Performance of smoke reservoirs protected by mechanical exhaust

Dr Weng Poh, Associate Director, Principal Fire Engineer, Umow Lai Pty Ltd
Maisam Mirbagheri, Fire Safety Consultant, Umow Lai Pty Ltd

ABSTRACT
The Building Code of Australia (BCA) requires smoke exhaust systems to be designed such that the smoke layer is contained within the smoke reservoirs.

Parametric studies using Computational Fluid Dynamics (CFD) analyses reveal that, with the BCA prescribed smoke exhaust rates, the smoke layer cannot be contained within reservoirs having a BCA prescribed minimum depth of 0.5m. For smoke containment, the necessary depths are significantly larger. Further studies also show that, to contain the smoke layer within a 0.5 m deep reservoir, the smoke exhaust rate will need to be significantly higher than that prescribed by the BCA and is unlikely to be practical.

An iterative procedure will likely be required to determine the appropriate combination of smoke reservoir depth and smoke exhaust rate to achieve the BCA specified performance. The results presented in this paper will provide useful guidance for the choice of initial trial values in the design process.

1. INTRODUCTION

1.1 Mechanical Smoke Exhaust
The Building Code of Australia (BCA) [1] generally requires large spaces in buildings to be protected by a mechanical smoke exhaust system designed in accordance with the requirements set out in Specification E2.2b of the BCA. Essentially, it requires the spaces to be divided at the ceiling level into smoke reservoirs to contain the smoke layer; and exhaust fan(s) installed to remove the smoke from each reservoir (see Figure 1).

Even though this is a Deemed-to-Satisfy solution, the BCA sets out both prescriptive and performance specifications that the system must be designed to satisfy.

1.2 Prescriptive Specifications
For the reservoir size, the BCA prescribes the following limits:
- maximum horizontal area, $A_{\text{max}} = 2000 \text{ m}^2$
- minimum reservoir depth, $d_{\text{min}} = 0.5\text{m}$

For the design of the mechanical smoke exhaust, it prescribes:
- heat release rate, $Q^s$, for a given building classification and sprinkler protection
- minimum smoke layer height, $h_{\text{min}} = 2\text{m}$
- smoke exhaust rate, $V^s$, for a given $h$ and $Q^s$ (see Figure 3)

1.3 Performance Specifications
In addition to the prescriptive specifications, the BCA also specifies the performance the smoke exhaust system must be designed to achieve. The key one is that the smoke layer must be contained within the smoke reservoir. Other performance specified relate to plug-holing, make-up air and other aspects of the system.

1.4 Design Process
No guidance is given in the BCA with respect to the analysis method or design process to achieve the specified requirements. Given that $V^s$, $h$ and $d$ are interdependent, an iterative design process may be required.

In a typical case where the ceiling height $H$ is known or fixed, the designer must therefore provide sufficient $d$ or $V^s$ to ensure the smoke layer can be contained within the reservoir (i.e. $h \geq (H - d)$). This may involve an iterative process as shown in Appendix A of this paper.

It is unclear what process has been adopted in the design of many of the existing buildings. Anecdotal experience from Computational Fluid Dynamics (CFD) analyses revealed that the performance of many existing smoke exhaust systems falls significantly short of that specified by the BCA. In these instances, it appears that only the prescribed limits on reservoir area and depth (i.e. $A_{\text{max}}$ and $d_{\text{min}}$) have been incorporated in their designs. The specified performance for smoke layer containment has either been ignored or not understood by their designers.

This raises the following fundamental questions with respect to the limits set by the BCA regarding the smoke reservoirs in the above situations:
Control humidity with Munters

Supplying air at a 7°C dewpoint dries more than just the air, it dries the building. To cool your building, you supply air colder than the desired space condition. Likewise, to control humidity you need to supply air drier than the desired humidity level. Munters’ equipment is designed to condition outside air to a 7°C dewpoint without overcooling it. This provides the perfect environment for your facility.

- Improve IAQ
- Help Prevent Mould Growth
- Reduce Operating Costs
- Affordable Comfort
- CO₂ Emission Reduction

It’s not the heat, it’s the humidity.

www.munters.com.au
Sydney • (02) 8843 1588
Melbourne • (03) 8795 4544
Brisbane • (07) 3826 0461
Perth • 1800 008 379
Auckland • (09) 524 0543
Given a BCA prescribed smoke exhaust rate $V^h$, can the smoke layer be contained within the smoke reservoir of the limiting size of $A_{\text{max}}$ and $d_{\text{min}}$?

- If not, what is the least $d$ value required for containing the smoke layer within the reservoir?
- Or alternatively, what is the least smoke exhaust rate necessary for containing the smoke layer within the smoke reservoir of the limiting size of $A_{\text{max}}$ and $d_{\text{min}}$?

In order to provide some answers to the above questions, three series of parametric studies were carried out using CFD analyses to examine the smoke filling of smoke reservoirs protected by smoke exhaust systems. These are described in subsequent sections of this paper.

2. PARAMETRIC STUDIES

2.1 FDS and Smokeview

The parametric studies were carried by simulating the smoke filling of smoke reservoirs using a CFD program, Fire Dynamic Simulator (FDS) [2] and Smokeview [3].

FDS is a computer model of fire-driven fluid flow and specifically developed for high-level fire engineering analyses. The software solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires.

Smokeview is a scientific visualisation program that was developed to display the results of an FDS model computation. It allows the viewing of FDS results in three dimensional snapshots or animations.

Since their development, FDS and Smokeview have increasingly being used in fire engineering design and research. Many publications can be found in the literatures on validation of various aspects of the softwares. However, there appears to be a paucity of studies on the comparison of the analysis results with test measurements involving smoke exhaust in large building spaces. The only notable one appears to be a study reported in [4], where smoke tests were carried out in an atrium space protected by a smoke exhaust system. In this study, the smoke layer interface height and air temperatures inside the atrium were simulated using FDS and compared with the data measured during the tests.

The study shows that FDS output compares well with the experimental results and demonstrates that FDS is capable of closely simulating smoke behaviour involving smoke exhaust in large building spaces.

2.2 Ideal Smoke Reservoir

For the purpose of the parametric studies, an ideal situation of a single smoke reservoir with an area of $A_{\text{max}}$ was examined using FDS. A BCA prescribed heat release rate ($Q^h$) of 5 MW was arbitrarily chosen as the fire size for the purpose of the studies. The fire was assumed to be located centrally on the floor within the smoke reservoir (see Figure 2).

For the sake of simplicity, the effects of plug holing were eliminated by modelling the ideal situation where the smoke was extracted uniformly over the entire surface of the smoke reservoir at the ceiling level. Any adverse effects of make-
up air were also eliminated by placing the smoke reservoir within an infinite space without any bounding walls.

It is important to note that the situation examined represents the best case scenario where all aspects were assumed to be the most advantageous for extraction of smoke from the reservoir.

Other model parameters and assumptions made in the analyses are summarised below:

- $A = 40 \times 50$ m$^2$ (i.e. $A_{\text{max}}$ of 2000 m$^2$)
- $h$ range examined = 2 to 15 m
- Total simulation time $t = 1800$ s
- $Q = 5$ MW and remains constant over the simulation time period

### SMOKE EXHAUST RATE

<table>
<thead>
<tr>
<th>Classification</th>
<th>Unsprinklered</th>
<th>Sprinklered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2 or 5</td>
<td>5 MW</td>
<td>1.5 MW</td>
</tr>
<tr>
<td>Class 6</td>
<td>10 MW</td>
<td>5 MW</td>
</tr>
<tr>
<td>Class 7 or 8</td>
<td>15 MW</td>
<td>5 MW</td>
</tr>
<tr>
<td>Class 9, generally</td>
<td>5 MW</td>
<td>1.5 MW</td>
</tr>
</tbody>
</table>

- Combustion reaction = timber (Douglas Fir)
- Effects of sprinklers on the smoke behaviour are ignored
- Smoke exhaust fan starts up instantaneously and operates at its full capacity $V/4$ over the entire simulation time period
- Model grid size = 0.5 m

For the purpose of determining the level of containment of the smoke layer, devices for measuring the smoke layer height were incorporated in the model. The smoke layer was considered to be contained within the smoke reservoir if $h \geq (H - d)$ over the total simulation time. This was further verified by visually examining the analysis results using Smokeview.

#### 2.3 SERIES 1: Testing BCA prescribed minimum reservoir depth, $d_{\text{min}}$

The first series of analyses was carried out by setting $d = 0.5$ m for each assumed $h$ values with the corresponding smoke exhaust rates as prescribed by the BCA (see Figure 3).

This was aimed at examining whether a smoke reservoir with the minimum $d_{\text{min}} = 0.5$ m could fulfill the requirement of smoke layer containment.

The results of the analyses in this series show that, in each case, the smoke layer falls below the smoke reservoir and the smoke spreads out of the reservoir.

Figures 4 and 5 show the Smokeview visualisations of two examples with a relatively small and a relatively large assumed $h$ values, respectively.
In all the cases examined, the reservoirs could not contain the smoke layer despite the fact that the smoke reservoirs and smoke exhaust were arranged in the most advantageous situation as discussed earlier. The performance would likely to be worse in less ideal situations. This leads to a firm conclusion that, with the BCA prescribed smoke exhaust rates, the prescribed minimum reservoir depth of 0.5 m is insufficient to contain the smoke layer within the reservoir for a constant 5 MW fire and for the $h$ values considered.

2.5 SERIES 2: Increasing reservoir depth, $d$

Having completed Series 1, a second series of analyses was carried out to determine the least smoke reservoir depths for smoke containment for various $h$ values and the corresponding BCA prescribed smoke exhaust rates.

This was achieved by increasing $d$ in steps of 0.5 m for each $h$ value until the smoke layer was contained within the smoke reservoir (i.e. $h \geq (H - d)$).
The results of the analysis of this series show that the d values required to contain the smoke layer within the reservoirs are significantly larger than the BCA prescribed minimum of 0.5m. The findings are summarised in Figure 6.

Figures 7 and 8 show the Smokeview visualisations of two examples with a relatively small and a relatively large h values, respectively, when the smoke layer is contained within the reservoirs.

It is noted that in this analysis series, by keeping h constant, H increases with increasing d. This differs from the design process discussed earlier where H is fixed.

Again, it is important to note that the situation analysed is an ideal case where the reservoir, fire and smoke exhaust are arranged in their most advantageous conditions. Hence, the resulting d values in Figure 6 apply only to these best case scenarios. The reservoir depths for smoke containment could be larger in less ideal situations.

### 2.6 SERIES 3: Increasing smoke exhaust rate,

A third series of analysis was carried out as a limited study to determine the smoke exhaust rate $V^e$ necessary to contain the smoke layer for the BCA prescribed $d_{min}$ of 0.5 m. For the purpose of this study, the case where $h = 4$ m was arbitrarily chosen. The BCA prescribed smoke exhaust rate in this case is approximately 30m$^3$/s (see Figure 3).

The study was carried by increasing in steps of 30m$^3$/s until the smoke layer was contained within the reservoir. Further analyses were then carried out to refine the limiting value to an accuracy of 5m$^3$/s.

The results of the analyses show that the smoke exhaust rate required for containing the smoke layer is approximately 155m$^3$/s.

Figures 9 and 10 show the Smokeview visualisations of two examples with different $V^e$ values in the series.

It can be seen from this case study that, with a reservoir depth of 0.5m, the smoke exhaust rate required to contain the smoke within the reservoir is significantly higher than the corresponding value prescribed by the BCA. The resulting high exhaust rate may also introduce significant issues with make-up air. The practicality of increasing the smoke exhaust rate alone in containing the smoke layer is therefore questionable.
3. COMMENTS ON BCA PRESCRIBED SOLUTIONS

Review of literature indicates that the BCA prescribed exhaust rates may find its root to a simple smoke production model devised empirically by Thomas in 1963 [5]. The smoke exhaust rates were derived simply by equating the exhaust rates to the respective smoke production rates. This gives smoke exhaust rates in the same format as that prescribed by the BCA (see Figure 3), i.e. $\frac{1}{4} = k_1Q + k_2h^2$, where and are constants.

An account of the derivation can be found in [6, 7].

If the Thomas model could accurately predict the smoke production rates, then the prescribed smoke exhaust would maintain the smoke layer for each of its corresponding $h$ value, and the smoke layer would be contained within the smoke reservoir. From this viewpoint, the choice of a minimum reservoir depth is somewhat arbitrary, since the smoke layer would be contained within a reservoir with any assumed depth.

The results of the parametric study using FDS, however, show different results. Not only the smoke layer could not be contained within smoke reservoirs with the prescribed minimum depth, the prescribed smoke exhaust rates also could not contain the smoke layer in deeper reservoirs. This calls into question the validity of the BCA prescribed exhaust rates, which are based on a simple model devised almost half a century ago.

FDS, on the other hand, is a modern CFD program that is scientifically based and numerically solves the fluid motion Navier-Stokes equations. Although, currently, there is a paucity of data in the published literatures on the comparison of FDS output with the experimental results, the limited comparison in [4] shows that it is capable of closely simulating smoke behaviour involving smoke exhaust in large building spaces. With its increasing use throughout the world in the fire engineering field, it is to be expected that there will be more testings and comparisons with FDS that could further validate the accuracy of the software.

The findings of this study point to the fact that the BCA prescribed solutions may need to be revised in light of the more advanced methods of analysis the engineering fraternity now has at its disposal. A new set of prescribed solutions that satisfy the desired performance can be derived. However, this will require further study, development and agreement by the appropriate authorities.

Meantime, engineers will still need to design smoke exhaust systems to satisfy the current prescribed requirements of the BCA, perhaps using FDS or other modern analysis methods. An iterative procedure will likely be required to determine the appropriate combination of smoke reservoir depth and smoke exhaust rate. In this instance, the results presented in this paper will provide useful guidance for the choice of initial trial values in the design process.

Another alternative to the above approach is for the designers to seek a performance-based fire engineering solution whereby the fire safety of the building is assessed holistically rather than examining the smoke exhaust system in isolation. This may mean that containment of smoke layer in each smoke reservoir may not necessarily form the governing criterion for the design, if it can be demonstrated that a high level of fire safety of the building occupants can be achieved using alternative design criteria.

4. CONCLUSIONS

Parametric studies using CFD analyses have been carried out to examine the smoke filling of smoke reservoirs. The studies reveal that with smoke exhaust rates as prescribed by the BCA, smoke reservoirs having a depth of 0.5 m are insufficient to contain the smoke layer within the reservoirs. For smoke layer containment, the necessary reservoir depths are significantly larger than the BCA prescribed minimum of 0.5 m. These were investigated in the parametric studies and the necessary depths for smoke containment in the ideal, best case situations are given in the paper.

Further studies were also carried out to investigate the smoke exhaust for a smoke reservoir with a depth of 0.5 m. The results show that the smoke exhaust rate required for containment of smoke within the reservoir is significantly higher than that prescribed by the BCA. The high exhaust rate is unlikely to be practical and may also introduce significant issues with make-up air, hence the viability of adopting the minimum reservoir depth and increasing the smoke exhaust rate for containing the smoke layer is questionable.

In order to achieve the performance specified by the BCA for smoke containment, it is necessary to use a reservoir depth greater than the BCA prescribed minimum. An iterative procedure will likely be required for determining the necessary reservoir depth and/or smoke exhaust rate to satisfy the BCA specified performance. The results presented in this paper will provide useful guidance for the choice of initial trial values in the design process. They may also be useful for use in gauging the performance of smoke reservoirs in general.

The findings of this study also indicate that the BCA prescribed solutions may need to be revised in light of the availability of more advanced methods of analysis. A new set of prescribed solutions that satisfy the desired performance can be derived. This will require further study, development and agreement by the appropriate authorities.

5. REFERENCES

6. NOMENCLATURE

- $A$ = Horizontal area of smoke reservoir (m)
- $A_{\text{max}}$ = BCA maximum allowable area for smoke reservoir = $2000$ m²
- $d$ = Depth of smoke reservoir (m)
- $d_{\text{min}}$ = BCA minimum smoke reservoir depth = $0.5$ m
- $h$ = Height to underside of smoke layer (m)
- $h_{\text{min}}$ = BCA minimum allowed smoke layer height = $2$ m
- $H$ = Height of enclosure containing the smoke reservoir (m)
- $Q^h$ = Heat release rate of fire (MW)
- $V^h$ = Smoke exhaust rate for the smoke reservoir (m³/s)
- $t$ = Elapse time from start of fire (s)

APPENDIX A: Determining $d$ and $V^h$ for known $h$

What is the legislation behind energy efficient design?
How will changes to Section J impact?

Find your way with Section J

Join our interactive 1 day course in August
Melbourne, Brisbane, Sydney

For more information or to register visit www.airah.org.au and click the Professional Development tab.
APPENDIX A: Determining \( d' \) and \( \nu^d \) for known \( h \)

![Flowchart diagram]

ABOUT THE AUTHORS

**Dr Weng Poh** is an Associate Director and the head of the fire engineering group at Umow Lai Pty Ltd. Throughout his career, Weng has completed numerous fire engineering projects. He has been closely involved in the development of methodology for fire safety designs of buildings in Australia and has published extensively in international journals, conferences and technical reports. Weng also gives lectures in postgraduate courses, aimed at training building practitioners in fire engineering design.

**Maisam Mirbagheri** is a Fire Safety Consultant at Umow Lai Pty Ltd. In the past two years, Maisam has been involved in the fire engineering design of commercial, educational, healthcare and retail buildings. He has recently completed his Graduate Diploma in Building Fire Safety and Risk Engineering and has been awarded the Best Student in the 2008 Graduate Diploma Class (CESARE) Award. He also has a vast and practical experience in the design of fire/hydraulic/mechanical pump and tank package systems for building services.