CHEMICAL ENGINEERING TRANSACTIONS

VOL. 26, 2012

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Guest Editors: Valerio Cozzani, Eddy De Rademaeker

ISBN 978-88-95608-17-4; **ISSN** 1974-9791

DOI: 10.3303/CET1226084

People Evacuation: Simplified Evaluation of Available Safe Egress Time (ASET) in Enclosures

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The evaluation of the Available Safe Egress Time (ASET) is essential for organizing people evacuation in case of fire in industrial premises, buildings or generic enclosures. This task is usually achieved by considering several performance criteria and then calculating the time for reaching established threshold limits for each of those criteria.
In the paper a sensitivity study for the ASET performance criteria is presented. To this aim the Fire Dynamic Simulator (FDS) has been adopted. A comparison between FDS results and an analytical approach for a quick estimation of the ASET in an enclosure is showed. The methodology may be usable as a decision support tool for emergency evacuation design and management.

1. Introduction

The rapid evacuation of people from a threatening area before the onset of fire-induced untenable conditions is a necessary requirement for people safety. The maximum time available to people to move away from the threatening area is defined as Available Safe Egress Time (ASET) and this time is usually used to evaluate the egress system performance. An egress system is correctly designed if people can evacuate before the ASET is reached. Several performance criteria can be adopted to evaluate the ASET (ISO 13571, 2007; Coté, 2000; ISO 16738, 2009), as shown in Table 1.

Table 1: Performance criteria for assessing the Available Safe Egress Time (ASET).

Group	Performance criterion	Symbol	Significance
A	Lower Layer Height	LLH	Minimum smoke-free layer above the floor
A	Upper Layer Temperature	ULT	Maximum tenability temperature of the upper layer of smoke
B	smoke Optical Density	OD	Degree of visibility in a smoke-filled environment
B	maximum Fractional Effective Concentration of irritant gases	$FEC_{irritant}$	Threshold limit for the concentration of irritant gases
B	maximum Fractional Effective Dose of toxic gases	FED_{toxic}	Threshold limit for the dose of asphyxiant gases
B	maximum Fractional Effective Dose of heat	FED_{heat}	Threshold limit for the dose of heat

Please cite this article as: Tosolini E., Grimaz S., Pecile L.C. and Salzano E., 2012, People evacuation: simplified evaluation of available safe egress time aset in enclosures, Chemical Engineering Transactions, 26, 501-506 DOI: 10.3303/CET1226084

In this work such criteria have been divided in two groups. Those of Group A are approximate criteria, because of they do not characterize the smoke composition and are usually used by adopting the so-called “zero exposure criteria”, i.e. the fire origin enclosure is assumed to be untenable for safe evacuation at such time that either the lower layer height (LLH) drops to some established level or the upper layer temperature (ULT) grows to some specified value (Cooper, 1983; Coté, 2000). Group B criteria are used when it is possible to characterize in detail the combustible characteristics, the combustion conditions, the products of combustions, their distribution in the enclosure, etc. Quite clearly, the use of these criteria needs the evaluation of the concentration of both toxic species and heat in every point of an enclosure. Hence, the use of fire simulation models is necessary for calculating Group B criteria. It is noteworthy that to adopt at least all the performance criteria of each Group in order to calculate the ASET is fundamental.
Some issues that arise when adopting different performance criteria (that is Group A or Group B criteria) concern the differences that can emerge when using two or more performance criteria at the same time, or the type of input data that cannot be neglected to calculate the ASET with an established performance criterion. In order to examine these aspects it could be suitable to carry out a sensitivity analysis among the different performance criteria.
For the aims of this analysis, the definition of the threshold limits for each criterion is fundamental. Table 2 reports the tenability limits adopted in this work. $FEC_{irritant}$ has not been used due to the lack of available data for its calculation. At the value adopted for OD a visibility distance in a smoke-filled environment of about 3 m is associated: with this visibility distance people usually turn back when negotiating an escape route (Purser, 1996; SFPE, 2003). The values of the FEDs concern the presence of susceptible population within the occupants (ISO 13571, 2007; Gann et al., 2001). All the Group B criteria were measured at the height of 1.8 m.

Table 2: Threshold limits adopted in this work for the sensitivity analysis of performance criteria.

Group	Performance criteria	Threshold limit	Source
A	LLH (m)	2.0	(Coté, 2000)
A	ULT (°C)	200	(ISO 16738, 2009)
B	OD (m^{-1})	0.33	(Purser, 2002)
B	FED_{toxic}	0.3	(ISO 13571, 2007)
B	FED_{heat}	0.3	(ISO 13571, 2007)

Referring to these threshold limits, the sensitivity analysis of the performance criteria in a specific test case was carried out with the Fire Dynamic Simulator (FDS) model (McGrattan et al., 2010). Results for the particular case are reported in the next section. Quite clearly, the general conclusion may be given only after several sample tests cases are performed.

2. Sensitivity analysis of ASET performance criteria

A preliminary sensitivity study of FDS for mesh refinement, thermal boundary conditions, and other combustion parameters was performed considering a sample case consisting of a shredded polyurethane pillow burning in a closed room. The room is 4 m x 4 m x 2.4 m with an open vent of 0.2 m^2 at the floor level. This study is not reported herein for sake of brevity.
Adopting the same geometry, the sensitivity analysis of the performance criteria were performed testing the variation of each criterion reported in Table 1 (with the exception of $FEC_{irritant}$).
The variables used in FDS to characterize the fire, and specifically the gas phase combustion reaction (herein the pyrolysis model is not examined), are the input data considered in this study. In particular the influence on the performance criteria of the peak Heat Release Rate (HRR) value, of the growth factor for conventional t-squared fires (α coefficient, see Drysdale, 1999), of the heat of combustion, of the fraction of fuel mass converted into carbon monoxide (y_{CO}) and into smoke particulate (y_s) were examined.

The input data were varied by adopting a scale with respect to a maximum value (val_{max}): a) val_{max}; b) 0.5•val_{max}; c) 0.25•val_{max}; d) 0.125•val_{max}; as reported in Table 3.

Table 3: Input data and corresponding val_{max} used in the sensitivity analysis of the performance criteria.

Input data	val_{max}	Comments
HRR_{peak} (kW)	650	val_{max} is the HRR of flashover calculated with Thomas' flashover correlation (Peacock et al. 1999)
Time to HRR peak - t_{HRR} (s)	450	val_{max} is the time to flashover for slow t-squared fires
Heat of combustion - H_c (kJ/kg)	50100	(Tewarson, 2002)
CO yield (y_{CO})	0.450	(Tewarson, 2002)
Soot yield (y_s)	0.300	(Tewarson, 2002; Gann et al., 2001)

Table 4 reports the performance criteria variation (in terms of percentage) with the changes to the considered input data. It can be easily seen that the less sensitive performance criteria is LLH, which changes only when the growth factor of the fire changes. The results of the simulations also showed that the ASET in the fire origin enclosure is essentially determined by LLH for Group A and by OD for Group B performance criteria (Figure 1). Hence, a quick estimation of the ASET could be based on LLH and/or OD calculation. Because of the OD variation is related to the changes of several input data (t_{HRR}, H_c and y_s), when calculating the ASET adopting OD it is necessary to characterize the fire with more input data than adopting the LLH parameter (refer to Table 4). Thus, for quick estimation purposes, and especially when the input data are limited, it seems reasonable to adopt LLH (thus referring to the zero exposure criteria). Figure 1 shows that the ASET calculations with LLH are comparable with those obtained with OD.

Table 4: Performance criteria variation with the changes to the input data.

Input data	Variation from val_{max} (%)	Variation of the performance criteria (%) LLH	ULT	OD	FED_{toxic}	FED_{heat}
HRR_{peak}	0	0	0	0	0	0
	50	0	2	0	15	9
	25	0	> 100[a]	0	> 100[a]	72
	12.5	0	> 100[a]	0	> 100[a]	> 100[a]
t_{HRR}	0 (slow)	0	0	0	0	0
	50 (medium)	38	46	34	31	37
	25 (fast)	65	70	63	54	69
	12.5 (ultrafast)	74	81	69	65	75
H_c	0	0	0	0	0	0
	50	0	0	29	30	5
	25	0	0	29	26	4
	12.5	0	0	43	40	5
y_{CO}	0	0	0	0	0	0
	50	0	0	0	21	0
	25	0	0	0	> 100[a]	0
	12.5	0	0	0	> 100[a]	0
y_s	0	0	0	0	0	0
	50	0	2	29	0	0
	25	0	2	64	0	2
	12.5	0	4	129	0	2

[a] Data are not specified because of ASET is not reached before flashover.

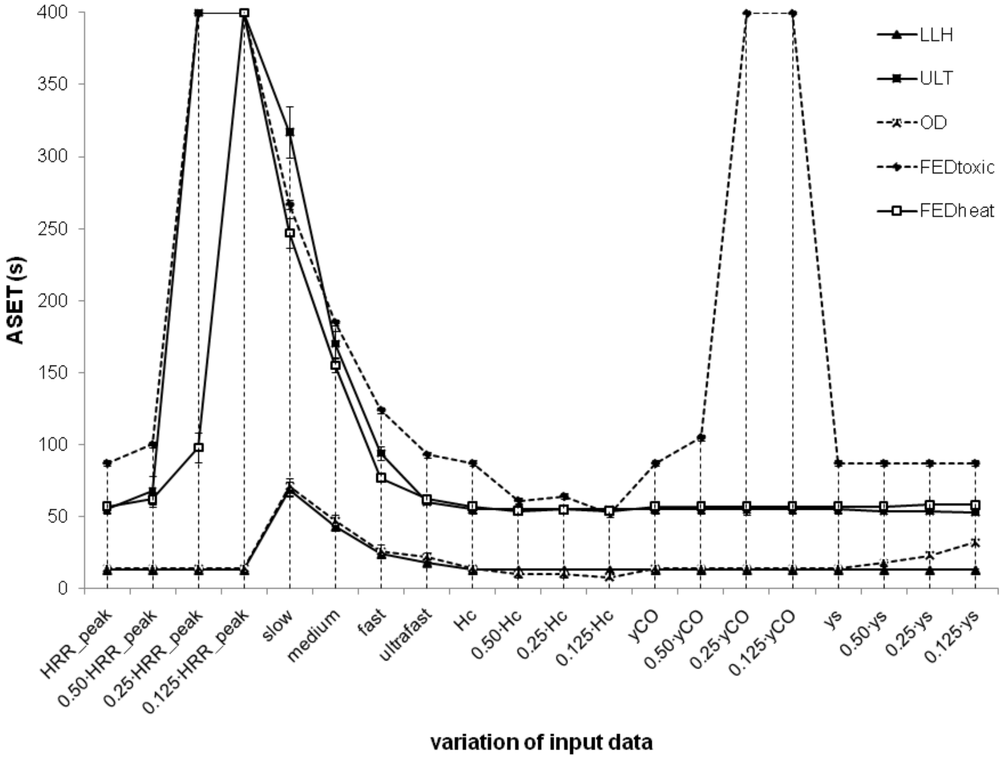

Figure 1: ASET (mean values and standard deviation) obtained for the five performance criteria in the different scenarios studied.

3. Development of a quick methodology for ASET estimation

From the outcomes of the sensitivity analysis of the performance criteria usable to calculate the ASET, it emerged that for preliminary estimations of ASET in the fire origin enclosure the LLH performance criterion can be adopted. The use of LLH gives advantage in terms of the limited input data required for estimating the ASET (i.e. only the growth rate of the fire). In this work a simple methodology for estimating the ASET in a fire-origin enclosure considering the LLH is proposed. The methodology was developed applying the conservation of mass and the conservation of energy equations in an enclosure with openings or leakage areas from the compartment to the surroundings that prevent build-up of pressure due to the volumetric gas expansion (Karlsson and Quintiere, 2000 for details). Some assumptions are made:

- The formation of an upper layer with hot smoke and of a lower smoke-free layer in the enclosure is supposed (zone model approach);
- The upper layer density is constant during the smoke-filling process;
- Heat exchange through the boundaries is negligible;
- The heat release rate of the fire is low with respect to the enclosure volume.

These conditions apply to rooms with closed doors and for the initial stages of a fire (pre-flashover fires). It is worth noticing that when dealing with the evacuation process from a fire origin enclosure, people is supposed to evacuate during the initial stages of a fire. Hence in this scenario generally pre-flashover fires are considered (Cooper, 1983; Karlsson and Quintiere, 2000; Krasny et al., 2001).
The balances of mass and energy conservation for t-squared fires in enclosures lead to the following equations:

$$ASET = \left[\frac{5}{2} \left(LLH^{-\frac{2}{3}} - H^{-\frac{2}{3}} \right) \frac{S}{k} \alpha^{-\frac{1}{3}} \right]^{\frac{5}{3}} \quad (1)$$

$$k = \frac{0.21}{\rho_g} \left(\frac{\rho_a^2 g}{c_p T_a} \right)^{\frac{1}{3}} \quad (2)$$

$$\rho_g = \rho_a \left[1 - \frac{\alpha \cdot ASET^3}{3(H - LLH) S \cdot c_p \cdot 353} \right] \quad (3)$$

where H is the enclosure height (m), S is the enclosure area (m^2), α is the growth rate factor for t-squared fires (kW s^{-2}), ρ_g is the upper layer density (kg m^{-3}), ρ_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, and g is the gravitational constant.
Quite clearly, the set of equations may be only solved by an iterative procedure. Hence, if a threshold limit for LLH is considered, as reported in Table 2, Eq.(1) can be adopted for the ASET estimation.
In order to check the accuracy of the set of Eqs. (1), (2) and (3), the results obtained by their application was compared with the outcomes of FDS simulations for the same geometrical configuration used for the sensitivity analysis of the performance criteria. The input data for the equations, along with the results and comparison of both methodologies, are reported in Table 5.

Table 5: Data used for estimating the ASET with Eqs. (1), (2) and (3) and results obtained.

Scenario	α	ρ_a (kg m^{-3})	ρ_g (kg m^{-3}) (from Eq. 3)	ASET (s) for LLH FDS	Eq. (1)
Slow t-squared fire	0.003	1.20	1.18	65 ± 5	31
Medium t-squared fire	0.012	1.20	1.17	43 ± 1	24
Fast t-squared fire	0.047	1.20	1.15	24 ± 2	18
Ultrafast t-squared fire	0.190	1.20	1.12	18 ± 2	13

From Table 5, it can be seen that Eqs. 1-3) estimate 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). However, trends are respected. The simplified methodology, therefore, can be considered valid as a quick and pre-screening approach for calculating the ASET, at least referring to the LLH criterion. Clearly the results concerning the validity of the Eqs. (1), (2) and (3) are related to this simple case study.
Further investigations with different geometries are necessary to enlarge the area of application (in terms of enclosure surface, height and width-length aspect ratio) of such equations. Furthermore, all the comparison was performed only against FDS outcomes, and not referring to large-scale experiments – see (Matheislová, 2010) for comparison between FDS simulations and large-scale experiments).

4. Conclusions

In this work a sensitivity analysis of the performance criteria for the available safe egress time (ASET) estimation in a fire origin enclosure was carried out. The considered performance criteria are the lower layer height (LLH), the upper layer temperature (ULT), the smoke optical density (OD), the fractional effective dose of toxic gases (FED_{toxic}), and the fractional effective dose of heat (FED_{heat}). Specifically, the sensitivity analysis was focused on examining the differences in reaching established ASET threshold limits for the different performance criteria. Moreover, the influence of the changes of the input data on the ASET estimations for each performance criterion was checked. The sensitivity analysis was performed using the Fire Dynamics Simulator (FDS) model. A preliminary sensitivity study of FDS for mesh refinement, thermal boundary conditions, and other combustion parameters was carried out in a simple geometry. No sensitivity study has been performed using data collected from large-scale experiments. The results obtained show that, using FDS, LLH is the less sensitive parameter, i.e. its estimation depends on less input data than the other performance criteria. Furthermore, it emerged that the ASET in a fire origin room is determined by LLH and/or OD, with slight differences between those performance criteria. Considering these results, a quick methodology for the ASET estimation referring to the LLH performance criterion is proposed. The accuracy of this methodology in estimating the ASET was checked in a single room comparing the outcomes obtained by using it with those from FDS simulations. The results demonstrated that using simple algebraic equations the ASET in a fire origin room can be quickly estimated and with a safe margin ranging from 1.2 to 2.0. Thanks to its quick use, this methodology may be useful for pre-design and management aid. It is worth noticing that all the results obtained refer to the room geometry that has been considered herein, and general conclusions may be given only after other test cases are performed. In order to enlarge the application area of the methodology, ongoing studies are carried out considering different room geometries (in terms of room surface, height and width-length aspect ratios).

Acknowledgments

This study was supported by the Workers Compensation Italian Authority (INAIL) which funded the ongoing PhD project on “Emergency Evacuation and Safety in Complex Environments”.

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