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# A Sensitivity Analysis of Available Safe Egress Time Correlation

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The people fire risk assessment in industrial premises, buildings or confined spaces can be accomplished by comparing the time for the onset of life threatening conditions (Available Safe Egress Time, ASET) with the time that people take to move away from the threatening zone and to reach a safe zone (Required Safe Egress Time, RSET). For a given scenario, people are considered safe if ASET is greater than RSET.
The ASET is usually assessed by using either analytical equations or fire simulation models. Due to their simplicity and quick use, analytical equations could be suitable for preliminary and routine assessment of people fire risk. On the other hand, fire simulation models are time-requiring tools (both for the modelling and simulation phases) but can be used for deterministic and design analyses, where much details are often required.
This study aims at comparing the results obtained by using the analytical equation proposed by Karlsson and Quintiere with the data obtained by using CFD simulations of the same scenarios. Furthermore, a sensitivity analysis on the main input data of the analytical equation has been performed. A non-adiabatic compartment has been modelled with floor, ceiling and walls at constant temperature (T = 293 K).

## 1. Introduction

The Available Safe Egress Time (ASET) may be calculated by setting performance criteria, as the minimum free-smoke layer above the floor (LLH), the maximum upper layer temperature (ULT), the degree of visibility in a smoke-filled environment (OD), the effective dose of both toxic or irritant gases and heat (FED) (ISO 13571, 2001; ISO 16738, 2009). Quite clearly, the definition of the threshold limit for each criterion is fundamental. Table 1 reports typical choices of tenability limits.

*Table 1. Performance criteria and typical threshold limits for the analysis of ASET.*

| Performance | | Unit | Threshold limit | Source |
|---|---|---|---|---|
| LLH | Lower Layer Height | m | 2.0 | Coté, 2000 |
| ULT | Upper Layer Temperature | °C | 200 | ISO 16738, 2009 |
| OD | smoke Optical Density | $m^{-1}$ | 0.33 | Purser, 2002 |
| $FED_{toxic, heat}$ | Fractional Effective Dose | - | 0.3 | ISO 13571, 2007 |

Among the given performance criteria, the OD and FED require the details of the fire scenario, including the evaluation of the concentration of toxic species and heat in every point of an enclosure (we neglected the irritant FED). Hence, the use of fire simulation models is necessary.
On the other hand, the LLH and ULT criteria do not require such details and their adoption is usually referred to as the “zero exposure criteria”, i.e. the enclosure is assumed to be untenable for safe evacuation when either LLH drops or the upper layer temperature (ULT) grows to some specified value,

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defined in Table 1 as threshold limit. These two criteria allow a fast and easy definition of the ASET and are adopted in the two-layers fire models (Figure 1).

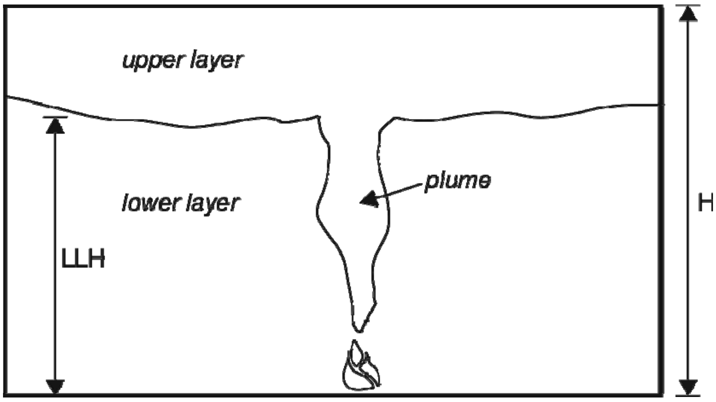


*Figure 1. Schematization of the two-layers model for a compartment fire.*

Aiming at evaluating the effect of LLH on the ASET for a sample case consisting of t-squared fires (Drysdale, 1999) in a room (4 m x 4 m x 2.4 m) with an open vent of 0.2 $m^2$ at the floor level, in a previous paper (Tosolini et al., 2012) we have applied the classical correlation for ASET reported by Karlsson and Quintiere (2000) (Eq. 1) and, at the same time, we have performed a CFD simulation using the Fire Dynamic Simulator (FDS) (McGrattan et al., 2010). FDS is a simulation model developed by NIST for studying fire dynamics in closed spaces. The model solves Navier-Stokes equations for low-speed, thermally-driven flow of smoke and heat from fires. Turbulence is modelled with either DNS or LES and the model is validated against numerous large scale experiments (see for example Matheislová, 2010).
The set of scenarios modelled in Tosolini et al. (2012) was developed by varying the main combustion parameters adopted by FDS to model a fire. The study aimed at analysing the effects of the variation of the combustion parameters on the ASET estimation as a function of the different performance criteria summarized in Table 1. The considered combustion parameters were the peak Heat Release Rate, the growth factor for conventional t-squared fires, the heat of combustion, and the fraction of fuel mass converted into carbon monoxide and into smoke particulate. Results showed that, referring to the scenarios studied, ASET can be quickly estimated by adopting the LLH as performance criterion, which requires less input data to be estimated and allows obtaining results comparable with the adoption of OD as performance criterion (which requires more input data). Hence, the correlation proposed by Karlsson and Quintiere (2000) can be used:

$$ASET = \left[ \frac{5}{2} \left( LLH^{-\frac{2}{3}} - H^{-\frac{2}{3}} \right) \left( 1 - \frac{\alpha_{HRR} \cdot ASET^3}{3(H - LLH) A_f \cdot c_p \cdot 353} \right) \frac{A_f \cdot (\alpha_{HRR})^{-\frac{1}{3}} \cdot \rho_a}{0.21 \left( \frac{\rho_a^2 g}{c_p T_a} \right)^{\frac{1}{3}}} \right]^{\frac{3}{5}} \quad (1)$$

where H is the enclosure height (m), $A_f$ is the enclosure floor area ($m^2$), $\rho_g$ is the upper layer density (kg $m^{-3}$), $\rho_a$ is the density of air at the temperature of air $T_a$ (assumed constant at 293 K), $c_p$ is the specific heat (1.0 kJ $kg^{-1}$ $K^{-1}$) of air, g is the gravitational constant and $\alpha_{HRR}$ is the growth rate factor for $t^2$ fires (kW $s^{-2}$) as reported in ISO 13387-2 (1999):

$$HRR(t) = \alpha_{HRR} \cdot t^2 \quad (2)$$

where HRR is the Heat of Release Rate of the fire (kW) and t is the time (s). Here it is worth mentioning that the conservativity of Eq. 1) in estimating the ASET has been verified up to 4800 $m^3$. For larger values, the threshold limit for the upper layer temperature (473 K) is reached before the lower layer height equals the established threshold limit (2 m). Therefore, there is a prevalence of the thermal hazards and these results are confirmed also in Delichatsios (2004). In order to estimate the ASET in larger volumes is then necessary to adopt both LLH and ULT performance criteria.

Quite clearly, Eq 1) may be only solved iteratively, i.e. by adopting the threshold limit for LLH (Table 1). Table 2 reports the obtained results with respect to $\alpha_{HRR}$ for the scenario adopted in (Tosolini et al., 2012). In the table, it can be seen that Eq. 1) estimates the ASET with a “safety coefficient” (referring to FDS results) that ranges from 1.2 (for ultrafast t-squared fires) to 2 (for slow t-squared fires), but however trends are respected. The simplified methodology, therefore, can be considered valid as a quick and pre-screening approach for calculating the ASET for volumes up to 4800 $m^3$, at least referring to the LLH criterion.

*Table 2. The ASET values obtained by analytical ASET formulation and FDS simulation.*

| | Scenario | $\alpha_{HRR}$ | ASET (s) for LLH | |
|---|---|---|---|---|
| | | | FDS | Eq. (1) |
| 1 | Slow t-squared fire (slow) | 0.003 | 65 ± 5 | 31 |
| 2 | Medium t-squared fire (medium) | 0.012 | 43 ± 1 | 24 |
| 3 | Fast t-squared fire (fast) | 0.047 | 24 ± 2 | 18 |
| 4 | Ultrafast t-squared fire (ultra-fast) | 0.190 | 18 ± 2 | 13 |

In this work, for the four conventional t-squared fire scenarios of Table 2, we have further extended the analysis by comparing the results of the ASET equation and FDS by varying the enclosure floor surface $A_f$ between 25 $m^2$ and 400 $m^2$, with constant height (H = 3 m) and by varying the enclosure height from 3 m to 12 m, with constant $A_f$ ($A_f$ = 25 $m^2$), given the threshold limit for LLH = 2 m. The non-adiabatic compartment has been modelled with floor, ceiling and walls at constant temperature (T = 293 K).

## 2. Results and Discussion

Figures 2 – 3 report the results obtained respectively by using Eq. 1) and FDS. The data show clearly that the effect of $A_f$ and H over the calculated ASET is approximately linear for $A_f$ greater than 100 $m^2$ and for H grater then 5 m either in Eq.1) and for FDS, for any $\alpha_{HRR}$. When the analytical expression is adopted, variation with $A_f$ is larger for Eq.1). On the contrary, the calculated value of ASET as a function of the variation of H is lower than the simulated value.

In order to evaluate the ability of the simplified correlation to obtain ASET estimations comparable with FDS results, we have defined a safety factor *SF* given by the following correlation:

$$SF = \frac{ASET_{FDS}}{ASET_{Eq.(1)}} \qquad (3)$$

Figure 4 reports the trend of *SF* as a function of the ratio of enclosure height H over the square root of surface $A_f$. Quite clearly, Eq. 1) gives conservative results in terms of available safe egress time for $H/A_f^{0.5}$ greater than 0.6, for any value of $\alpha_{HRR}$, wheres for ratios lower than 0.6 conservative results can be obtained by multiplying Eq. 1) by the *SF* related to the ratio adopted.

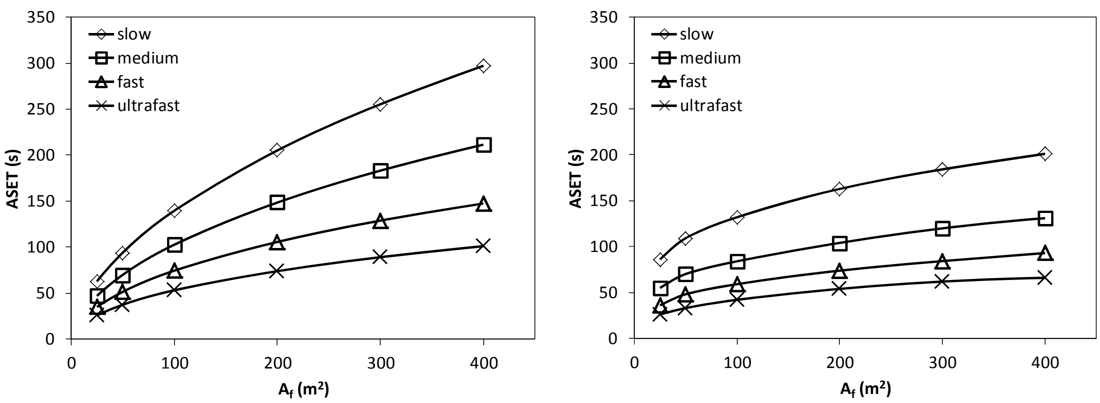


*Figure 2. ASET values obtained by using Eq.1) (left) and FDS (right) by varying the enclosure surface $A_f$.*

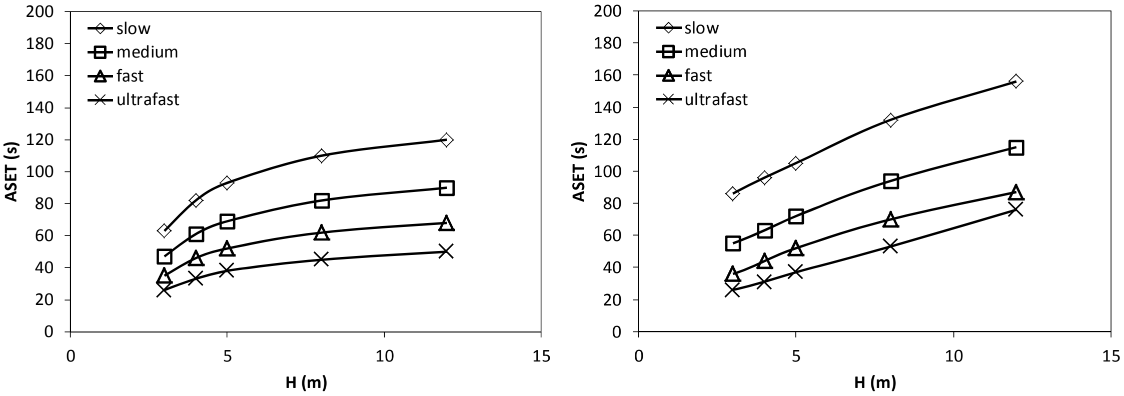


*Figure 3. ASET values obtained by using Eq.1) (left) and FDS (right) by varying the enclosure height H.*

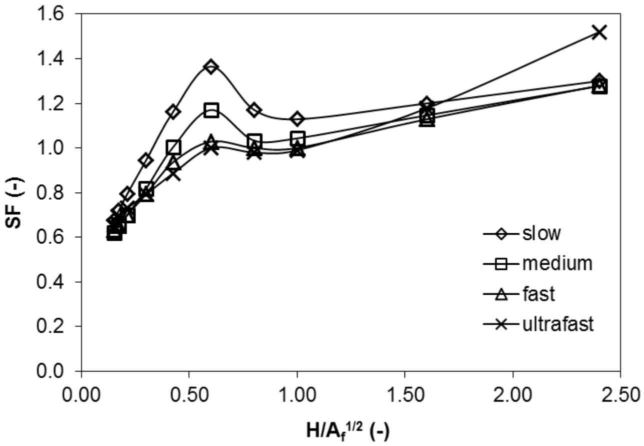


*Figure 4. Trend of safety factor SF as function of $H/A_f^{0.5}$.*

## 3. Sensitivity analysis

Given a generic physical system which may vary with time t as:

$$\frac{dy}{dx} = f(y, \Phi, t) \qquad y(0) = y^i \tag{4}$$

where *y* is the independent variable and *m* is the vector of input parameters, it can be demonstrated that (Morbidelli and Varma, 1999):

$$s(y;\phi_j) = \frac{\partial y(t,\phi_j)}{\partial \phi_j} = \lim_{\Delta\phi_j \to 0} \frac{y(t,\phi_j + \Delta\phi_j) - y(t,\phi_j)}{\Delta\phi_j} \tag{5}$$

where *s* is defined as the local sensitivity of y with respect to □$_j$, which may be normalized through the correlation:

$$S(y;\phi_j) = \frac{\phi_j}{y} \cdot \frac{\partial y}{\partial \phi_j} \tag{6}$$

For the Eq. (1), □ = ($\alpha_{HRR}$, $A_f$, $H$) and we can write:

$$S(ASET;\phi_j) = \frac{\phi_j}{ASET} \cdot \frac{d\,ASET}{d\phi_j} \qquad \phi = (\alpha_{HRR}, A_f, H) \tag{7}$$

Figures 5 and 6 report the *S* value with respect to $A_f$ and H parametrically with $\alpha_{HRR}$.

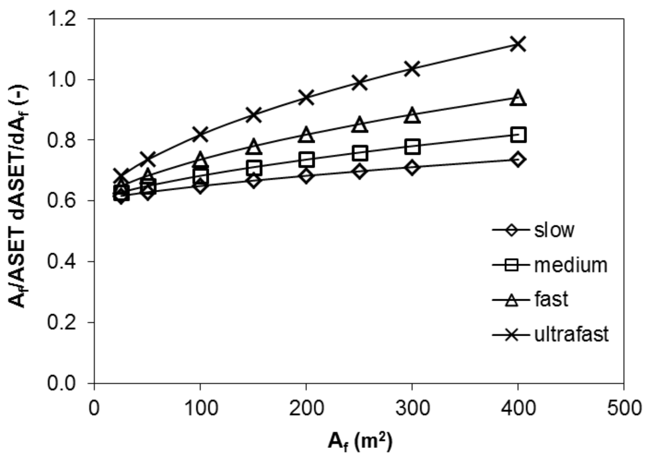


*Figure 5. Sensitivity analysis of ASET with respect to $A_f$.*

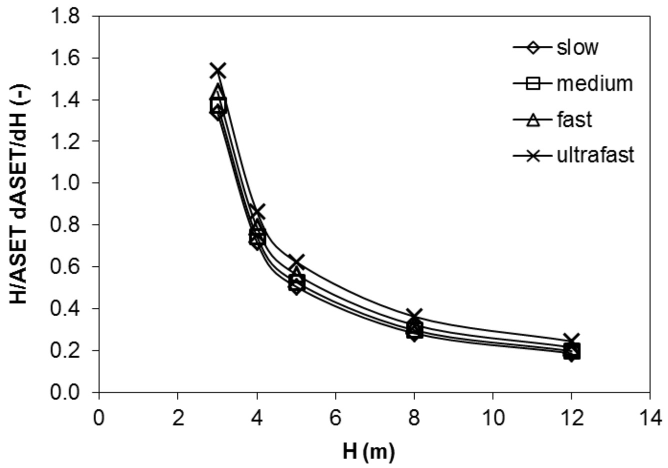


*Figure 6. Sensitivity analysis of ASET with respect to H.*

Figure 5 shows that S(ASET) increases consistently with the surface area of the room for fast and ultra-fast fires only. Therefore, small variations of the surface area affect the ASET more for higher $A_f$ and for fast and ultrafast fires. On the other hand, Figure 6 shows that the S(ASET) decreases strongly with H whatever the fire velocity. That means the small variation of H implies large variation of ASET for room with heights less than 8 m, and that details on this parameter are essential for safety purposes. However, as emerges from the analysis of Figures 5 and 6, the ASET variation is small (maximum 1.6 %), hence the analytical correlation is robust with respect to $\alpha_{HRR}$, surface area and height of the room.

## 4. Conclusions

In this work we have extended the analysis performed in a previous work of the analytical correlation proposed by Karlsson and Quintiere usable for estimating the ASET in an enclosure as a function of the lower layer height (LLH). Trends as a function of the variation of the growth factor for conventional t-squared fires, of the enclosure floor area, and of the enclosure height have been analysed and compared with the results obtained by simulations performed with FDS model. Furthermore, a sensitivity analysis of the analytical correlation has been performed.

Results show that the trends obtained with the analytical correlation are comparable with the FDS simulations and that a conservative ASET estimation, referring to the LLH as performance criterion, can be obtained for enclosure volumes up to 4800 $m^3$ and with enclosure height over area root square ratios ($H/A_f^{1/2}$) greater than 0.6 for any value of $\alpha_{HRR}$. For $H/A_f^{1/2}$ values less than 0.6 a conservative assessment can be obtained by adopting a safety factor equal to 0.6. From the sensitivity analysis, it has been verified that the correlation is robust with respect to the input data that it requires.

The results presented may be used to establish the application range of the analytical correlation, which can be adopted as a decision support tool for a preliminary and routine assessment of people risk in case of compartment fires.

## Acknowledgments

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