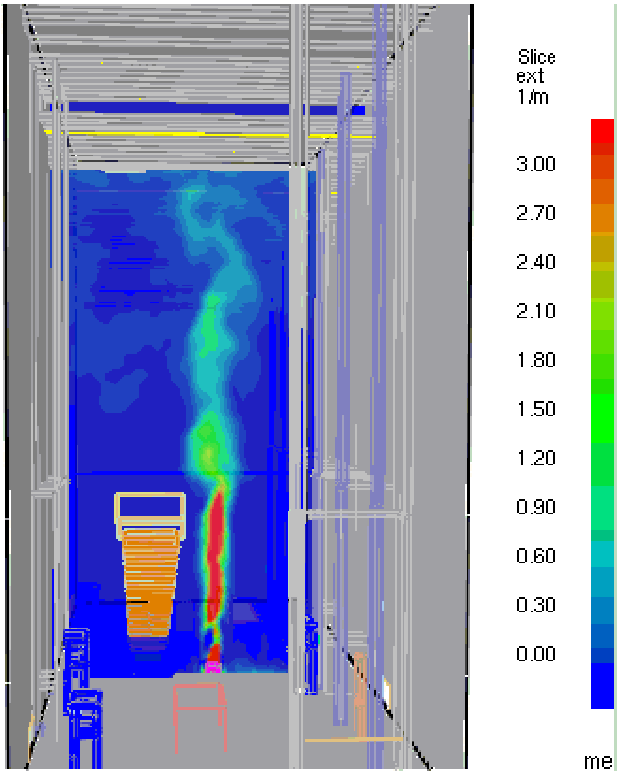


Figure 9: Smoke from an ultra-fast fire reaching to ceiling without stratifying

DISCUSSION

1. **Height and spacing of sampling soles**
   Extra care should be taken when ventilation columns are used as sampling pipe locations. This is because the flow rate of fresh air blown out through these ventilation columns is relatively high at 4800 l/sec. The airflow is nearly horizontal at the height of six meters. These may prevent the smoke from reaching the ventilation columns at the early stage of the fire development, especially when the fire starts at a distance far away from the columns.

2. **Location of protection zones**
   From simulated 1 to 5MW fires, the smoke reaches the ceiling quite quickly, even at 60m high ceiling, due to strong plume force. Therefore it is recommended to install additional detectors to provide ceiling detection.

3. **Additional requirements**
   Consider re-positioning the pipe network for detector number (11) near one of the return air vents (Figure 5). For all investigated fire locations, it was the only detector with the earliest response time longer than 60 seconds. For example, if the pipe network in zone 5, which is protected by detector number (11) was repositioned to be closer to the return air area, the response time for *Alert* and *Action* would be shortened from 72 sec and 74 sec to 28 sec and 29 sec respectively.

CONCLUSIONS

There are many aspects of fire safety system design for large open space buildings. The fire detection system is one of the most important elements. Reliable and early detection ensures life safety and minimises damage to building and assets, therefore maintaining business continuity.

After extensive application-based research, testing, verification and validation, it has been proven that VESDA very early warning fire detection system based on air sampling smoke detection technology is a fit-for-purpose solution for large open spaces protection. CFD model can be applied to aid and verify system design to achieve an optimal result via value-engineered approach. It is concluded that:

- FDS is capable of simulating smoke propagation and concentration in a wide range of enclosures. Simulated smoke properties have similar acceptable accuracy to other thermal dynamic properties such as heat and temperature.

- Combined with VESDA ASPIRE® pipework design and modelling software, in conjunction with Vision Fire & Security developed computation and integration method, FDS can be used to evaluate the detection performance of the ASD system. The simulated ASD system response time, agree with in-situ test quite well even in an extremely high ceiling (i.e. over 60 meters) large open space environment.

- Another important smoke property, hot layer height prediction, matches very closely with the test results as well. This proves that it is a challenge to use other detection technologies such as beam detectors when the hot layer height varies and the forming of the smoke plume is uncertain.

- The simulation results agree with the ASD detection performance assessment. According to the FDS simulation results using a fire growth trend up to 5MW, the current VESDA pipe network layout adequately provides early warning protection to meet the overall fire safety system design requirements.

- It has been demonstrated that a certain percentage of smoke, when the fire size reaches a certain level, will get to the ceiling level even in the presence of temperature gradient. The investigated upper hot layer temperature gradient condition has a minor stratification effect on the studied fire growth rates. It highlights the fact that very high sensitivity VESDA detectors are suitable for all assessed stratification scenarios.

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