Technical Recommendation

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Room size limits when using a fire zone model for smoke-filling calculations

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1. SCOPE

The following guidance is intended to apply when using a fire zone model for smoke-filling calculations as part of an analysis conducted in accordance with the C/VM2 Verification Method: Framework for Fire Safety Design [1].

This guidance has been developed based on analysis using the BRANZFIRE zone model [2]. It is also considered applicable to the B-RISK model [3] and may additionally apply to other similar fire zone models. It is expected the guidance could be modified or improved with further research and ongoing comparisons with both experimental data and other valid models.

The guidance provided here is intended to help fire engineers assess the suitability of using a zone model for a given combination of fire size and compartment dimensions. However, the criteria described should not be treated as absolute constraints as they are not the only factors that may affect the decision to use a zone model or not. The complexity of the building geometry and fire safety systems, the perceived risk associated with the design, and the fire safety objectives and purpose of the analysis may also influence the model selection decision. It is expected the engineer and peer reviewers will consider the full range of factors applicable to the specific building before agreeing on the appropriate model to use for a given analysis.

2. INTRODUCTION

2.1 General

A fire zone model is a computer-based calculation method for predicting the fire environment within a room or collection of rooms connected by openings. The calculations solve conservation of mass and energy equations applied separately to control volumes that vertically divide each room into one or more zones. At any instant in time the properties (e.g. gas temperature, species concentrations) of each zone and the position of the smoke layer interface above the floor are assumed to be uniform.

The fire is treated as a user-prescribed source of mass and energy that is transported to the ceiling, along with surrounding entrained air, via a plume. This is illustrated in Figure 1.

The zone modelling approach is discussed extensively in the literature [4, 5, 6].

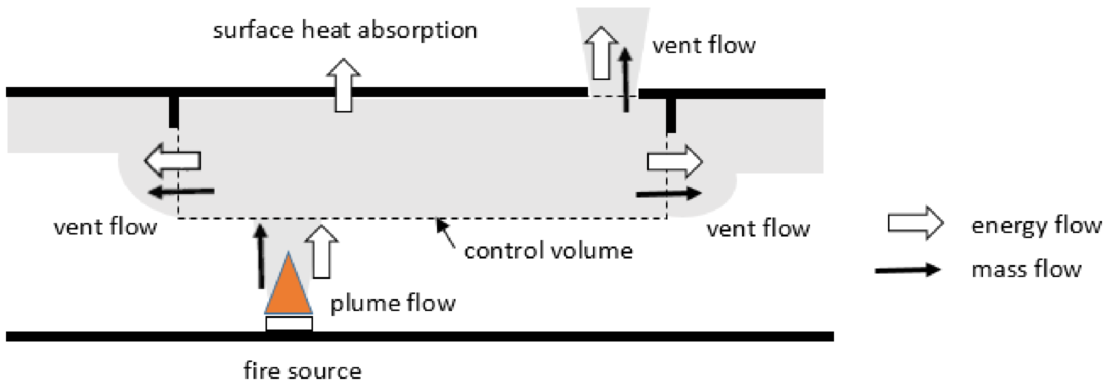

Figure 1 Schematic of a zone model

For fires that are either quite small or very large relative to the dimensions of the enclosure it is likely that the smoke layer will become increasingly non-uniform. For small fires there will be only a small rise in the gas temperature near the ceiling and a clear separation between a hot upper layer and cool lower layer across the area of the enclosure is not likely to occur due to smoke transport delays, excessive cooling and the influence of air currents or ambient thermal gradients. For large fires, the increased velocity and strength of the ceiling flows will lead to more pronounced vertical flows at the bounding wall surfaces and greater mixing between the layers, as well as increased thermal radiation effects from the fire plume itself becoming more significant.

This technical recommendation addresses the general applicability of a zone model's uniform property assumption within the smoke layer for different enclosure sizes. It suggests criteria intended to help the model user identify when the application of a zone model is more likely to generate acceptable estimates of the smoke-filling process within a room of fire origin of given dimensions based on a uniform smoke-filling assumption.

The criteria given are not relevant to sub-models that are not strongly influenced by the general smoke-filling process such as the ceiling jet characterisation and response of sprinklers or detectors using the ceiling jet properties.

2.2 Previous research

Previously Wade and Robbins [7] made comparisons between a zone model (BRANZFIRE [2]) and a computational fluid dynamics model (FDS [8]) simulating a fast t-squared fire with a peak heat release rate (HRR) of 10 MW for a variety of compartment sizes ranging from 625 m^2 up to 5000 m^2 in area and 6, 9 and 12 m high. They suggested that a single room up to 1200 m^2 or several virtual rooms with a total floor area up to 5000 m^2 provided satisfactory agreement with FDS (version 5.0.0) based on comparing the smoke layer height and upper layer temperature predictions from the two models for each of the compartments considered. Also within the Wade and Robbins study comparisons of experimental work and earlier FDS versions were considered during the literature review and these showed comparable results. However, direct comparison between experimental data sets and the modelled generic warehouse scenario was not performed.

Subsequently, Bong [9] conducted an investigation making use of non-dimensional analysis which compared BRANZFIRE with FDS predictions of layer height and gas temperatures for a selection of experiments from the literature, and for a variety of exemplar warehouses with floor areas ranging from 2500 to 10,000 m^2, compartment heights of 6, 9 and 12 m and aspect ratios of 1:1 and 1:3. While the experimental data generally included a growth rate to the fire, only instantaneous steady-state fires were modelled in the exemplar warehouses.

Bong used non-dimensional parameters from Zukoski [10] with a non-dimensional heat release rate parameter $\dot{Q}^*$ calculated using enclosure height as the length scale as follows:

$$\dot{Q}^* = \frac{\dot{Q}}{\rho_a c_p T_a \sqrt{g} H_e^{5/2}} \tag{1}$$

For $\rho_a = 1.2$ kg.m^{-3}, $c_p = 1.0$ kJ.kg^{-1}.K^{-1}, $T_a = 293$ K, $g = 9.81$ m.s^{-2}, $\dot{Q}^*$ can be simplified to:

$$\dot{Q}^* = \frac{\dot{Q}}{1110 H_e^{5/2}} \tag{2}$$

For the purpose of this calculation, the average enclosure height may be used.

Bong also determined a dimensionless shape factor [11] for an enclosure as being:

$$SF = \frac{A_f}{H_e^2} \tag{3}$$

For enclosures with steady-state fires Bong found that BRANZFIRE and FDS agreed well with each other on fire sizes and enclosures within a reasonable range. However, for growing fires the agreement was less favourable and Bong recommended a smoke transport lag time allowance be added, otherwise noting that BRANZFIRE gave conservative estimates of layer height compared to FDS.

Bong [8] found that there was reasonable agreement between BRANZFIRE and FDS for the exemplar warehouse comparisons for $\dot{Q}^*$ between 0.002 and 0.15 (he investigated compartments with $\dot{Q}^*$ as high as 0.4). However, since those comparisons were based on instantaneous steady-state fires, he recommended a more conservative upper limit of 0.03 corresponding to that applying to the available experimental comparisons. Thus his recommended range for $\dot{Q}^*$ using BRANZFIRE for smoke-filling in large compartments was 0.002 to 0.03 with a shape factor in the range of 0.4 to 69.

Wade and Robbins' [7] analysis included a comparison between BRANZFIRE and FDS for a 6 m high compartment and a fast t-squared fire up to 10 MW with good agreement during the growth period for compartment dimensions of 50 x 25 m (i.e. an aspect ratio of 2:1). This case corresponded to $\dot{Q}^* = 0.1$ at the peak HRR, and shape factor = 34.7. They also compared a 100 x 50 x 12 m compartment with FDS entailing the same fire characteristics with good agreement corresponding to $\dot{Q}^* = 0.018$ at the peak HRR, and shape factor = 34.7.

Given the very fast growth rate of the rack storage fires in C/VM2, and the widespread use of fast t-squared fires for most other applications, it is considered that Bong's original $\dot{Q}^*$ upper limit of 0.15 for the exemplar warehouses with steady-state fires could be maintained for C/VM2 use, as well as maintaining the same limits on shape factor as given by Bong other than rounding the upper limit from 69 to 70.

An upper limit of $\dot{Q}^* = 0.15$ requires a minimum 6.8 m ceiling height for a 20 MW fire or a minimum 9.8 m ceiling height for a 50 MW fire assuming the compartment is still occupied at the time those fire sizes are reached. For a C/VM2 design that considers occupant egress, if the actual ceiling heights are lower it will be necessary to check $\dot{Q}^* \leq 0.15$ at the time evacuation is completed (RSET) or during the period of interest.

While the zone model BRANZFIRE was used in the investigations described above, the results and guidance included herein are considered to be applicable to other similar zone models such as B-RISK.

2.3 Interpreting Q^*

Small $\dot{Q}^*$ values are not thought to be of concern for practical design purposes given they correspond to small temperature rises where conditions are generally not expected to be hazardous.

High $\dot{Q}^*$ corresponds to greater energy and momentum in the ceiling jet flows which, for a given compartment, would translate to larger or more pronounced wall jet effects when the ceiling flows intercept the vertical wall surfaces and travel downward with the flow of smoke then returning toward the fire source. It also corresponds to a likely greater non-uniformity in the smoke layer properties including temperature across the area of the space, especially closer to the fire, where for larger fires the radiation from the fire plume will be more pronounced.

3. ZONE MODEL LIMITS FOR C/VM2 CALCULATIONS

3.1 Recommended limits on non-dimensional HRR and shape factor

For $\dot{Q}^* \leq 0.15$ and 0.4 $\leq$ SF $\leq$ 70, a single-room two-zone model is considered satisfactory.

For $\dot{Q}^* \leq 0.15$ and SF > 70, a multi-room two-zone model (with virtual rooms) is considered satisfactory with each room having a shape factor of 0.4 $\leq$ SF $\leq$ 70.

For SF < 0.4, there is a higher likelihood of the plume intercepting the walls before it reaches the ceiling and requiring special consideration. A two-zone model may therefore predict a layer height which is too high and the space should preferably be treated as a "shaft".

In all cases it is assumed that the internal compartment geometry is relatively simple and without extensive internal obstructions interfering with the flow of smoke.

3.2 Compartments remote from the fire

Conditions in compartments remote from the room of fire origin were not assessed in the Wade and Robbins study [7] nor by Bong [9].

While the shape factor calculation can be applied separately to each compartment, the calculation of $\dot{Q}^*$ is only strictly appropriate for the room of fire origin during the period of interest. For life safety calculations this is expected to correspond to the period of time the room of fire origin is occupied. The zone model results at a later time may still be useful for assessing conditions in remote compartments assuming that the flow of gases through any openings connecting the compartments is representative of the average upper layer properties in the room of fire origin.

Further research investigating multi-compartment configurations would be valuable for developing more detailed guidance on compartments remote from the fire.

4. RECOMMENDED PROCEDURE FOR VM2 ANALYSIS

1. Calculate shape factor (SF) for the compartment from Equation 3.
2. Calculate $\dot{Q}^*$ from Equation 1 or 2:
    a. For a VM2 design scenario challenging fire (CF) analysis – calculate $\dot{Q}^*$ using $\dot{Q}$ at either the time evacuation is complete (RSET) or from the peak HRR given for the design fire in VM2.
    b. For VM2 design scenario fire-fighting operations (FO) analysis – calculate $\dot{Q}^*$ using the peak HRR given for the design fire in VM2.
    c. For a sprinkler-controlled fire – $\dot{Q}^*$ may be determined from the HRR at the time of sprinkler activation.

3. Determine which of the above cases are applicable (if any) and whether a zone model analysis is suitable.

If the above limits and restrictions cannot be met, then additional benchmarking data should be provided to support use of a zone model; or else analysis using computational fluid dynamics (CFD) is recommended.

4.1 Using "virtual rooms"

A virtual room (sometimes called a pseudo-room) approach involving subdividing a larger compartment in several small compartments connected by a non-physical or fictional vent has been previously discussed in the literature [12, 13]. The use of virtual rooms does not correctly address the physics of the gas flow at the vent boundaries. However, it does serve to mimic the drag and cooling effects as the flow of smoke spreads laterally beneath the compartment ceiling by introducing or mixing entrained air from the lower layer into the upper layer at the location of the "virtual vent", delaying the spread of smoke between the two connected spaces and reducing the smoke layer height in the adjoining enclosure.

In general terms this approach should only be considered for relatively simple geometries. Complex room geometries affecting the flow of smoke are best analysed with a CFD model.

The following recommendations apply:

- If the shape factor for the compartment exceeds 70 then a multi-room two-zone model may be used where the number of "virtual" rooms is determined by the need for individual rooms to comply with the recommended shape factor restrictions.
- It is preferred that at least two sides of a virtual room be bounded by "real walls", i.e. no more than two sides should be represented as full-width "virtual vents", and each side of a full-width vent shall be bounded by a "real wall".
- A full-width vent with full-height opening may be used to connect two adjacent virtual rooms. This is expected to give better prediction of the gas temperature in the furthest compartment with a shorter impingement time. A flow coefficient of 1.0 for the vent is suggested.

4.2 Effect of compartment ceiling height on dimensionless rate of heat release

The exemplar warehouse comparisons with FDS by Wade and Robbins [7] and by Bong [9] all had a 6 m minimum ceiling height. Where the ceiling height was lower, the maximum fire size required to limit $\dot{Q}^*$ was also less. The following table shows the maximum fire size during the period of interest over a range of different ceiling heights in order to limit $\dot{Q}^*$ to not greater than 0.15.

Table 1 Ceiling height versus rate of heat release for $\dot{Q}^*$ = 0.15

Ceiling height (m)	2.4	2.7	3.0	4.0	6.0	8.0	10.0
Max $\dot{Q}$ (kW) for $\dot{Q}^*$ = 0.15	1485	1995	2595	5325	14,682	30,140	52,652

4.3 Relationship between compartment ceiling height and floor area

In order to ensure a shape factor of no greater than 70, the following maximum compartment floor areas dependent on the compartment ceiling height apply to a room or virtual room.

Table 2 Ceiling height versus floor area for shape factor = 70

Ceiling height (m)	2.4	2.7	3.0	4.0	6.0	8.0	10.0
Max A_f (m^2) for SF = 70	403	510	630	1120	2520	4480	7000

4.4 Alternative approaches

The above guidance should not preclude the use of other comparative studies between a zone model and either CFD models or experiments that demonstrate satisfactory agreement or conservative predictions by the zone model, taking into account the purpose of the analysis and any relevant building-specific factors used to support employing the zone model for other similar designs.

5. EXAMPLES

The examples presented follow the general approach for determining the required safe egress time (RSET) outlined in C/VM2 [1].

5.1 Example 1

We have a large compartment used for bulk storage warehousing with dimensions of 80 x 80 x 12 m high with a stated rack storage height of 8 m.

Calculate the maximum floor area for a shape factor of 70 and compartment height of 12 m such that – $A_{f,max} = SF.H_e^2 = 70 \times 12^2 = 10{,}080$ m^2.

Since the actual compartment floor area of 80 x 80 = 6400 m^2 is less than $A_{f,max}$ the compartment geometry is suitable for a single-room zone model.

Assuming queuing and congestion are not critical and a maximum travel speed of 1.2 m/s applies, for a travel path length of 160 m, the travel time is 160/1.2 = 134 s.

Assuming from a separate analysis a heat detector responds at 130 s, with a notification time of 30 s and pre-travel activity time of 30 s, then the RSET can be determined – RSET = 130 + 30 + 30 + 134 = 324 s.

The VM2 design fire for this occupancy is $\dot{Q} = 0.00068\, t^3\, H_{st}$ with a peak HRR of 50 MW. Therefore the HRR at 324 s, with a storage height of 8 m, is 50,000 kW.

Check $\dot{Q}^*$ at RSET (324 s) = $\frac{\dot{Q}}{1110H_e^{5/2}} = \frac{50{,}000}{1110(12)^{5/2}} = 0.09\ (\leq 0.15, \mathrm{OK})$.

Therefore the zone model analysis is considered suitable.

ASET > RSET must now be shown.

Note – $\dot{Q}^*$ calculated above based on $\dot{Q} = 50{,}000$ kW is also applicable to the VM2 design scenario FO, in which case it will be necessary to demonstrate the conditions specified in Clause 3.8 of the Building Code are met.

5.2 Example 2

We have a large compartment used for heavy industry with dimensions of 50 x 100 x 6 m with storage height < 3m.

Calculate the maximum floor area for a shape factor of 70 and compartment height of 6 m such that – $A_{f,max} = SF.H_e^2 = 70 \times 6^2 = 2520$ m^2.

Since this is less than the actual compartment floor area of 5,000 m^2, the compartment geometry is not suitable for a single-room analysis and we should model it using two virtual rooms, each with a floor area no larger than 2520 m^2.

Assuming uncongested flow and a maximum travel speed of 1.2 m/s, similar to Example 1, for a travel path length of 150 m, the travel time is 125 s.

Assuming from a separate analysis a heat detector responds at 210 s, with a notification time of 30 s and the pre-travel activity time of 30 s, then – RSET = 210 + 30 + 30 + 125 = 395 s.

The VM2 design fire is $\dot{Q} = 0.0469\mathrm{t}^2$ with a peak HRR of 20 MW. Therefore the HRR at 395 s is 7318 kW.

Check $\dot{Q}^*$ at RSET (395 s) = $\frac{\dot{Q}}{1110H_e^{5/2}} = \frac{7318}{1110(6)^{5/2}} = 0.075\ (\leq 0.15, \mathrm{OK})$.

Therefore the two-room two-zone model analysis is considered suitable.

ASET > RSET must now be shown.

5.3 Example 3

We have a large compartment used for bulk storage warehousing with dimensions of 25 x 50 x 9 m high with rack storage height of 7m.

Calculate the maximum floor area for a shape factor of 70 and compartment height of 9 m – $A_{f,max} = SF.H_e^2 = 70 \times 9^2 = 5670$ m^2.

Since the actual compartment floor area of 1250 m^2 is less than $A_{f,max}$ the compartment geometry is suitable for a single-room zone model.

Assuming uncongested flow and a maximum travel speed of 1.2 m/s, a travel path length of 75 m gives a travel time of 63 s.

Assuming from a separate analysis a heat detector responds at 105 s, with a notification time of 30 s and pre-travel activity time of 30 s, then – RSET = 105 + 30 + 30 + 63 = 228 s.

The VM2 design fire for this occupancy is $\dot{Q} = 0.00068\, t^3\, H_{st}$ with a peak HRR of 50 MW. Therefore the HRR at 228 s with a storage height of 7 m is 50,000 kW.

Check $\dot{Q}^*$ at RSET (228 s) = $\frac{\dot{Q}}{1110H_e^{5/2}} = \frac{50{,}000}{1110(9)^{5/2}} = 0.185$ (> 0.15, NOT OK).

For a zone model analysis to proceed, the options are:

a. Increase the ceiling height to 10 m.

b. Redesign the compartment egress and/or fire detection so that $\dot{Q}^*$ at RSET $\leq$ 0.15.

Alternatively, use a CFD model such as FDS for the analysis or provide other benchmarking data supporting the use of a zone model for the particular application.

5.4 Example 4

We have a compartment used for offices with dimensions of 20 x 20 x 2.4 m high.

Calculate the maximum floor area for a shape factor of 70 and compartment height of 2.4 m such that – $A_{f,max} = SF.H_e^2 = 70 \times 2.4^2 = 403$ m^2.

Since this is more than the actual compartment floor area of 400 m^2, the compartment geometry is suitable for a single-room analysis.

Using a maximum travel speed of 1.2 m/s, for a travel path length of 40 m, the travel time is 34 s.

Assuming from a separate analysis a smoke detector responds at 27 s, with a notification time of 30 s and the pre-travel activity time of 30 s, then – RSET =27 + 30 + 30 + 34 = 121 s.

The VM2 design fire is $\dot{Q} = 0.0469t^2$ with a peak HRR of 20 MW. Therefore the HRR at 121 s is 687 kW.

Check $\dot{Q}^*$ at RSET (121 s) = $\frac{\dot{Q}}{1110H_e^{5/2}} = \frac{687}{1110(2.4)^{5/2}} = 0.07$ (≤ 0.15, OK).

Therefore the one-room two-zone model analysis is considered suitable.

ASET > RSET must now be shown.

6. NOMENCLATURE

A_f	Compartment floor area (m^2)
c_p	Specific heat capacity of air (kJ.kg^{-1}.K^{-1})
g	Gravitational constant (m.s^{-2})
H_e	Compartment height (m)
H_{st}	Storage height (m)
$\dot{Q}$	Rate of heat release (kW)
$\dot{Q}^*$	Non-dimensional rate of heat release (-)
SF	Shape factor (-)
T_a	Gas temperature, ambient (K)
ASET	Available safe egress time (s)
RSET	Required safe egress time (s)
ρ_a	Density air, ambient (kg.m^{-3})

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